

Compilation and mapping of hydrogeological data for the Tadla irrigation perimeter

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Abstract. With its lush fields and neighboring mountains, the Tadla Plain in central Morocco is an important agricultural area. Its climate is semi-arid to arid, with a dry season from June to September and a rainy season from October to May. Summer temperatures exceed 30°C, while winter temperatures fall below 5°C. The area, which is a part of the Oum Erbia River basin, is mostly dependent on groundwater for industry, agriculture, and drinking. In this study, 58 wells (42 from ORMVAT and 16 from ABHOER) were analyzed to determine the water table levels and groundwater quality. Different physico-chemical and bacteriological parameters were analyzed, such as, pH, EC, Cl⁻, NO₃⁻, SO₄²⁻, etc. As well as hydrodynamic data including permeability, transmissivity, storage coefficients, and piezometric levels. With permeability between 10⁻⁵ and 10⁻³ m/s and transmissivity between 1×10⁻³ and 5×10⁻² m²/s, groundwater flows from northeast to southwest, indicating moderate to strong water transmission. Moderate storage capacity is indicated by storage coefficients ranging from 3×10⁻² to 6×10⁻². However, the quality of groundwater varies; many wells, particularly in the Beni Amir nappe, exhibit poor quality. Concentrations of electrical conductivity (EC) and chloride ions (Cl⁻) are high in most wells.

Keywords. Groundwater quality, hydrogeology, hydrology, hydrochemistry, hydrodynamics, GIS, Tadla plain.

1 Introduction

Groundwater pollution problems are currently a major concern and require worldwide attention. This pollution, caused by human activities, can become a serious threat to public health when it reaches critical levels [6].

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The Tadla plain is an important agricultural region located in central Morocco, between the High Atlas mountain range to the east and the Middle Atlas mountain range to the west.

This fertile plain extends primarily over the northern part of the Beni Mellal-Khénifra region [7]. Hydrology is closely connected to the geographical and climatic characteristics of the region, hydrogeology mainly focuses on the Tadla aquifer, which plays an essential role in irrigating agricultural lands, the primary economic activity in the area. The groundwater is theoretically subject to threatening qualitative degradation. In this study, we examine the hydrochemical indicators of this pollution. Our analyses are based on data supplied by bodies such as the Regional Office for Agricultural Development of Tadla (ORMVAT) and the Agency for Hydraulic Basin of Oum Er-Rbia (ABHEOR). Later, we will present the results of analyses carried out by ORMVAT and ABHEOR to illustrate more precisely the spatialization of pollutant parameters.

GIS and mapping are valuable tools in groundwater management. They enable the collection, analysis, and visualization of data on water levels, physicochemical and bacteriological quality of wells. This information is essential for making informed decisions on groundwater resource management, and for developing long-term conservation strategies.

2 Study area

The Tadla Plain is a vast agricultural region located in central Morocco, approximately 200 km southeast of Casablanca [2]. It stretches over a large area of around 3,600 km², mainly in the northern part of the Beni Mellal-Khenifra region, between the High Atlas mountain ranges to the east and the Middle Atlas to the west, creating a striking contrast between the mountains [7].

The plain is located to the east of the Oum Er-Rbia watershed and is traversed by the Oum Er-Rbia River, one of the major rivers in Morocco. It extends for 125 km in length and reaches a maximum width of 50 km at its center [7].

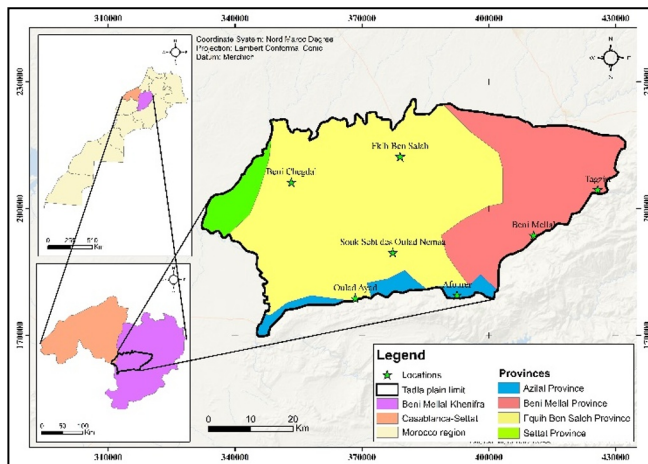


Fig. 1. Geographical location of the Tadla plain

The Tadla Plain is primarily situated between 400 and 500 meters in altitude, offering generally flat or slightly undulating terrain. Although there may be slightly higher areas reaching up to 600 meters, these elevations remain modest. Mountains and hills surround the region, with surrounding reliefs often exceeding 1,000 meters in altitude, creating transition zones between the plain and the mountainous regions. Overall, the plain features gentle

slopes ranging from 0° to 6° , which facilitate the flow of watercourses such as the Oued Oum Er-Rbia, with steeper slopes of up to 12° along their courses. At the edge of the plain, slopes can be steeper, up to 68° , characterizing transition zones with neighboring mountainous regions.

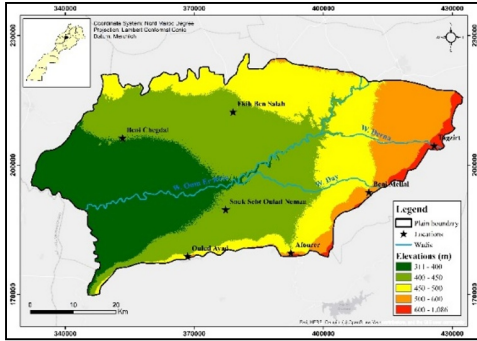


Fig. 2. Hypsometric Map of the Tadla Plain

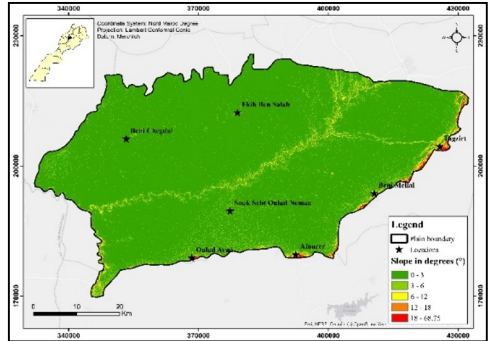


Fig. 3. Slope maps (in degrees) of the Tadla plain

3 Materials and methods

4.1 Data used

The data used in this study come from various sources and cover several aspects of the studied region. They primarily consist of:

- Climatic data: The climatological framework was based on the most complete and up-to-date series of climatological data (1983-2021) acquired from the Oum Er- Rbia water basin agency, from the following climatological stations: Beni Mellal, Mechra Edahk and Ahmed Hansali. The main climatic parameters studied are precipitation, temperature and wind.

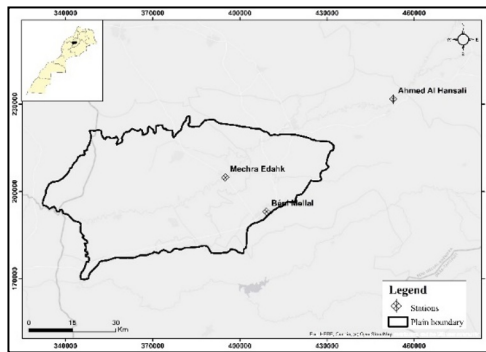


Fig. 4. Location of climatological stations studied

- Sentinel-2 images: Sentinel-2 sensors offer richer spatial and spectral content and enhanced operational capabilities [8]. Multispectral data, although affected by atmospheric conditions and limited to daytime acquisition, can be used to differentiate land cover classes based on spectral changes in their specific characteristics [9].

- Digital Elevation Model (DEM): We downloaded two 30-meter resolution digital elevation models (DEMs) in TIFF format. We then combined them into a mosaic using ArcGIS

software, after changing the coordinate system from GCS_WGS_1984 to North_Maroc_Degree.

- Piezometric Data: The piezometric data for wells in the study area, covering the period from 1995 to 2022, were collected from the Regional Office for Agricultural Development of Tadla (ORMVAT).

- Physicochemical and biological quality data: Covering the period from July 2022, collected from Regional Office for Agricultural Development of Tadla (ORMVAT), and other data from the Agency for Hydraulic Basin of Oum Er-Rbia (ABHOER).

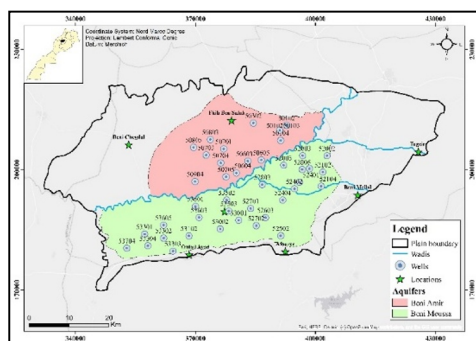


Fig. 5. Location of wells (ORMVAT)

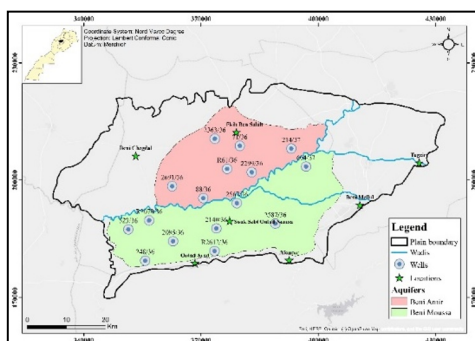


Fig. 6. Location of wells (ABHOER)

4.2 Methods used

- Georeferencing: This involves integrating non-referenced data into a reference system in two stages: selecting control points and adjusting the geometry of the data according to the projection system [3].

- IDW (Inverse Distance Weighting): IDW is an interpolation method that estimates unsampled values based on data from neighboring points, facilitating spatial analysis in GIS [4].

- Kriging: is a spatial interpolation method that estimates values at unsampled points using the values of neighboring points while accounting for the spatial dependence structure of the data. It provides unbiased predictions with minimal variance and can incorporate auxiliary variables [5].

- DEM mosaic: combines several DEMs into a single, continuous and seamless representation of the relief of a given region.

- Supervised classification: This method uses user-supplied training samples for each class. ArcGIS extracts the spectral signatures of these samples and uses them to classify the entire image.

- Resampling: is the process of altering the spatial resolution or pixel size of an image. It is used to align images from different sources or resolutions or to adjust the resolution for further processing.

- Layer stacking: also known as, "image stacking", is the process of combining several image or raster layers into a single composite layer.

4 Results of the hydrogeological study of the Tadla aquifer

4.1 Piezometry

The piezometric level indicates the height of water in an aquifer relative to a reference point, reflecting the quantity of water stored and the pressure exerted. In the study area, levels vary from 2.78 to 24 meters, suggesting a shallow water table with areas of subsidence to the southwest and northeast. This variation indicates a northeast-southwest flow of the water table.

Piezometric levels show annual variations, with a general trend of gradual increase in well N° 50303 until 2008, followed by stabilization or slight rise until 2019. Recently (2020-2022), wells 52603 and 53304 show a more marked upward trend, perhaps indicating increased groundwater recharge or other environmental factors.

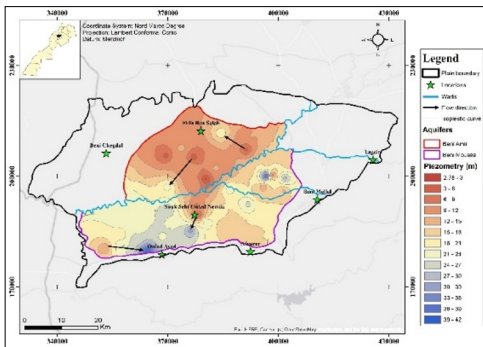


Fig. 7. The piezometric level of the Beni Amir and Beni Moussa aquifers (end of winter 2022)

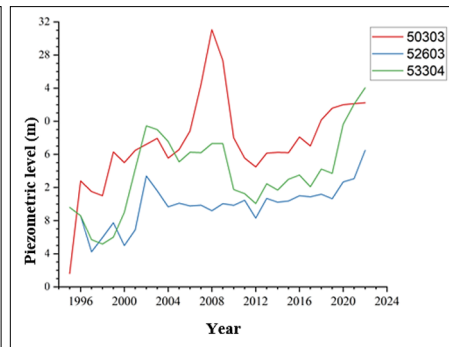


Fig. 8. Changes in piezometric levels from 1995 to 2022

4.2 Hydrodynamic characteristics

Transmissivity measures the aquifer's ability to transmit water. In the Tadla plain, it varies from $1 \cdot 10^{-3} \text{ m}^2/\text{s}$ to $5 \cdot 10^{-2} \text{ m}^2/\text{s}$ [1], indicating a moderate capacity to flow groundwater and allowing significant circulation over long distances.

Permeability, expressed in meters per second, measures a material's ability to allow the movement of water through it. It varies from 10^{-5} to 10^{-3} m/s (ABHOER) in the region, suggesting moderate to high permeability and favoring good groundwater flow.

The storage coefficient measures the aquifer's capacity to store water. In the region, it is generally between $3 \cdot 10^{-2}$ to $6 \cdot 10^{-2}$ [1], indicating a relatively good groundwater storage capacity and promoting better availability of water resources.

4.3 Hydrochemical characteristics

The study analyzes the hydrochemical characteristics and physico-chemical parameters of groundwater quality in the Beni Amir and Beni Moussa aquifers on the Tadla plain. Water pH varies between 7.3 and 7.72, indicating slightly alkaline water. Electrical conductivity shows high salinity in the Beni Amir nappe (2,000 to over 6,000 $\mu\text{s}/\text{m}$) and variable salinity in the Beni Moussa nappe (630 to over 6,000 $\mu\text{s}/\text{m}$). Groundwater temperature varies between 20.1°C and 26.5°C, with cooler water in the Beni Amir nappe. Chloride concentrations exceed Moroccan standards, indicating poor water quality, while nitrate

(16.97-46.41 mg/l) and sulfate (33.20-870 mg/l) levels suggest contamination. Ammonium (0.016-0.14 mg/l) and nitrite (0.01-0.151 mg/l) concentrations remain below regulatory thresholds. Biological parameters show significant faecal contamination, with high levels of total coliforms (45.75-34,000/100 ml), faecal coliforms (13.3-64,000/100 ml) and faecal streptococci (10.95-39,000/100 ml), particularly marked in the north-west of both aquifers.

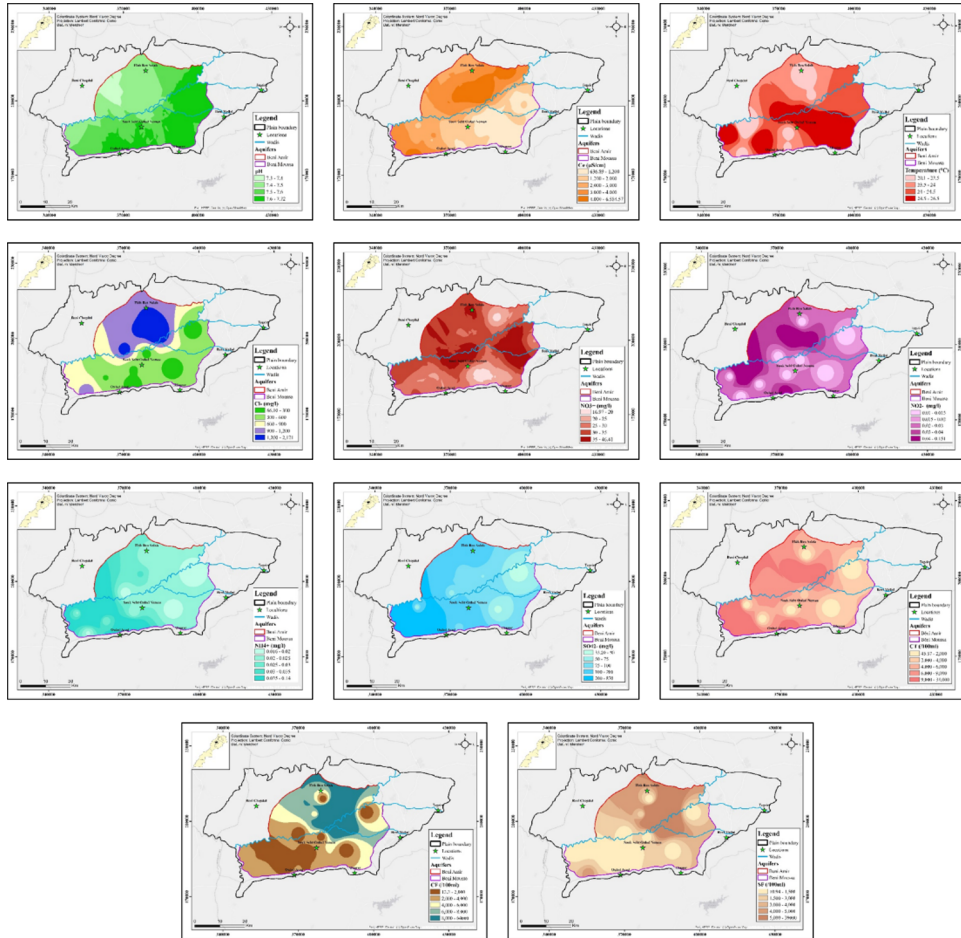


Fig. 9. Spatial distribution of Physico-chemical and Biological parameters from the Beni Amir and Beni Moussa aquifers (July 2022)

4.4 Groundwater quality status

Groundwater quality is assessed on the basis of a simplified grid comprising five indicator parameters for physical-chemical, organic, nitrogenous and bacterial pollution (Table 1). These parameters are:

- Conductivity and chloride ions, which provide information on the mineralogical quality of the water.
- Nitrates, the main indicator of groundwater pollution.
- $[\text{NH}]_4^{+}$ reduced form of nitrogen.
- Oxidizable matter determined by KMnO_4 oxidability.

- Faecal coliforms.

Table 1. Simplified Groundwater Quality Grid

Quality parameter	Cond (µs/cm)	Cl (mg/l)	NO ₃ ⁻ (mg/l)	NH ₄ ⁺ (mg/l)	MO mgO ₂ /l	CF (CF/100ml)
Excellent	<400	<200	<5	≤0,1	<3	≤20
Good	400-1300	200-300	5-25	0,1-0,5	3-5	20-2000
Average	1300-2700	300-750	25-50	0,5-2	5-8	2000-20000
Poor	2700-3000	750-1000	50-100	2-8	>8	>20000
Very poor	>3000	>1000	>100	>8	-	-

4.4.1 Beni Amir Aquifer

The results of the water quality classification of the Beni Amir aquifer are summarized in Table 2.

- Mineralogical quality: Very poor, due to high conductivity and chloride values.
- Nitrate quality: Good to average.
- Ammonium quality: Excellent.
- Organic matter quality: Excellent.
- Bacteriological quality: Variable (excellent, good, average and very poor).
- Mineralization, particularly conductivity and chlorides, degrades the quality of water points in the Beni Amir aquifer, classifying them as very poor quality.

Table 2. Groundwater quality in the Beni Amir aquifer

STATION NAMES	N°IRE	Cond	Cl ⁻	NO ₃ ⁻	NH ₄ ⁺	MO	CF	Global quality
		µs/cm	mg/l	mg/l	mg/l	mgO ₂ /l	CF/100ml	
Radaoui Razouani well	2299/36	6150	2122	52,30	0,02	1,65	64000	Very poor
well	2363/36	-	-	-	-	-	-	dry
Moflih drilling	2691/36	-	-	-	-	-	-	dry
Kadir drilling	R61/36	4650	1321	27,18	0,031	1,66	4800	Very poor
Ait Hajallal drilling	71/36	3830	1235	44,18	0,021	1,63	6	Very poor
El Bachir drilling	88/36	3770	1414	35,67	<0,016	1,32	170	Very poor
Centre Had Bradia well	214/37	-	-	-	-	-	-	A sec

Legend: «<» value below the limit of quantification.

4.4.2 Beni Moussa Aquifer

The results of the water quality classification of the Beni Moussa aquifer are summarized in Table 3.

- Mineralogical quality: Average to poor, with two stations (N°IRE 248/36 and N°IRE 523/36) showing very poor quality. Conductivities range from 783 µs/cm to 4,540 µs/cm, and chlorides from 66 mg/l to 1,040 mg/l.
- Nitrate quality: Average for most stations, but poor for N°IRE 604/37 and N°IRE 2567/36.

- Ammonium quality: Generally satisfactory, with values below 0.016 mg/l. Excellent for most stations, except N°IRE R2070/36 where it is good.
- Organic matter quality: Excellent, with values ranging from 0.47 to 1.31 mg O₂/l.
- Bacteriological quality: Overall good to average, except for station N°IRE R2070/36 where it is excellent.

Table 3. Groundwater quality in the Beni Moussa aquifer

STATION NAMES	N°IRE	Cond	Cl ⁻	NO ₃ ⁻	NH ₄ ⁺	MO	CF	Global quality
		µs/cm	mg/l	mg/l	mg/l	mgO ₂ /l	CF/100ml	
Khawa Abdellah drilling	R2070/36	1840	353	36.90	0,148	<0,47	20	Average
Sonacos drilling	2587/36	783	66	26.92	<0,016	<0,47	32	Average
Zoubaidi well	604/37	995	114	58.40	<0,016	<0,47	46	Poor
Douar Mgouna well	R2612/36	1190	119	37.47	0,061	1,31	1900	Average
Douar Oulad R'mich well	248/36	4540	1040	46.19	0,019	<0,47	3500	Very poor
Well Douar Oulad Mahmoud	523/36	4100	881	36.99	0,024	1,08	2100	Very poor
Commune Souk Sebt well	2140/36	1630	235	36.90	<0,02	<0,47	45	Average
Ferme Benhayyouné well	2085/36	2640	271	46.21	0,026	<0,47	40	Average
Nouaimi Salah well	2567/36	1280	147	57.93	<0,02	<0,47	280	Poor

Legend: «<» value below the limit of quantification.

The downgrading parameter for water quality is mineralization (high conductivity and chloride) and nitrate content (IRE N ° 604/37 and IRE N ° 2567/36). Water from the Beni Moussa aquifer is of average to very poor quality.

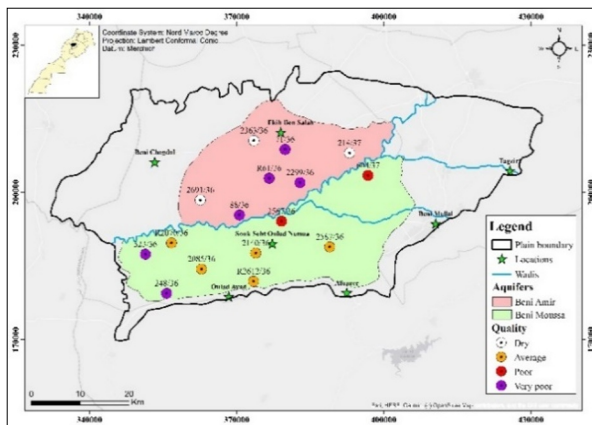


Fig. 10. Overall groundwater quality map of the Beni Amir and Beni Moussa aquifers

5 Conclusion

The Oum Er Rbia wadi irrigates the Tadla plain, with its semi-arid to arid climate. Geologically flat, it has a shallow water table with piezometric levels ranging from 2.78 to 24 meters, and favorable hydrodynamic characteristics.

Analyses show slightly alkaline to neutral water, with high electrical conductivity and varied sulfate levels, indicating significant mineralization. Water temperatures range from 20.1°C to 26.5°C, cooler in the Beni Amir nappe and warmer in the Beni Moussa nappe. High chloride and nitrate concentrations, as well as variable bacterial contamination, reveal potential pollution problems. These problems are linked to excessive fertilizer use, inadequate waste management and inefficient drainage practices, underlining the need for better water resource management.

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Author contribution

All authors contributed to this research. Chaimae Iharzi conceptualized and executed the study, including data collection and analysis, as well as the drafting of the manuscript. Abdessamad Najine, Amina Kassou and Ali Essahlaoui provided supervision, critical revisions, and guidance on hydrogeological aspects. Amroumousa Benmoussa supported data processing and performed quality control on the compiled hydrogeological data. Ouafae Mouzoun and Abdelali Khrabcha assisted with GIS mapping and validation of spatial results.

Ethics approval and consent to participate

Not applicable.

Consent for publication

All the authors have agreed to publish this article.

Competing interests

The authors declare that they have no competing interests.

Data availability statement

Not applicable.

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