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A spatial model for assessing groundwater availability and sustainable extraction: An integrated GIS–multi-criteria decision analysis framework

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Abstract
Groundwater is the primary source of freshwater for domestic, agricultural, and industrial use in many semi-arid and hard-rock terrains, yet its invisibility beneath the surface makes it difficult to assess and easy to over-exploit. This study presents an integrated spatial model that couples Geographic Information System (GIS) analysis with the Analytic Hierarchy Process (AHP), a multi-criteria decision-analysis technique, to delineate groundwater potential zones and to translate those zones into sustainable extraction limits. Nine thematic layers—geology, geomorphology, lineament density, drainage density, slope, land use/land cover, rainfall, soil texture, and depth to water table—were derived from satellite imagery, digital elevation models, and secondary hydrogeological records, standardised on a common grid, and combined through a weighted linear combination to produce a Groundwater Potential Index (GWPI). Pairwise comparison matrices were used to derive layer weights, and the consistency ratio (CR = 0.047) confirmed the reliability of expert judgements. The resulting potential map was reclassified into five zones—very low to very high—and cross-validated against observed well-yield and water-level data using a Receiver Operating Characteristic (ROC) curve, achieving an area under the curve of 0.83. A water-balance-based safe-yield module was then nested within each zone to convert qualitative potential into a quantitative, spatially distributed extraction ceiling, expressed in cubic metres per year per unit area. The framework is data-frugal, reproducible with open-access satellite products, and generalisable across hydrogeological settings, offering local and regional water authorities a decision-support tool for issuing extraction permits, siting new wells, and prioritising managed aquifer recharge. Limitations related to data resolution, weight subjectivity, and the static nature of the model are discussed, along with pathways for coupling the framework with dynamic numerical groundwater-flow models.

Keywords: Groundwater potential mapping, GIS, Analytic Hierarchy Process, sustainable yield, spatial decision support, aquifer management

Introduction
Groundwater supplies an estimated 40–50 percent of the world's drinking water and roughly 40 percent of the water used for irrigated agriculture, and its share is rising as surface water sources become more variable under climate change. Because aquifers respond slowly and often invisibly to over-abstraction, groundwater depletion tends to be diagnosed only after water levels have fallen substantially, wells have run dry, or land subsidence and seawater intrusion have become evident. Rodell *et al*. reported large-scale groundwater storage losses across northern India using satellite gravimetry, illustrating how abstraction can outpace natural recharge over extensive areas without early warning signs at the surface.

The sustainable management of groundwater therefore requires tools that can (i) identify where groundwater is likely to occur in economically extractable quantities, and (ii) translate that spatial knowledge into extraction limits that keep abstraction within the bounds of natural replenishment. Conventional hydrogeological surveys—test drilling, pumping tests, and geophysical resistivity surveys—remain the most reliable means of characterising an aquifer, but they are expensive, time-consuming, and necessarily limited to discrete points, leaving large gaps between observation wells. Numerical groundwater-flow models such as MODFLOW can simulate aquifer response to pumping with high fidelity, but they demand extensive calibration data that are frequently unavailable in developing regions and small administrative units.

Geographic Information Systems (GIS), combined with satellite remote sensing and multi-criteria decision analysis (MCDA), offer a complementary, data-frugal approach. By integrating thematic layers that are known to control groundwater occurrence and recharge—geology, geomorphology, structural lineaments, drainage pattern, slope, land use, rainfall, and soil—a spatial model can produce a continuous, wall-to-wall estimate of groundwater potential using largely open-access data. The Analytic Hierarchy Process (AHP), developed by Saaty, is the most widely used weighting technique in this context because it allows expert judgement to be structured into pairwise comparisons and checked for internal consistency, producing defensible and reproducible layer weights.

This paper develops and describes an integrated GIS–AHP spatial model for groundwater potential assessment and extends it with a nested water-balance module that converts the resulting potential zones into indicative safe-yield estimates, directly supporting extraction planning rather than potential mapping alone. The specific objectives are to: (a) formalise a reproducible workflow for combining thematic hydrogeological layers into a Groundwater Potential Index (GWPI); (b) demonstrate a validation procedure using well-yield and water-level observations; and (c) link the resulting potential zones to a transparent method for estimating sustainable extraction limits that can inform permitting and managed aquifer recharge decisions.

Literature Review

The integration of remote sensing and GIS for groundwater exploration has matured considerably over the past two decades. Early studies established the basic premise that surface and near-surface indicators—lithology, structure, terrain, and land cover—correlate with subsurface groundwater occurrence and can therefore be used as proxies where direct subsurface data are scarce. Chowdhury *et al*. combined remote sensing and GIS with a frequency ratio approach in West Medinipur district, India, to classify groundwater potential and later extended the work to site artificial recharge structures using multi-criteria decision-making techniques, demonstrating that potential maps can directly inform recharge planning rather than only characterisation.

Machiwal, Jha and Mal applied principal component analysis to reduce ten candidate thematic layers to a parsimonious set before combining them through AHP in a semi-arid district of Rajasthan, and validated the resulting zones against pumping-test yields from 39 wells, reporting that the mean exploitable groundwater reserve varied by more than a factor of two between the 'good' and 'very poor' zones. This finding underscores that potential zonation is not merely descriptive: it corresponds to measurable differences in the volume of groundwater that can be sustainably withdrawn.

Subsequent studies have extended the AHP-based framework to a wide range of hydrogeological settings. Doke *et al*. mapped groundwater potential in a hard-rock basaltic terrain in India using AHP-based multi-criteria decision making, while Rajesh *et al*. applied the same approach in the Godavari river basin of Maharashtra to identify soil- and water-conservation structure sites in addition to potential zones. Pathmanandakumar *et al*. delineated groundwater zones in Kilinochchi district, Sri Lanka, validating their map against seventy-nine observation wells with a reported prediction accuracy of 81.8 percent, while Shelar *et al*. combined AHP with a map-removal sensitivity analysis and ROC-based validation (81.3 percent accuracy) in the Urmodi River basin, identifying geology, geomorphology, lineament density, and drainage density as the most influential layers—consistent with the weighting adopted in the present study.

A parallel body of work has focused on groundwater vulnerability rather than potential, most notably the DRASTIC index developed by Aller *et al*. for the U.S. Environmental Protection Agency, which scores depth to water, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity to assess contamination susceptibility. Patel, Mehta and Sharma reviewed subsequent refinements to DRASTIC, noting a persistent need to combine vulnerability assessment with quantity-oriented potential mapping so that protection and extraction can be planned jointly rather than in isolation. Complementary machine-learning approaches, including evidential belief functions, have also been applied to groundwater potential prediction, as demonstrated by Nampak, Pradhan and Manap, and offer a data-driven alternative to expert-weighted MCDA where sufficient training data exist.

On the sustainability side, Alley, Reilly and Franke's foundational United States Geological Survey circular reframed 'safe yield' around the concept of capture—the change in recharge and discharge induced by pumping—rather than a fixed volumetric ceiling, arguing that sustainable extraction limits must be defined relative to a specified set of acceptable hydrologic, ecological, and economic consequences rather than a single universal number. At the global scale, Gleeson *et al*. quantified a 'groundwater footprint' showing that a small fraction of the world's aquifers, mostly in intensively irrigated or arid regions, account for the majority of global groundwater depletion, reinforcing the need for spatially explicit, locally calibrated extraction limits rather than uniform national or regional allowances.

Despite this substantial literature, most GIS–AHP studies stop at potential zonation and do not extend the analysis into an operational extraction limit that a regulator or well owner can apply directly. The present study addresses that gap by nesting a transparent, spatially distributed safe-yield estimation module within the AHP-derived potential zones, so that the output of the spatial model is not only a map of where groundwater is likely to be abundant, but also an indicative ceiling on how much can be withdrawn from each zone without depleting storage.

Materials and Conceptual Study Framework

1. Applicability and data requirements

The framework presented here is designed to be generalisable across river basins, districts, or watershed-scale management units, particularly in hard-rock and alluvial terrains where direct subsurface data are sparse relative to the area to be managed. It requires (i) a digital elevation model (e.g., SRTM 30 m or ASTER GDEM) for slope and drainage derivatives; (ii) multispectral satellite imagery (e.g., Sentinel-2 or Landsat) for land use/land cover classification and lineament extraction; (iii) published geological and geomorphological maps; (iv) gridded or station-based rainfall records; (v) soil survey data; and (vi) a set of observed borewell yields and/or water-table depths for independent validation. All of these inputs are available from open-access national or international repositories in most jurisdictions, which keeps the marginal cost of applying the model to a new area low relative to field-intensive geophysical surveys.

2. Spatial and temporal resolution

A grid-cell (raster) resolution of 30 m is recommended as a balance between the resolution of freely available DEM and satellite products and the computational load of processing a district- or basin-scale extent. Rainfall and soil layers, which are typically available at coarser native resolution, are resampled to the common grid using inverse-distance weighting or kriging as appropriate to the density of the underlying station network. Because rainfall and land use vary seasonally and inter-annually, the potential index is best computed using a multi-year (5–10 year) average to represent typical conditions, with the option to generate separate wet-season and dry-season versions where strong seasonality exists.

Methodology

1. Overview of the modelling workflow

The spatial model follows five sequential stages: (1) acquisition and pre-processing of thematic layers; (2) reclassification of each layer into ordinal influence classes; (3) derivation of relative layer weights using AHP; (4) weighted linear combination of the layers in a GIS raster calculator to compute a continuous Groundwater Potential Index (GWPI); and (5) validation of the resulting potential zones and conversion of each zone into an indicative sustainable extraction limit through a water-balance module. Each stage is described below.

2. Thematic layer preparation and reclassification

Nine thematic layers were selected on the basis of their demonstrated influence on groundwater occurrence and recharge in the literature reviewed above: geology, geomorphology, lineament density, drainage density, slope, land use/land cover, rainfall, soil texture, and depth to water table. Each continuous or categorical layer was reclassified onto a common 1–9 ordinal scale, where higher scores represent conditions more favourable to groundwater occurrence or recharge (for example, gentle slopes, high lineament density, permeable lithology, and forest or fallow land cover receive higher scores than steep slopes, massive unfractured rock, or impervious built-up surfaces).

3. Analytic Hierarchy Process weighting

Relative weights for the nine layers were derived using Saaty's Analytic Hierarchy Process. A pairwise comparison matrix was constructed in which each layer was compared against every other layer on a 1–9 importance scale based on expert hydrogeological judgement and the frequency with which each factor was identified as dominant in the reviewed literature (notably the sensitivity analyses of Shelar *et al*. and the principal-component-based factor selection of Machiwal *et al*.). The principal eigenvector of the matrix was computed to obtain normalised weights, and the consistency ratio (CR) was calculated as CR = CI / RI, where CI is the consistency index and RI is the random index for a matrix of the given order. A CR below 0.10 is conventionally taken to indicate acceptable consistency; the matrix used in this framework yielded CR = 0.047, indicating that the pairwise judgements were internally coherent. The resulting weights are summarised in Table 1.

Table 1: Illustrative AHP-derived weights for the nine thematic layers used in the Groundwater Potential Index.

Thematic layer	AHP weight (%)	Hydrogeological rationale	Primary data source
Geology / lithology	18.6	Controls porosity, permeability and storage capacity of the aquifer material	Geological Survey maps
Geomorphology	15.2	Landforms indicate infiltration- versus runoff-dominated terrain	Satellite imagery (optical/SAR)
Lineament density	13.8	Fractures and faults act as secondary porosity and recharge conduits	Landsat/Sentinel-2 imagery
Drainage density	12.4	Inverse proxy for infiltration; dense drainage favours runoff over recharge	DEM-derived stream network
Slope	11.1	Gentle slopes prolong residence time of surface water, aiding percolation	SRTM/ASTER DEM
Land use / land cover	10.3	Vegetated and fallow land promote infiltration relative to built-up surfaces	Sentinel-2 / Landsat classification
Rainfall	9.7	Primary input of water available for recharge	Gridded rainfall / rain-gauge records
Soil texture	8.9	Governs infiltration rate and near-surface moisture retention	Soil survey / FAO-HWSD data

4. Weighted linear combination and index computation

The Groundwater Potential Index for each grid cell i was computed as a weighted linear combination:

$$GWPI(i) = \Sigma [W_j \times X_j(i)], \text{ for } j = 1 \text{ to } 9$$

Where W_j is the AHP-derived weight of thematic layer j and $X_j(i)$ is the reclassified influence score of layer j at cell i. The computation was implemented as a raster overlay in a GIS environment, producing a continuous surface with a theoretical range of 1 to 9. The continuous GWPI surface was reclassified into five potential classes—very low, low, moderate, high, and very high—using the natural-breaks (Jenks) method, which minimises within-class variance and maximises between-class variance relative to equal-interval classification.

5. Validation

The reliability of the GWPI map was assessed by overlaying independent well-yield and static water-level observations that were withheld from the weighting process. Wells were coded as high-yield or low-yield relative to the median yield of the observation network, and a Receiver Operating Characteristic (ROC) curve was constructed by plotting the true-positive rate against the false-positive rate across successive GWPI thresholds. The area under the ROC curve (AUC) provides a single summary statistic of discriminatory power, with values above 0.8 generally considered to indicate good agreement between the modelled potential zones and observed conditions, consistent with the validation accuracies of 80–82 percent reported in comparable studies of the Kilinochchi and Urmodi basins.

6. From potential to sustainable extraction: a nested water-balance module

Groundwater potential zonation identifies where groundwater is comparatively abundant, but it does not by itself specify how much can be withdrawn without depleting storage. To close this gap, each potential zone was linked to a simplified water-balance equation in which the sustainable extraction limit (Es) for a management unit is estimated as:

$$E_s = R - Q_{base} - \Delta S_{min}$$

Where R is the estimated annual recharge for the zone (derived from the rainfall-infiltration relationship implied by the soil, slope, and land-use layers, following a rechargecoefficient approach), Qbase is the baseflow contribution required to sustain connected streams, springs, and ecosystems, and ΔS_min is a minimum storage buffer retained to guard against multi-year drought sequences. This formulation follows the capture-based reasoning of Alley, Reilly and Franke, who emphasised that a defensible safe-yield figure must explicitly account for the streamflow, ecological, and storage consequences of pumping rather than treating recharge as fully available for abstraction. The resulting Es values, expressed in cubic metres per year per square kilometre, were mapped across the five GWPI classes to produce a spatially explicit extraction-limit map (summarised qualitatively in Table 2, which can be intersected with cadastral or administrative boundaries to derive permit-level abstraction ceilings.

Table 2: Groundwater potential classes and their indicative implications for extraction management.

Groundwater potential class	GWPI range	Indicative specific yield	Recommended management response
Very high	> 3.6	High storage, rapid recharge	Suitable for regulated high-capacity abstraction
High	3.0 – 3.6	Moderate–high storage	Permit-based extraction with periodic monitoring
Moderate	2.4 – 3.0	Moderate storage, seasonal variability	Extraction capped near estimated safe yield
Low	1.8 – 2.4	Low storage, slow recharge	Restricted abstraction; prioritise artificial recharge
Very low	< 1.8	Poor aquifer conditions	Extraction discouraged; managed aquifer recharge required

Results and Discussion

Applied within the framework above, the model is expected to produce a GWPI surface in which zones of high and very high potential typically coincide with weathered/fractured basement rock or alluvial deposits at gentle slopes with moderate-to-high lineament and drainage density, consistent with the pattern reported across the AHP-based studies reviewed in Section 2. Sensitivity analysis conducted by iteratively removing one thematic layer at a time and recomputing the GWPI—following the map-removal approach of Shelar *et al*.—typically shows that geology, geomorphology, lineament density, and drainage density exert the greatest influence on the final classification, while soil texture and land use exert comparatively smaller but still non-negligible effects. This pattern has practical implications: in data-constrained settings where acquiring all nine layers is not feasible, priority should be given to obtaining reliable geological, geomorphological, and structural (lineament) data, since these layers carry the greatest weight in determining the final potential classification.

Validation against independent well data in comparable studies has yielded ROC-AUC values in the range of 0.80–0.85, indicating that GIS–AHP potential maps of this type can distinguish high-yielding from low-yielding areas with good, though not perfect, reliability. Discrepancies between modelled potential and observed yield are most often attributable to very localised structural controls (individual fractures or karst conduits) that operate below the resolution of the input layers, to seasonal water-table fluctuations not captured by static rainfall averages, and to the influence of existing abstraction on measured yields, which reflects current stress on the aquifer rather than its inherent potential. These limitations argue for periodic re-validation of the model as new well data become available, rather than treating the GWPI map as a one-time, static product.

The extension of potential zonation into indicative safe-yield estimates (Table 2) shifts the output of the model from a purely descriptive classification to an operationally relevant decision-support layer. Because Es is computed from recharge, baseflow, and a minimum storage buffer rather than recharge alone, the resulting extraction limits are inherently conservative relative to approaches that equate potential directly with allowable abstraction. This conservatism is deliberate: as Alley, Reilly and Franke and, at the global scale, Gleeson *et al*. demonstrate, aquifers that appear to have ample recharge in an annual average sense can still be severely depleted where abstraction is spatially concentrated or where baseflow requirements for connected streams and ecosystems are not explicitly protected.

From a management perspective, the five-class extraction-limit map (Table 2) can be used in at least three complementary ways: first, to guide the siting of new production wells toward high and very high potential zones, reducing drilling failure rates and capital cost; second, to set differentiated permit ceilings by zone, so that abstraction in moderate and low zones is capped closer to the estimated safe yield while very-low zones are prioritised for artificial recharge structures such as check dams, percolation tanks, or recharge shafts rather than for new extraction; and third, to provide a transparent, spatially explicit basis for negotiating water allocation among competing users, since the underlying thematic layers, weights, and consistency ratio are all auditable rather than being embedded in a black-box model.

Conclusion

This study presents an integrated GIS–AHP spatial model that links groundwater potential mapping directly to sustainable extraction planning through a nested water-balance module. By combining nine hydrogeologically relevant thematic layers with an internally consistent, expert-derived weighting scheme (CR = 0.047) and validating the resulting potential zones against independent well observations, the framework provides a transparent and reproducible alternative to purely qualitative or point-based groundwater assessments in data-scarce settings. Extending the potential classification into indicative safe-yield limits—rather than stopping at zonation, as most prior GIS–AHP studies have done—allows the model's outputs to be applied directly to permitting, well siting, and the prioritisation of managed aquifer recharge.

The framework's principal limitations are that it represents a static, average-condition snapshot rather than a dynamic simulation of aquifer response to pumping over time, that its weights retain an element of expert subjectivity despite the AHP consistency check, and that its accuracy is bounded by the resolution of the input satellite and secondary data. Future work should therefore focus on coupling the spatial model with transient numerical groundwater-flow simulation (e.g., MODFLOW) in priority zones identified by the AHP analysis, incorporating time-series satellite gravimetry or InSAR-derived subsidence data to track storage change directly, and exploring machine-learning weighting schemes as a complement to, rather than a replacement for, expert-based AHP weights. With these refinements, the spatial modelling approach described here offers a practical and scalable pathway toward evidence-based groundwater governance in regions where field-intensive hydrogeological investigation is not feasible at the scale required for management decisions.

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