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Geothermal potential assessment using Integrated GIS and machine learning approaches

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Abstract. Growing global demand for clean and reliable energy highlights the need for sustainable alternatives that can also contribute to water scarcity mitigation in semi-arid regions. Geothermal energy provides a constant, low-carbon resource capable of enhancing long-term energy security and environmental resilience. This study develops an integrated, data-driven assessment of geothermal potential in northern Tunisia, applying a multidisciplinary framework that combines Geographic Information Systems (GIS), Remote Sensing (RS), Multi-Criteria Decision-Making (MCDM), Principal Component Analysis (PCA), and Kohonen Self-Organizing Map (SOM) clustering. Twelve thematic layers including geomorphological, geological, hydrogeological, structural, and climatic were analyzed, with weighted indices assigned to key factors, such as lithology, aquifer depth, fault and lineament density, slope, precipitation, and land surface temperature. Results show that approximately 48% of the region exhibits favorable to highly favorable geothermal conditions, with 22% classified as very good and 26% as good. The highest-potential zones align with the Tell Atlas structural corridor, characterized by intense faulting, permeable lithologies, deep aquifer systems, and active hydrothermal circulation, while low-potential zones occur in compact, poorly fractured aquifer units. The integrated approach offers a robust and reproducible method for mapping geothermal resources and supporting sustainable energy development in northern Tunisia.

1 Introduction

Water scarcity and renewable energy needs are intensifying globally due to population growth, industrialization, and climate change, including rising temperature and declining precipitation [1]. Geothermal resources are increasingly recognized as a sustainable solution for clean energy and water supply, particularly in arid and semi-arid regions [2-3] Beyond energy production, geothermal water is crucial for agriculture, industry, and domestic use, making its sustainable management essential. However, challenges such as overexploitation, geogenic contamination, and anthropogenic pollution remain significant [4-5]. These issues are documented across global geothermal fields, including California and Nevada [6], Iceland [7], East Africa [8], the Philippines [9], Turkey [10], and Tunisia [11-12]. Governance frameworks such as the GSAP (Geothermal Sustainability Assessment Protocol) provide guidance for environmental and technical performance [13-14], while reinjection, corrosion mitigation, and seismic monitoring support resource sustainability [15-18]. Geothermal potential assessment depends on factors such as storage capacity, recharge, precipitation, and climate impacts [12-19], requiring integrated analyses of geological, hydrothermal, and geomorphological conditions. GIS and RS have proven effective for processing diverse datasets and generating geothermal potential maps. Increasingly, Machine Learning (ML) methods such as Artificial Neural Networks (ANN), Random Forest Models (RFM), Decision Tree Models (DTM), and regression models enhance prediction accuracy [20]. Despite advances in GIS-, RS-, and ML-based geothermal exploration [21-22], applications remain limited in the Mediterranean region.

This study aims to map geothermal potential zones in northern Tunisia by integrating GIS, RS, parametric modeling, and ML. By combining structural, geological, and climatic factors with advanced analytical techniques, the study provides a methodological framework to support sustainable geothermal development and resource governance in regions facing similar energy and water challenges.

2 Study Area

The study focuses on northern Tunisia (Fig. 1A), a Mediterranean region characterized by wet winters and dry summers, where precipitation ranges from 700–1000 mm in coastal mountains, such as Kroumirie and Mogods [23-24], to 400–600 mm in inland plains [25]. The Medjerda River plays a key role in aquifer system recharge. Geologically, the area belongs to the Tellian domain of the Alpine orogeny and is composed of Mesozoic Cenozoic sedimentary rocks, including the Numidian Flysch [26-27]. Active tectonics, with major faults such as Nefza–Tabarka and Korbous Cap Bon, control groundwater flow [28-29]. Quaternary, Mio-Pliocene, and Cretaceous formations dominate the stratigraphy [30]. Hydrogeologically, the region contains interconnected shallow alluvial aquifers in coastal plains and valleys [31-32], semi-deep Mio-Pliocene aquifers in mountainous zones [33], and deep Cretaceous and Albian aquifers that serve as major groundwater reservoirs [34-38].

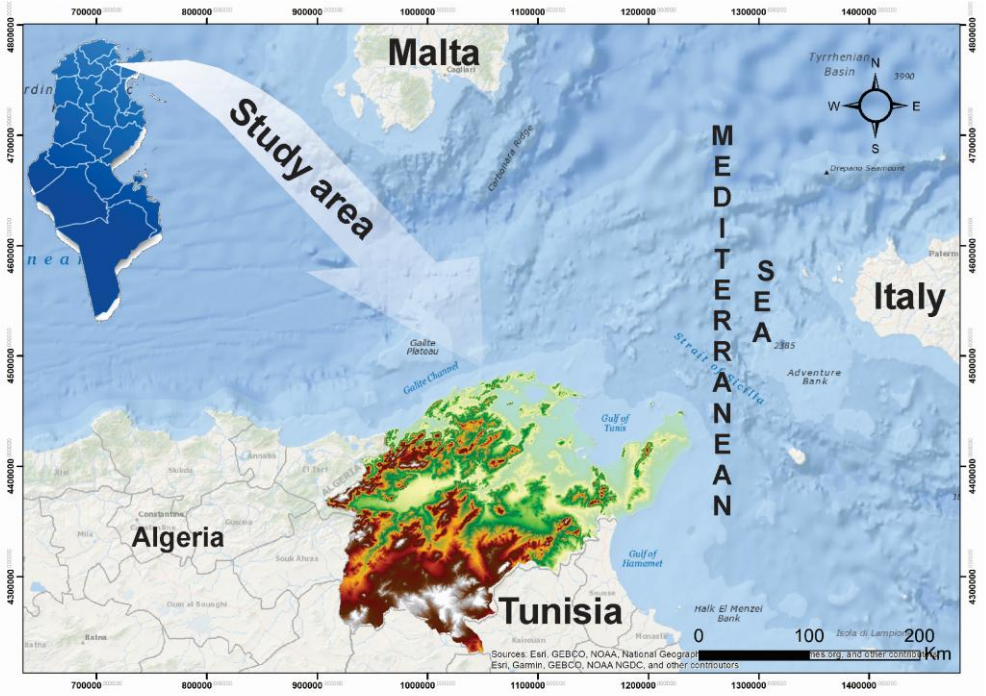

Fig.1. Study area presentation.

Human pressures overextraction, urban and agricultural demand are causing declining groundwater levels and salinization processes, especially from seawater intrusion in coastal areas [39-40].

3 Methodology

The geothermal potential will be assessed through an integrated approach combining Multi-Criteria Decision-Making (MCDM), Kohonen Self-Organizing Maps (K-SOM), and Geographic Information Systems (GIS). Geothermal resources are influenced by multiple factors, including topography, lithology, structural features, hydrogeology, land cover, and climatic conditions. A comprehensive geospatial database was developed using geological, hydrogeological, geomorphological, and climatic datasets, grouped into five key indices: Geomorphology, Geology, Hydrogeology, Structural, and Climate. Lithological maps were digitized from local geological sources, while Land Cover was derived from Landsat 8 imagery at 30 m resolution (Fig. 2).

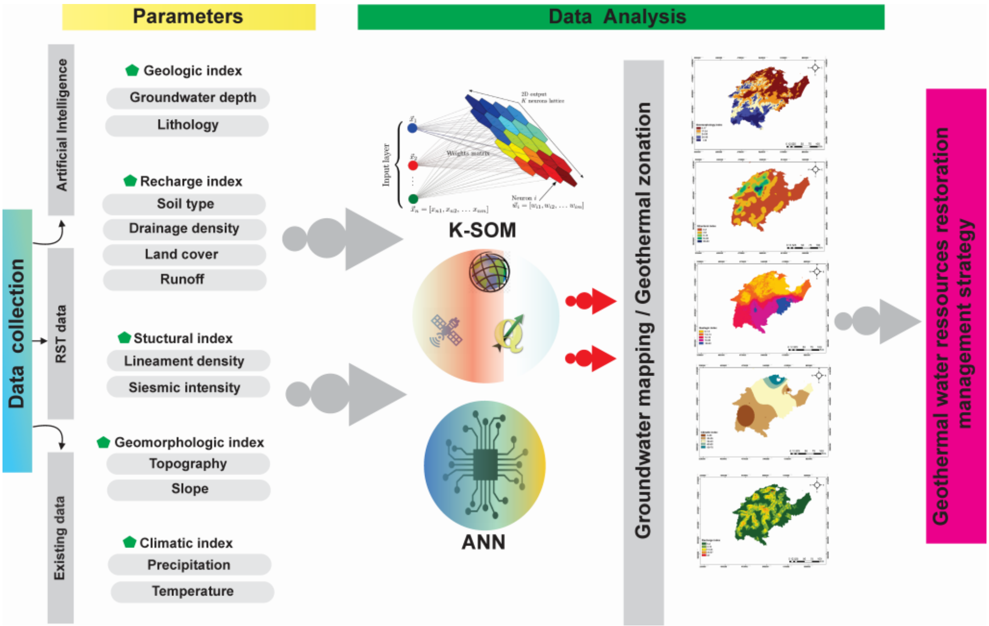

Fig. 2. Flowchart of applied methodology.

The different indexes will be presented:
Geomorphology Index (GI) integrates slope (S) and topography (T) to reflect landform control on runoff and recharge:

$$GI = (T + S)^{1/2} \tag{1}$$

Geology Index (GeI) incorporates lithology (L) and aquifer depth (Ad), which influence permeability and geothermal gradients:

$$GeI = (L + Ad)^{1/2} \tag{2}$$

Hydrogeology Index (HgI) includes soil type (St), runoff (Ro) drainage density (Dd), and land cover (Lc), with Ro calculated from precipitation and slope:

$$HgI = (St + Ro + Dd + Lc)^{1/4} \tag{3}$$

Structural controls are captured through the Structural Index (SI), combining tectonic density (Td) and lineament density (Ld):

$$SI = (Td + Ld)^{1/2} \tag{4}$$

Climate effects are represented by precipitation (P) and surface temperature (Ts):

$$CI = (P + Ts)^{1/2} \tag{5}$$

K-SOM, an unsupervised neural network Kohonen, was applied to classify geothermal potential conditions, preserving the topology of multidimensional data. Performance was evaluated using quantization error (Qe) and topographic error (Te). The factors were assigned weights and scores (1–10) based on their influence on geothermal systems, following inter-parameter relationships from previous studies. The weighted integration of the indices in ArcGIS enabled the delineation of high, moderate, and low geothermal potential zones, providing a robust and reproducible framework for sustainable geothermal resource assessment [41].

4 Results and discussion

The integrated hydrogeological framework of northern Tunisia combines geomorphology, structural, geological, climatic, and recharge indices to assess geothermal potential. Geomorphology influences heat transfer, with gentle topographic areas enhancing geothermal processes, while steep relief disrupts subsurface heat pathways. The structural index shows that high fault and fracture density, especially along the Atlassic chains, promotes deep circulation and heat transfer. Geological conditions, including permeable carbonates and Cretaceous–Jurassic formations, enhance geothermal systems, whereas clay-rich and compact Neogene–Quaternary deposits inhibit fluid flow. Climatic factors influence thermal conductivity, with humid northern regions favoring geothermal activity. Recharge availability regulates thermal fluid circulation, with high recharge enhancing heat transport [39-42-43].

Integrated indices highlight the north-central Tell-Atlas corridor as the most favorable geothermal zone, while peripheral basins show weaker potential [44]. Geospatial analysis combined with PCA and SOM clustering (Fig. 3) reveals strong spatial variability in geothermal favorability [12-45]. Northern and northwestern areas show "*very good*" to "*good*" potential, controlled by fault density and permeability [46-47]. Southern zones display "*low* to *very low*" geothermal potential due to stable geology and low heat flow [48-49].

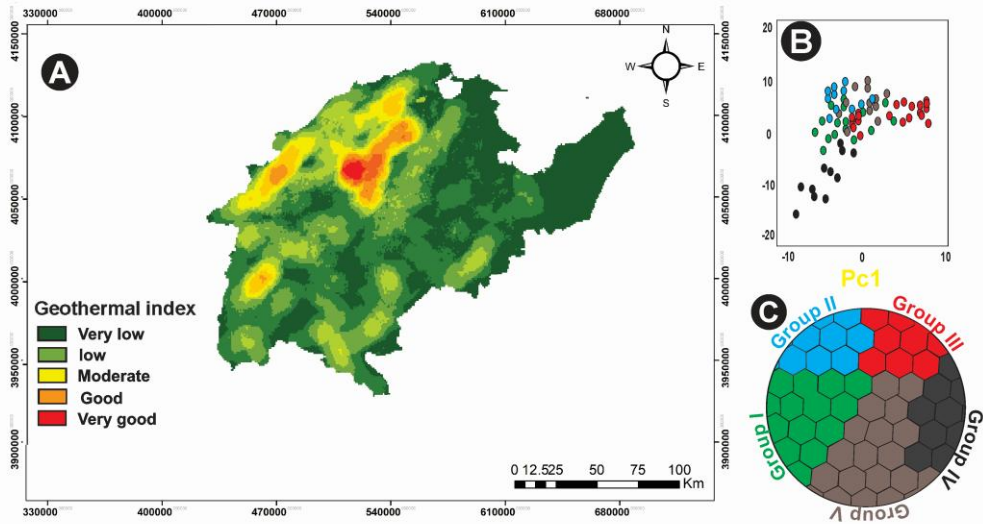

Fig. 3. Geothermal potential index (A), PCA of geothermal parameters (B), and cluster grouping of geothermal zones (C).

The PCA analysis (Fig. 9B) identifies surface temperature, fault density, lithology, and groundwater circulation as dominant controls [12]. Otherwise, SOM clustering (Fig. 9C) will define five geothermal potential groups, with Groups I and II covering nearly half of the area and representing the highest potential (Table 1).

Table 1. Classification of potential geothermal zones and respective occurrence

Geothermal Potential Class	Corresponding SOM Group	Area (%)	Characteristics
Very good	Group I	22 %	High heat flow, faulted area, shallow aquifers, and strong hydrothermal circulation.
Good	Group II	26 %	Favorable structural control, moderate-to-high geothermal gradient, and good fluid recharge.
Moderate	Group III	18 %	Transitional zone; moderate fault density and partially developed geothermal systems.
Low	Group IV	20 %	Weak geothermal gradient, compact lithology, limited permeability, and subdued heat flow.
Very low	Group V	14 %	Thick sedimentary cover, low structural influence, and poor geothermal manifestation.

A north–northeast geothermal corridor emerges as the primary exploration target, aligning with structural lineaments and thermal anomalies [50-51]. The combined GIS-PCA-SOM approach provides a high-resolution, data-driven framework for geothermal assessment, consistent with global applications. Recent studies conducted in China (2023–2025) demonstrate similar methodological success, while earlier research highlights the value of machine learning approaches in geothermal studies.

Overall, approximately 48% of the study area shows favorable conditions for clean-energy development, providing strategic guidance for sustainable geothermal exploitation and policy planning [53].

5 Conclusion

This study demonstrates that integrating GIS, PCA, and SOM clustering provides a robust framework for high-resolution geothermal potential assessment. Results reveal strong spatial variability, with the northern and northwestern sectors being most favorable due to high fault density, elevated heat flow, and enhanced hydrothermal circulation. Approximately 48% of the area is suitable for geothermal exploitation. The combined approach improves multi-factor data interpretation, strengthens classification reliability, and allows precise delineation of high-potential zones, as confirmed by the alignment of PCA factors, SOM clusters, and GIS-based geothermal maps.

Future research could integrate Remote Sensing (thermal or hyperspectral), hydrochemical, geophysical, and geomechanical data, and to apply the method temporally to monitor geothermal activity. This framework is transferable to other complex regions, supporting renewable energy planning, targeted exploration, and sustainable geothermal management.

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