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Spatial assessment of groundwater recharge, agricultural pumping, and hydrodynamic stress in the complexe terminal aquifer (Ghardaïa, Algeria) using GIS and Remote Sensing

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Abstract: This study develops an integrated GIS-ArcGIS, remote sensing (NDVI), and multi-criteria decision analysis (FAHP) framework to evaluate the water balance of the unconfined Complexe Terminal aquifer in the hyper-arid region of Ghardaïa, Algeria. While classical macro-spatial approaches suggest a reassuring surplus balance of +12.65 hm^3/year with modeled natural recharge (sim 47.81 hm^3/year) exceeding actual satellite-derived agricultural pumping (sim 35.16 hm^3/year) granular top-down discretization using Thiessen polygons exposes severe localized hydrodynamic stress. Historic oasis perimeters like Mansourah and Bounoura face acute groundwater mining conditions, where real volumetric abstractions overwhelm localized recharge by a factor of 10 to 12.7, resulting in irreversible piezometric drawdown. Conversely, massive, uncultivated peripheral cells in Guerrara mathematically distort the macro-balance. To mitigate local depletion, the validated FAHP model successfully maps optimal upstream green-engineering retention sites along Wadi M'zab and Wadi Metlili to maximize floodwater infiltration and artificially stabilize vulnerable water tables.

Keywords: ArcGIS, Remote sensing, Satellite imagery, Agricultural pumping, Groundwater recharge, Ghardaïa, Algeria.

1. Introduction

Groundwater constitutes a vital natural resource for drinking water supply, domestic use, livestock, and agricultural irrigation, particularly in arid and semi-arid regions where surface water availability is structurally limited [1,2]. Over recent decades, rapid population growth, industrial expansion, and the development of intensive agricultural activities have led to an exponential increase in demand on global aquifers [3,4]. This widespread dependency and the resulting overexploitation are causing a rapid and alarming decline in

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piezometric levels worldwide [4,5]. Faced with this major water security challenge, the accurate estimation of hydrological balance components notably pumped volumes and recharge rates has become a fundamental prerequisite for the sustainable management and preservation of these limited resources [6-8].

However, spatially and temporally quantifying the inflows (recharge) and outflows (discharge/pumping) of a complex aquifer system remains a major challenge due to high uncertainties associated with direct measurement methods [6,9]. To overcome these limitations, the integration of remote sensing (RS) technologies and Geographical Information Systems (GIS) has emerged over the last thirty years as a powerful, cost-effective, and essential approach for groundwater resource exploration, mapping, and modeling [10-13]. These tools enable the storage, manipulation, and analysis of large volumes of spatial data while extracting detailed information across vast or poorly accessible areas [14-16].

In the scientific literature, coupling remote sensing and GIS is widely deployed along two main paths: delineating potential recharge zones and quantitatively estimating water balances. On one hand, groundwater recharge potential zones (GWRZ) mapping frequently relies on multi-criteria decision analysis (MCDA), where multiple thematic layers such as geology, geomorphology, slope, drainage density, land use/land cover, and soil types—are integrated and weighted [11,14,17]. This weighting is generally executed via Saaty's Analytic Hierarchy Process (AHP) [1,18] or the influencing factors (IF) technique [17]. Numerous studies, such as those conducted in India [11,19,20], Saudi Arabia [1, 2, 18], Pakistan [15], Egypt [3, 21], Iraq [22,23], or Ethiopia [16], have demonstrated the efficacy of these methods in locating optimal sites for natural infiltration or the implementation of artificial recharge structures such as spreading basins, injection wells, and check dams [24, 25, 26]. To optimize and validate these surface-level models, several authors advocate coupling GIS mapping with field data, such as piezometric monitoring [24], pumping tests, or geophysical prospecting (geoelectrical methods via vertical electrical soundings, VES) to better characterize the geometry and productivity of deep reservoirs [3,21,27]. Additionally, recent incorporation of advanced statistical models and machine learning algorithms (such as logistic regressions or Random Forest) further enhances the spatial precision of aquifer productivity estimation [3,13].

On the other hand, remote sensing contributes significantly to reducing uncertainties in quantitative hydrogeological modeling. Satellite imagery (such as Landsat, SPOT, Sentinel, or ASTER) provides accurate and dynamic monitoring of land cover and vegetation indices [1,2]. These surface data are critical because environmental changes—whether anthropogenic or induced by natural disasters—directly affect soil hydrodynamic properties and permanently alter aquifer recharge capacities [13]. Moreover, implementing algorithms based on thermal and multispectral imagery allows for a more precise estimation of actual evapotranspiration (ET) and vegetation-driven discharge [6, 7], two major components controlling the global water balance [8,24]. Integrating these spatialized fluxes into distributed hydrological models has proven essential for faithfully simulating aquifer responses to rising pumping rates and predicting future resource deficit scenarios [4,6,8].

Algeria, and more specifically its Saharan regions, is no exception to this global issue of escalating pumping and climate vulnerability, requiring the joint application of GIS and geophysics to guide exploration campaigns [27]. The Ghardaïa region, characterized by a hyper-arid climate, relies almost exclusively on groundwater resources to sustain its rapidly expanding oasis agriculture and fulfill the needs of a growing population. In this context of extreme aridity, natural recharge is low, while the estimation of volumes extracted by agricultural boreholes and the overall understanding of recharge dynamics remain fragmented.

To address these local challenges, this study aims to apply an integrated approach combining ArcGIS software, remote sensing, and multispectral satellite imagery to accurately estimate pumped water volumes and evaluate groundwater recharge potential in the Ghardaïa region (Algeria). Drawing upon the proven methodology of water balance models and multi-criteria spatial analysis, this work seeks to provide a robust decision-support tool for local water managers, thereby contributing to the formulation of sustainable management frameworks to preserve this strategic aquifer in a Saharan environment.

2. Description of the study region

The study area spans the territory of the Ghardaïa Wilaya, located in the northern part of the Algerian Sahara, between latitudes 31° and 33° North and longitudes 2° and 5° East. It covers a vast area characterized by a rocky plateau topography known as the M'zab Chebka, which is deeply incised by morphologically steep wadi valleys (Wadi M'zab, Wadi Metlili, Wadi Sebseb, Wadi Berriane).

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From a climatic standpoint, the region is subjected to a hyper-arid Saharan regime. Rainfall is characterized by its extreme scarcity (an interannual mean between 60 and 80 mm) and its torrential and unpredictable nature. A single exceptional rainfall event can trigger devastating flash floods and contribute more than 50% of the annual total accumulative rainfall. Summer mean temperatures regularly exceed 45°C, inducing substantial potential evapotranspiration (ET0), which imposes major thermal and water constraints on crops.

Geologically and hydrogeologically, the bedrock of the region is dominated by Upper Cretaceous sedimentary formations. The plateaus (hamadas) are capped by rigid Cenomanian and Turonian limestones and dolomites, forming a structural slab with low matrix permeability but local fracturing. Valley floors and endorheic depressions accumulate Quaternary deposits of alluvial, colluvial, and aeolian origin (sands, gravels, silts). The aquifer targeted by this study is the unconfined water table of the Complexe Terminal (CT). It is primarily replenished through direct infiltration of floodwaters through permeable wadi beds and fracture zones, while its discharge occurs via massive abstractions from irrigation boreholes and natural outflow toward the chotts located further to the northeast (Figure 1).

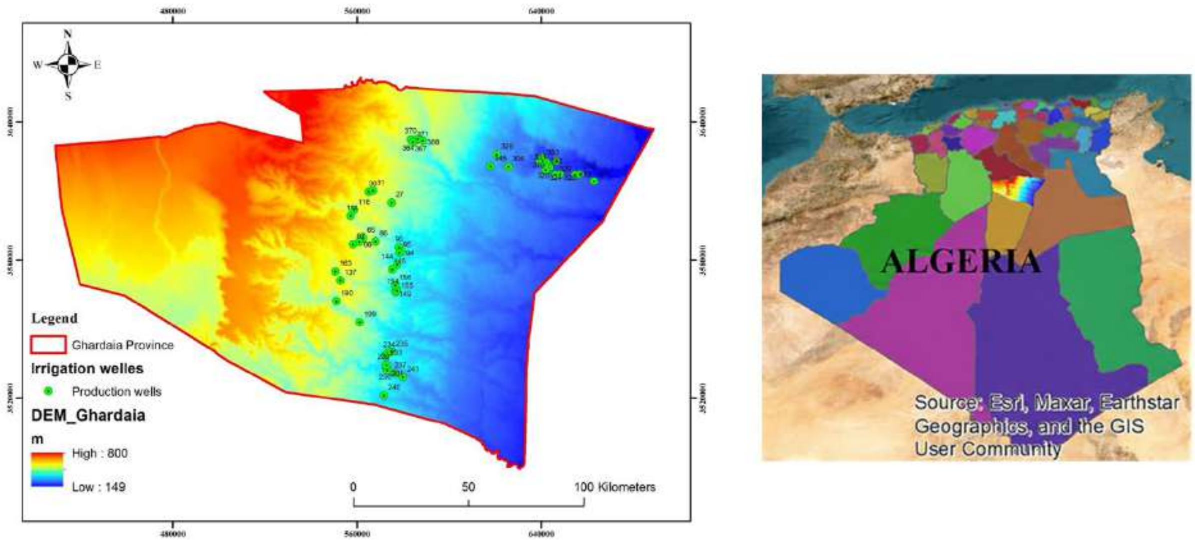

Figure. 1 Localization of the study area

3. Methodological framework

The implemented methodological protocol relies on the systemic integration of multi-source data (satellite, climatic, geological, and borehole engineering) structured around three fundamental axes under the ArcGIS environment.

3.1 Agricultural Surface Mapping via Remote Sensing (NDVI)

To identify the exact geometry of cultivated areas independently of often-obsolete administrative declarations, the Normalized Difference Vegetation Index (NDVI) was calculated across the entire Wilaya from the reflectances of the Red (R) and Near-Infrared (NIR) channels: eq.1

$$NDVI = \frac{NIR - R}{NIR + R} \qquad \text{eq. 1}$$

Since the Saharan matrix presents a strong reflectance signature due to the brightness of bare soils and the limestone slab, a strict analytical threshold of NDVI ≥ 0.25 was established to isolate exclusively surfaces in active photosynthetic activity (dense palm groves, greenhouse vegetable crops, tree concessions, and large cereal pivots). The validated pixels were converted into vector polygons to extract the spatial variable VALUE_1, representing the net agricultural area (in m²) controlled by each hydraulic structure.

Received: March 10, 2026 Published: June 30, 2026

3.2 Modeling of Net Irrigation Requirement (Bn) and Extracted Volumes

The calculation of actual water consumption is based on the FAO-56 method. The net irrigation requirements (Bn, in mm) are defined by the formula: eq. 2

$$Bn = ETc - Peff \quad \text{eq. 2}$$

Where ETc corresponds to crop evapotranspiration under standard conditions (ETc = Kc × ET0) and Peff represents the effective rainfall fraction. In hyper-arid Saharan zones during the vegetative development season, effective rainfall is considered negligible (Peff ≈ 0). The crop coefficient (Kc) was continuously spatialized from NDVI by adapting empirical transfer equations validated for arid environments in North Africa.

The actual annual volume consumed for each water point (V_real, in m^3/year) is then derived by applying the principle of continuity on the rasterized agricultural surface (VALUE_1): eq. 3.

$$V\text{real} = \left(\frac{Bn}{1000}\right) \times VALUE\_1 \quad \text{eq. 3}$$

3.3 Modeling of Net Irrigation Requirement (Bn) and Extracted Volumes

To geographically evaluate the hydrogeological supply, a Fuzzy Analytic Hierarchy Process (FAHP) approach was developed. It integrates four fundamental thematic layers: outcropping formation lithology, topographic slope derived from a Digital Elevation Model (DEM), drainage density of the hydrographic network (proximity to wadis), and land use. The fuzzy membership function enabled the standardization of criteria between 0 (zero potential) and 1 (maximum potential). Matrix weights were validated by calculating the consistency index (CI < 0.1). Combining these rasters via map algebra generated a Recharge Potential Index map, which was subsequently discretized into a physical value of annual infiltrated water depth (mm/year).

3.4 Spatial Discretization via Thiessen Polygons

To locally confront localized oasis demand (boreholes) with diffuse or linear recharge (oueds), the geometric structures of Thiessen polygons (Voronoi) were generated around the 54 listed boreholes. Each borehole was assigned an exclusive polygonal area of influence, representing its hydrogeological catchment and capture zone.

The ArcGIS Zonal Statistics as Table tool was executed to extract the mean value of the infiltrated water depth (MEAN Lame in mm/year) over the surface of each Thiessen polygon (Area_Polygone in m^2). The specific recharge volume for each mesh (V_recharge in m^3/year) is formulated by: eq. 4

$$Vrecharge = \left(\frac{MEAN\ Lame}{1000}\right) \times Area\_Polygone \quad \text{eq. 4}$$

The final spatialized mass balance (ΔV, in m^3/year) at the scale of each influence cell is governed by the equilibrium equation: eq. 5

$$\Delta V = Vrecharge - V\text{real} \quad \text{eq. 5}$$

4. Results and discussion

4.1 Agricultural surface mapping via remote sensing (NDVI)

The application of the multi-spectral satellite image processing protocol yielded an objective visualization of plant dynamics throughout the study territory.

The raw Normalized Difference Vegetation Index (NDVI) map across the Wilaya scale shows strong spatial polarization. The Saharan matrix overwhelmingly displays NDVI values close to 0 or slightly negative (represented by light and neutral hues), matching the bare limestone slabs of the M'zab Chebka and the hamadas lacking any vegetative cover. The most dynamic reflectance contrasts (highest NDVI values, displayed in dark

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and dense hues) are strictly confined to the linear corridors carved by the deeply incised hydrographic network, as well as the intensive agricultural expansion hubs of Guerrara and Mansourah (Figure 2).

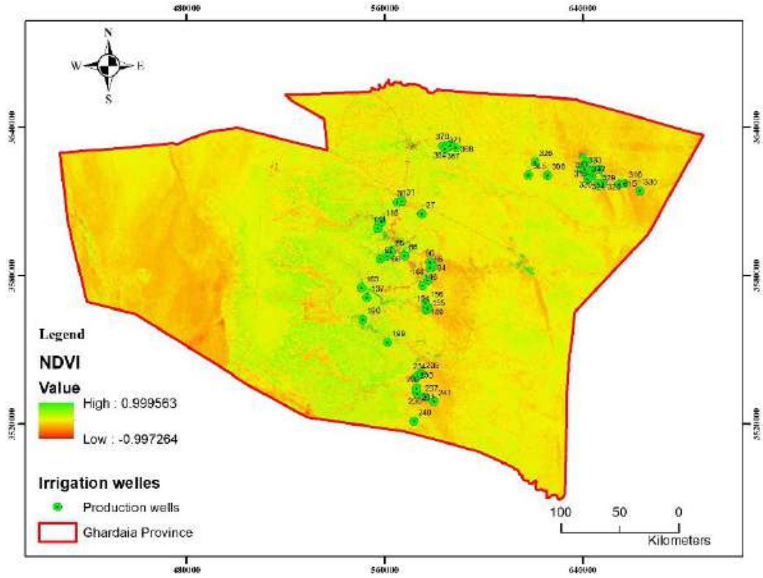

Figure. 2 The raw normalized difference vegetation index (NDVI) map

Applying the strict analytical threshold (NDVI > 0.25) on this second map successfully isolated the background noise of bare soils digitally, allowing the system to binarize space and extract the spatial variable VALUE_1 (net Agricultural Surface Area). The validated vector polygons reveal heavily contrasting agrarian layouts: on one hand, a traditional dense oasis fabric structurally restricted to wadi valley beds (Wadi M'zab at Ghardaïa, Bounoura, and El Atteuf); on the other hand, a territorial fragmentation highlighted by massive circular pivot irrigation projects established in the middle of the desert within the Guerrara municipality. This mapping provides clear evidence that the actual agricultural surface cultivated on the ground deviates significantly from past administrative and cadastral declarations (Figure 3).

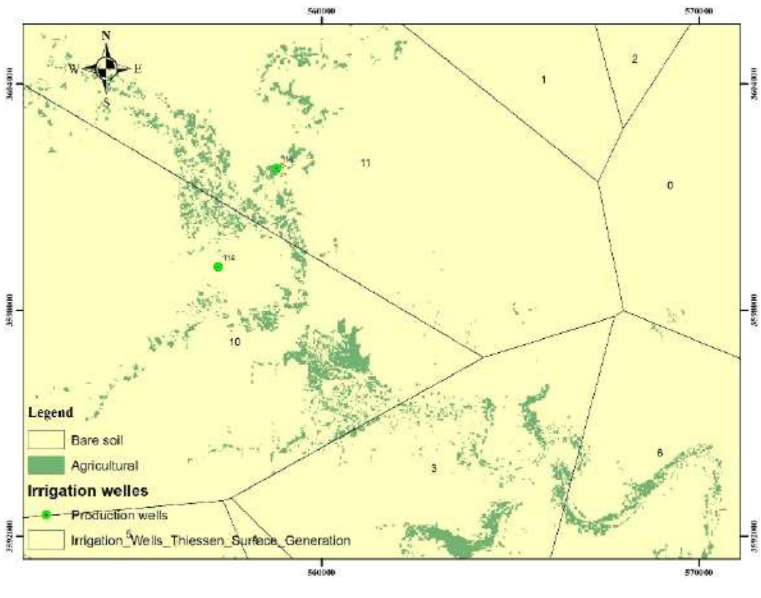

Figure. 3 Agricultural Surface Delimitation via NDVI

4.2 Modeling of Net Irrigation Requirement (Bn) and Extracted Volumes

The spatialization of irrigation water requirements is derived directly from the continuous monitoring of the spatio-temporal distribution of photosynthetically active crop tissue (Figure 4).

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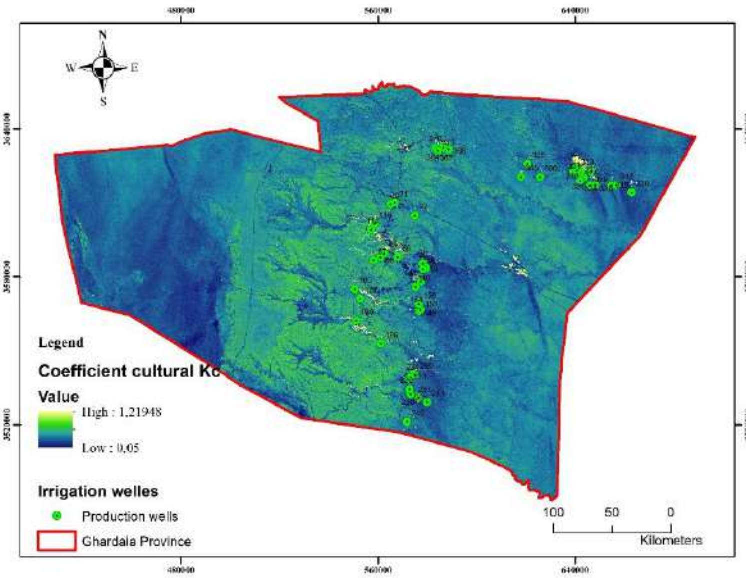

Figure. 4 Crop Coefficient Kc

The spatialized crop coefficient (Kc) map translates the vegetative development phase of crops across the agricultural grids. The Kc values vary continuously across the agricultural area. The lowest values represent transition fringes and young plants with low soil cover, whereas peak values (near or exceeding 1.0) match the hearts of dense palm groves and pivots during full canopy development. This distribution demonstrates the high intra-plot heterogeneity of water transpiration demands within the irrigated perimeters.

The crop evapotranspiration map under standard conditions (ETc) represents the product of the prior crop coefficient map and the regional baseline climatic demand (ET0). It quantifies the annual water depth (in mm/year) potentially returned to the atmosphere by the soil-plant system. The high-intensity evaporative zones precisely replicate the isolated agricultural patches. The extreme hyper-aridity of the surrounding environment amplifies the local microclimatic gradient above these green oases (oasis effect), pushing crop water extraction requirements to critical thresholds during the summer season (Figure 5).

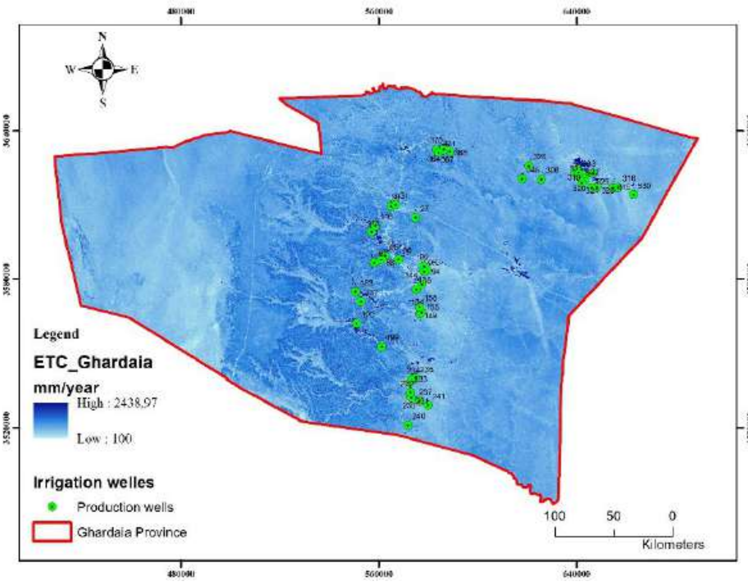

Figure. 5 Crop Evapotranspiration Map ETc

By accounting for the zero effective rainfall fraction typical of this hyper-arid climate (Peff approx 0), the net irrigation water requirement (Bn) map embodies the real hydric constraint that must be artificially compensated by groundwater extraction. Based on this geographical information layer, the actual annual volume consumed for each water point (Vreal) was simulated by applying the spatial continuity principle over the

Received: March 10, 2026 Published: June 30, 2026

cultivated surface (VALUE_1). It highlights that every single square meter of active vegetation relies on heavy, uninterrupted volumetric withdrawals from the unconfined Complexe Terminal aquifer (Figure 6).

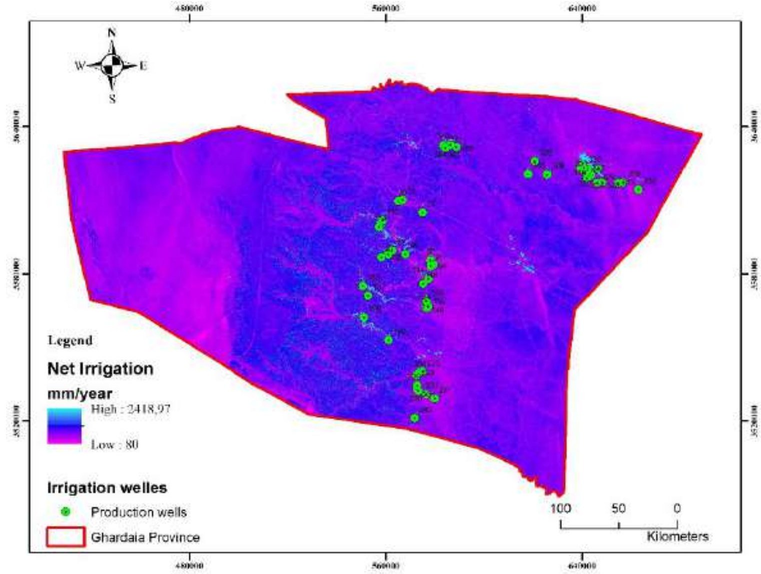

Figure. 6 Net Irrigation Requirements

4.3 Fuzzy Analytic Hierarchy Process (FAHP) and Recharge

Shifting the focus to the hydrogeological supply side requires a standardized multi-criteria approach (Figure 7).

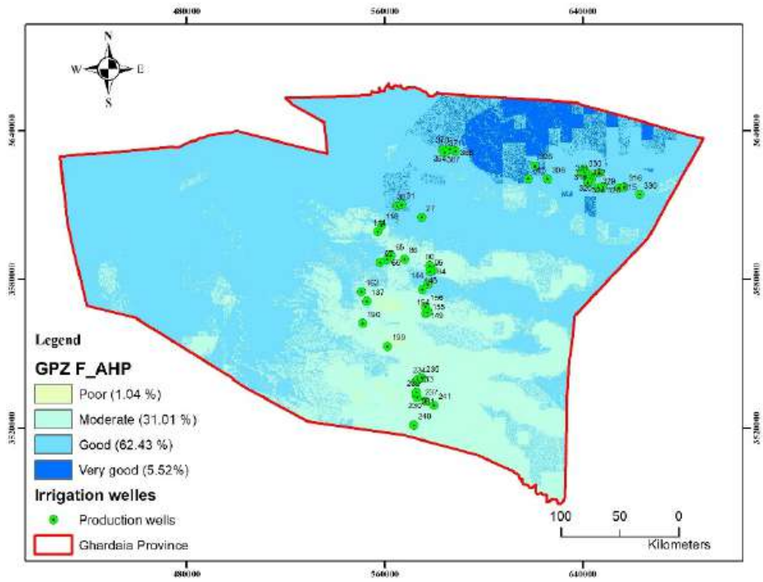

Figure. 7 The Groundwater Potential Zones (GWPZ) map

The Groundwater Potential Zones (GWPZ) map, processed using the Fuzzy Analytic Hierarchy Process (FAHP), categorizes the regional territory based on its propensity for surface water percolation. Zones classified as "Very Low" to "Low" potential occupy the vast majority of the Wilaya, pointing to the structural outcropping of rigid, unfractured Cenomanian-Turonian limestone plateaus. Conversely, "High" to "Very High" potential classes align flawlessly along the structural beds of Wadi M'zab, Wadi Metlili, and Wadi Sebseb. These preferred paths benefit from the combination of high porous matrix permeability (coarse Quaternary alluvial sediments) and flat terrain slopes (< 3%) which maximize surface water stagnation and downstream infiltration of floodwaters.

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The annual recharge depth map (R in mm/year) acts as the quantitative physical translation of the prior qualitative potential index map. It defines the actual water depth originating from sporadic torrential rainfall that successfully percolates to the unconfined water table. Infiltration depths (MEAN Lame) peak exclusively within the main active channels and terminal flood spreading zones, supplying the continuous numerical inputs required to build localized mass balance equations for each hydrogeological cell (Figure 8).

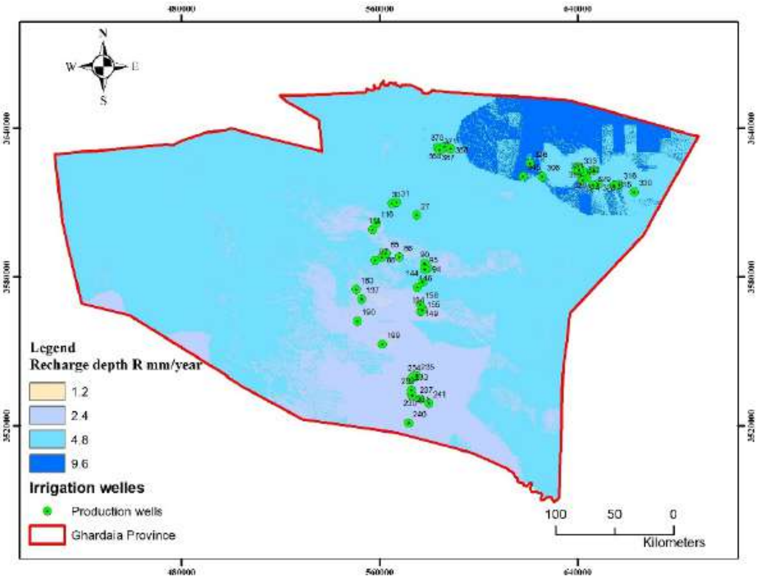

Figure. 8 Recharge Depth R

4.4 Spatial Discretization via Thiessen Polygons

To locally confront localized oasis demand (Figure 6) with diffuse or linear recharge via infiltration (Figure. 8), the study area was geometrically discretized (Figure 9).

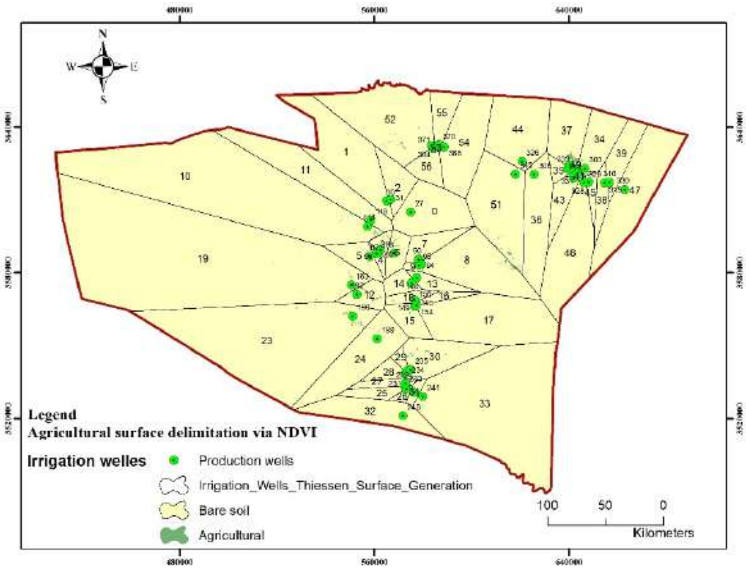

Figure. 9 Irrigation Boreholes and Thiessen Surface Areas

The final map (Figure 9) details the territorial division of the Wilaya into 54 unique Thiessen (Voronoi) influence polygons centered on operational boreholes. This map scientifically exposes the geometric masking bias of classical macroscopic approaches and demonstrates acute local groundwater stress (Delta V). High-density, micro-sized cells clustered in the historic oases and industrial-agricultural corridors of Mansourah and Bounoura point to a critical concentration of boreholes. Data crossing confirms that the actual volume pumped (Vreal) outweighs the localized natural recharge (Vrecharge) by a critical factor of 10 to 12.7 (e.g., boreholes

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232, 235, and 65). These cells operate under acute hydrodynamic pressure, characterizing a severe groundwater mining situation with a continuous decline in piezometric water levels.On the other hand, geographically immense peripheral cells located in the Guerrara region (such as borehole 320) incorporate massive desert areas with zero agricultural demand. Consequently, they mathematically intercept large theoretical wadi recharge volumes, which falsely skews the global macro-balance of the Wilaya toward an apparent surplus (+12.65 hm3/year), hiding the severe, localized drying out experienced by the actual agricultural production centers.

Exploiting the consolidated database derived from the ArcGIS model, which integrates the physical data of 54 major hydrogeological boreholes distributed across key municipalities of the Wilaya (Mansourah, Guerrara, Metlili, Sebseb, Bounoura, Daya, Berriane, and Ghardaïa), initially enabled the compilation of a global macroscopic balance (Table 1).

Table 1. Quantitative evaluation of the groundwater balance in the study area

Subterranean Balance Parameter	**Modeled Value (m^3/year)**	**Equivalent (hm^3/year)**
Actual Volume Consumed (V_real_total)	35157516.16	35.16
Authorized Regulatory Extraction Rate (Q_ext_total)	44050536.00	44.05
Modeled Infiltrated Recharge Volume (V_recharge_total)	47806686.03	47.81
Global Macroscopic Apparent Balance (ΔV_global)	+12649169.87	+12.65

Analyzing these macroscopic results shows that, at the scale of the entire Wilaya, the unconfined aquifer of the Complexe Terminal exhibits an apparent surplus balance of +12.65 hm^3/year when referring to actual abstractions determined by remote sensing. It is also observed that the actual volume consumed by agriculture (35.16 hm^3/year) remains nearly 9 hm^3/year lower than the maximum authorized regulatory extraction volume set by hydraulic services (44.05 hm^3/year). According to classical non-spatialized approaches, this overall situation would reflect a state of hydrogeological safety and a comfortable margin for granting new drilling permits. However, this macroscopic conclusion is biased by the geometric masking effect of the large Thiessen polygons and the extreme spatial heterogeneity of agricultural extraction centers.

The territorial discretization into Voronoi meshes shattered this illusion of a global balance by highlighting alarming local hydrogeological disparities (Table 2).

Table 2. Characteristics and volumetric balance of wells by municipality

Well No.	**Municipality**	**Area (m^2)**	**V_Real (m^3/year)**	**V_Recharge (m^3/year)**
232 / Ain Lessaig	Mansourah	1 559 700	753 374.25	58929.28
65 / N'tissa 1 F9	Bounoura	3 382 200	1 713 210.04	165346.13
235 / Oued Ghzalet 3	Mansourah	3 345 600	1 908 230.52	329580.08
320 / Drine 3 R-A	Guerrara	0	0.00	3661562.68

In sectors with historical and geometrical high borehole concentrations, such as the Mansourah municipality (wells 232, 235) and the industrial/agricultural zone of Bounoura (well 65), local balances collapse. At borehole 232 (Ain Lessaig historic palm grove), the actual volume extracted via remote sensing (753,374.25 m^3/year) exceeds by more than 12.7 times the theoretical rainfall infiltration capacity calculated within its own area of influence (58,929.28 m^3/year). The finding is similar for borehole 65 of N'tissa 1 in Bounoura, where the abstracted volume (1,713,210.04 m^3/year) overwhelms local recharge (165,346.13 m^3/year) by a factor of 10.3. These numerical indices characterize a groundwater mining exploitation scenario, leading to a continuous and irreversible decline in piezometric levels.

Conversely, influence cells located primarily in the Guerrara municipality (such as borehole 320 of Drine 3 R-A) display immense internalized recharge volumes (3,661,562.68 m^3/year) against zero consumption (0.00 m^3/year). This phenomenon is explained by the geometric immensity of their Thiessen polygons in peripheral areas with low infrastructure density. This accumulation of virtual water volumes in unexploited desert zones creates the illusion of an overall surplus balance at the Wilaya scale, whereas actual agricultural production zones suffer severe hydrodynamic drying up.

Received: March 10, 2026 Published: June 30, 2026

To reverse the piezometric degradation trends observed in the critical meshes of Mansourah and Bounoura, the fuzzy multi-criteria approach (Fuzzy-AHP) was utilized to rigorously map Groundwater Potential Zones (GWPZ). The objective was to precisely locate optimal sites for installing artificial aquifer recharge structures (check dams, flood spreading dykes, forced infiltration basins).

By crossing factors of high hydraulic conductivity (Quaternary coarse alluvial formations), flat topography (slope < 3% favoring water stagnation), and surface runoff concentration (main channels of Wadi M'zab and Wadi Metlili), sectors showing maximum infiltration capacity (mean water depth > 2.5 mm/year) were identified. These preferential sites are geographically situated immediately upstream hydraulically of the deficit agricultural perimeters. The targeted deployment of green retention structures in these keys meshes would slow down ephemeral torrential flash floods, optimize the volume of water infiltrating into the Complexe Terminal, and artificially stabilize the piezometry of drawdown cones induced by the wells.

5. Conclusion

The integrated use of multispectral satellite remote sensing through the NDVI index, combined with GIS-based map algebra techniques, has enabled the limitations of conventional hydrogeological balance assessments to be overcome in the Wilaya of Ghardaïa. The semi-automated extraction of active vegetation structures provided an objective, up-to-date, and spatially explicit representation of oasis irrigation water demand associated with a network of 54 production boreholes. By rigorously quantifying net crop water requirements (Bn), while considering the negligible contribution of effective Saharan rainfall, the annual groundwater abstraction attributable to actual pumping was estimated at 35.16 hm^3/year. This value was compared with the natural recharge volume calculated using a geospatial Thiessen polygon approach, estimated at 47.81 hm^3/year.

Although the hydrogeological system appears globally sustainable, exhibiting an apparent positive balance of approximately +12.65 hm^3/year, the detailed spatial analysis adopted in this study reveals significant local disparities that remain concealed by aggregated assessments. Several groundwater influence zones are subjected to severe hydrodynamic stress, particularly in the Mansourah sector (boreholes 232 and 235) and the Bounoura sector (borehole 65), where abstraction rates exceed natural recharge by factors ranging from 10 to 12.7. These findings highlight the inadequacy of relying solely on regional-scale water balance indicators and underscore the necessity of localized management strategies.

Furthermore, the integration of the AHP and Fuzzy-AHP multicriteria decision-making approaches proved effective in identifying priority areas for artificial recharge and green engineering interventions within the M'zab and Metlili wadis. Beyond its local application, the methodological framework developed in this study constitutes a transferable decision-support tool for sustainable groundwater management in arid and hyper-arid environments. Its implementation can contribute to strengthening the resilience of oasis agroecosystems and ensuring the long-term preservation of groundwater resources under increasing climatic and anthropogenic pressures.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, E.M. and B.M.; methodology, E.M.; software, A.F.; validation, E.M., B.M., and A.F.; formal analysis, E.M. and B.M.; investigation, E.M.; resources, B.M., H.B; data curation, A.F.; writing-original draft preparation, E.M.; writing-review and editing, B.M. and A.F.; visualization, A.F., B.M, E.M., H.B., A.B. and Y.S.; supervision, B.M.; project administration, E.M.; funding acquisition, B.M. All authors have read and agreed to the published version of the manuscript.

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