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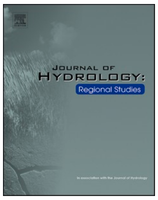

Groundwater storage depletion and contamination trade-offs under contrasting irrigation practices in drought-stressed Morocco

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ABSTRACT

Study region: The Haouz Plain, Tensift basin, central Morocco.
Study focus: The Haouz region has undergone a clear trend toward aridification over the last four decades, with a severe drought from 2019 through 2025. This study investigates how contrasting irrigation practices influence groundwater quality and quantity using a multi-indicator approach combining tryptophan-like fluorescence (TLF), nitrate, microbial indicators (E. coli, S. enterica), stable isotopes ($\delta^{18}O$, $\delta^{2}H$), and tritium (^{3}H). Traditional surface-water irrigation areas exhibit elevated TLF (up to 11.3 QSU), nitrate (>15 mg/L), and microbial contamination, indicating influence from wastewater and surface-derived inputs. Shallow water tables (<40 m) and high tritium (>3 TU) confirm recent recharge pathways facilitating contaminant migration. In contrast, modern drip-irrigated areas relying on intensive groundwater abstraction show limited contamination (TLF ≤0.9 QSU; nitrate mostly <20 mg/L; the absence of fecal coliforms), longer mean residence times (>60 years), extraction of older groundwater, and groundwater storage depletion.
New hydrologic insights for the region: Results reveal a trade-off in dryland agricultural systems: traditional irrigation sustains recharge but increases vulnerability to contaminant transport, whereas modern irrigation limits contaminant propagation yet accelerates depletion of stored groundwater reserves. Wastewater infiltration may occur independently of irrigation practices, but abstraction intensity largely governs aquifer storage declines. Under intensifying drought conditions, sustainable groundwater management in the Haouz Plain requires integrated strategies combining optimized irrigation, controlled abstraction, and strengthened wastewater treatment and reuse.

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1. Introduction

Groundwater is a critical resource for drinking water and irrigation in dryland regions, where surface water is often insufficient to meet demands (Llamas and Martínez-Santos, 2005). Increasing drought severity in these areas, driven by climate variability and climate change, has accelerated groundwater depletion and placed additional stress on aquifers (Bierkens and Wada, 2019). At the same time, in low- and middle-income countries, farmers have relied on untreated or poorly treated wastewater to compensate for surface water shortages, raising concerns about water quality and public health (Murtaza et al., 2010; Singh, 2021).

When sewerage infrastructure and treatment facilities are absent or inefficient, and wastewater is used for irrigation, these untreated effluents can infiltrate into aquifers. Pathogens and contaminants of emerging concern can migrate into aquifers, with shallow unconfined systems being particularly vulnerable (Sorensen et al., 2016; Thaw et al., 2022). However, excessive pumping of deeper aquifers may also draw contaminated shallow water into deep groundwater, thereby increasing the risks of longer-term pollution accumulation (Jasechko et al., 2017; Thaw et al., 2022).

In many hydrogeological settings, including the present study area, groundwater quality monitoring remains limited by the scarcity of spatially and temporally resolved data. This limitation is partly due to the reliance on traditional microbial indicators such as thermotolerant coliforms, which are time-consuming, require laboratory infrastructure, and are difficult to deploy at high monitoring frequency (Savichtcheva and Okabe, 2006; Sorensen et al., 2015). In this context, *in situ* tryptophan-like fluorescence (TLF) has emerged as a rapid, reagent-free proxy for wastewater contamination that can be deployed directly in the field, offering improved temporal and spatial coverage (Khamis et al., 2015; Nowicki et al., 2019; Sorensen et al., 2021). Its performance relative to fecal coliforms has been demonstrated across a range of hydrogeological contexts with numerous studies confirming its applicability for real-time contamination assessment (Sorensen et al., 2016; Frank et al., 2018; Sorensen et al., 2018a, 2018b; Bedell et al., 2022; Mladenov et al., 2024). When combined with environmental tracers such as stable isotopes and tritium, TLF provides new opportunities to link contamination signals to recharge dynamics and land use practices.

The Haouz Plain in central Morocco is a major agricultural region dependent on groundwater, which has been heavily exploited for irrigation in recent decades. Traditional irrigation systems, sustained for centuries, divert mountain runoff through unlined canals that enhance aquifer recharge but also create pathways for contaminant transfer (Bouimouass et al., 2020, 2022). In addition, the Haouz plain lacks adequate sewerage infrastructure in most urban and all rural agglomerations. Currently, more than 10 Mm^3 of raw wastewater from small urban towns is released into the environment without treatment, often into nearby ephemeral streambeds (AGIRE, 2016), including into these traditional irrigation canals. In contrast, modern irrigation practices based on intensive pumping have led to widespread groundwater declines (Fakir et al., 2026). The prolonged drought in Morocco from 2019 to 2025 may have increased reliance on untreated wastewater for irrigation.

Despite growing concerns, no previous studies have investigated groundwater fecal contamination risk in the largest alluvial aquifer in Morocco. The objective of this study is therefore to evaluate the current state of groundwater regarding fecal contamination

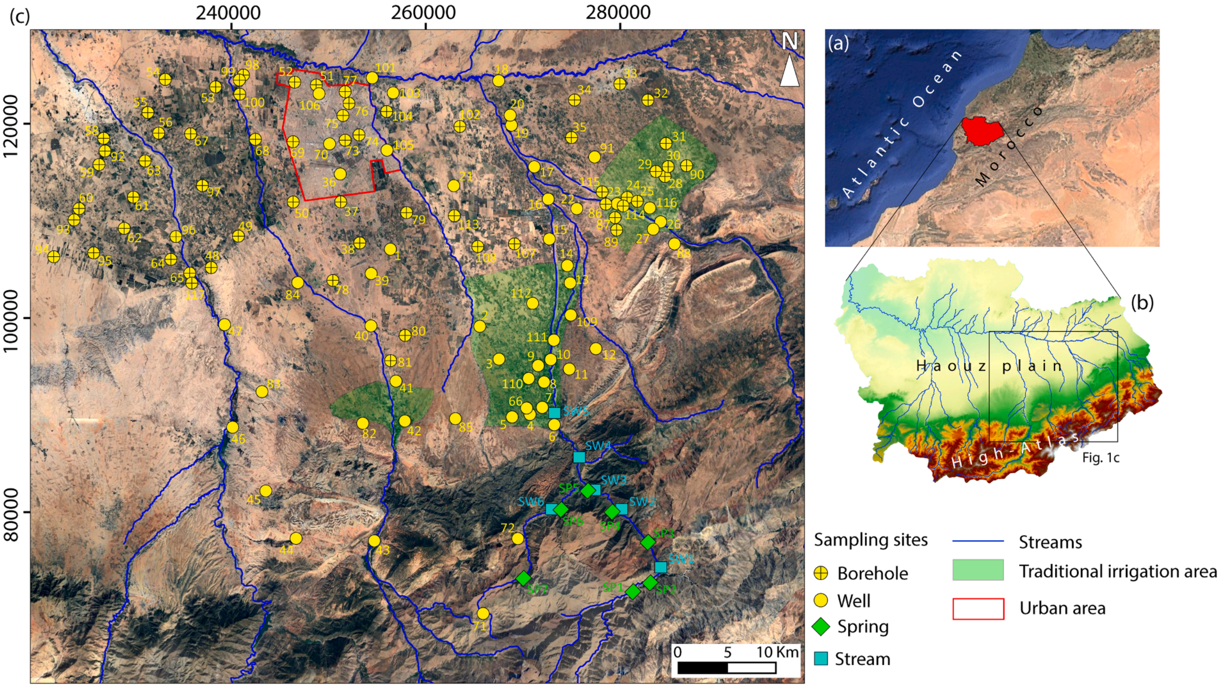

Fig. 1. (a) Location of the Tensift basin in Morocco, (b) position of the study area within the basin, (c) spatial distribution of groundwater sampling sites.

in the Haouz aquifer under different land use settings. By comparing mountainous valleys, traditional irrigation zones, modern irrigation perimeters, and urban areas, and by integrating fluorescence, microbial, chemical, and isotopic indicators, this work provides new insights into the combined effect of human pressure, climate change, and hydrogeological conditions on groundwater quality in the Haouz aquifer.

2. Study area

The study area encompasses the central Haouz Plain (approximately 4600 km^2) and the adjacent High Atlas Mountains within the Tensift Basin, Morocco (Fig. 1). The area includes both rural and urban communities, with a population of more than 2 million inhabitants in 2014, of which 43% live in Marrakech city and 57% in rural villages ("douars") and small towns (AGIRE, 2016). The Haouz Plain has an arid Mediterranean climate, with average annual precipitation of about 200 mm, contrasted with potential evapotranspiration exceeding 1600 mm (Er-Raki et al., 2010). In the High-Atlas Mountains, precipitation reaches 500 mm/year, largely as snow, creating a "water tower" that supplies the plain through ephemeral streams discharging into the Tensift River (Jarlan et al., 2015; Hanich et al., 2022). Since 2019, the region has been under severe drought, with marked decreases in rainfall and streamflow.

The Haouz alluvial aquifer is the largest in Morocco, extending over ~6000 km^2 (Sinan and Razack, 2009). It is composed of Neogene and Quaternary deposits derived from Atlas erosion, ranging from coarse gravels to clays and marls (Razack and Huntley, 1991). Recharge is mainly indirect, via infiltration of irrigation return flows and stream losses in ephemeral channels (Bouimouass et al., 2020; Fakir et al., 2021). More recently, subsurface inflows from the High-Atlas have been recognized as an important contribution (Bouimouass et al., 2024). Mountain-front recharge zones, where surface water is diverted into unlined canals (locally called Seguias), remain the most important recharge areas (Bouimouass et al., 2022; Hajhouji et al., 2022).

Agriculture dominates land use, with wheat and olives as the main crops, alongside expanding orchards supported by state-funded irrigation programs (Ouassanouan et al., 2022). Traditional irrigation systems date back to the 12th century and include seguias and

Fig. 2. Examples of wastewater management and reuse in the study area. Panels (a), (b), and (d) show direct discharging of untreated wastewater into traditional irrigation canals. These practices illustrate the potential for untreated effluents to enter recharge pathways and contaminate groundwater.

qanats (“locally called Khettaras”) (Héritier-Salama, 2019). While seguias remain locally important, Khettaras have largely fallen into disuse due to groundwater decline (El Faiz and Ruf, 2010). Over the last decades, irrigation shifted from surface water diversion to intensive groundwater pumping. Groundwater now supplies over 80% of total water demand in the Tensift basin (Kuper et al., 2016).

The Haouz aquifer has lost nearly half of its saturated thickness since the 1970s due to unsustainable pumping (Fakir et al., 2026). Climate change has exacerbated water scarcity: precipitation decreased by 28% and streamflow by 40% between 1965 and 2018 (Ouassanouan et al., 2022). At the same time, rural sanitation is poorly developed as 68% of wastewater is discharged into unsealed pit latrines, 29% directly released into the environment, and only 3% is treated (AGIRE, 2016). These pits are not emptied; instead, when they reach capacity, a new pit is excavated. In the High-Atlas, touristic hotspots such as the Ourika Valley, further increase wastewater loads during peak seasons (Kusi et al., 2020). Emerging practices such as discharging untreated wastewater into irrigation canals have been observed in some mountain-front areas (Fig. 2). Using this water for irrigation constitutes a serious health risk in the area. Overall, the Haouz Plain illustrates a dual challenge: (i) groundwater depletion in modern groundwater irrigation areas, and (ii) wastewater contamination risks in traditional irrigation areas where recharge is high but poorly protected.

3. Materials and methods

Drought conditions in the Haouz region were assessed using monthly reanalysis data from the Copernicus Climate Change Service (C3S) ERA5-Land dataset. ERA5-Land is a high-resolution (0.1° × 0.1°) global land surface reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) within the Copernicus Climate Change Service. It provides continuous meteorological and hydrological variables describing land surface processes and the evolution of the water and energy cycles from 1950 to the present, with updates available with a delay of about 2–3 months (Bodjrènou et al., 2025; Bordoni et al., 2023; Muñoz-Sabater et al., 2021). In the present study, the total precipitation and potential evaporation were retrieved for the period January 1980–December 2025 within the study area. Precipitation and potential evaporation were converted from meters to millimeters and spatially averaged over the study area. The Standardized Precipitation–Evapotranspiration Index (SPEI) was subsequently computed at 3-month (SPEI-3) and 6-month (SPEI-6) accumulation periods using the *spei* Python library.

The Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975) is a widely used non-parametric method for detecting monotonic trends in time series, particularly in hydro-meteorological studies (Afamondji et al., 2026; Ouassanouan et al., 2022). In this study, the MK test was applied together with Sen’s slope estimator (Sen, 1968) to evaluate long-term trends in SPEI-3 and SPEI-6. While the MK test assesses the statistical significance of trends, Sen’s slope provides an estimate of their magnitude, allowing a robust characterization of temporal changes in drought conditions.

3.1. GRACE data

GRACE (Gravity Recovery and Climate Experiment) and its successor GRACE-FO are satellite gravimetry missions that monitor temporal variations in Earth’s gravity field to quantify large-scale mass redistribution, including terrestrial water storage (TWS) dynamics (Vishwakarma et al., 2021). These measurements are expressed as Total Water Storage Change (TWSC), integrating groundwater, soil moisture, surface water, atmospheric moisture, and cryospheric components (Vishwakarma et al., 2021). In this study, the JPL mascon GRACE dataset (100 km resolution) for the period 2002–2025 was used to assess TWS variations during the last two decades in the study area.

3.2. Groundwater level monitoring

Groundwater depths were measured in 99 wells across the study area (13–110 m depth range), providing a synoptic view of aquifer conditions during the sampling campaigns (Fig. 1d; Table S1). Flow directions were derived from water table gradients, indicating a general north-northwestward flow from the mountain-front to the plain.

3.3. In-Situ measurements

At 134 sites (117 wells, 7 springs, 6 stream sites), temperature, pH, electrical conductivity (EC), tryptophan-like fluorescence (TLF), and colored dissolved organic matter (CDOM) were measured in situ during two field campaigns (July-August and November 2022). TLF and CDOM were quantified using portable UviLux fluorometers. The TLF and CDOM peaks were measured at excitation/emission peaks of 280/360 and 280/450 nm, respectively. Field repeatability using these instruments was previously estimated as 0.5 and 0.3 QSU for TLF and CDOM, respectively (Sorensen et al., 2020b). CDOM was included to account for spectral overlap that may interfere with TLF readings due to potentially high organic matter presence in waters. Sites were selected to cover different landscape settings: (i) High-Atlas touristic valleys, (ii) mountain-front areas with traditional surface-water irrigation, (iii) modern groundwater-based irrigation perimeters, (iv) non-irrigated lands, and (v) urban areas.

3.4. Sampling and laboratory analyses

From the measured sites for TLF and CDOM, 44 groundwater samples (41 well/borehole and 3 springs) and 5 stream samples were collected for stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$), tritium (^{3}H), and nitrates (NO_3^-). Stream and springs were collected at different elevations within Ourika catchment in the High-Atlas Mountains, and groundwater samples were collected from hand-dug wells and

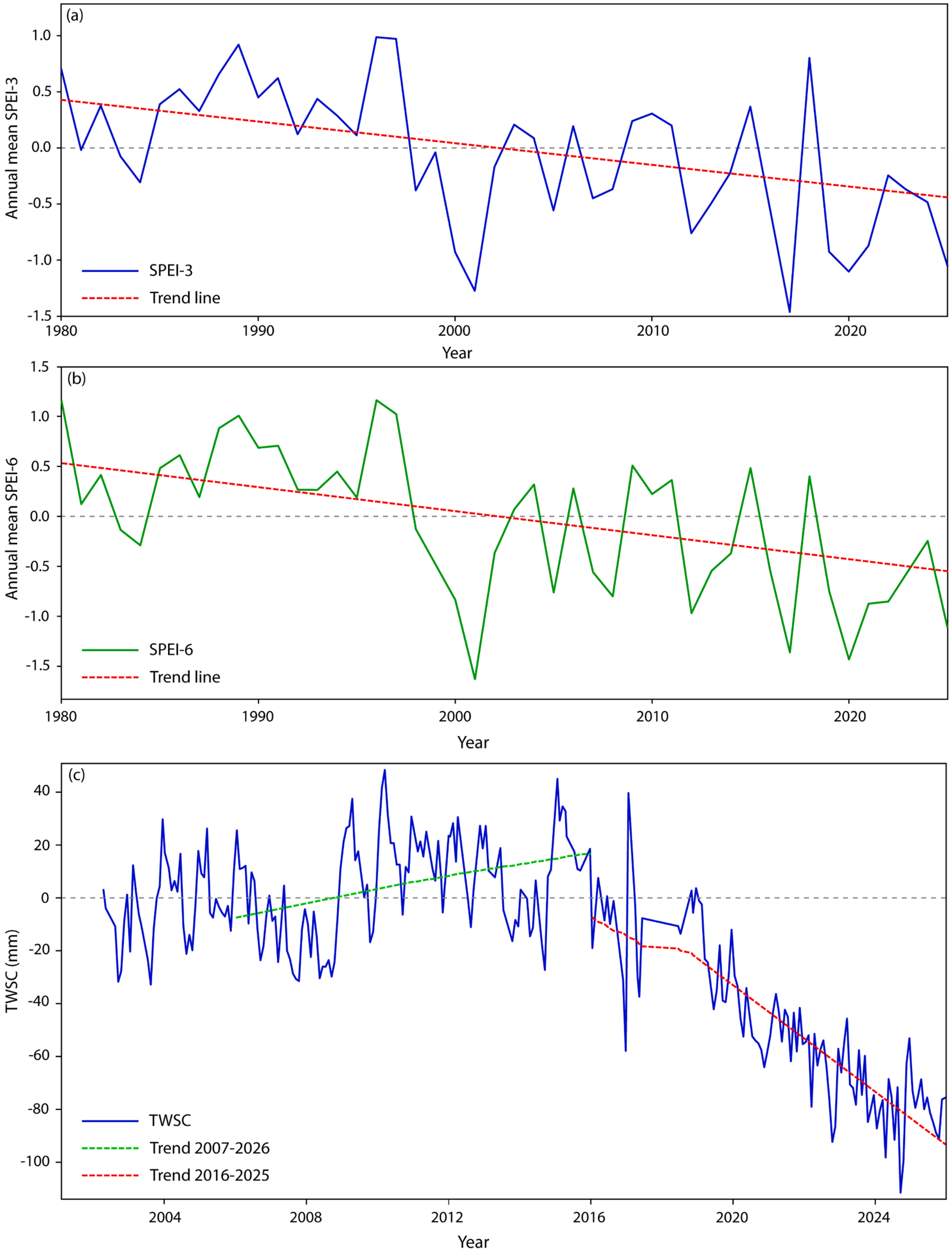

Fig. 3. Temporal evolution of drought conditions in the Haouz region between 1980 and 2025 based on the SPEI: (a) seasonal scale (SPEI-3), (b) multi-seasonal scale (SPEI-6), and (c) TWCS from GRACE data.

boreholes from the Haouz alluvial aquifer with depths ranging from 20 to 150 m. The groundwater samples were collected during or immediately after pumping. Samples for δ^{1} ^{8}O and δ^{2}H were collected in 30 mL amber glass bottles, in 250 mL high-density polyethylene bottles for NO_3^-, and in 2 L high-density polyethylene bottles for ^{3}H. All samples were preserved in cold until analysis.

δ^{1} ^{8}O and δ^{2}H were analyzed using a Picarro Analyzer L-2130i (precision: ±0.1‰ for δ^{18}O, ±1‰ for δ^{2}H). ^{3}H was analyzed by liquid scintillation counting (detection limit <0.5 TU). NO_3^- was analyzed by ion chromatography (detection limit: 0.01 mg/L). All the chemical and isotopic analyses were carried out in the Hydrogeology Laboratory of Avignon University, France.

27 sites, including 22 groundwater samples (20 well/borehole and 2 springs) and 3 streams were collected for fecal coliforms analyses. The samples were taken in 0.5 L sterile glass bottles and transported to the lab in a clean and cool box. The analyses were performed two to five hours after sampling using the membrane filtration method. The membrane is cultured on a specified agar medium after a 100 mL water sample is filtered. Tergitol-TTC medium was employed in this investigation to count total coliforms and fecal coliforms (AFNOR,1990). Coliform bacteria form yellow-orange colonies on Tergitol-TTC media (incubation 24 and 48 h at 37 and 44 °C for total coliforms and fecal coliforms, respectively). Colonies were then counted and results were expressed in colony-forming units (cfu/100 mL).

4. Results

4.1. Climate trends and drought evolution

The Haouz region has experienced a clear trend toward aridification over the past four decades (1980–2025). Analysis of the SPEI-3 and multi-seasonal SPEI-6 timescales indicates that interannual fluctuations between wet and dry conditions are superimposed on a persistent long-term drying trend. The MK test reveals statistically significant negative trends for both indices. SPEI-3 shows a significant decreasing trend ($p = 0.0012$; Sen's slope = −0.0243), while SPEI-6 exhibits a similarly strong decline ($p = 0.0011$; Sen's

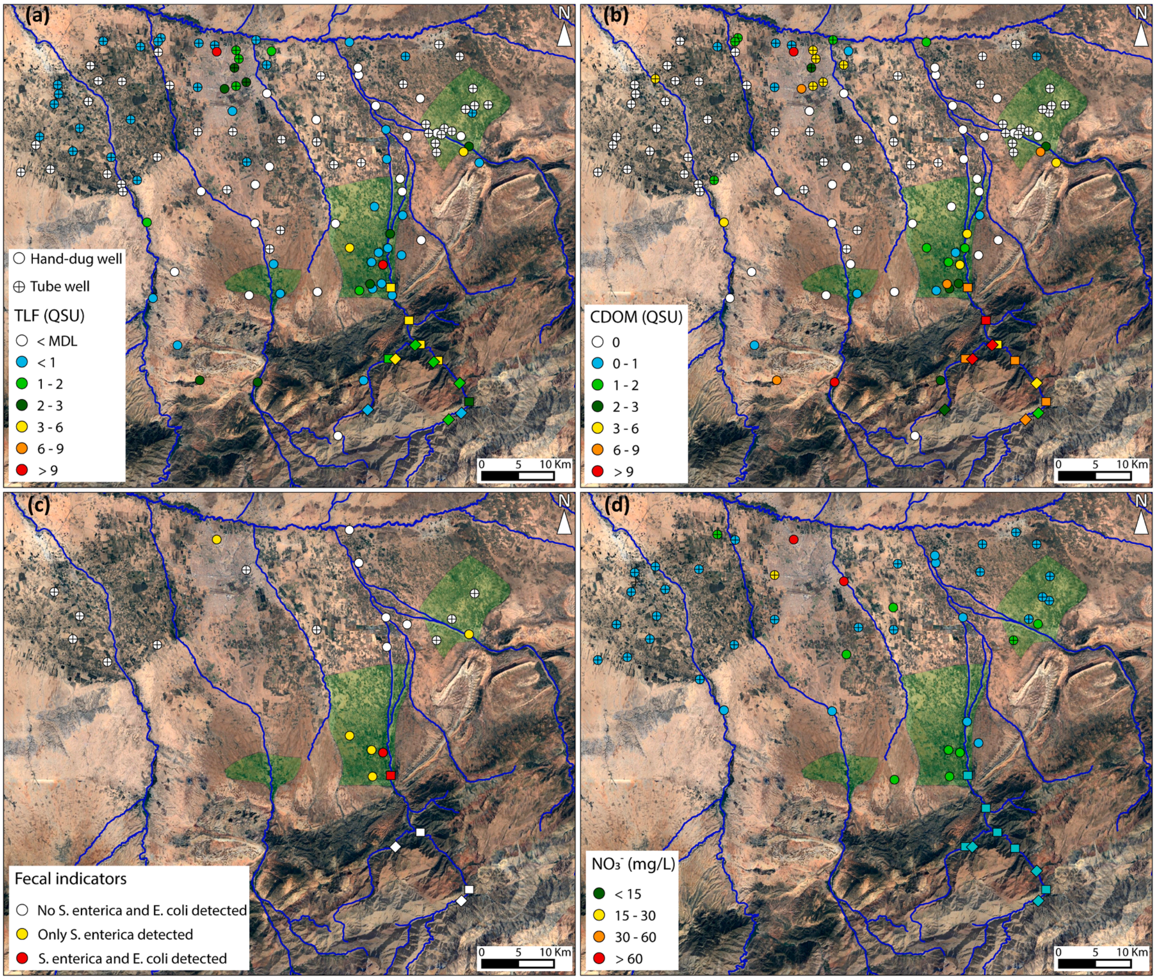

Fig. 4. Spatial distribution of contamination indicators across the study area: (a) tryptophan-like fluorescence (TLF), (b) colored dissolved organic matter (CDOM), (c) microbial indicators (thermotolerant coliforms including fecal coliforms and S. enterica), and (d) nitrate concentrations.

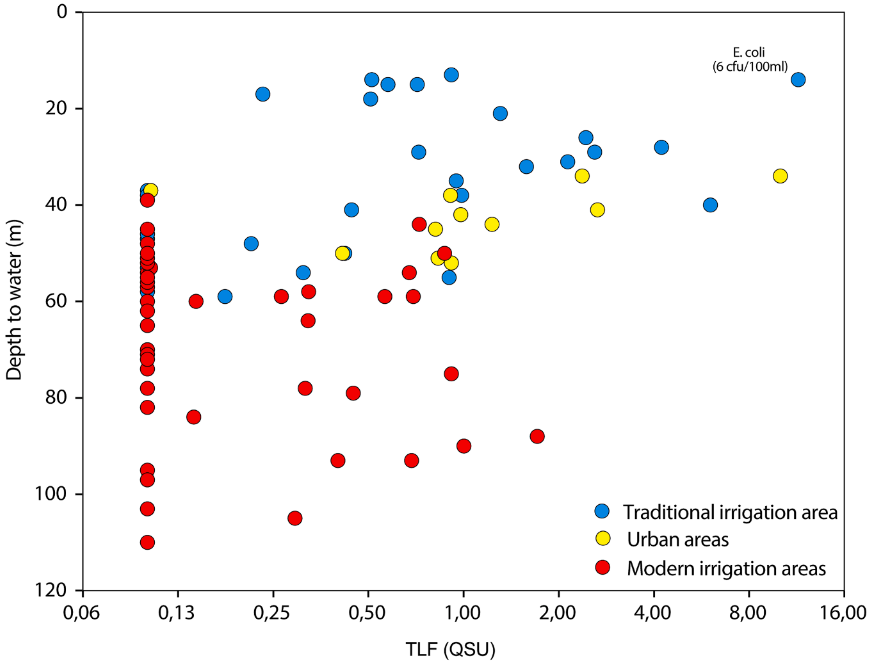

Fig. 5. Relationship between tryptophan-like fluorescence (TLF) and groundwater depth, indicating that wastewater contamination is most pronounced in shallow aquifers (< 40 m). For visualization purposes, 0.1 QSU was added to all TLF values due to the high frequency of zero measurements.

slope = −0.0298). These results indicate a progressive intensification of drought conditions in the study area, reflecting a long-term shift toward increased aridity affecting both short-term meteorological water availability and medium-term agricultural water balance. Fig. 3 also confirms that the drought episode beginning in 2019 ranks among the most intense and persistent events of the last five decades.

The analysis of TWSC in the Haouz region (Fig. 3c) shows a sharp decline during the period between 2019 and 2025 with anomalies reaching approximately −100 mm, reflecting a significant depletion of water storage in the region.

4.2. Characteristics and spatial variation of contamination indicators

TLF measurements show marked spatial differences across the study area. Surface water in the Ourika stream exhibits consistently elevated TLF values (2.0–4.0 QSU; mean 3.2 QSU). Mountain springs and wells mostly show values below or close to the detection limit (mean 1.5 QSU). Groundwater on the mountain-front and plain displays a wider range of TLF values (below MDL to 11.3 QSU; mean 0.7 QSU). Among wells with detectable TLF, dug wells present higher values (mean 3.3 QSU; median 2.2 QSU) than tubewells (mean 0.8 QSU; median 0.7 QSU). Furthermore, wells with detectable TLF are concentrated in two zones: the Marrakech urban area and the traditional irrigation area in the mountain-front along the Ourika wadi, which together account for 45.6% of all wells above the detection limit. Sixteen of the eighteen wells with the highest TLF values are located within these two areas (Fig. 4a, b).

Possible interferences from temperature, turbidity, and dissolved organic matter can affect TLF values potentially leading to misinterpretation. In this dataset, temperature varied between 20.0 °C and 29.6 °C (temperature mean = 25.9 °C; range = 9.6 °C), driven by differences in altitude affecting local climate. These values fall in a range considered to have less influence on the observed values of TLF (Khamis et al., 2015). Turbidity was not explicitly considered in this study because the investigated wells tap deep groundwater within the matrix-flow Haouz aquifer, where suspended particulate matter is typically very low due to natural filtration through the porous medium. Therefore, turbidity-related optical interference is expected to be negligible. The relationship between TLF and CDOM signals measured by the UviLux sensors was examined to assess potential optical interference. A moderate to strong linear relationship was observed ($R^2 = 0.57$; slope = 1.36), indicating that increases in TLF were generally accompanied by increases in CDOM. While such a relationship may suggest potential optical crosstalk due to partial spectral overlaps, the strength of the correlation is insufficient to indicate dominant or systematic interference. Instead, it likely reflects both limited optical interaction and natural co-variation between organic matter fractions in the studied waters.

The relationship between TLF and groundwater depth (Fig. 5) highlights a clear stratification of contamination signals. TLF was generally detected in wells with shallow water tables (<40 m), particularly in the traditional irrigation areas of the mountain front. In contrast, wells with depths exceeding 40 m, typical of the modern groundwater irrigation areas, showed predominantly non-detectable or less than 1 QSU values.

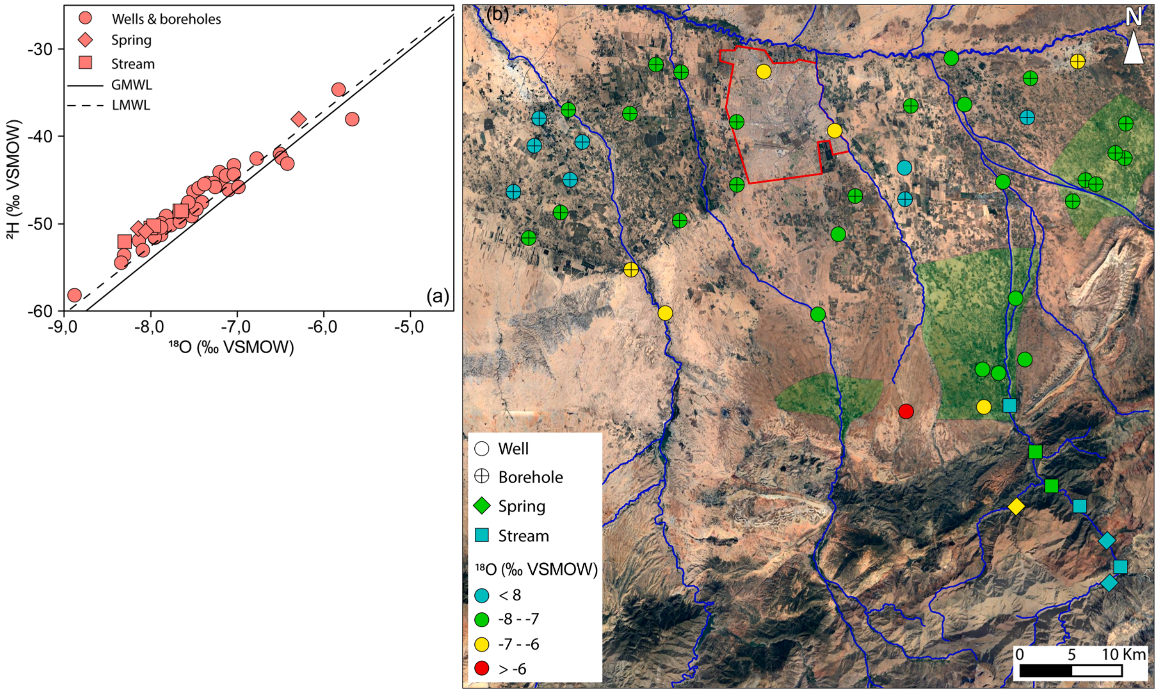

Fig. 6. (a) Relationship between δ^{18}O and δ^{2}H values in groundwater and surface waters compared with the Global and Local Meteoric Water Lines, and (b) spatial distribution of δ^{18}O values across the Haouz Plain.

Fecal coliforms were detected in only two samples out of 27, one hand-dug well (well 8 with 6 cfu/100 mL) and one surface water site (S5 with 163 cfu/100 mL), both located on the traditionally irrigated mountain-front (Fig. 4c). These sites also had elevated TLF: Well 8 is a shallow well (depth to water is 14 m) with a TLF concentration of 11.3 QSU, the highest in this study, and the surface site S5 is in the mountain-front immediately downstream of a small town with a TLF concentration of 3.2 QSU. Furthermore, non-lactose fermenters, known to appear as red-colored colonies with a blue periphery in Tergitol-TTC media, were detected in 6 wells and the S5 surface water site with concentrations ranging from 6 to 63 cfu/100 mL. Five of the wells are located in the traditional irrigation area of the mountain-front and one in the Marrakech urban area, all having elevated TLF values.

Nitrate concentrations in stream waters were low (0.7–2.3 mg/L, mean 1.7 mg/L), while groundwater samples showed a much broader range, from 0.7 to 166 mg/L (mean 17.4 mg/L) (Fig. 4d). Although most wells remained below the World Health Organization guideline of 50 mg/L (WHO, 2022), three wells (69, 105, and 106) located within Marrakech urban area exceeded this threshold, both exhibit elevated TLF values (wells 105 and 106) (Fig. 4d). In contrast, nitrate levels in the modern groundwater irrigation perimeter were consistently low, with two-thirds of wells containing < 10 mg/L.

4.3. Stable isotopes

δ^{18}O values ranged from −8.52 to −5.67‰ and δ^{2}H values from −55.7 to −34.7‰. Most samples plotted close to the global and local meteoric water lines (Fig. 6a), indicating recharge by modern meteoric waters with limited evaporation. However, several samples, notably from Marrakech urban area and the mountain-front non-irrigated area, were displaced toward more enriched values (δ^{18}O up to −5.7‰). The most depleted signatures were recorded in High-Atlas springs and deep wells in the plain downstream ($\delta^{18}O \leq -8.1$‰).

4.4. Tritium and groundwater residence times

Tritium values in groundwater ranged from below detection to > 3 TU, providing insight into aquifer residence times and recharge dynamics (Fig. 7a). Shallow wells, particularly in the mountain-front, showed the highest values (mean 2.9 TU). By contrast, deeper wells, particularly those in the N'fis modern irrigated perimeter, had tritium values between below detection and 1.3 TU. A moderate negative correlation was observed between depth to groundwater and tritium ($R^2 = 0.55$), confirming that younger waters dominate shallow zones while older, less renewable waters characterize deeper aquifers (Fig. 7a). Spatially, high tritium concentrations

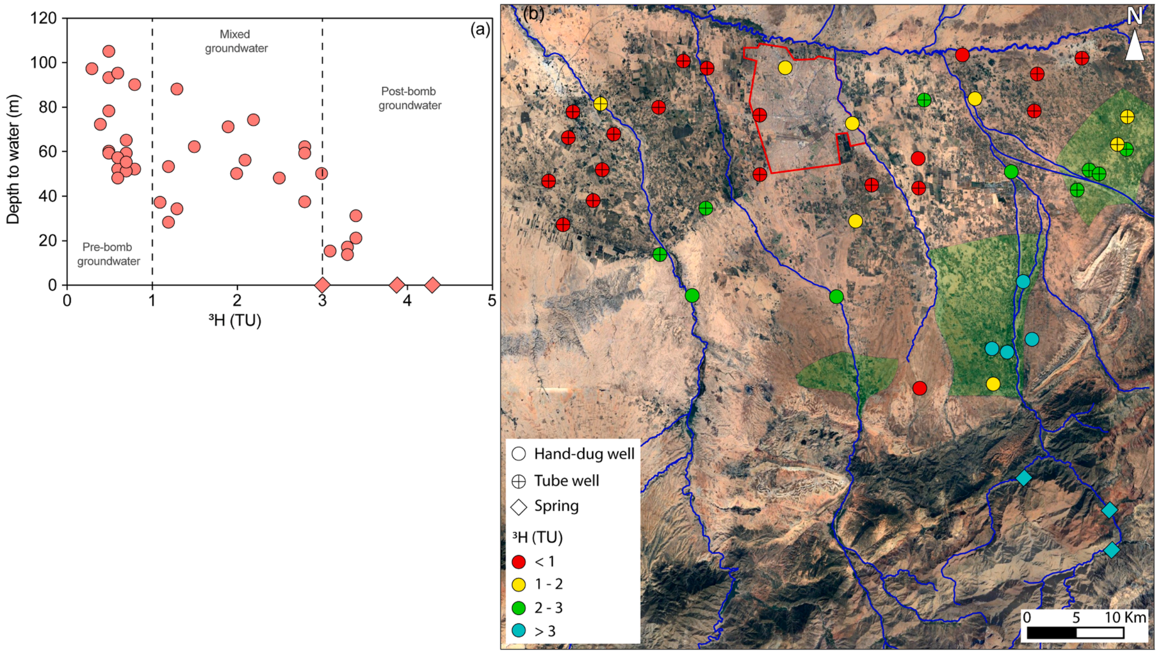

Fig. 7. (a) Relationship between tritium (^{3}H) content and groundwater depth, showing higher values in shallow aquifers (<30 m) and low values in deeper wells (>80 m), and (b) spatial distribution of ^{3}H across the study area.

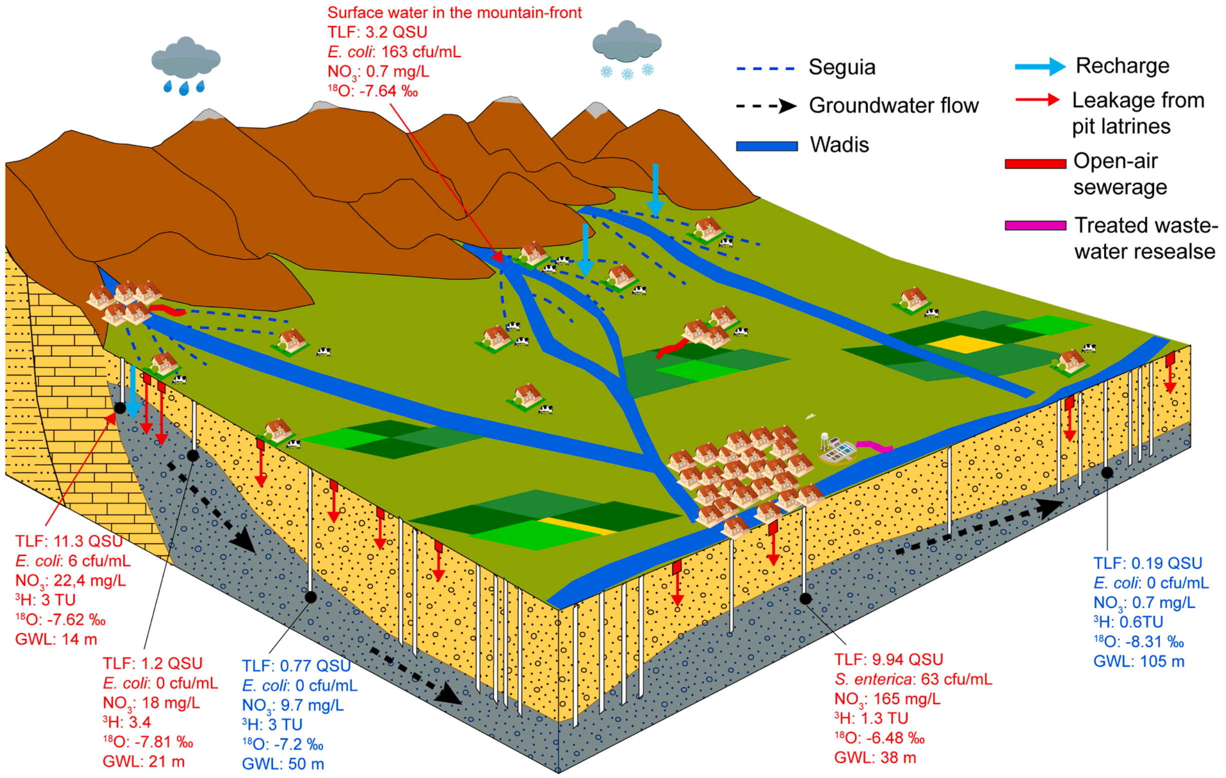

Fig. 8. Conceptual diagram summarizing hotspots of faecal contamination in the study area.

coincided with areas where surface water irrigation is present, whereas low tritium signatures prevailed in areas dominated by modern groundwater irrigation (Fig. 7a).

5. Discussion

As presented in Section 4.2, the highest TLF values were found in the Ourika stream (mean = 3.2 QSU), the springs of the Ourika watershed (mean = 1.9 QSU), the wells in the Marrakech urban area (mean = 2.3 QSU), and the traditional irrigation area in the mountain-front (mean = 2.2 QSU). In the Ourika watershed, elevated TLF values may be caused by intensive touristic activities in the valleys where there are no wastewater treatment infrastructure and sewage are mainly released to unsealed pit latrines and wadi channels. In the Marrakech urban area, the contamination may be caused by inefficiencies of the sewerage systems (AGIRE, 2016). In the traditional irrigation area on the mountain-front, several contamination sources can converge. These sources include the absence of wastewater treatment facilities for small urban centers, often resulting in wastewater being released into wadi channels and irrigation canals, and the use of unsealed pit latrines or even abandoned wells to evacuate wastewater in rural agglomerations. Similar patterns have been reported in other low-income regions where unlined canals, unsealed pit latrines, and untreated wastewater reuse contribute to contaminant transfers to groundwater (Graham and Polizzotto, 2013; Chuah and Ziegler, 2018).

In addition to anthropogenic factors, the hydrological and hydrogeological settings also play an important role in controlling groundwater contamination. Stable isotopes and tritium in the central part of the Haouz plain showed that groundwater mostly originated from indirect recharge processes, including traditional surface water irrigation practices and streamflow losses. These results are consistent with findings from recent studies (Bouimouass et al., 2020, 2024, 2025; Fakir et al., 2021). Currently, the primary recharge areas are largely limited to the mountain front where traditional gravity-fed irrigation still prevails (Bouimouass et al., 2025), while most of the plain relies on modern groundwater irrigation, resulting in rapid groundwater depletion and thick unsaturated zones, thus delaying recharge. The spatial distribution of TLF values showed that the highest values were mainly observed in the traditional irrigation area of the mountain front, corresponding to the recharge area, suggesting a relationship between recharge and contamination. In addition, higher TLF values were observed in the traditional irrigation areas, especially around Ourika wadi, where groundwater levels were lower (average of 22 m), compared to modern irrigation areas (average of 78 m), mainly due to delayed recharge.

TLF values in groundwater of the Haouz plain are generally low, with 60% of wells showing signals below the MDL. Significant differences were observed between dug-wells and tubewells, with mean values of 3.3 QSU and 0.8 QSU, respectively, indicating a clear contrast related to well type and likely vulnerability to near-surface contamination sources. Similar contrasts between shallow, manually excavated wells and deeper boreholes have been reported in TLF studies conducted in India, where dug-wells consistently exhibit stronger fluorescence signals than tubewells due to their higher exposure to surface-derived inputs (Sorensen et al., 2016). The distribution pattern observed in the Haouz plain is generally consistent with the general behavior reported for wastewater-impacted and vulnerable groundwater systems in an intergranular aquifer. Across TLF studies, elevated signals are typically associated with shallow sources, urbanized settings, or poorly protected water points (Sorensen et al., 2021).

To link TLF with fecal contamination risk in groundwater, Sorensen et al. (2018a), (2018b) proposed a TLF threshold of 1.3 ppb to differentiate sites classed as medium risk and above according to WHO categories (WHO, 2011), i.e., where fecal indicator organisms exceeded 10 cfu/100 mL. If we suppose that all the groundwater samples in our study area adhere to this criterion, only 28% of the samples would be considered as medium risk or higher. However, among all groundwater samples collected in this study, only one had detected fecal coliforms and six with non-lactose fermenters, most of them located in the mountain front. Sorensen et al. (2020b) showed that samples with elevated TLF and no fecal coliforms may still indicate a risk of fecal contamination in an intergranular aquifer, as associated fluorophores are predominantly extracellular in groundwater and less prone to straining than fecal indicator organism (Sorensen et al., 2020a). Furthermore, TLF is more temporarily resilient in groundwater than fecal indicator organisms, and at sites with elevated dry season, TLF can relate to fecal indicator organisms in the wet season and not the dry season (Sorensen et al., 2021), which is when we sampled. Alternatively, elevated TLF could relate to the presence of other contaminants, e.g. polycyclic aromatic hydrocarbons (PAH), or overlap from a neighboring fluorescent peak (Carseta et al., 2010; Sorensen et al., 2018a, 2018b).

In traditional irrigation areas, declining streamflow may have concentrated pollutants and increased reliance on wastewater reuse during the drought period from 2019 to 2025. In modern irrigation areas, drought has reduced recharge even further and deepened dependence on dwindling groundwater reserves. Similar trade-offs have been documented in Spain (Pool et al., 2021) and South Asia (MacDonald et al., 2016), where irrigation modernization shifted pressures from groundwater contamination to groundwater depletion. Furthermore, the climate projections are warmer in the area with more recurrent droughts and less rainfall (Schilling et al., 2012; Tuel et al., 2022). Without intervention, traditional systems will face escalating contamination risks as the proportion of wastewater reuse increases, while modern systems will continue to deplete groundwater reserves. Therefore, building resilience requires a dual strategy: (i) protecting recharge areas from wastewater by upgrading sanitation infrastructure, such as wastewater treatment in tourist hotspots, sealed septic systems in rural villages, and stricter regulation of wastewater reuse, and (ii) managing pumping to safeguard long-term storage.

Finally, strengthening monitoring systems is essential in this data-scarce region. *In situ* fluorescence sensors, as demonstrated in this study, offer a rapid and low-cost tool for tracking contamination risks, complementing traditional microbial analyses that are labor-intensive and slow. Expanding such monitoring networks would generate better spatial coverage of data and enable near real-time data collection, helping managers to design adaptive policies that balance groundwater quantity and quality under increasing climate stress.

6. Conclusions

The Haouz Plain example illustrates how drought can simultaneously magnify groundwater depletion and contamination risks, but the implications extend well beyond Morocco. Similar trade-offs between recharge and quality versus depletion and sustainability are increasingly observed in drylands worldwide. Traditional irrigation systems, while essential for sustaining aquifer recharge, expose shallow groundwater to wastewater infiltration where sanitation infrastructure is lacking. Conversely, irrigation practices that have been modernized based on intensive pumping and drip systems, show less impact of wastewater contamination, but drive aquifer depletion. This duality highlights the need to evaluate irrigation strategies not only in terms of efficiency or recharge returns but also in terms of their consequences for groundwater quality and resilience. For policymakers and managers, the study highlights the importance of investing in rural sanitation and wastewater treatment to protect recharge areas, while also adopting groundwater governance measures such as pumping regulation, managed aquifer recharge, and conjunctive use of surface and groundwater. Methodologically, the integration of rapid fluorescence sensors with isotopes and tritium proved to be effective in distinguishing recent recharge from older groundwater, and for linking contamination pathways to hydrogeological dynamics. This combined approach can be adapted to other dryland regions facing similar challenges, providing both a diagnostic framework and a decision-support tool. Ultimately, the findings point to a broader lesson: sustaining groundwater in drought-prone agricultural systems requires balancing quality and quantity objectives. Without integrated approaches, communities risk choosing between contaminated but renewable shallow aquifers and less contaminated but non-renewable deeper reserves. Addressing this dilemma is critical for ensuring water security under a changing climate.

CRediT authorship contribution statement

M. Babic: Investigation. **Leblanc Marc:** Writing – review & editing. **Tweed Sarah:** Writing – review & editing, Funding acquisition, Conceptualization. **Sorensen James:** Writing – review & editing. **Bouimouass Houssne:** Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Fakir Younes:** Writing – review & editing. **Oufdou Khalid:** Writing – review & editing. **Sahraoui Hamza:** Writing – review & editing, Investigation. **Sahlaoui Tarik:** Writing – review & editing, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2026.103393.

Data availability

Data will be made available on request.

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