From Darcy to Deep Learning: Evolution of Groundwater Potential Assessment Techniques

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Abstract

Groundwater is fundamental component of global freshwater resources. In India, dependence on groundwater is very high with withdrawal about 230 cubic kilometres annually. This dependence highlights the urgent need of systematic assessment of groundwater potential zones, to ensure long term sustainability. The advancement from traditional, field base hydrological characterisation to revolutionary geospatial modelling has fundamentally transform our interpretive approach to groundwater potential. This study highlights a critical delineation of the methodological trajectory in aquifer mapping, especially the transition from conventional methods, geospatial and geostatistical approach to data-intensive machine Learning (ML) and Deep learning (DL). This study proposes integrated approach that enhances methodological rigor and provides adaptive insights for sustainable groundwater management and policy relevant frameworks.

Introduction

The foundation of socio-economic development and ecological sustainability largely depend on global water resources. Groundwater has many intrinsic advantages to emerge as a crucial and reliable water source in all climatic zones, including both rural and urban areas (Kanetkar et al.,2025). Groundwater demand increased over a period of time, which resulted in improper extraction which led to water stress areas. The spatial and temporal variability of these resources along with anthropogenic pressures, increases the necessity of their systematic study. Globally, 50 % of population depends on groundwater for drinking water and 43 % for irrigation needs. In India, the situation is even more indistinct, according to groundwater assessment 2024, estimated annual recharge at 446.9 billion cubic meters (bcm), with extraction at 245.6 bmc, corresponding to stage of extraction of 60.47% (CGWB,2026). India is the largest extractor of groundwater globally, withdrawing about 230 cubic kilometres annually. The scenario proceeds with the need for systematic groundwater studies which should be both cost and time efficient. Groundwater is not readily observable, making its assessment entirely depend on hydrological survey, geospatial modelling and advance analytical techniques. Groundwater significance lies in dual dimensions of quantity and quality. The systematic groundwater research arises from resource quantification to provide insights of aquifer characteristics, aquifer recharge-discharge for long term sustainability, groundwater quality monitoring which evaluates the suitability for drinking and other various purposes, climate and land use impact helps to understand aquifer vulnerability. This study elaborates the conceptual framework that blends hydrogeological inputs, geospatial data and machine learning models, reinforces by validation to elevate groundwater potential interpretation. This integrated approach enhances the methodological precision, uncertainty reduction and contributes actionable insights for sustainable groundwater resource management at global and local level.

Methodological Evolution

Groundwater potential assessment engrossed with a varied spectrum of methods that span field-based hydrogeology, geospatial analysis, geostatistical interpretations, process-based models and machine learnings.

1. Conventional Hydrological Methods

Conventional hydrological methods represented as toolkit for characterising groundwater system and aquifer evaluation. Historically, scientific study of groundwater originated in nineteenth century with foundational experiments and laws describing the flow through porous medium by Henry Darcy. Henry Darcy's experiments and formulation of Darcy's law established the basics of aquifer analysis and subsequently developed by Dupuit and Theis (Simmon,2008). The cumulative progression from Darcy's laboratory experiment to Dupuit's analytical field approximations and then to transient well test solutions by Theis formulates the historical lineage of conventional hydrological methods used today. Field-based methods start with well inventory and lithological logging. Dynamic parameters like well depth, screened interval, seasonal water -level fluctuation, yield observed and documented as traditional practice. Pumping tests provides estimates of transmissivity, hydraulic conductivity, storage coefficient analysis and recovery curve using well observations. Temporal variability to be studies by water table mapping and time-series monitoring. Geophysical surveys like electrical resistivity, seismic refraction, electromagnetic methods, ground-penetrating radars contributes in delineating the aquifer geometry and subsurface heterogeneity (Majumdar et.al,2020). Limitations like spatial sparsity in observation well, discontinuities in record monitoring, high cost and logistic complexities of extensive field work, calibrate the necessity to progressively adopt geospatial approach in groundwater studies.

2. Geospatial Approach and Geostatistical Techniques

The groundwater potential evaluation has significantly advanced by the advent of remote sensing and Geographic Information System (GIS). This approach enables the large-scale mapping through various thematic layers providing spatially and quantitatively robust insights into aquifer system. Integration of various thematic layers such as slope, drainage density, geology, geomorphology, land use-landcover, soil results in delineation of groundwater potential zones. Multi-Criteria Decision Analysis (MCDA) methods like Analytical Hierarchy Process (AHP), Multi-Influencing factors (MIF) (Pande et al.,2021, Kanetkar et al.,2025) are widely used in India and abroad. This approach based on assigning the relative weights to controlling factors to generate composite maps that highlights groundwater potential zones. Lineament analysis enhances the identification of fracture zones and recharge areas, making this approach more effective in arid and semi-arid areas (Varade et al.,2017). Geostatistical techniques such as Inverse Distance Weighting (IDW) and Kriging provide the quantitative reliability by interpolating and modelling groundwater parameters across the area to enhance predictive accuracy. These techniques are valuable for data sparse areas, enabling generation of continuous surface from and limited point data. These approaches bridge the gap between local field observation data and regional-scale groundwater assessment.

3. Machine Learning Models

The data driven approach of Machine Learning has significantly grown becoming the powerful tool to analyse complex and non-linear relationships among hydrological, geospatial and climatic variabilities. Large and heterogenous datasets can process ML algorithms and identifies the parameters that influences groundwater occurrence, depth and quality (Lary et al., 2016, Saha &Pal,2025). Most widely used Random Forest (RF) model applied in delineating the groundwater potential zones offering ensemble accuracy and variable importance measures. Support Vector Machines (SVM/SVR) predicts groundwater depth and water quality index. Aquifer recharge estimation, groundwater-surface interaction, contamination study performed by Artificial Neural Networks (ANN) highlighting its flexible architecture. Recent advances such as Convolutional Neural Networks (CNN) excellent for geospatial data while Long-Short Term Memory (LSTM) effective for time series prediction contributing groundwater level fluctuation forecasting and spatio-temporal groundwater modelling (Kouadri et al.,2021).

4. Integrated and Hybrid Approach

This approach combines the conventional, geospatial analysis, geostatistical techniques and ML model to overcome the individual methodological limitations. It ensures methodological rigor by enhancing predictive performance (Subramani et al.,2025). It facilitates decision support for sustainable groundwater management and guiding adaptive resource management strategies.

Research Gap and Future Directions

Despite significant advances in groundwater studies, certain research gap remains. Spatial and temporal sparce monitoring limits the groundwater assessment. Many studies mainly rely on static datasets only. The integration of groundwater quality with geospatial and ML framework is still limited. Inconsistent weighting system in MCDA makes difficult for comparative and reproducibility of the research.

Future direction emphasizes the need for multi-disciplinary integration combining hydrology, geostatistical and artificial intelligence with robust field validation. Developing long-term monitoring network, incorporating real-time sensor data and employing deep learning models with geospatial and climatic variability parameters will enhance predictive reliability.

Conclusion

Groundwater acts as a central pillar of water security. This study aims to systematically dissect the evolution in hydrological assessment methods from field based conventional methods, geospatial revolution to advanced ML and DL architecture. This study identifies the future of this discipline lies in smarter integration of methodologies. Ultimately, amalgamation of empirical data,

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spatial analysis and ML modelling offers a robust way to evolve holistic, adaptive and sustainable water resources management.

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