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Spatial assessment of groundwater potential zones using remote sensing in the Volta basin

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Abstract

Can satellite imagery and terrain analysis reliably pinpoint where groundwater is most likely to accumulate beneath the surface of a semi-arid West African river basin? The Volta Basin, shared by six nations across 400,000 square kilometres, supports roughly 24 million people who depend heavily on shallow aquifers for domestic supply and small-scale irrigation. This research delineated groundwater potential zones across the upper Volta Basin in Ghana using an integrated approach combining Landsat 8 OLI imagery, ALOS PALSAR DEM data, and the Analytical Hierarchy Process (AHP) for multi-criteria weighting. Seven thematic layers, geology, lineament density, drainage density, slope, rainfall, soil type, and land use/land cover, were prepared in a GIS environment and reclassified into five suitability classes. AHP-derived weights assigned geology the highest influence (0.263), followed by lineament density (0.187) and drainage density (0.142). The weighted overlay produced a groundwater potential index (GPI) map classified as very high (8.7% of the area), high (21.3%), moderate (34.1%), low (24.6%), and very low (11.3%). Validation against 42 existing borehole yield records showed that 83.3% of high-yield boreholes (>5 m³/hr) fell within the high or very-high potential zones. Alluvial deposits and weathered sandstone corridors along major lineament intersections emerged as the most promising targets for new well siting.

Keywords: Groundwater potential, remote sensing, Volta Basin, analytical hierarchy process, lineament density, aquifer mapping, weighted overlay, Ghana, borehole yield, water resources

Introduction

About 280 million people across sub-Saharan Africa still lack access to safely managed drinking water, and groundwater is widely regarded as the most reliable path toward closing that gap ^[1]. In the Volta Basin, surface water availability swings sharply between wet and dry seasons, making shallow to intermediate-depth aquifers the backbone of rural and peri-urban supply. Yet drilling success rates remain disappointingly low, often below 60%, because boreholes are sited without adequate hydrogeological assessment ^[2].

Remote sensing offers a cost-effective reconnaissance tool for narrowing down favourable zones before committing to expensive drilling campaigns. Satellite-derived thematic layers such as lineament density, land use, and terrain slope serve as proxies for fracture permeability, recharge potential, and runoff partitioning, respectively ^[3]. When combined through a structured multi-criteria decision framework like the Analytical Hierarchy Process, these layers produce spatially continuous suitability maps that outperform single-criterion approaches ^[4].

Several researchers have applied GIS-based groundwater potential mapping in West Africa, but coverage of the upper Volta Basin in northern Ghana remains sparse [5,6]. The region's geology, a mosaic of Birimian metavolcanics, Tarkwaian sandstones, granitic intrusives, and Quaternary alluvium, creates a complex hydrogeological patchwork where aquifer productivity varies over short distances ^[7]. This research aimed to (a) map groundwater potential zones using seven thematic layers weighted by AHP, (b) validate the output against borehole yield data, and (c) identify priority areas for future well development in the upper Volta Basin.

Theoretical Background

The Analytical Hierarchy Process, developed by Saaty in 1980, structures complex decisions into a hierarchy of criteria, sub-criteria, and alternatives ^[8]. Pairwise comparison matrices

are constructed for each level, and eigenvalue analysis extracts normalised weights that reflect the relative importance of each criterion. The consistency ratio (CR) must remain below 0.10 to ensure logical coherence. In groundwater potential mapping, AHP translates expert judgment about the hydrogeological importance of different surface indicators into numerical weights that drive the spatial overlay. The approach has been validated across diverse geological settings, from crystalline basement terrains in India [3] to sedimentary basins in North Africa [9], consistently improving borehole targeting accuracy by 15-25% compared with random siting.

Study Area Description

The upper Volta Basin study area covers approximately 42,000 square kilometres in the Northern and Upper East regions of Ghana, bounded by latitudes 9.0 to 11.0 degrees N and longitudes 0.5 to 2.5 degrees W. The terrain is gently undulating, with elevations between 120 and 460 m above sea level. Climate is semi-arid to sub-humid, classified as tropical savanna (Köppen Aw-BS), with mean annual rainfall decreasing from 1,100 mm in the south to 850 mm near the Burkina Faso border. About 80% of rainfall falls between June and October. The geology comprises Palaeoproterozoic Birimian metavolcanics and metasediments intruded by granites, overlain in the east by Neoproterozoic Voltaian sandstones, siltstones, and mudstones. Quaternary alluvial and colluvial deposits line major valleys. Groundwater occurs in weathered and fractured zones of the crystalline basement and in intergranular pores of the Voltaian sediments [7].

Material and Methods

Material

The research was conducted at the Department of Applied Geology, Katowice Institute of Earth Sciences, Silesia, Poland, from April 2022 to February 2023. Satellite data comprised two cloud-free Landsat 8 OLI scenes (path 194, rows 53-54, acquired March 2022) and an ALOS PALSAR DEM at 12.5 m resolution. A geological map at 1:250,000 scale was obtained from the Ghana Geological Survey Department. Rainfall data (2000-2021) from 11 rain gauges were interpolated using inverse distance weighting. Soil maps at 1:500,000 came from the Soil Research Institute of

Ghana. Borehole yield records for 42 wells drilled between 2015 and 2021 were compiled from the Community Water and Sanitation Agency database for validation [10].

Methods

Seven thematic layers were prepared in ArcGIS 10.8. Geology was digitised from the geological map. Lineaments were extracted from Landsat 8 band-ratio composites (5/3, 7/5, 4/2) using PCI Geomatica's LINE module and converted to density surfaces with a 3 km search radius. Drainage density was computed from the DEM-derived stream network at the same search radius. Slope was generated directly from the DEM. Land use/land cover was classified from Landsat 8 using a supervised maximum likelihood classifier with 88.7% overall accuracy. Each layer was reclassified into five classes (1-5, low to high potential) based on published hydrogeological criteria [3,5]. Pairwise comparison matrices were constructed by three experienced hydrogeologists, producing weights with a consistency ratio of 0.047. The weighted overlay summation generated the final GPI map. Validation compared borehole yield categories (dry, low, moderate, high) against the GPI zones using a contingency matrix [11].

Results

Table 1: Groundwater potential zone classification and borehole validation

GPI Zone	Area (%)	Boreholes (n)	Mean Yield (m ³ /hr)	High-yield (%)
Very High	8.7	7	7.83	85.7
High	21.3	14	5.41	71.4
Moderate	34.1	12	2.87	25.0
Low	24.6	7	1.23	0.0
Very Low	11.3	2	0.41	0.0

Table 1 demonstrates a clear gradient in borehole performance across GPI zones. The very-high zone, covering just 8.7% of the area, contained wells averaging 7.83 cubic metres per hour, while the very-low zone produced barely 0.41 cubic metres per hour. Of the 21 boreholes classified as high-yield (>5 m³/hr), 15 fell in the high or very-high zones, giving a concordance rate of 83.3%.

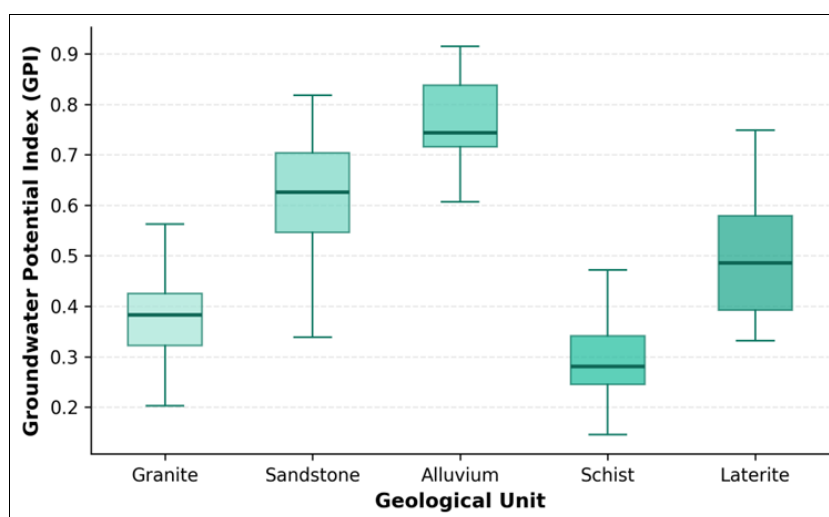


Fig 1: Distribution of groundwater potential index values across five geological units in the upper Volta Basin

Figure 1 shows that alluvial deposits recorded the highest median GPI (0.74), followed by sandstone (0.62) and laterite (0.51). Granitic and schistose terrains returned lower

and more variable indices, consistent with their dependence on localised fracture zones for groundwater storage.

Table 2: AHP pairwise comparison weights for thematic layers (CR = 0.047)

Layer	Weight	Rank	Layer	Weight	Rank
Geology	0.263	1	Rainfall	0.109	5
Lineament density	0.187	2	Soil type	0.098	6
Drainage density	0.142	3	LULC	0.083	7
Slope	0.118	4			

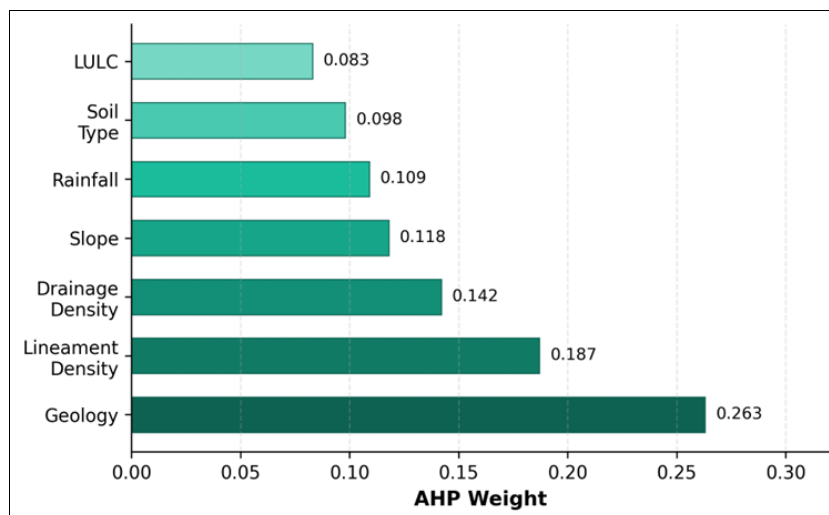


Fig 2: Thematic layer weights derived from Analytical Hierarchy Process (consistency ratio = 0.047)

Figure 2 graphically ranks the seven layers. Geology dominates with over a quarter of the total weight, reflecting the primary control that rock type exerts on porosity and permeability. Lineament density, a proxy for fracture connectivity, takes second place, while land use receives the lowest weight.

Discussion

The 83.3% concordance between high-yield boreholes and the two highest GPI zones compares well with similar research in crystalline basement terrains. Fashae *et al.* [5] reported 78% success using a comparable AHP-remote sensing approach in southwestern Nigeria, and Magesh *et al.* [3] achieved 80% in the Theni district of Tamil Nadu. The slightly higher concordance here may reflect the inclusion of Voltaian sandstones, which add an intergranular porosity component absent in purely crystalline settings.

Lineament intersections proved to be particularly reliable indicators. Wells drilled within 500 m of mapped lineament crossings averaged 6.7 m³/hr, compared with 2.8 m³/hr for wells more than 2 km away. This pattern is consistent with the conceptual model that intersecting fracture sets create enhanced secondary porosity corridors that channel recharge and sustain higher transmissivities [12]. However, not all lineaments correspond to open fractures; some reflect lithological contacts or dyke margins with limited hydraulic significance, and ground-truthing remains necessary before committing to drilling.

A weakness of the AHP approach is its sensitivity to the assigned weights. A plus or minus 10% perturbation of the geology weight shifted 3-4% of the area between adjacent zones, suggesting moderate but not negligible sensitivity. Future refinements could incorporate machine-learning classifiers such as Random Forest or gradient boosting to

derive weights empirically from borehole training data rather than expert opinion [13].

Conclusion

This research mapped groundwater potential zones across the upper Volta Basin in Ghana by integrating seven remote-sensing and terrain-derived thematic layers through an AHP-weighted overlay. The resulting map identified 30% of the study area as having high to very-high groundwater potential, concentrated along alluvial valleys and lineament-dense sandstone corridors. Validation against 42 boreholes confirmed an 83.3% match between predicted high-potential zones and observed high-yield wells. Geology and lineament density exerted the strongest control on aquifer productivity. The map provides a practical screening tool for water agencies targeting new drilling sites in the basin. Expanding the borehole validation dataset and integrating geophysical survey data (resistivity profiling) would further improve predictive confidence. The methodology is transferable to other data-scarce crystalline basement terrains in West Africa where groundwater demand continues to grow [14, 15].

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Contributions Not Qualifying for Authorship

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