



Spatial analysis techniques for assessing groundwater vulnerability: a strategic approach to proactive conservation and mitigation strategies

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Abstract

Groundwater is a critical resource that supports agriculture and ecosystems which is increasingly threatened by anthropogenic activities and climate change. Despite the advancements in spatial analysis methods, there remains a lack of comprehensive reviews that synthesize these techniques specifically for groundwater vulnerability assessment as existing literature often focuses on isolated methodologies without integrating them into a cohesive framework that addresses the complexities of groundwater systems. Hence, the need for proactive conservation and mitigation strategies on how spatial analysis can enhance groundwater vulnerability assessments is crucial for developing effective policies and practices aimed at safeguarding this vital resource. This review evaluates various spatial analysis techniques used in assessing groundwater vulnerability, identify their strengths and limitations, and propose a strategic framework for their application in conservation efforts. A systematic literature review was conducted, focusing on peer-reviewed articles published in the last two decades. Techniques such as remote sensing (RS), Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and statistical modelling were analyzed in terms of their applicability to groundwater vulnerability assessments. The findings reveal that spatial analysis techniques significantly enhance the accuracy of groundwater vulnerability assessments (GVAs) by incorporating diverse data sources such as land use, soil characteristics, and hydrological features. Key results indicate that GIS-based models provide robust frameworks for identifying vulnerable areas, while MCDA facilitates stakeholder engagement by integrating socio-economic factors into decision-making processes. The study concludes that a strategic approach combining various spatial analysis techniques offers a promising pathway for enhancing groundwater vulnerability assessments. This integrated methodology not only aids in identifying vulnerable areas but also supports informed decision-making processes regarding conservation efforts. However, future research should focus on developing standardized protocols for integrating diverse spatial analysis methods as well as longitudinal studies to assess the long-term effectiveness of implemented conservation strategies based on these assessments.

Keywords Groundwater management · Vulnerability assessment · Geographical information system · Remote sensing · Risk mapping · Hydrogeological modeling · Land use planning

Introduction

Groundwater vulnerability (GV) is a critical aspect of water resource management, especially in the context of increasing anthropogenic pressures and environmental changes (Machwal et al. 2018; Jain 2023; Wang et al. 2023; Li et al. 2023). Geospatial assessment techniques have emerged as powerful tools for evaluating GV, providing valuable insights into the susceptibility of aquifers to contamination and depletion (Wang et al. 2023; Nourani et al. 2024; Ourarhi et al. 2024a). Effective management and mitigation strategies rely heavily

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on accurate assessments of GV, enabling policymakers and stakeholders to make informed decisions to safeguard this vital resource (Cao et al. 2023; Vasileva et al. 2023; Sánchez-Gómez et al. 2024). Groundwater vulnerability assessment (GVAs) is crucial for the effective management and mitigation of groundwater resources (Garg et al. 2020; Ourarhi et al. 2023). It helps identify potential threats to groundwater quality and quantity, enabling proactive measures to protect this valuable resource (Nourani et al. 2024; Ourarhi et al. 2022). Risk assessments help evaluate risks posed by activities such as industrial operations, agriculture, or improper waste disposal, enabling policymakers to prioritize intervention areas and implement targeted mitigation strategies (Atenidegbe and Mogaji 2023).

Land-use planning decisions are guided by GVAs, which provide insights into the relationship between land use practices and potential impacts on groundwater quality (Machiwal et al. 2018). This information guides land-use planning decisions to prevent contamination and overexploitation of aquifers (Lavoie et al. 2015; Dai et al. 2007). Emergency response preparedness is also essential, as understanding the vulnerability of groundwater sources allows for the development of contingency plans and emergency response strategies in case of accidental spills, pollution incidents, or natural disasters that could threaten groundwater quality (Vasileva et al. 2023). Regulatory compliance is often required for activities with the potential to impact groundwater resources, and incorporating VAs into regulatory frameworks can enforce protective measures effectively. Community engagement in GVAs fosters awareness about the importance of protecting water resources and leads to collaborative efforts in implementing sustainable management practices and mitigating risks to groundwater sources (Anandhi et al. 2022). By understanding the susceptibility of aquifers to contamination and depletion, policymakers can make informed decisions to safeguard this precious resource for current and future generations.

Methods for assessing GV include the overlay index, statistical method, and process simulation method (Geng et al. 2023; Moraru and Hannigan 2018). Overlay index methods are widely used for assessing groundwater vulnerability as they integrate multiple spatial data layers representing factors influencing groundwater quality (Machiwal et al. 2018; Vu et al. 2021). The steps in this method include data collection (gathering relevant data layers like land use, soil type, hydrogeological characteristics, and potential contaminant sources), weight assignment (assigning weights to each layer based on their importance in contributing to groundwater vulnerability, which can be done through expert judgment or statistical techniques), layer overlaying (using GIS to overlay these layers, creating a composite score that indicates areas of varying vulnerability levels), and classification (scores are then classified for easier interpretation and

decision-making) (Steiakakis et al. 2023; Jain 2023; Vu et al. 2021; Ourarhi et al. 2024b). This method is beneficial for visually representing vulnerable areas and adapting to local conditions. However, statistical methods are used to analyze historical data on groundwater quality and potential contaminant sources to identify patterns and correlations indicating vulnerability (Moraru and Hannigan 2018). These methods involve data compilation (groundwater quality parameters), statistical analysis (regression analysis or multivariate analysis to determine the relationship between groundwater quality and various influencing factors), and vulnerability index development (Zhang et al. 2022b). These methods provide a quantitative basis for understanding groundwater quality over time but may require extensive datasets for reliable results (Machiwal et al. 2018).

The process-based simulation method, based on water and pollutant transport models, utilizes deterministic physical and chemical equations to simulate the transport and transformation of pollutants (Kc et al. 2022; Dai et al. 2005). This method involves model selection, parameter calibration, scenario analysis, and output interpretation (Gogu and Darsargues 2000). Model selection involves choosing an appropriate hydrological model, calibrating parameters using field data, running simulations under various scenarios, and analyzing model outputs to identify vulnerable zones based on predicted contaminant concentrations (Moraru and Hannigan 2018). This approach allows researchers to explore future scenarios and evaluate the effectiveness of management strategies for protecting groundwater resources. A systematic sorting of methods should prioritize the transport of pollutants in the vadose zone and consider sources and sinks for assessing GV because the lack of systematic sorting hinders the mainstream trend in GV evaluation. GV to contamination poses a significant threat to its quality and availability, while geospatial assessment techniques offer a powerful tool for evaluating GV by integrating various spatial data layers to identify areas at risk of contamination (Vasileva et al. 2023; Ourarhi et al. 2022).

Additionally, weighting and ranking assign weights to different vulnerability parameters to calculate a composite vulnerability index, prioritizing areas of higher vulnerability for targeted management strategies. The criteria for assigning weight to different vulnerability parameters include expert judgment (which involves assessing the significance of each factor based on their experience and knowledge, often through surveys or interviews), statistical analysis (such as regression analysis, can determine the contribution of each parameter to the overall vulnerability score), Analytic Hierarchy Process (AHP) (a structured technique used for organizing and analyzing complex decisions based on mathematics and psychology), Multi-Criteria Decision Analysis (MCDA) [methods that evaluate multiple conflicting criteria in decision-making environments using

techniques like Weighted Sum Model (WSM) or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)], field surveys and stakeholder input (which provide insights into the most important factors, and ensuring that weights reflect community values and priorities), and literature review (which helps to identify commonly accepted weights assigned to various parameters in similar contexts, providing a baseline for adjustments based on local conditions or new findings) (Elzain et al. 2023, 2022).

Furthermore, the quantitative metrics are used to measure the impact of parameters (such as rainfall intensity and soil saturation levels, on flood vulnerability) most especially when quantitative data is scarce or unavailable, providing insights into how different parameters interact (Garg et al. 2020; Yi et al. 2024). After assigning weights, sensitivity analysis helps to determine the most influential parameters and their weights by validating against real-world outcomes or case studies to ensure they accurately reflect vulnerabilities observed during actual events (Afrifa et al. 2022). GIS analysis integrates spatial datasets, analyzes relationships between layers, and visualizes VA results in maps or models where the validation and calibration of the vulnerability model may be necessary to improve its accuracy and reliability (Sangawi et al. 2023; Sánchez-Gómez et al. 2024). In a study by Gogu et al. (2001) to describe the creation of a hydrogeological GIS database, confirmed that integrating various spatial datasets, including geological information, topographical maps, and hydrogeological parameters, facilitating advanced hydrogeological modeling. The GIS enables the generation of maps and vertical cross-sections that illustrate groundwater flow and contaminant transport. The study further emphasized the use of statistical and geostatistical methods, such as kriging, to analyze spatial data effectively, thereby supporting groundwater vulnerability assessments through visual representations of spatial phenomena like wells and hydraulic head.

In Seeboonruang (2015)'s study, GIS multicriteria data treatment was employed to map groundwater vulnerability to climate change by integrating various hydrogeological parameters. The researchers conducted two calculations: one focusing on the typology of aquifer behavior under different climate scenarios and another combining this typology with mean aquifer recharge to produce vulnerability maps. Drought resistance indicators were also included to assess aquifer resilience, demonstrating the capacity to visualize the impacts of climate variability on groundwater systems (Aslam et al. 2018). Furthermore, Machdar et al. (2018) identified high pollution potential areas, underscoring the effectiveness of GIS in groundwater vulnerability assessment by providing detailed visualizations that inform local planners and administrators. The study applied the DRASTIC model within a GIS framework to assess groundwater vulnerability by employing seven criteria, including depth

to groundwater and hydraulic conductivity, to generate vulnerability maps categorized into five levels, from less vulnerable to very high vulnerability. Also, the study of Chatrabhuj et al. (2024) combined groundwater vulnerability and hazard assessments to create index-based maps at a 30 arc-second spatial resolution. The evaluation utilized the DRASTIC index method and incorporated public datasets, revealing that less than 1% of the basin was at high or very high contamination risk. The comprehensive approach to data integration and visualization in GIS demonstrates its utility in regional groundwater assessments. By following these steps within a geospatial framework, stakeholders can better understand and address GV, leading to more effective protection and sustainable management practices.

Groundwater is a vital freshwater resource that is being threatened by overexploitation, pollution, and mismanagement globally. Many major aquifers around the world are experiencing rapid depletion, with water levels declining by tens to hundreds of meters (Adedotun et al. 2023). This depletion is linked to increased vulnerability to chemical contamination, where the demand for groundwater is expected to continue growing in the future, driven by factors like population growth, agricultural expansion, and climate change. Several qualitative, quantitative, and statistical methods have been developed over the past few decades to evaluate aquifer vulnerability, both for "resource protection" of the entire aquifer and "source protection" of specific water sources like wells and springs. The emergence of GIS technology has enabled the widespread application of these VA methods, particularly the DRASTIC approach (Baki and Ghavami 2023; Ourarhi et al. 2024b). Previous studies have employed various spatial analysis techniques to evaluate GV; however, there remains a significant gap in integrating these techniques into a cohesive framework that addresses both conservation and mitigation strategies effectively. Firstly, they often focus on specific spatial analysis methods, such as GIS or remote sensing, without considering the broader strategic approach needed for real-world conservation efforts. Secondly, they often overlook the complex interactions between environmental factors such as socio-economic variables that influence GV. Thirdly, the literature often focuses on specific geographic areas, which may not represent global groundwater challenges. Fourthly, some studies rely on outdated data and techniques, which may not incorporate recent advancements in technology or data collection techniques. Finally, the lack of stakeholder engagement in previous research can lead to impractical or unfeasible recommendations in real-world scenarios. Hence, this review paper proposes a novel framework for assessing GV using an integrated spatial analysis approach by combining various techniques like GIS, remote sensing, and hydrological modeling to create a comprehensive framework for multi-dimensional assessments. The framework considers

environmental and socio-economic factors, recognizing their interdependencies and impact on groundwater resources. It aims to be globally applicable while adjusting to local contexts. Advanced technologies like machine learning and big data analytics will enhance predictive capabilities and also involves a stakeholder-centric approach, involving local communities and stakeholders to ensure the strategies are practical, relevant, and likely to be adopted in real-world applications.

Geospatial data collection and preprocessing

The geospatial framework for GVA involves key steps such as data collection, hydrogeological conceptualization, vulnerability indices, weighting, GIS analysis, validation, scenario analysis, and reporting (Anandhi et al. 2022; Zhao et al. 2024). This structured approach helps stakeholders understand factors influencing GV and prioritize management strategies (Garg et al. 2020). Hydrogeological setting characterization is crucial in assessing GV, as it provides insights into how groundwater interacts with surface water, geological formations that store and transmit water, and potential contaminants that may affect groundwater quality which involves data collection, analysis of geological formations, and understanding hydrological processes (Barthel and Banzhaf 2016). It should be noted that data collection and analysis include geological mapping, hydraulic conductivity measurements, aquifer properties, and water table mapping (Dindi et al. 2024). However, the key hydrogeological parameters considered include soil type and thickness, depth to the water table, recharge areas, geochemical properties, and land use practices. Different soil types have varying capacities to filter contaminants, with clay soils providing better filtration than sandy soils due to lower permeability because shallow water tables are more vulnerable to surface contamination, while recharge areas identify areas where surface water infiltrates into aquifers (Barthel and Banzhaf 2016; Dai et al. 2007). However, the interaction between surface water and groundwater is a complex process that requires numerical modeling for accurate solutions. Such was revealed by Ntona et al. (2022) that an increasing trend to integrate water resources, with new software and updated codes simplifying groundwater-stream interaction simulations with the dominant approach of MODFLOW-SWAT, but data scarcity and lack of high-frequency field measurements are the main limitations. The study ascertained that multidisciplinary approaches are essential for understanding stream-groundwater interaction, and modeling ethics should not be neglected during the process.

The integration of groundwater-surface water into wider models can be categorized based on the number of processes

and elements of the hydrological cycle, the conceptual/mathematical representation of these processes and elements, the degree of linkage between them, the nature and type of model components and process descriptions, the temporal aspects of model discretization and coupling, and the objectives, problem sets, and focus of interest, including issues such as data availability (Barthel and Banzhaf 2016). These characteristics help to understand the interplay between different processes and elements of the hydrological cycle, ensuring a comprehensive understanding of the system. Geochemical properties influence how contaminants behave once they enter the aquifer system, such as pH levels affecting the solubility and mobility of certain pollutants (Dindi et al. 2024; Li et al. 2023). Also, land use practices can significantly impact groundwater quality, and assessing land use helps predict potential sources of contamination. VAs are then incorporated using modeling techniques like the DASTIC Model, which combines multiple hydrogeological factors to produce a vulnerability index score for different areas within a study region (Ourarhi et al. 2024b, 2023). Geographic Information Systems (GIS) allow for spatial analysis of hydrogeological data, allowing researchers to visualize areas at higher risk for contamination. Statistical methods help correlate hydrogeological parameters with historical contamination events to refine vulnerability predictions further.

Effective communication of assessment findings is crucial for engaging stakeholders, raising awareness, and facilitating informed decision-making for groundwater protection and sustainable management (Steiakakis et al. 2023). To facilitate this process, researchers typically employ various mechanisms, such as stakeholder engagement workshops, reports and executive summaries, online platforms and databases, policy briefs, collaboration with local agencies, public forums and community meetings, and Multi-Criteria Decision Analysis (MCDA). Stakeholder engagement workshops bring together various stakeholders, including local government officials, community representatives, environmental organizations, and industry representatives, to present the assessment findings in an accessible format. These sessions allow stakeholders to ask questions, provide feedback, and discuss implications for groundwater management. Reports detailing the assessment findings include comprehensive data analysis, methodologies used in the study, and recommendations for action. The study by Villada-Canela et al. (2021) highlighted significant barriers to effective communication on a study focusing on public participation in groundwater management. They noted that public participation was limited due to power imbalances among stakeholders and a lack of continuity in participatory processes. Hence, their recommendations included decentralized decision-making and the integration of technical and non-technical

knowledge, which could potentially enhance stakeholder involvement and underscores the importance of creating inclusive communication strategies to foster engagement and informed decision-making.

Also, online platforms and databases allow users to explore data interactively, often featuring visualizations of data to convey complex information clearly such as collaboration with local agencies can enhance the dissemination process by aligning findings with ongoing initiatives and regulatory frameworks. The public forums or community meetings serve as platforms for sharing research outcomes with the general public, encouraging community involvement in discussions about groundwater management strategies based on study findings. Additionally, the study by Jadoon et al. (2024) assessed groundwater quality and highlighted the need for improved communication regarding water quality issues which included hydrochemical analysis and health risk assessments, provided a comprehensive view that could inform stakeholders and decision-makers. The results indicated that a significant portion of the water quality sites fell into the poor drinking water category, emphasizing the necessity for targeted communication strategies to protect vulnerable populations. The research conducted by Ataei et al. (2024) introduced an intelligent Decision Support System (DSS) designed for groundwater management. This DSS utilized telemetry data from wells to inform decision-making and integrated expert operational knowledge through the Classical Delphi technique. However, the incorporating MCDA into the decision-making process allows stakeholders to evaluate multiple conflicting criteria when making decisions regarding groundwater management options. This structured framework helps prioritize different aspects such as economic viability, environmental impact, social acceptance, and technical feasibility based on quantitative data derived from assessments. By employing these mechanisms collectively, researchers can ensure that their findings effectively inform decision-making processes related to groundwater management and protection.

The dissemination of study results, particularly in the context of groundwater management and protection, is crucial for ensuring that stakeholders and decision-makers are informed and can make evidence-based decisions. By leveraging data analytics and expert knowledge, this system facilitated effective communication of findings, bridging the gap between theoretical research and practical application (Ataei et al. 2024). Mechanisms such as community engagement, decision support systems, multi-criteria decision analysis frameworks, and technology-driven tools play vital roles in facilitating informed decision-making. By prioritizing effective communication strategies and stakeholder involvement, these study efforts contribute to the overarching goal of sustainable groundwater management and protection. Also, implementing this framework can lead to improved

protection and management practices, ultimately contributing to groundwater's long-term sustainability.

Integrating geospatial tools and techniques such as GIS play a crucial role in enhancing the effectiveness and reliability of the assessment. However, before data integration, each dataset must undergo preprocessing to ensure compatibility which includes cleaning to remove irrelevant information, aligning all datasets to a common coordinate system, and normalizing to a common scale or format (Li et al. 2015). Various techniques can be employed to integrate the datasets, such as overlay analysis, spatial interpolation, and data fusion. Overlay analysis combines multiple layers of geospatial data to identify relationships between them, while spatial interpolation estimates values based on surrounding known points. Data fusion, on the other hand, combines different types of data, such as remote sensing imagery with ground-based survey results, to enhance overall analysis quality by leveraging strengths from each source (Chatrabhuj et al. 2024; Hu et al. 2024a). Harmonization of data ensures compatibility between integrated datasets in terms of scale, resolution, and format (Bill et al. 2022). It involves standardizing attributes across different datasets using consistent naming conventions and units; temporal alignment for time-sensitive data and quality assessment to evaluate the accuracy and reliability of each dataset before final integration (Blaschke et al. 2011). This comprehensive dataset can be used for VAs by applying analytical models considering factors like exposure levels, susceptibility characteristics, and adaptive capacity within specific regions. The study of Geng et al. (2023) introduces a mathematical formula to assess vulnerability and create a comprehensive index by quantifying evaluation factors. This method's key advantage lies in its ability to describe and estimate the impacts of physical, chemical, and biological processes on GV and pollutant distribution over time and space. Advancements in field monitoring technology and numerical methods increase reliance on process-based models for accurately predicting GV across various hydrogeological conditions (Atenidegbe and Mogaji 2023; Ourarhi et al. 2024b). RS, GIS, and artificial intelligence's potential should be maximized for VA. Adopt new tools and technologies to enhance spatial decision support systems for better decision-making in water resource management and land use planning (Sangawi et al. 2023).

Sources of geospatial data

Various sources of geospatial data can aid GVA, as indicated in (Table 1). The table offers a comprehensive overview of the sources of geometric data techniques, assessment, calibration, mechanisms, and the limitations of each of the mentioned techniques for GVA. Satellite imagery is a widely used form of geospatial data, providing high-resolution images of the Earth's surface for

Table 1 Sources of geometric data techniques, assessment, mechanisms, advantages and limitations

Techniques	Calibration	Assessment	Mechanisms	Validation	Advantages	Disadvantages	References
Geographical Information Systems (GIS)	Through sensitivity analysis, and integrates hydrological, geological, and land use data	Vulnerability Mapping	Hydrogeological Modeling	Comparing predictions against independent datasets or ground truth observations	Provides spatial visualization of GV, helps in decision-making processes	Requires specialized training and software, data accuracy may vary	(Hu et al. 2024b)
Multi-Criteria Decision Analysis (MCDA)	Determining the weights based on expert judgement	GOD Method (Groundwater occurrence, Overlying strata characteristics, Depth to water table)	Groundwater Contamination Source Identification	Comparing MCDA results with actual outcomes or decision made in similar context	Integrates multiple factors for decision-making, considers uncertainties	Subjective weighting of criteria may introduce bias, time-consuming process	(Lu et al. 2023)
Thermal Imaging Surveys	Sensitivity analysis	Source Water Protection Planning	Groundwater Recharge Estimation	Cross-validation techniques to test robustness of the decision-making process	Helps in prioritizing mitigation strategies based on multiple criteria	Subject to uncertainties in input data and criteria weighting	(Steiakakis et al. 2023)
Geostatistical Analysis	Establishing a relationship between thermal readings and actual groundwater conditions	Risk Assessment for Wellhead Protection Areas	Natural Attenuation Mechanisms Evaluation	Correlating thermal imaging results with direct measurements of groundwater temperature	Detection of thermal anomalies indicating groundwater flow paths	Interpretation complexity due to various factors affecting temperature readings	(Baki and Ghavami 2023)
Isotope Hydrology Techniques	Fitting variograms to empirical data to estimate spatial correlation structure	DRASTIC Model (Depth to Water, Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone and Conductivity)	Groundwater Pollution Risk Assessment	Cross-validation	Incorporates spatial variability into assessments, aids in risk prioritization	Limited by data availability and quality, complex calculations involved	(Barbulescu 2020; Kumar and Krishna 2018)
Groundwater Flow Modeling	Establishing baseline isotopic signatures for different water sources	Vulnerability Zoning Mapping	Managed Aquifer Recharge Strategies Development	Comparing isotopic data against known benchmarks	Tracing sources of groundwater contamination	Limited availability of isotopic labs	(Jain 2023; Li et al. 2024)
	Adjusting hydraulic parameters within flow models until simulated groundwater levels matched observed levels	Aquifer Vulnerability Index (AVI)	Groundwater Recharge Estimation	Running the model under different scenarios and comparing simulated outputs with independent datasets not used during calibration	Helps in understanding groundwater flow patterns, predicts potential contamination sources	Data-intensive, requires expertise for interpretation and calibration	(Adedotun et al. 2023)

Table 1 (continued)

Techniques	Calibration	Assessment	Mechanisms	Validation	Advantages	Disadvantages	References
Remote Sensing	Adjusting satellite imagery or aerial photographs using ground-truth data collected from field surveys	Vulnerability Mapping	Hydrogeological Modeling	Assessing the accuracy of RS classification through confusion matrices that compare classified images against reference datasets obtained through field verification	Efficient data collection over large areas	Limited resolution for detailed analysis	(Abdulraheem et al. 2023)
Ground Penetrating Radar (GPR)	Correlating radar signals with known subsurface conditions obtained	Aquifer VA	Contaminant Transport Simulation	Comparing GPR interpretations with physical observation made during excavation	Non-invasive and rapid data acquisition	Depth limitations in certain terrains	(Sangawi et al. 2023)
Seismic Refraction Survey	GPS Technology	Vulnerability Index Calculation	Groundwater Monitoring Network Design	Accurate interpretation of observations	Enables non-invasive subsurface imaging for assessing aquifer characteristics	Limited penetration depth in certain geological conditions	(Adedotun et al. 2023)
Electrical Resistivity Tomography (ERT)	Correlating seismic wave velocities obtained from refraction survey with known geological formations identified	Source Protection Area Delineation	Groundwater Recharge Estimation	Seismic results are compared against borehole data or other geophysical methods	Quick surveying of large areas	Weather-dependent operations	(Varady et al. 2016)
Water Quality Monitoring Networks	Adjusting resistivity values based on known soil moisture content and lithological characteristic	GV Index Calculation Pollution Risk Mapping	Flow Path Analysis Managed Aquifer Recharge Techniques	Comparing ERT result with direct measurement taken from soil sample and resistivity profiles established through drilling operations	High spatial resolution for subsurface mapping	Costly equipment and expertise required	(Chelioti et al. 2023) (Adedotun et al. 2023)
	Ensuring that water quality sensors are accurately measuring parameter by comparing sensor reading with laboratory analyses	Infiltration Capacity Estimation	Pump-and-Treat Systems Implementation	Long-term monitoring data are analyzed statistically to confirm trends and pattern align with expected environmental changes	Offers high-resolution imaging of subsurface resistivity variations for detecting pollution plumes	Expensive to establish and maintain networks	(Foster et al. 2013)

Table 1 (continued)

Techniques	Calibration	Assessment	Mechanisms	Validation	Advantages	Disadvantages	References
Soil Sampling and Analysis	Establish baseline nutrient levels and contaminants through initial sampling rounds before applying statistical methods	Pollution Risk Assessment	Aquifer Remediation Techniques Evaluation	Repeating soil tests at selected sites over time, comparing results against previous findings to ensure consistency and reliability in soil health assessments related to GV	Direct measurement of soil properties	Labor-intensive and time-consuming process	(Abdulraheem et al. 2024a)
Pumping Tests Analysis	Refining aquifer parameters based on observed draw-down curves during controlled pumping experiments compared against theoretical models	Groundwater Quality Monitoring	Artificial Recharge Methods	Corroborating pumping test results with long-term monitoring well data that reflect natural aquifer responses over time following pumping events	Provides quantitative data on aquifer properties and hydraulic conductivity	High cost and durability	(Faltynkova and Wagner 2023)

various applications such as land use classification, vegetation analysis, and environmental monitoring. Common sources of satellite imagery include the Landsat Program, Sentinel Satellites, and WorldView Satellites (Abduljaleel et al. 2024; Hu et al. 2023). Remote sensing data, including aerial photography, multispectral imagery, and LiDAR, can provide valuable information for mapping terrain features and land use dynamics (Abdulraheem et al. 2023). LiDAR data, an advanced remote sensing technology, uses laser light to create accurate three-dimensional representations of terrain and vegetation, useful for topographic mapping, vegetation analysis, and groundwater monitoring (Chatrabhuj et al. 2024). Groundwater monitoring data involves measurements from wells and piezometers, crucial for hydrological studies and water resource management. However, aerial photography captures images from aircraft or drones at various altitudes, providing higher-resolution images for localized studies. Climate data includes historical weather patterns, temperature records, precipitation levels, and other meteorological information collected from ground stations or satellite observations. These datasets are essential for environmental impact assessments and agricultural planning.

GIS software allows for the integration, analysis, and visualization of geospatial data layers, enabling the identification of spatial relationships and patterns influencing GV. The study of Taghavi et al. (2022) highlights the use of ArcGIS to extract data across 31 variables related to groundwater vulnerability. They generated a probability map visualizing areas susceptible to groundwater-quality degradation, employing logistic regression analysis to identify significant correlations between various geospatial data layers. This integration of statistical modeling with GIS showcases the versatility of GIS in assessing groundwater vulnerability. Integrating socioeconomic datasets with geospatial information allows researchers to analyze human impacts on the environment, such as population density maps, economic activity indicators, or land ownership records (Bill et al. 2022; Blaschke et al. 2011). By combining these diverse datasets through GIS techniques, researchers can conduct comprehensive spatial analyses that inform decision-making in areas such as urban development, resource management, environmental conservation, and disaster response (Blaschke et al. 2011; Abduljaleel et al. 2024). The integration process often involves using software tools like ArcGIS or QGIS to visualize relationships between different datasets and perform spatial analyses such as overlay analysis or buffer analysis.

By incorporating these diverse sources of geospatial data into the assessment framework, stakeholders can gain a comprehensive understanding of GV and make informed decisions to protect and sustainably manage this vital resource.

Methods for data preprocessing and integration

Geospatial assessment of GV is a crucial aspect of environmental management, evaluating the susceptibility of groundwater resources to contamination (Garg et al. 2020; Ourarhi et al. 2024a). In the geospatial assessment of GV, data preprocessing and integration are crucial steps to ensure the accuracy and reliability of the analysis because it involves cleaning, transforming, and standardizing the data to make it suitable for analysis. Data cleaning involves removing duplicate records, handling missing values, and addressing outliers to maintain accuracy. Normalization standardizes data across different layers to prevent certain features from dominating the analysis. Spatial interpolation methods, such as Kriging or Inverse Distance Weighting, estimate values at unsampled locations based on known data points. Feature selection helps identify variables affecting GV and reduces computational complexity. However, the Principal Component Analysis (PCA) and Recursive Feature Elimination (RFE) help identify relevant variables and improve model performance. Data integration is crucial for conducting a comprehensive GVA. Key approaches include fusion techniques, geodatabase development, and model integration. Fusion techniques provide a holistic understanding of GV, while geodatabases facilitate seamless querying, visualization, and analysis of interconnected information within a GIS environment (Lu et al. 2023) while the model integration allows for a more comprehensive evaluation of GV by considering various influencing factors simultaneously (Geng et al. 2023; Yi et al. 2024). By applying these methods for data preprocessing and integration, stakeholders can ensure that the geospatial assessment of GV is based on high-quality data, effectively captures key factors influencing vulnerability, and provides valuable insights for sustainable management practices.

Geospatial assessment of groundwater vulnerability

Geospatial assessment of GV is a process that uses spatial data and analysis techniques to evaluate the susceptibility of groundwater resources to contamination or depletion (Ourarhi et al. 2024a). This involves integrating various geospatial datasets, such as hydrogeological parameters, land use/land cover, soil characteristics, topography, and proximity to potential contamination sources, to identify areas at higher risk of GV. Data collection involves collecting relevant geospatial datasets, such as hydrogeological data, land use/land cover maps, soil maps, topographic data, and information on potential contaminant sources (Abdulraheem et al. 2023). Data preprocessing involves cleaning and preprocessing the datasets, developing a conceptual

model of the groundwater system, calculating vulnerability indices, assigning weights to different vulnerability factors, using GIS software to integrate and analyze the datasets, validating the results through field observations, monitoring data, or comparison with existing studies, and conducting scenario analysis to assess the potential impact of land use changes, climate scenarios, or contamination sources on GV (Sánchez-Gómez et al. 2024). In evaluating GV through scenario analysis, Anornu and Kabo-bah (2013) conducted a comparative study of the DRASTIC method and the Aquifer Vulnerability Index (AVI) for assessing groundwater vulnerability. Their analysis highlighted the significance of urbanization and climate change as critical factors influencing groundwater resources. The DRASTIC method, which incorporates parameters such as depth to water, net recharge, and aquifer media, was found to be more precise and representative of groundwater vulnerability compared to the oversimplified AVI method. The authors suggested that while AVI might be applicable for larger basins, it overlooks the localized impacts of environmental changes, particularly in urbanized areas where groundwater vulnerability is heightened due to increased anthropogenic pressures and climatic variations (Anornu and Kabo-bah 2013). Also, the study of Meng et al. (2020) when exploring the impact of agricultural irrigation activities on groundwater pollution using the DRASTIC method in a semi-arid region with three scenarios indicated that Scenario 2 exhibited the highest pollution risk, with 40.60% of the area classified as high risk due to the inclusion of irrigation return water. Conversely, Scenario 3 demonstrated a significant reduction in the high-risk area, underscoring the importance of accurate infiltration parameters in evaluating groundwater vulnerability. This study illustrates how variations in recharge sources and methods can drastically alter the assessment of pollution risks in groundwater (Meng et al. 2020).

Furthermore, Sun et al. (2019) utilized nine distinct scenarios, combining three climate change models and three crop rotation practices and the findings showed that continuous corn cropping led to significantly higher nitrate concentrations compared to other rotation scenarios. The study underscored the effectiveness of best management practices, which resulted in lower nitrate levels, thereby emphasizing the critical role of agricultural practices in groundwater quality management. These scenarios and their evaluations provide crucial insights into the interconnections between agricultural practices, climate change, and groundwater vulnerability (Sun et al. 2019). The Integrated Modelling System employed in the study by Lyra et al. (2021) assessed various indicators such as Crop Water Productivity, Partial Factor Productivity, and Economic Water Productivity which is an indication of how different irrigation practices could lead to diverse outcomes regarding groundwater quantity and quality, emphasizing the need

for sustainable agricultural practices to mitigate negative impacts on groundwater resources. Gao et al. (2021) focused on the impacts of climate change on water quality within the Lisbon water supply system through evaluating scenarios based on two climate change models, A2 and B2 to assess potential threats such as competition for water resources and the deterioration of water quality. The findings highlighted the importance of managing groundwater extraction and quality to mitigate the adverse effects of climate change on water resources.

Moreover, Stuart et al. (2017) enhanced the BGS Nitrate Time Bomb model to include spatially and temporally distributed nitrate input functions. The model was applied to evaluate the impacts of different land use and management measures on groundwater nitrate levels through scenario testing. This highlights the long-term implications of agricultural practices on groundwater quality, showcasing how scenario analysis can be utilized to assess groundwater vulnerabilities related to nitrate contamination. (Baena-Ruiz and Pulido-Velazquez 2021) introduced the GIS-SWIAS tool, which assesses seawater intrusion dynamics at the aquifer scale. The tool allows for the analysis of historical and potential future scenarios related to seawater intrusion, highlighting the importance of understanding how management scenarios can impact groundwater vulnerability. This study emphasizes the relevance of scenario analysis in evaluating aquifer resilience under different conditions.

In a study by Bancheri et al. (2022) for the assessment of specific GV, the system handles data collection, storage,

and visualization through a Geospatial Cyber-Infrastructure (GCI) was built on open-source libraries and applications (Fig. 1a). The DSS tools are launched, and users can choose their Region of Interest (ROI) in addition to supporting real-time modeling applications. The findings indicated the change in mass arrival% at the groundwater table depth over time due to the characteristics of the graphical user interface (Fig. 1b). The graphs show the proportion of mass arrival at the groundwater table depth over time for three soil profiles with varying behaviors, colored according to the map's polygons and considering three different climatic scenarios (past, future RCPs 4.5 and 8.5).

Overview of the geospatial assessment framework

A geospatial assessment framework is a structured method that uses spatial data, analysis techniques, and modeling methods to evaluate environmental, natural resource, or infrastructure-related issues (Anandhi et al. 2022). In the context of GVA, it typically involves gathering relevant geospatial datasets, such as hydrogeological data, land use/land cover information, soil characteristics, topographic data, groundwater quality parameters, and potential contamination sources (Ourarhi et al. 2022). Data preprocessing is crucial for ensuring data quality and compatibility for further analysis. Spatial analysis is performed using Geographic Information Systems (GIS) tools and techniques to analyze the integrated datasets, calculate spatial relationships, identify patterns, and derive meaningful insights related to

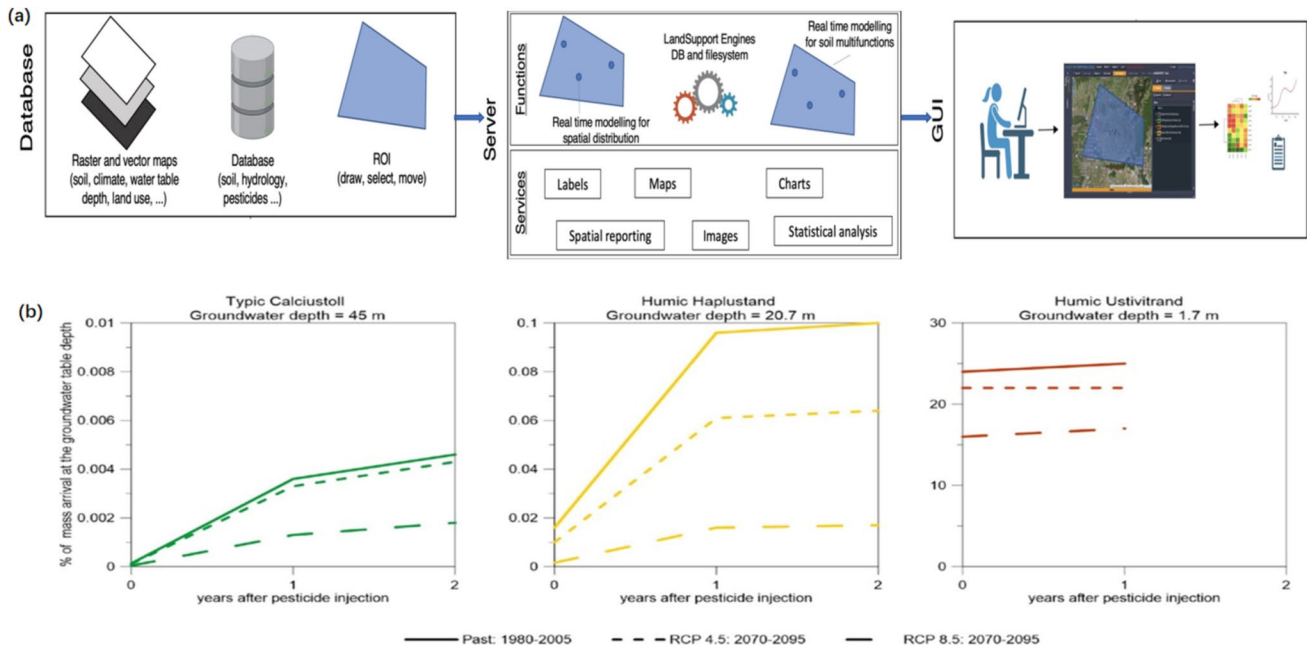


Fig. 1 Geospatial decision support system (a) Workflow schematic structure with technological components and function (b) varying groundwater table depth percentage (Bancheri et al. 2022). Open Access available @ Elsevier, 2022

GV. Model development is done by building mathematical models or spatial algorithms to quantify GV based on factors such as aquifer properties, land use practices, soil characteristics, recharge rates, and proximity to contamination sources (Abdulraheem et al. 2024a; Adedotun et al. 2023).

Vulnerability indices or scores are calculated to indicate the relative susceptibility of different areas to groundwater contamination, depletion, or other risks. Maps are generated to visually represent the spatial distribution of GV levels, allowing stakeholders to identify high-risk areas and prioritize management efforts accordingly (Gong et al. 2024). Validation is done through field data collection, groundwater monitoring, historical records, or comparison with existing vulnerability studies to ensure the accuracy and reliability of the assessment outcomes. Scenario analysis is conducted to simulate the potential impacts of different scenarios, such as land use changes, climate variations, or contamination events, on GV levels and assess the effectiveness of mitigation measures. Decision support is provided to decision-makers, stakeholders, and the public with actionable information, recommendations, and visualizations derived from the geospatial assessment to support informed decision-making and sustainable groundwater management practices.

Description of the steps involved in the strategic approaches

Geospatial assessment of GV is a systematic process that evaluates the susceptibility of groundwater resources to contamination based on factors such as land use, hydrogeological conditions, and human activities (Goyal et al. 2021; Song et al. 2015). The framework includes several key steps, including data collection, preprocessing, hydrogeological modeling, vulnerability mapping, risk assessment, validation and calibration, and decision support system. Preprocessing ensures the data's quality and compatibility for further analysis such as hydrogeological modeling simulates the flow of water through the subsurface, identifying potential contamination pathways (Zhu et al. 2023). Vulnerability mapping integrates different vulnerability indicators, such as soil permeability, depth to water table, hydraulic conductivity, land use practices, proximity to pollution sources, and recharge rates (Lavoie et al. 2015; Ourarhi et al. 2023). Risk assessment evaluates the likelihood of contaminants reaching groundwater sources based on their transport mechanisms and potential impact on human health and the environment.

Validation and calibration of assessment results ensure accuracy and reliability when comparison with field data. For instance, the modified DRASTIC model showed a substantial improvement in vulnerability assessment accuracy through validation against actual nitrate concentration data collected from 44 groundwater samples, achieving an improved coincidence rate of 82% compared to the

standard model's 67% (Boufekane et al. 2022). Similarly, the validation of the DRASTIC model involved calibration using nitrate concentration data, which ranged from 8 to 33 mg/l, to ensure that the model accurately reflected real-world conditions (Faryabi 2019). In comparative with other studies, Baena-Ruiz and Pulido-Velazquez (2020) compared the modified DRASTIC model with the COP (C: Concentration of flow; O: Overlaying layers above water table; P: Precipitation) method for vulnerability assessments in carbonate aquifers. The validation analysis indicated that the COP method provided more reliable assessments, highlighting the importance of contextual adaptation of vulnerability models. Moreover, the modified DRASTIC and SINTACS models were validated against nitrate concentrations, demonstrating that the modified SINTACS model outperformed others, reaffirming the need for model comparisons in vulnerability assessments (Noori et al. 2019). The participatory flood vulnerability assessment described by de Brito et al. (2018) employed expert involvement as a qualitative validation method. Experts were engaged throughout the modeling exercise, ensuring that the assessments incorporated multiple perspectives. This approach not only validated the model but also enriched the understanding of vulnerability criteria. The analytical hierarchy process (AHP) and analytical network process (ANP) methods were utilized for structuring vulnerability criteria based on expert feedback, further enhancing the model's accuracy.

For statistical analysis and sensitivity testing, the study by (Faryabi 2019) used sensitivity analysis to identify the key parameters affecting groundwater vulnerability, which was then calibrated using field data on nitrate concentrations. Furthermore, the study on machine learning classifiers for groundwater vulnerability highlighted the use of ROC curve and Precision-Recall curves for validating model performance, demonstrating that machine learning models could significantly outperform traditional methods (Khan et al. 2022). Furthermore, Noori et al. (2019) performed a single parameter sensitivity analysis to identify significant parameters influencing the modified DRASTIC and SINTACS models, allowing for adjustments of model weights to enhance predictive performance. The calibration process in the Mitidja plain involved modifying rating classes based on actual nitrate concentrations, demonstrating an effective calibration strategy that directly linked model outputs to observed data (Boufekane et al. 2022; Dai et al. 2005). In the study of Goyal et al. (2021) to explore different tools and methods used to assess groundwater scarcity and pollution globally confirmed that geostatistical interpolation and index-based methods are often used for preliminary investigations, assuming homogenized parameter distributions, but can overlook local variations. Also, that numerical model provides more elaborate and quantitative assessments, but requires extensive data that may not always be available,

especially at larger scales. To overcome these limitations, coupling Geographic Information Systems (GIS) with numerical models has gained prominence. Major parameters influencing GV include depth to water table, vadose zone properties, aquifer characteristics, and recharge. Furthermore, Taghavi et al. (2022) highlights the major challenges in GVA, including the lack of a clear definition of GV and the need to develop universally recognized methods appropriate for all hydrological situations.

Decision support systems provide valuable insights for sustainable groundwater management practices by identifying high-risk areas, recommending mitigation measures, and guiding policy interventions (Garg et al. 2020). By following these steps, informed decisions can be made to protect valuable groundwater resources from contamination threats effectively. Geospatial assessment of GV is a systematic process that evaluates the susceptibility of groundwater resources to contamination based on factors such as land use, hydrogeological conditions, and human activities (Ourarhi et al. 2024a). The framework includes several key steps, including data collection, preprocessing, hydrogeological modeling, vulnerability mapping, risk assessment, validation and calibration, and decision support system (Table 2).

Characteristics of aquifers in groundwater resources

The characterization of aquifers plays a crucial role in the effective management and sustainable utilization of groundwater resources. Aquifers can be categorized based on their physical and geological characteristics and the primary types include karst, alluvial, and fractured aquifers, each exhibiting unique attributes that influence groundwater flow and quality. Studies have shown that karst aquifers can exhibit rapid groundwater flow due to the presence of conduits formed by dissolution processes. For instance, a study by Leketa and Abiye (2021) revealed a significant groundwater flow rate of 11 km/year in a karst aquifer, indicating deep circulation and complex hydrodynamic behaviors that must be considered in aquifer management strategies. Furthermore, the interaction between karst springs and surface water has implications for water quality and availability, as evidenced by the hydrochemical evolution observed in karst springs (Cao et al. 2023; Leketa and Abiye 2021). Also, the assessment of an alluvial aquifer highlighted the importance of parameters such as depth to the water table and hydraulic conductivity, which were integrated into a vulnerability assessment model for groundwater management (Dindi et al. 2024). The depth to the water table in this region was noted to be critical for understanding the aquifer's susceptibility to pollution, emphasizing the need for detailed characterization. In a study focused on groundwater potential mapping in a fractured terrain, Benjmel et al. (2022) demonstrated that understanding aquifer characteristics, including depth to the

water table and hydraulic conductivity, is vital for predicting groundwater availability.

Additionally, the study on manganese contamination in karst aquifers indicated that similar hydrological behaviors could be expected in fractured aquifers, where the interplay between lithology and hydrological conditions is crucial for water quality (Hinkle et al. 2024; Dai et al. 2007). In the aspect of the water table that influences groundwater availability and vulnerability to contamination, Ekwe et al. (2006) identified significant variability in water table depth, ranging from 12 to 153 m, underlining the need for localized assessments to inform management approaches. In contrast, the exploration of groundwater potential reported average depths of 7.26 m to 57.75 m across various locations, indicating a relatively shallow water table in some areas, which could be susceptible to surface contamination (Nwachukwu et al. 2023). However, the study of Opara (2012) reported hydraulic conductivity values ranging from 9.21 to 10.27 m/day, suggesting moderate water yielding capacity. Similarly, Sultan et al. (2022) recorded hydraulic conductivity values that varied significantly across different locations, reflecting the heterogeneous nature of unconfined aquifers. While karst aquifers have been extensively studied, particularly regarding their hydrodynamic behaviors and interaction with surface water, alluvial and fractured aquifers require more focused research to delineate their unique attributes and challenges. Also, there is an apparent need for a deeper exploration into the hydraulic properties of fractured aquifers, especially concerning how fracture networks influence hydraulic conductivity and groundwater flow patterns.

Algorithms, mathematical models, and artificial intelligence in geospatial assessment of GV

In the study of geospatial assessment of GV, algorithms, mathematical models, and artificial intelligence play crucial roles in developing effective management and mitigation strategies. These tools help in analyzing and understanding the complex interactions between various factors influencing GV, thus enabling stakeholders to make informed decisions and implement targeted interventions. Geospatial assessment of GV plays a crucial role in effective management and mitigation strategies to ensure the sustainable use of this vital resource. The integration of algorithms, mathematical models, and artificial intelligence (AI) has significantly enhanced the accuracy and efficiency of assessing GV.

Algorithms in geospatial assessment

Algorithms are at the core of geospatial assessment methodologies for GV. These algorithms process large datasets

Table 2 Steps involved in the strategic approaches for geospatial assessment of GV

Techniques/key steps	Descriptions	Mechanisms	Advantages	Disadvantages	References
Data Collection	Gather relevant geospatial data such as land use, soil type, hydrogeology etc	Integration of various datasets to assess vulnerability factors	Provides a comprehensive understanding of the study area	Time-consuming and resource-intensive	(Vasileva et al. 2023; Anandhi et al. 2022)
Data Processing	Clean and preprocess the collected data to ensure accuracy and consistency	Data standardization, normalization, and quality control	Enhances the reliability of VAs	Requires expertise in data processing techniques	(Barbulescu 2020; Saqr et al. 2021)
Vulnerability Mapping	Generate geospatial maps depicting GV zones based on the assessment results	Spatial visualization of vulnerability levels for easy interpretation	Facilitates spatial planning and management strategies	Interpretation may vary depending on scale and resolution of maps	(Steiakakis et al. 2023; Msadek et al. 2022; Boufekane et al. 2022)
Hydrogeological Modelling	Developing numerical models to simulate groundwater flow and contaminant transport	MODFLOW, MT3DMS, FEFLOW software	Allows for understanding of groundwater behavior	Complex model setup and calibration process	(Chen et al. 2024; Gogu et al. 2001)
Validation and Calibration	Validate the VA results against field data or existing studies	Ground-truthing and comparison with observed groundwater contamination incidents	Ensures the accuracy and reliability of the VA	Availability of ground truth data may be limited	(Abdulraheem et al. 2024a; Khosravi et al. 2018)
Sensitivity Analysis	Evaluate the sensitivity of the vulnerability model to parameter changes	Testing model robustness by altering input parameters systematically	Helps in understanding the model's reliability and uncertainty levels	May require advanced statistical knowledge for analysis	(Raisa et al. 2024; Kirilas et al. 2023; Abduljaleel et al. 2024)
Vulnerability Index Calculation	Calculate vulnerability index based on weighted factors using GIS tools	Weighted overlay analysis to assign importance to different factors	Quantifies GV for decision-making purposes	Subjectivity in assigning weights may introduce bias	(Foster et al. 2013; Gogu and Dassargues 2000; Yu et al. 2021)
Risk Assessment	Evaluating the likelihood of contamination based on vulnerability mapping results	Probabilistic analysis, scenario evaluation	Identifies high-risk areas for prioritized management actions	Uncertainties in risk estimation	(Lavoie et al. 2015; Kumar and Krishna 2018; Jain 2023)
Decision Support System	Implementing a system to aid decision-making based on vulnerability and risk assessments	Geospatial platforms, web-based tools	Facilitates informed decision-making for groundwater protection measures	Initial setup costs may be high; ongoing maintenance needed	(Kirilas et al. 2023; Bancheri et al. 2022; Saqr et al. 2021)

comprising geological, hydrological, and land-use parameters to evaluate the susceptibility of an area to groundwater contamination. By employing algorithms like machine learning and spatial analysis techniques, researchers can identify patterns and relationships within these datasets that are not easily discernible through traditional methods (Raisa et al. 2024). Furthermore, Elzain et al. (2022) utilized advanced machine learning models like Radial Basis Neural Networks (RBNN), Support Vector Regression (SVR), and ensemble Random Forest Regression (RFR) to assess groundwater contamination vulnerability. By rating eight factors of DRASTIC-L with the modified DRASTIC model (MDM) as input data, the ensemble RFR model demonstrated superior performance and accuracy in identifying the most vulnerable contamination areas compared to SVR and RBNN models. The modified DRASTIC vulnerability index (MDVI) of MDM is represented as Eq. (1):

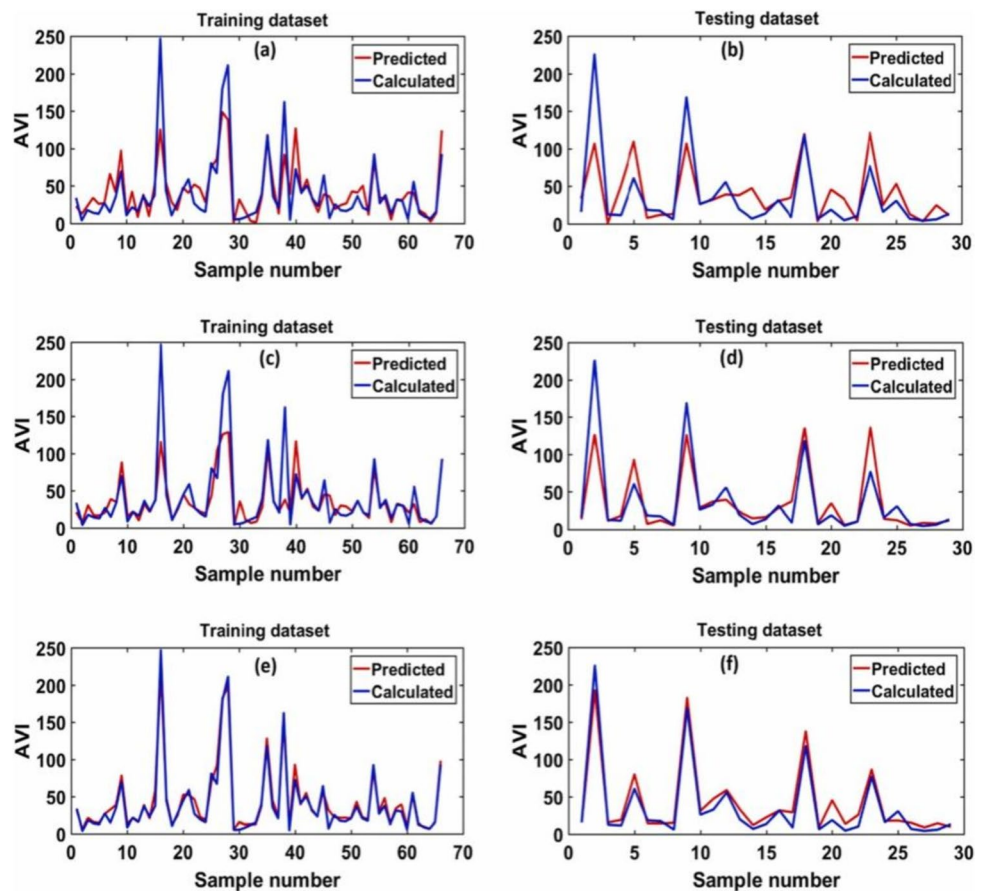
$$\text{MDVI} = D_r D_w = R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w + L_r L_w \dots \quad (1)$$

where the subscript of r and w represent the rating value (1–10) and the weight value (1–5), respectively. Thus, ensemble RFR is a robust tool for improving groundwater

contamination VA and promoting environmental safety. This allows for a more comprehensive assessment of GV across different spatial scales. Other commonly used algorithms include DRASTIC (Depth to Water, Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone), GOD (Groundwater Occurrence, Depth to Water Table), and SINTACS (Sensitivity Index Method). These algorithms assign weights to different parameters based on their significance in determining vulnerability levels.

Furthermore, the fitting curves of AVI values predicted by different ML models as studied by Elzain et al. (2022) was illustrated at (Fig. 2). The RBNN model tended to overestimate high AVI values and underestimate low AVI values (Fig. 2b). This discrepancy was particularly noticeable for high AVI values. It may be due to the Gaussian function's limitations in capturing extreme values in the RBNN model. SVR exhibited a more accurate fit than RBNN (Fig. 2d) but still had some overestimations. On the other hand, the RFR model (Fig. 2f) showed a good alignment between predicted and calculated AVI values.

Fig. 2 Fitting plot curve of predicting AVIs in training and testing phase for; **a, b** RBNN, **c, d** SVR, and **e, f** RFR models (Elzain et al. 2022) (Copyright permission available @ Elsevier, 2023)



Mathematical models for GV

Mathematical models are essential for simulating the behavior of groundwater systems and predicting how contaminants may spread through aquifers under various scenarios (Afrifa et al. 2022; Dai et al. 2005). These models incorporate hydrogeological principles, physical processes, and mathematical equations to simulate the flow of water and contaminants in subsurface environments. Models such as MODFLOW (MODular Finite-difference Flow model) and MT3DMS (Multi-species Transport in 3-Dimensions) are commonly employed to predict contaminant transport pathways and assess potential risks to groundwater quality (Zhu et al. 2023). By calibrating these models with field data, researchers can better understand the vulnerability of groundwater sources to pollution and develop strategies to mitigate potential risks.

Artificial intelligence applications

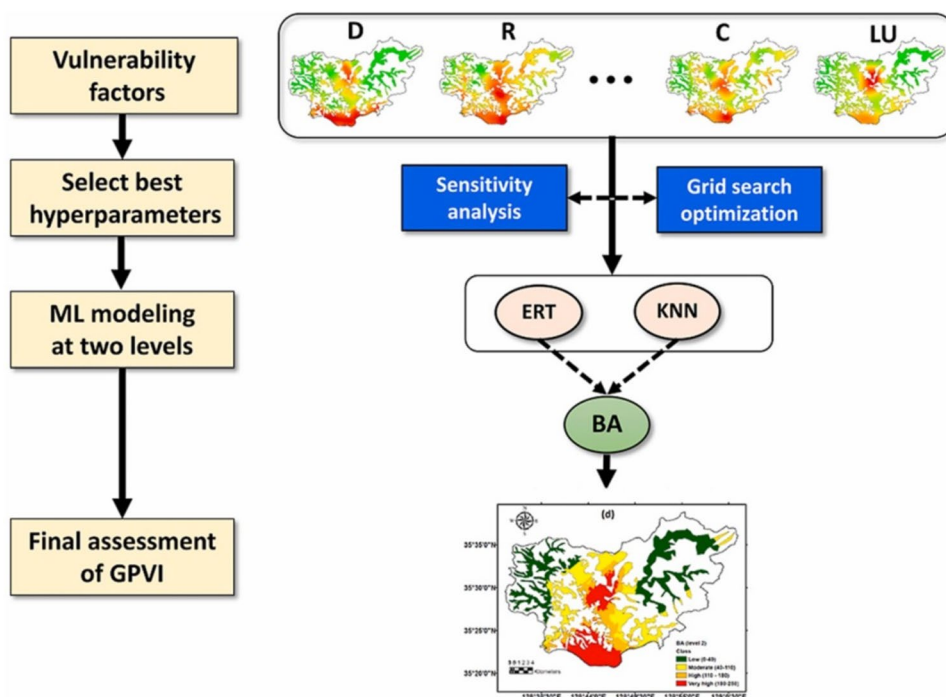
Artificial intelligence techniques have revolutionized geospatial assessment by enabling advanced data processing, pattern recognition, and predictive analytics. Machine learning algorithms such as support vector machines (SVM), random forests, and neural networks are utilized to analyze vast amounts of geospatial data and identify hidden patterns related to GV. In a study by Elzain et al. (2023) to enhance the DRASTIC-LU model using Machine Learning (ML) techniques like k-nearest Neighbors (KNN), ensemble Extremely Randomized Trees (ERT), and ensemble Bagging

Regression (BA) to forecast groundwater pollution vulnerability index (GPVI) values (Fig. 3). The level 2 ensemble BA model outperformed the individual KNN and level 1 ensemble ERT models, yielding accurate results for new data and averting overfitting problems during testing. This indicates that employing ML modeling at two tiers could be a proactive strategy for safeguarding groundwater resources from contamination.

AI-based approaches can also optimize sampling strategies, predict future scenarios, and assist in decision-making processes for effective groundwater management (Msaddek et al. 2022). By leveraging AI techniques, stakeholders can gain valuable insights into the factors influencing GV and optimize management and mitigation strategies accordingly. ML techniques, particularly random forest (RF), support vector machines (SVM), and artificial neural networks (ANN), heavily influence groundwater level change predictions (Afrifa et al. 2022). Ensembles in ML aid in managing computational complexity and enhancing performance and training efficiency. In contrast to mathematical models, ML methods offer superior accuracy. Hence, researchers should integrate novel ML techniques alongside traditional mathematical models to predict groundwater level changes.

The synergy between algorithms, mathematical models, and artificial intelligence enhances the overall accuracy and reliability of GVAs. By combining the strengths of these approaches, researchers and policymakers can gain deeper insights into the spatial distribution of vulnerable areas, prioritize mitigation efforts, and develop sustainable management strategies for safeguarding groundwater resources.

Fig. 3 Machine algorithms to predict the GV (Elzain et al. 2023) (Copyright permission available @ Elsevier, 2023)



In conclusion, the integration of algorithms, mathematical models, and artificial intelligence in the study of geospatial assessment of GV offers a comprehensive framework for effective management and mitigation strategies. By harnessing the power of these tools, researchers and stakeholders can better understand the dynamics of groundwater systems, identify potential risks, and implement targeted interventions to safeguard this vital resource for future generations.

Case studies of real-world examples of geospatial assessment of GV and mitigation strategies

Groundwater is an important global water resource, but increasing industrial and agricultural activities have led to widespread contamination issues. Assessing aquifer vulnerability helps policymakers understand potential impacts and adopt effective management strategies. The three main types of GVA methods are index-based qualitative methods, statistical methods, and process-based quantitative methods (Fanakh and Farsang 2022; Kc et al. 2022). Each method has advantages and limitations in terms of data requirements, applicability to different aquifer types, and reliability of VAs. These methods should be coupled with data on specific pollutant sources and activities to enhance the reliability of VAs for informing groundwater management and protection strategies.

Groundwater presents significant advantages compared to surface water due to its protection from surface pollutants (Steiakakis et al. 2023). However, the growing world population, urbanization, and increased demands from agriculture and industry are putting intense pressure on groundwater resources, which are also threatened by climate change and pollution (Voudouris and Kazakis 2021; Abdurraheem et al. 2024b). To address these challenges, GV and pollution risk mapping are important tools for groundwater management

and protection. GV can be classified as intrinsic (based on the physical environment) or specific (considering contaminant properties). Li et al. (2014) focuses on nitrate pollution in agricultural landscapes using a GIS model and found a positive correlation between nitrate concentrations and GV in sampled wells (Fig. 4b). Also, a gradual mixing between recently replenished high-nitrate groundwater and slowly circulating, denitrified discharged groundwater from upland areas is most likely the cause of the reduced nitrate content at the valley bottom (Fig. 4a). The findings suggest that modeling regional groundwater pollution risk in other locations could be successfully achieved. Assessing GV and pollution risk allows authorities to identify areas most susceptible to contamination and implement appropriate protection measures.

Land use and topography were identified as the most critical parameters in single-parameter sensitivity analysis, while hydraulic conductivity had the most negligible impact. Three vulnerability models were validated using nitrate concentrations from groundwater samples, with the Nitrate NV index being the most accurate, followed by Pesticide DRASTIC-LU and Nitrate SINTACS-LU (Kirlas et al. 2023; Kumar and Krishna 2018). The study highlighted the importance of GVA for the sustainable management of groundwater resources which serve as a guideline for policymakers and authorities in decision-making at a regional scale, emphasizing the need for systematic monitoring, regulation of agricultural activities, and implementation of sustainable practices to prevent further groundwater quality deterioration. Furthermore, Zhang et al. (2023) identified valley regions, karst subsidence areas, and mined-out coastal areas as the most vulnerable, covering 1.463 km², and the findings were supported by the groundwater pollution index, validating them with an R² coefficient of 0.961. The study recommended that the relevant departments address these concerns by improving and developing groundwater resources, implementing effective

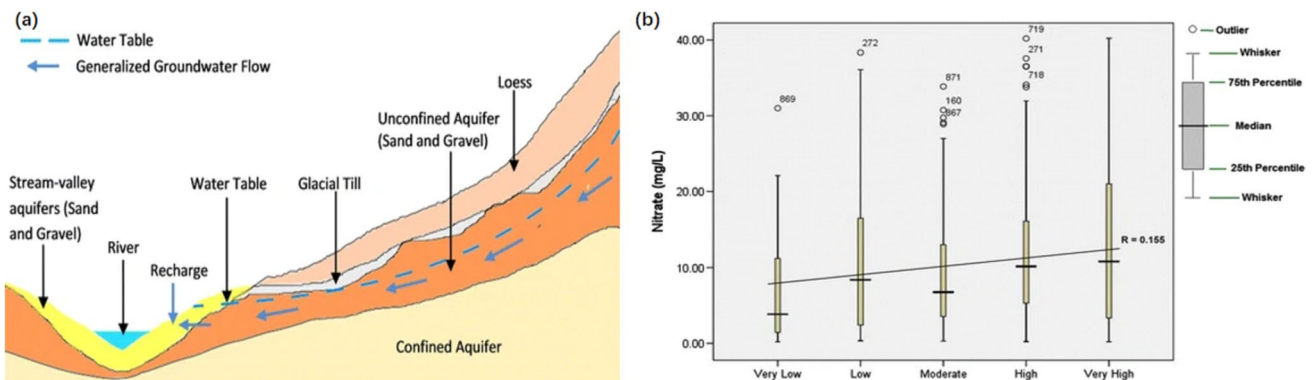


Fig. 4 Geospatial approach for assessing groundwater vulnerability (a) groundwater flow in river valley (b) relationship between classification of GV and nitrate concentrations (Li et al. 2014)

pollution control measures, and undertaking remediation efforts to restore polluted groundwater. Another study aimed to improve the DRASTIC model for assessing GV shows that net recharge is the most significant factor in GV, while the impact of the vadose zone and hydraulic conductivity were the least effective factors (Khosravi et al. 2018). The weights-of-evidence method demonstrated the highest predictive power, and including more factors in the DRASTIC model improved GVA. However, Sadeghi-Jahani et al. (2024) examines the connection between sustainable development and water shortages, focusing on vegetation, land cover, population, and climatological conditions. As shown in (Fig. 5), the groundwater vapor levels decreased between 2006 and 2011 and between 2012 and 2018, however they remained steady between 2003 and 2006. The Kaftar lakes' second cluster (C2) is made up of sub-basins surrounding the Sivand River, which had a constant groundwater level from 2003 to 2006 and a steadily declining groundwater level after that. Throughout the time, the groundwater level condition in the third cluster (C3) sub-basins bordering the southern and southeast areas of the Tashk and Bakhtegan lakes was steady; nevertheless, between 2008 and 2010, there was a modest downward tendency. Nevertheless, in the years that followed, this tendency was curbed. The Maharloo Lake sub-basin and the area downstream of the first cluster, towards the Kor River, are included in the fourth cluster (C4). The GWL loss in C4 aquifers is the most severe; over the anticipated period, several of these aquifers had a decline in GWL of over 20 m. The study emphasizes the

necessity for more investigation to determine the fundamental reasons behind aquifer GWL decreases.

GV maps are essential for evaluating vulnerability and planning land use. However, there isn't one most reliable method, as each depends on various factors such as aquifer characteristics, land use, data availability, parameters, weightings, and ratings assigned to each parameter (Barbulescu 2020). The DRASTIC method uses readily available geo-data instead of experimental data and includes numerous parameters, which sometimes leads to comparisons with field-collected data. Some of the results and lesson learned from various studies are presented in (Table 3).

Recent advancements in GIS-based VA methods have improved reliability by integrating groundwater quality data, considering land use patterns, and using optimization schemes (Elçi 2012). The calibrated vulnerability map of their studies showed significant changes in the spatial distribution and proportions of vulnerability classes, emphasizing the importance of optimization for more reliable VAs (Song et al. 2014; Gong et al. 2024). Another study by Cao et al. (2023) introduces an improved COPK method to assess GV, outperforming the original COP method where the study area is categorized into five levels of vulnerability, with most areas exhibiting moderate to low vulnerability. The assessment results are validated by analyzing nitrate concentration in groundwater, showing significant variations and the improved COPK method has significantly enhanced performance compared to the original COP method. These demonstrate a stronger relationship with nitrate concentration, supporting its effectiveness in assessing GV in the study area.

Fig. 5 Groundwater vulnerability level variations in clustering sub-basin region (Sadeghi-Jahani et al. 2024) (Copyright permission available @ Elsevier, 2024)

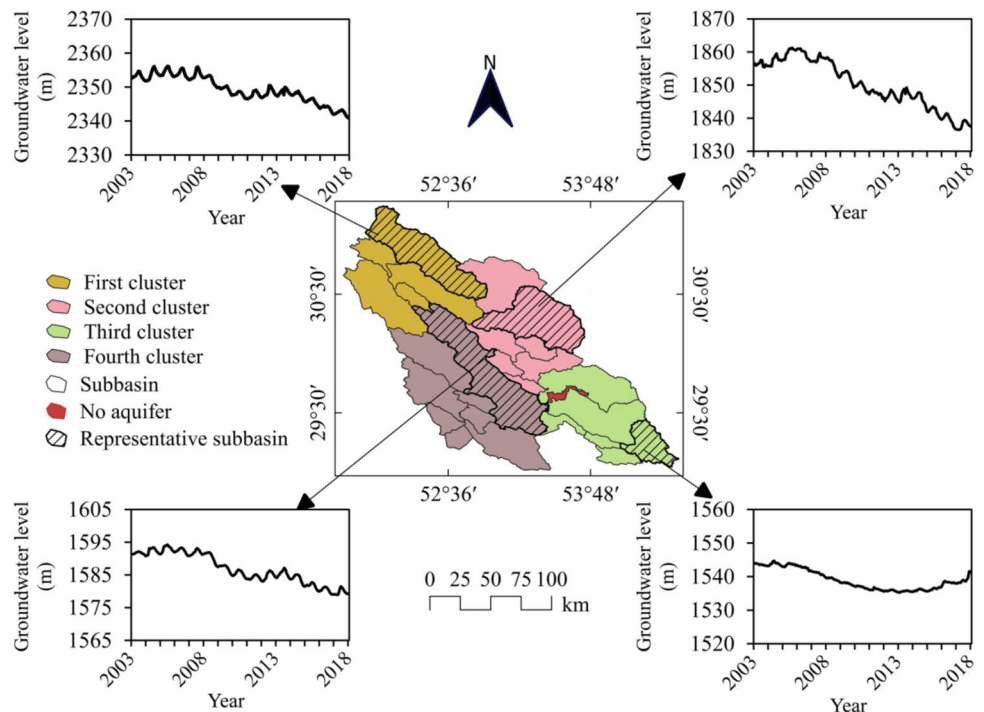


Table 3 Description of the results and lessons learned from the case studies

Study	Objectives	Methods	Results	References
GVA in a Coastal Region	To evaluate the vulnerability of groundwater to contamination in a coastal aquifer system	<ul style="list-style-type: none"> Used DRASTIC model for VA—Conducted field surveys and collected water samples—Analyzed land use and hydrogeological data 	<ul style="list-style-type: none"> Identified high vulnerability zones near industrial areas—Recommended stricter regulations for waste disposal in vulnerable zones 	(Zhang et al. 2023)
Geospatial Analysis of GV in an Urban Setting	To assess the vulnerability of urban groundwater to pollution sources	<ul style="list-style-type: none"> Utilized GIS techniques to map land use and hydrogeological features—Integrated statistical analysis to quantify vulnerability levels 	<ul style="list-style-type: none"> Found high vulnerability around landfills and industrial sites—Suggested improved monitoring and remediation strategies for contaminated areas 	(Wang et al. 2023)
GV Mapping in Agricultural Regions	To determine the susceptibility of groundwater to agricultural pollutants	<ul style="list-style-type: none"> Employed numerical modeling to simulate pollutant transport—Collected soil and water samples for analysis 	<ul style="list-style-type: none"> Identified areas at risk of nitrate contamination from agricultural activities—Proposed better agricultural practices to reduce pollution impact on groundwater 	(Raisa et al. 2024)
Remote Sensing Applications for GVA	To explore the use of remote sensing for assessing GV	<ul style="list-style-type: none"> Utilized satellite imagery for mapping land cover changes—Applied machine learning algorithms for predictive modeling 	<ul style="list-style-type: none"> Detected changes in land cover affecting groundwater quality over time—Demonstrated the potential of remote sensing in monitoring vulnerable areas efficiently 	(Sangawi et al. 2023)
GVA in Karst Terrains	To evaluate the vulnerability of karst aquifers to contamination sources	<ul style="list-style-type: none"> Conducted dye tracing experiments to understand flow paths in karst systems—Integrated geophysical surveys to map subsurface features 	<ul style="list-style-type: none"> Highlighted rapid transport of contaminants through karst conduits—Recommended enhanced protection measures for karst groundwater resources 	(Lavoie et al. 2015; Lu et al. 2023)
GV Mapping in Mountainous Regions	To analyze the vulnerability of mountainous aquifers to contamination risks	<ul style="list-style-type: none"> Utilized remote sensing data for mapping land cover changes over time—Conducted tracer tests to determine groundwater flow paths and velocities—Developed a spatial model incorporating topographic factors and recharge rates 	<ul style="list-style-type: none"> Detected areas prone to rapid contaminant transport due to steep slopes and high recharge rates—Proposed interventions such as reforestation and erosion control measures for protection 	(Hadžić et al. 2015)
GVA using GIS-based methods	Efficient groundwater management in areas with intensive anthropogenic activities and pollution	<ul style="list-style-type: none"> DRASTIC method used, which includes seven hydrogeological parameters Weighted linear combination formula used to calculate DRASTIC Index 	<ul style="list-style-type: none"> Increasing water scarcity due to climate change effects in regions Study aids policymakers in preserving aquifer system from future deterioration 	(Hamed et al. 2024)
Assessment of GV	To highlight vulnerable areas for decision-makers to protect groundwater quality	<ul style="list-style-type: none"> Two DRASTIC models used: generic and pesticide, to assess vulnerability levels to pollution 	<ul style="list-style-type: none"> GIS plays a significant role in assessing and predicting groundwater pollution potential 	(Tahlawi et al. 2016)

Also, overlay and index methods combine maps of various geographic attributes to create vulnerability maps, while process-based models use mathematical equations to simulate contaminant transport (Khosravi et al. 2018). These methods create vulnerability maps, simulate contaminant transport, and relate water quality to environmental factors with uncertainties arising from data collection errors, natural variability, and model conceptualization limitations. These uncertainties can be analyzed using techniques like first-order uncertainty analysis and Monte Carlo simulation. Also, Hadžić et al. (2015) in an attempt to analyze various methods for assessing GV, focusing on the source of groundwater confirmed that mapping GV is a valuable tool for assessing with various methods available depending on data availability, scale mapping, spatial distribution, hydrogeological characteristics, and other parameters.

Mitigation strategies for groundwater vulnerability

Groundwater, a crucial resource, is at risk of contamination from diverse sources like agriculture, industry, and natural disasters, and its vulnerability are influenced by geology, land use, and potential contaminants (Jain 2023). Assessing GV and implementing risk mitigation strategies are essential for ensuring the resource's sustainability. Standard methods include index-based, statistical, and GIS-based approaches to evaluate geology, hydrogeology, and land use that impact vulnerability. Risk mitigation strategies like land-use planning, pollution prevention, and remediation technologies can lower the risk of groundwater contamination and its associated impacts (Lavoie et al. 2015). A deep understanding of site-specific factors and community engagement is needed to implement these strategies. In the future, integrating various approaches to assess GV and mitigate risks can better protect groundwater resources (Varady et al. 2016). Incorporating social and cultural factors, as well as advancing modeling and monitoring techniques, can further enhance our ability to identify and address GV and contamination (Saqr et al. 2021). Continued research and innovation in this field are crucial to ensuring the sustainability of this vital resource for generations to come. Below are some descriptions of different types of mitigation strategies to minimize the impacts of various threats to our environment.

Source protection

This strategy involves safeguarding potential sources of contamination to prevent pollutants from entering groundwater system through managing water sources to ensure their quality and quantity. This can be achieved through various measures such as watershed management, aquifer recharge,

and source control (Zhang et al. 2022a). Watershed management includes managing land and water resources, such as reforestation, soil conservation, and wetland restoration, to reduce soil erosion and protect aquatic habitats. Aquifer recharge replenishes groundwater resources by allowing rainwater or surface water to infiltrate the ground using artificial or managed aquifer recharge (Adedotun et al. 2023; Khawaja et al. 2021). Source control prevents water resource contamination by regulating industrial discharges, controlling agricultural practices, and managing urban runoff.

Water conservation

Water conservation strategies aim to reduce the amount of water that needs to be extracted from groundwater sources by implementing practices such as fixing leaks, efficient irrigation, demand management, and promoting water-saving behaviors (Calliera and Capri 2022). Efficient irrigation techniques include drip, precision, and mulching; water can be reused for irrigation and industrial cooling while demand management includes pricing policies, metering systems, and public education campaigns to promote efficient water use and reduce wastage. This helps in sustaining water resources and protecting ecosystems.

Contaminant removal

Contaminant removal involves eliminating water pollution to safeguard human health and the environment. This is accomplished through advanced treatment methods such as membrane filtration, ion exchange, UV disinfection, treatment plants, bioremediation techniques to clean up contaminated sites, and ozone treatment. Monitoring and enforcement efforts aim to implement regulations to prevent contamination, including those related to industrial discharges, agricultural practices, and urban runoff.

Erosion control

Erosion control measures help prevents soil erosion and sedimentation caused by weather events or human activities. These can transport sediment and pollutants into groundwater sources through techniques such as planting vegetation, constructing retention ponds, implementing erosion control structures, and maintaining proper land use practices that can minimize the impact of erosion on groundwater quality.

Habitat restoration

Habitat restoration projects aim to restore natural ecosystems that provide significant groundwater recharge and quality maintenance services. Activities such as wetland restoration, protection of riparian zones, reintroduction of native

species to damaged habitats, and reforestation efforts can improve the natural filtration capacity of the landscape and safeguard groundwater resources.

Green infrastructure

Green infrastructure refers to nature-based solutions that imitate natural hydrological processes to manage storm-water and encourage absorption into the ground. It helps address environmental issues such as urban heat islands, air pollution, green roofs, permeable pavements, rain gardens, and constructed wetlands, all assist in reducing surface runoff and replenishing local aquifers.

Climate adaptation

“Climate adaptation strategies aim to prepare for and respond to the impacts of climate change on groundwater resources. This includes adjusting water management practices, improving monitoring systems to detect changes in groundwater levels or quality, and creating resilience plans to deal with extreme weather events and sea-level rise.” By combining these different types of mitigation strategies tailored to specific vulnerabilities in a given area, communities can effectively protect their groundwater resources from contamination and depletion.

Conclusion

In conclusion, the review paper presents a framework for geospatial assessment of groundwater vulnerability that integrates geospatial data and techniques with hydrogeological and statistical analyses which provide a better understanding of the potential risks and develop appropriate management strategies for land contaminant sources that affect groundwater quality and quantity. The methodologies examined include remote sensing, GIS and statistical modeling, which were evaluated based on their effectiveness in different geographical contexts. These technologies serve as pivotal components in developing and implementing effective groundwater management and mitigation strategies, allowing for the optimization of water use, the protection of water quality, and the sustainability of water resources in the face of growing environmental pressures. The findings reveal that spatial analysis techniques significantly enhance the accuracy of groundwater vulnerability assessments by incorporating diverse data sources such as land use, soil characteristics, and hydrological features. Key results indicate that GIS-based models provide robust frameworks for identifying vulnerable areas, while MCDA facilitates stakeholder engagement by integrating socio-economic factors into decision-making processes. While traditional GIS

methods remain widely used, there is an increasing trend towards incorporating advanced computational techniques such as machine learning. These methods enhance predictive accuracy and allow for more nuanced analyses of complex environmental interactions affecting groundwater quality. Furthermore, case studies demonstrate successful applications of these techniques in various regions, highlighting their potential for improving water resource management.

This study underscores the necessity for adopting advanced spatial analysis techniques in groundwater management policies globally. By enhancing the precision and effectiveness of vulnerability assessments, geospatial technologies empower stakeholders to implement proactive measures, ensuring the resilience and security of groundwater resources. The paper contributes to scientific knowledge by providing a thorough evaluation of contemporary spatial analysis methods for assessing groundwater. It highlights their relevance not only at local levels but also in addressing global challenges related to water scarcity and pollution—issues that resonate with international sustainability goals. For future studies, the paper advocates for advancing geospatial methodologies and integrating novel data sources, such as UAVs to improve the granularity and accuracy of GVAs. Additionally, it calls for more transdisciplinary research that bridges the gap between hydrogeological science and policy-making, emphasizing the need for a collaborative effort to develop inclusive, equitable, and sustainable groundwater management policies.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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