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Establishment of protection perimeters for the Taïcha catchment field (Maâmora aquifer, Gharb region)

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ABSTRACT

This study presents a scientifically grounded delineation of protection perimeters for the Taïcha groundwater catchment field, located in the Maâmora aquifer (Gharb region, Morocco), in response to the lack of formally established protective measures and the growing risk of contamination from human activities such as agriculture, urban sprawl, and unmanaged waste. The approach combines hydrogeological analysis, spatial mapping, and regulatory frameworks. Field data from boreholes and technical reports were analyzed using ArcGIS to produce thematic maps (land use, piezometry, soil types, pollution sources), while several analytical models (Cylinder & Lillich) were applied to calculate the 50-day isochrone and delineate the protection zones. The immediate protection perimeter includes fenced areas surrounding each operational well. The close protection perimeter, determined by the travel time required for natural pathogen attenuation, extends over 170 hectares. The distant protection perimeter coincides with the aquifer recharge area, covering about 72 km². Results highlight increasing vulnerability of the aquifer due to overexploitation and proximity to pollution sources. The study emphasizes the need to enforce these protection zones to ensure sustainable water supply for the population. A limitation of this work is the partial unavailability of real-time hydrological monitoring data, which required reliance on regional averages for infiltration rates and recharge estimation. Despite this, the adopted methodology remains robust and replicable. The findings are of practical relevance to decision-makers, offering a technical basis for defining groundwater protection zones. This study represents one of the first attempts in Morocco to integrate GIS tools and hydrogeological modeling for this purpose, contributing to national water resource protection strategies.

Keywords: groundwater protection, hydrogeology, GIS, Taïcha aquifer, pollution risk, protection zones.

INTRODUCTION

Groundwater resources play a critical role in sustaining ecosystems, supporting agricultural activities, and providing drinking water to communities (Vernoux and Buchet, 2010). However, these vital resources are increasingly under threat from pollution caused by human activities such as industrial discharges, agricultural runoff, and urbanization (Custodio & Llamas, 2013). Protecting groundwater quality has therefore become a priority to ensure its availability for current and future generations.

Although the Taïcha catchment field has long contributed to the region's drinking water supply, it currently operates without officially established protection perimeters, leaving the Maâmora aquifer increasingly exposed to pollution risks from surrounding human activities.This institutional gap represents a critical vulnerability, as land use pressures continue to intensify due to agriculture, deforestation, and urban development. In this context, the study aims to develop a scientific and spatially explicit method to delineate protection zones and assess groundwater vulnerability. The final objective is to provide a practical framework that can support decision-making and guide future groundwater protection efforts in Morocco.

One of the most effective strategies to safeguard groundwater is the establishment of protection perimeters around catchment areas. These perimeters serve as controlled zones where specific regulations and measures are enforced to limit or prevent activities that could introduce contaminants into the aquifer. Such measures include restrictions on industrial developments, the application of agricultural chemicals, and the construction of infrastructure that could potentially affect groundwater quality (Foster & Chilton, 2003). Protection perimeters are designed based on hydrogeological criteria, including aquifer vulnerability, recharge rates, and pollutant transport dynamics, to maximize their effectiveness (Bussard, 2005).

The importance of protection perimeters is underscored by environmental and water management laws in many countries, which mandate their definition and implementation. For example, the European Water Framework Directive (Directive 2000/60/EC) emphasizes the need for integrated water resource management, including the protection of groundwater through legally defined zones. These laws aim to ensure the sustainability of groundwater resources by minimizing the risks of contamination and promoting responsible land use practices (Renald, 2003). In addition to legal compliance, protection perimeters also contribute to integrated water resource management strategies, aligning with global efforts to achieve sustainable development goals related to clean water and sanitation (UNESCO, 2022).

This study focuses on the establishment of protection perimeters for the Taïcha capture field, which relies on the Maâmora aquifer. By defining these zones, the objective is to mitigate risks of pollution, preserve the quality of the aquifer, and ensure a reliable supply of groundwater for multiple uses. This process involves hydrogeological assessments, risk analysis, and the application of regulatory frameworks tailored to the local context (Döll et al., 2012).

MATERIAL AND METHODS

The study integrates data from multiple sources: borehole logs (ONEE), topographic maps (1:25,000), satellite imagery, urban planning documents, and previous regional hydrological assessments (PDAIRE, 2004; ONEE, 1995, 2014). Data were analyzed using ArcGIS for spatial visualization, while hydraulic calculations relied on analytical models (cylinder, Jacob-Bear, Hoffmann & Lillich, etc.) following Zeghoud (2014). Where applicable, original values used in calculations are reported, and methods are described step by step to allow reproducibility.

The Taïcha site is located within the territory of the Sidi Taïbi commune. It is situated in the coastal zone, about 5 km southwest of the city of Kénitra and a few kilometers from the Sidi Taïbi commune. This location is on the national road between Salé and Kénitra, making it a popular stopping point for travelers and transporters. It is bounded by:

- the periphery of the city of Kénitra to the north,
- the rural commune of Sidi Taïbi to the south,
- The Maâmora central forest to the east,
- The Sidi Boughaba lake to the west.

The Taïcha site covers an area of 13,000 hectares of the Maâmora forest, featuring a "quasi-triangular elongated" shape toward the northwest, with a monotone landscape consisting of a natural forest organized in unevenly distributed stands (Laaribya et al., 2011) (Fig. 1).

The Taïcha catchment field comprises four wells. Their numbers, coordinates, altitudes, depths, and initial water levels are provided in the following Table 1. The four boreholes in the Taïcha catchment field were constructed at different times between 1963 (well 1220/13) and 2012 (well 38/412), reflecting a phased development of the water capture infrastructure. Despite its long operational history, the field lacks officially established protection zones, which is a concern due to evolving land uses and increasing groundwater exploitation. Hence, this study aims to address the urgent need for structured water resource protection (Fig. 2, 3).

The 1220/13 catchment (currently the only one in operation) has a concrete shelter, fencing, and telemetry equipment. A dosing pump is installed, and the water is disinfected before distribution. The catchment field has a production capacity of 250 liters per second.

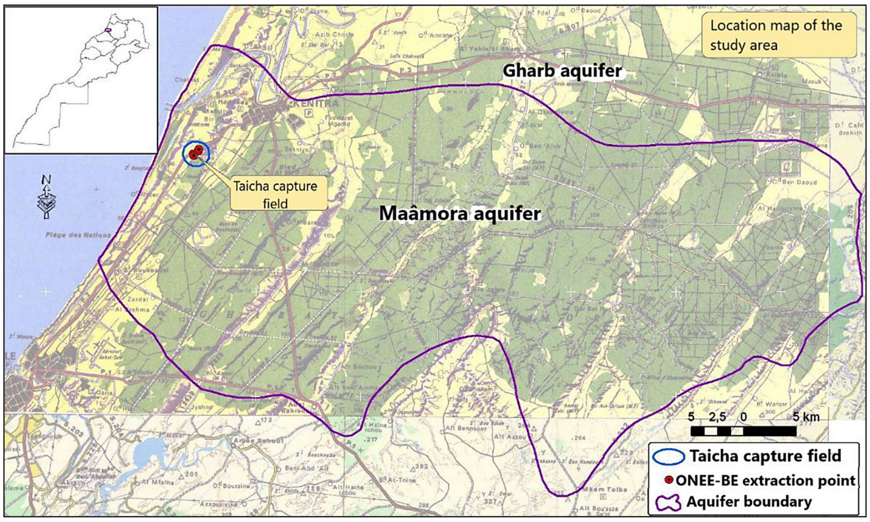

Figure 1. Location map of the Taïcha capture field in relation to the Maâmora aquifer

Table 1. Numbers, coordinates, altitudes, depths, and water levels of the wells in the Taïcha catchment field (ONEE)

Number	X (m)	Y (m)	Z (m)	Year of completion	Total depth (m)	Water level (m/ground)
1220/13	384 035	403 150	25.1	1963	50	24.2
01/409 (Taïcha I)	384 105	402 950	24.8	2009	75	22
02/409 (Taïcha II)	384 475	403 375	36.2	2009	95	36.3
38/412 (Taïcha III)	384 575	403 550	36.8	2012	135	37.3

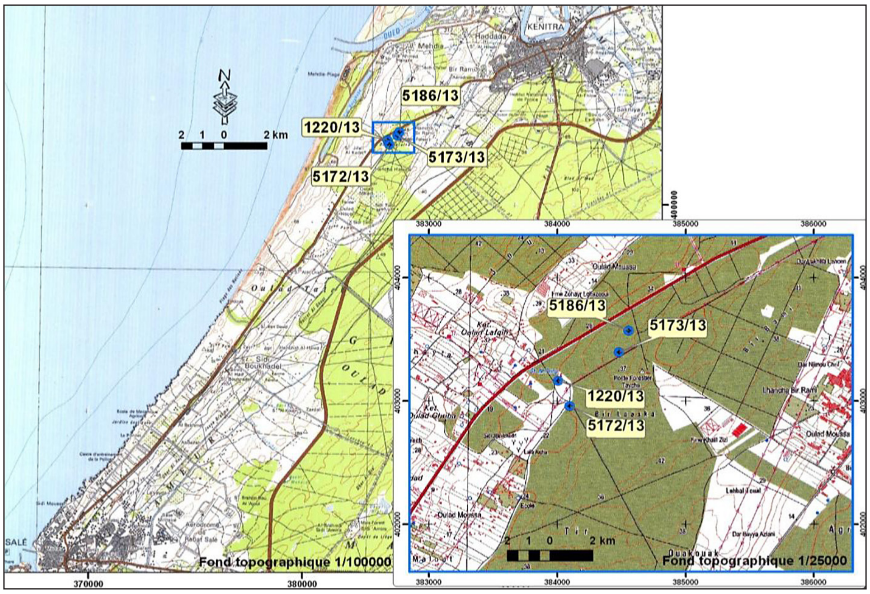

Figure 2. Geographic location of the ONEE Taïcha wellfield area

Immediate protection perimeter (IPP)

The close protection perimeter is designed to effectively prevent contamination of the water catchment by limiting the underground migration of pollutants (Marchal, 2007). According to (Nassah and Omdi, 2011), it defines a specific area where any localized or accidental pollution can rapidly reach the catchment, either through surface runoff or by infiltrating the aquifer. The delineation of this zone is based on several factors, including:

IRE N°: 1220/13: Operational wellfield

IRE N°: 5172/13: View of the North-Western part

IRE N°: 5186/13: View of the Eastern part

IRE N°: 5173/13: View of the Northern part

Figure 3. Some photographic illustrations of the wellfields

- the physical properties of the aquifer and the characteristics of groundwater flow;
- the maximum pumping rate;
- the vulnerability level of the aquifer;
- the source and nature of pollutants that may affect groundwater quality.

The immediate protection perimeter must cover, at a minimum, the catchment point and its annexes (drains, galleries, protective structures, concrete slabs, etc.), as well as the facilities necessary for the operation of the structure (Riccardo et al., 2004).

This zone surrounds the extraction point, where pollution constraints are high (Nassah and Omdi, 2011).

Its dimensions are independent of geological and hydrogeological contexts in a porous environment, which allowed us to define four zones for the immediate protection perimeter, each surrounding an operational structure (Sferdjli, 2015).

Protection zone (PPR)

The purpose of the protection zone is to effectively safeguard the wellfield from the underground migration of pollutants (Smires and Ihbach, 2013). The sizing of this zone depends on geological and hydrogeological contexts. Before starting our study, preliminary planning is necessary (Vernoux., 2007). This planning consists of several studies to be conducted, including:

- geological study – analyzes lithology and the type of aquifer, and examines the purifying capacity of the unsaturated zone,
- hydrogeological/hydrological study – indicates the hydraulic gradient and flow direction,
- land use study – aims to inventory activities within the study area,
- pedological study – analyzes the purifying capacity of the soil,
- pollution source study – locates the different sources and areas of pollution.

After completing the preliminary planning, it was necessary to create a map for each study. The lithology of the aquifer reservoir is described based on borehole logs from the Taïcha catchment field (boreholes 5172/13, 5173/13, and 5186/13). It reveals a dominance of sands, sandstones, and calcarenite (Fig. 4).

The piezometric analysis highlights a continuous decline in the water table level, reaching approximately 4 meters in the immediate vicinity of the Taïcha catchment field (Fig. 5). This gradual decrease reflects increasing overexploitation, particularly in this area, where the SE-NW drainage axis is well-defined. This trend may result from a reduction in recharge, influenced by climate change and the intensification of withdrawals for drinking water supply (Xanthoulis, 1993).

The analysis of land use in the Taïcha area is based on satellite imagery, 1/25,000 scale topographic maps, and the urban development plan of

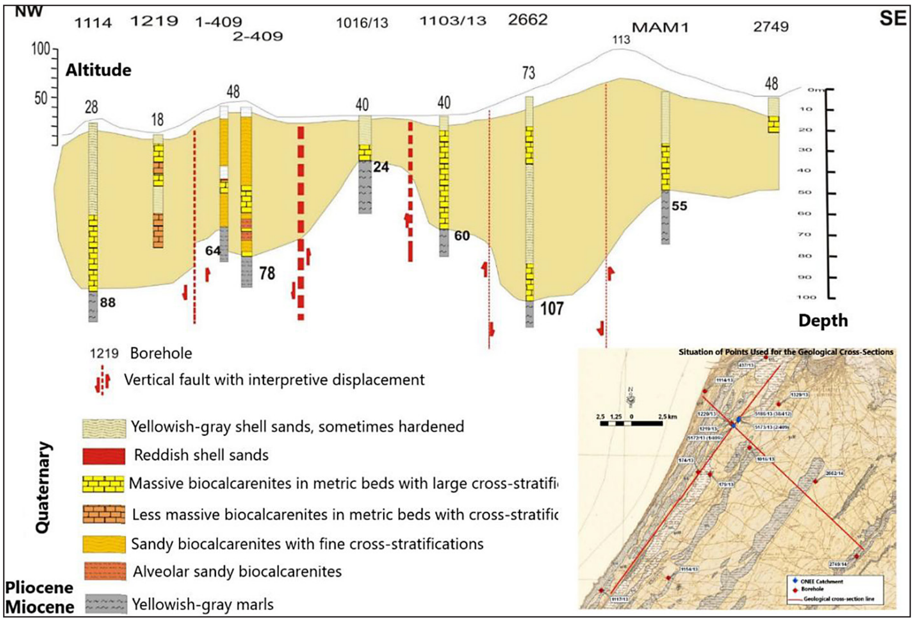

Figure 4. Geological cross-section in the Taïcha area perpendicular to the coast (ONEE, 2014)

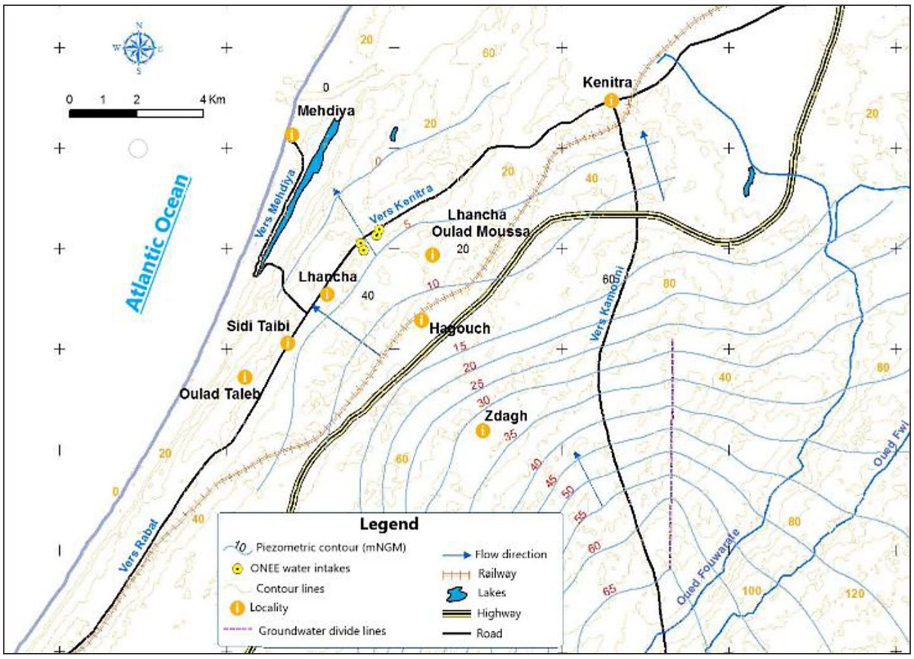

Figure 5. Piezometric map of the aquifer in the Taïcha region (ONEE, 2014)

southern Kénitra. This study identified the main land use categories and their distribution (Fig. 6).

The Maâmora forest dominates the landscape, covering 70.4% of the total area (Laaribya et al., 2011). It is primarily composed of cork oak and eucalyptus, providing raw materials for local industries such as Liège du Maroc and Cellulose Maroc.

Residential areas (both urban and rural) account for about 12% of the total surface, with concentrations in Kénitra, Sidi Taïbi, and nearby localities (ONEE, 1995).

Water bodies include Lake Sidi Boughaba, a Ramsar-listed protected site, and several dayas (temporary ponds) such as Dayet Moussmen and Dayet Oulad Zid, which play a significant role in groundwater recharge (Marchal, 2007). Agricultural land covers 4.5% of the area and is associated with risks of nitrate and pesticide pollution (Nassah & Omdi, 2011).

The pedological study of Taïcha aims to assess the soil's purifying capacity. Five soil types were identified, influenced by humification, leaching, and hydromorphy. Seven cartographic units were defined based on sand composition and thickness, allowing for the analysis of their filtration and drainage capacity (Fig. 7).

The groundwater of the Taïcha catchment field is threatened by various pollution sources, mainly agriculture (fertilizers, pesticides), domestic wastewater, and solid waste. A survey conducted in March 2017 identified five types of pollution sources with varying impacts. Solid waste pollution, especially during the rainy season, poses a major risk. Approximately 127 tons of waste are produced by three localities, generating 14.5 m³ of leachate, which is scattered as black spots around these areas (Fig. 8) (PDAIRE, 2004).

For a quick estimation of the protection zone in an unconfined aquifer with interstitial porosity, the 50-day isochrone was calculated using five rapid estimation methods (cylinder method, Wyssling method, Jacob-Bear method, and Hoffmann and Lillich method) (Zeghoud, 2014). It is important to note that the boundaries determined by these methods are theoretical and not valid in practice due to the spatial variability of aquifer characteristics and external factors, such as the pumping activities by RAK, which withdraw 12 Mm³ from the area.

The application of these methods requires the following data:
- transmissivity or permeability of the aquifer;
- thickness of the aquifer;
- pumping rate and drawdown;
- effective porosity.

To evaluate the behavior of the groundwater table, a 45-hour pumping test was conducted,

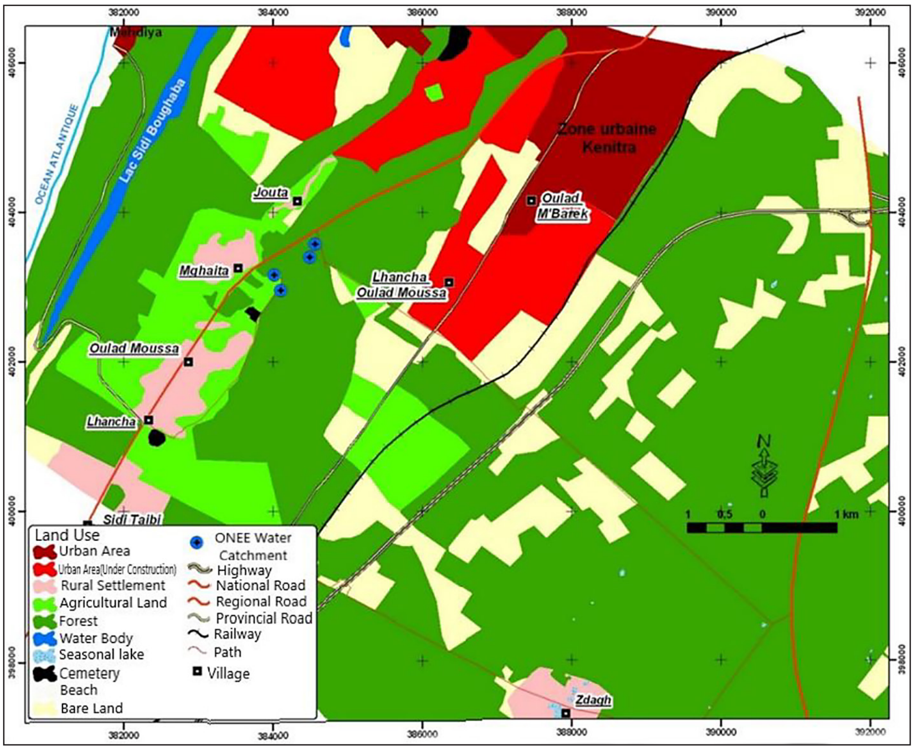

Figure 6. Land use map of the Taïcha Nassah & Omdi, 2011

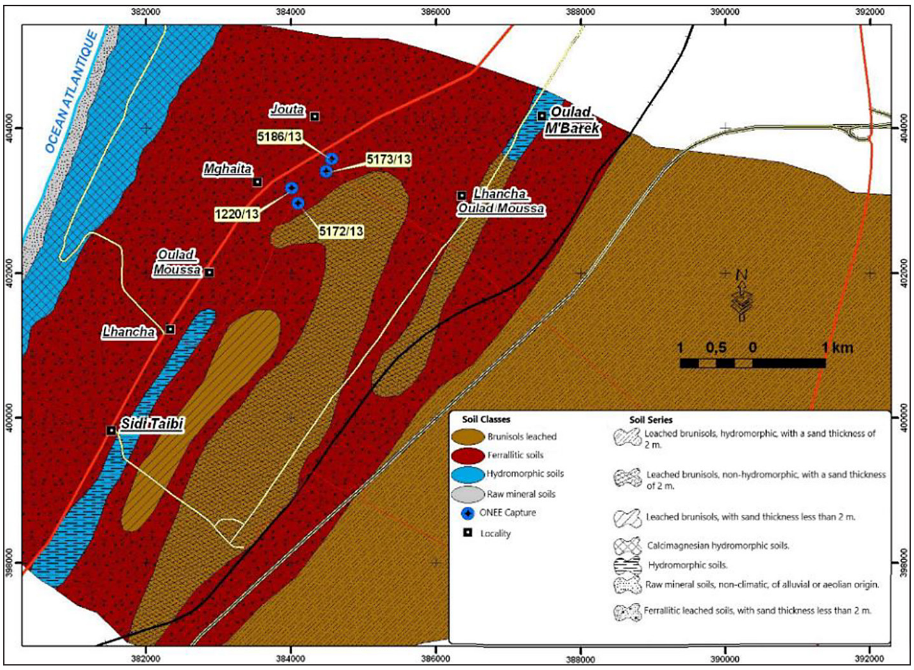

Figure 7. Soil map of the Taïcha area (ONEE, 2014)

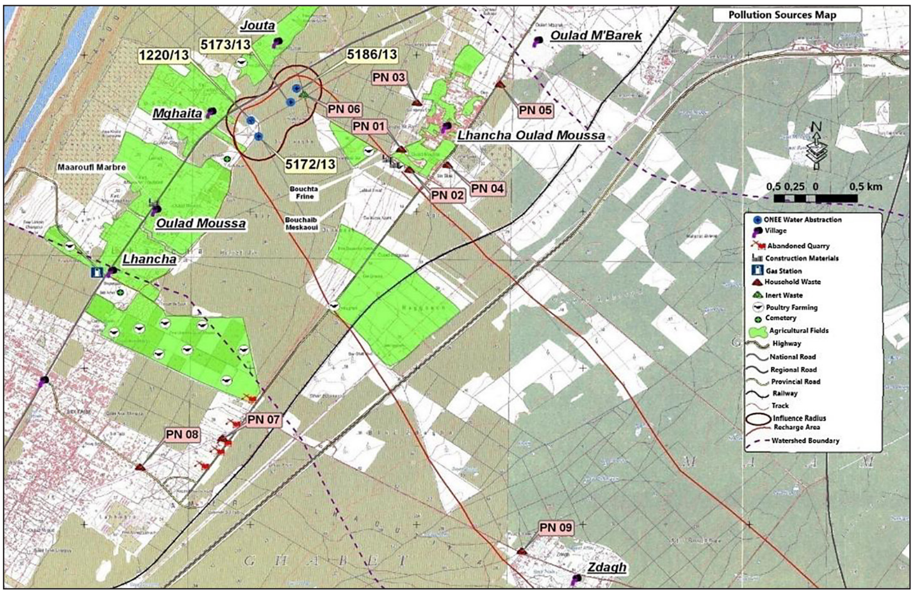

Figure 8. Pollution source map of the Taïcha area (ONEE, 2014)

following a 14-hour pause to allow water levels to stabilize. An average discharge rate of 84.5 liters per second was maintained. Monitoring of water levels in two wells allowed the plotting of drawdown evolution and the aquifer recovery rate. Despite the cessation of pumping, the water level had not fully recovered after 14 hours, remaining 1.89 meters below the initial level. During pumping, the water level dropped continuously, with a slope of 0.14%, until stabilization was reached after approximately 32 hours. No initial delay was observed, indicating a quick response from the aquifer. After pumping stopped, the water level gradually rose, with a slope of 0.18%, and stabilized after about 12 hours. These data were used to calculate the aquifer's characteristics, including transmissivity and storage coefficient, using the Jacob method. The calculated transmissivity values are as follows:

- at the well: 1.14×10^{-1} m²/s (drawdown), 1.02×10^{-1} m²/s (recovery);
- at the piezometer: 4.5×10^{-1} m²/s (drawdown), 2.27×10^{-1} m²/s (recovery).

To estimate the aquifer's ability to store and release water, the storage coefficient (S) was calculated using the formula:

$$S = \frac{2.25 \times T \times t0}{r2} \quad (1)$$

where: T =1.14×10−1 m²/s; r = 225 m ; t_0 = 4000 s; T – transmissivity in m²/s; r – distance between the pumping well and the piezometer (r = 225 m); t_0 – intercept of the drawdown curve at the piezometer with the time axis.

By inserting the measured values (transmissivity, distance, and time), a coefficient of 2.2% was obtained. This means the aquifer can release 2.2% of the water volume contained in one square meter of horizontal section for each meter of drawdown in the piezometric level. Even though well 1220/13 does not penetrate the full thickness of the aquifer, it is possible to estimate the average permeability using the average thickness observed (44 m) in other wells. By relating the transmissivity to this thickness, a permeability of 2.8×10^{-3} m/s was obtained, indicating good soil capacity for water flow. The raw data used for the pumping test and aquifer characterization (water levels, flow rates, well depths, transmissivity, etc.) were obtained from technical reports provided by the National Office of Electricity and Drinking Water (ONEE). Although these datasets are not available through open-access repositories, they may be consulted upon request from ONEE.

Distant protection zone (PPE)

The distant protection zone theoretically corresponds to the entire recharge area (or zone) of the wellfield. Its definition is based on the delineation of the recharge area where the flow lines are directed toward the utilized wellfield (Marchal, 2007). In the Taïcha area, the recharge area is extensive, making it necessary to limit the delineation of the distant protection zone to the aquifer recharge area to balance the maximum flow rate produced by the wellfield (Ezzaouaq et al., 1995). The recharge area can be calculated using the following formula:

$$S = Q/I \times 10^{-3} \quad (2)$$

where: S – recharge area [km²], Q – maximum discharge [m³/year], I – infiltration [mm].

The infiltration I is equal to the average annual precipitation multiplied by the infiltration rate. The average annual precipitation is calculated based on the nearest possible meteorological stations to the catchment or the capturing field.

RESULTS AND DISCUSSION

This study's main achievement lies in the delineation of scientifically and spatially justified protection perimeters for the Taïcha well field. Using a combination of pumping test analysis, hydrogeological modeling, and GIS-based mapping, we identified and defined three protection zones – immediate, close, and distant – that reflect the aquifer's behavior, recharge dynamics, and vulnerability to pollution. This integrated approach not only provides a technical basis for the protection of the Maâmora aquifer but also offers a methodological framework that can be replicated in other groundwater catchments across Morocco.

Immediate protection perimeter (IPP)

The vulnerability of the aquifer requires the establishment of a significant immediate protection perimeter (more than 30 meters). The borehole 1220/13 is already equipped with a fence (30 × 40 m) that meets this requirement. The ONEE (National Office of Electricity and Drinking Water) needs to acquire land around boreholes 1/409, 2/409, and 38/412 for the installation of fences of similar dimensions.

Close protection perimeter (CPP)

Piezometric analysis indicates groundwater flow from SE to NW with an average hydraulic gradient of 0.0015. Pumping tests revealed a transmissivity of 1.14×10^{-1} m²/s, a storage coefficient of 2.2%, and an average permeability of 2.8×10^{-3} m/s for an aquifer with an average thickness of 44 m. The maximum extraction rates for the wells range between 50 and 80 l/s (Table 2). The calculations of the 50-day isochrone length are shown below.

Table 2. Extraction rates of wells in the Taïcha catchment field

Well	Extraction rate (l/s)
1220/13	80
5172/13 (1/409)	50
5173/13 (2/409)	70
5186/13 (38/412)	50

Cylinder method

The results of this method are presented in the Table 3.

Wyssling method

The Wyssling method produced 50-day isochrone lengths ranging from 1.5 km for well No. IRE 1220/13 to 1.4 km for wells No. IRE 5172/13 and 5186/13. However, these results are considered unrealistic because the calculated Su value exceeds X0, which is inconsistent. Therefore, this method is not suitable for transmissive aquifers like those in Taïcha (Table 4).

Hoffmann and Lillich method

The 50-day isochrone length is approximately 1547 m (Table 5).

Jacob-Bear method

The Jacob-Bear method evaluates the 50-day isochrone at more than 1 km upstream of the wells. For the Taïcha catchment field, the calculations considered the simultaneous operation of 4 wells, represented by a fictitious well located at the barycenter of the wells with a total flow rate of 250 l/s (sum of the flow rates of the 4 wells) (Fig. 9). This method, based on analytical elements, accounts for the simultaneous operation of the wells. The results are presented in Table 6. This method estimates the length of the 50-day isochrone at 1470 m, of which 1255 m is located upstream of the hydraulic gradient of the pumping field. It is worth noting that the aquifer exploited by the Taïcha pumping field resembles a homogeneous sedimentary environment with interstitial permeability. It is estimated that after 50 days of circulation in the saturated zone of this aquifer, most of the pathogens are eliminated. The boundary of the close protection perimeter is therefore chosen to correspond to the position of the 50-day isochrone (Fig. 10). The boundary of this perimeter is slightly adjusted to account for certain field realities.

Table 6. Results of the Jacob-Bear method applied to the pumping field

Designation	Taïcha pumping field
Flow rate (l/s)	250
Distance upstream (m)	1255
Distance downstream (m)	215
Length of the isochrone (m)	1470

Table 3. Results of the cylinder method

IRE No.	1220/13	5172/13 (Taicha I)	5173/13 (Taicha II)	5186/13 (Taicha III)
Flow rate (l/s)	80	50	70	50
Radius (m)	354	280	331	280

Table 4. Results of the Wyssling method

IRE No.	1220/13	5172/13 (Taïcha I)	5173/13 (Taïcha II)	5186/13 (Taïcha III)
Flow rate (l/s)	80	50	70	50
Capture radius X0 (m)	76	48	67	48
Flow front B (m)	480	300	420	300
Upstream hydraulic distance So (m)	949	904	934	904
Downstream hydraulic distance Su (m)	132	86	117	86
Isochrone length = So + Su (m)	1081	990	1051	990

Table 5. Results of the Hoffmann-Lillich method

N°IRE	1220/13	5172/13 (Taicha I)	5173/13 (Taicha II)	5186/13 (Taicha III)
Flow rate (l/s)	80	50	70	50
Radius r (m)	0.02	0.02	0.02	0.02
Upstream hydraulic distance (m)	774	774	774	774
Downstream hydraulic distance (m)	774	774	774	774
Isochrone length (m)	1547	1547	1547	1547

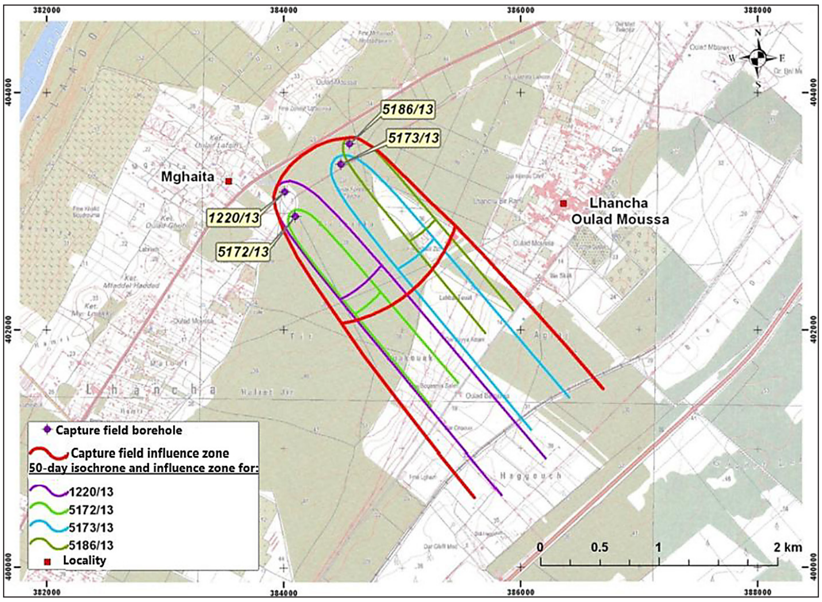

Figure 9. Delimitation of the influence zone of the Taïcha pumping field using the analytical method (Jacob-Bear)

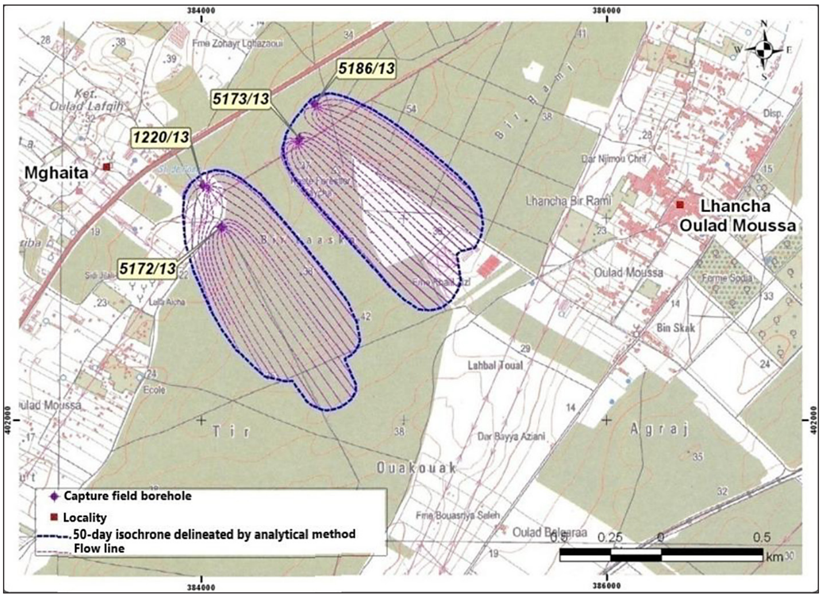

Figure 10. Delimitation of the 50-day isochrone using the analytical elements method

Distant protection perimeter

The boundary of the distant protection perimeter is chosen to correspond to the limit of the recharge area of the Taïcha pumping field. It covers an area of approximately 72 km².

CONCLUSIONS

This study successfully delineated the immediate, close, and distant protection perimeters of the Taïcha groundwater catchment field using a combination of pumping test interpretation, hydrogeological modeling, and spatial analysis with GIS tools. The results confirm the vulnerability of the Maâmora aquifer and provide a technical basis for establishing regulatory protection zones.

The immediate perimeter includes fenced areas around each borehole, while the close perimeter – based on the 50-day isochrone and pathogen attenuation criteria – covers an area of approximately 170 hectares, extending 450 meters upstream and 345 meters downstream of the well field. The distant perimeter corresponds to the recharge area of the aquifer and spans about 72 km².

A major contribution of this work lies in its integration of multi-model isochrone estimation (Cylinder, Jacob-Bear, Hoffmann & Lillich) with thematic mapping of piezometry, land use, and pollution sources – methodology not previously applied to the Taïcha field. This fills a significant gap in Morocco's groundwater protection framework, where many catchments still lack scientifically defined perimeters.

The outcomes provide a replicable model for other Moroccan aquifers, supporting future implementation by water authorities and planners. They also highlight the need for institutional coordination, access to real-time hydrological data, and the integration of scientific tools into national groundwater protection strategies.

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