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Groundwater resource assessment methods in the Ethiopian Rift Valley Basin: a systematic review

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Water resources, particularly groundwater underpin the socio-economic development and ecological integrity of hydrogeologically complex regions such as the Ethiopian Rift Valley Basin (ERVB), where groundwater resources exhibit significant spatial variability due to active faulting, volcanic processes and heterogeneous geological condition. This systematic review synthesises groundwater assessment methods applied in the ERVB, drawing on 80 peer-reviewed primary studies published between 2016 and 2025 and adhering to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 reporting guidelines. The synthesis characterises methodological trends, evaluates tool performance, critically appraises study quality and identifies evidence-based priorities for advancing hydrogeological research. Original articles were identified from Scopus, Web of Science, GeoRef and Google Scholar. The review reveals methodological evolution, including a marked increase in publications since 2022 and a broad shift towards integrated, simulation-based assessment frameworks. Hydrological modelling (26.25%) and integrated geospatial techniques (20.0%) are the dominant methodological categories used to characterise and quantify groundwater resource dynamics. Persistent data scarcity and limited long-term monitoring networks are the critical constraints on model calibration, uncertainty assessment and predictive reliability. Thus, the reliability of future groundwater studies depends on bridging the gap between advanced simulation tools and the persistent field-based data scarcity. Specifically, it supports SDG 6 (Clean Water and Sanitation) by improving regional groundwater monitoring and protection; SDG 2 (Zero Hunger) by enabling precise assessments for effective irrigation planning; and SDG 13 (Climate Action) by identifying tools to mitigate climate impacts and enhance local resilience.

Keywords: environment/geohydrology/geophysical survey/groundwater/groundwater potential mapping/groundwater resource assessment/hydrochemistry/hydrological modelling/hydrology and water resource/Main Ethiopian Rift/PRISMA/systematic review UN SDG 2: Zero hunger/UN SDG 6: Clean water and sanitation/UN SDG 13: Climate action

1. Introduction

Water resources are essential for sustaining life and ensuring long-term water security (Hulluka *et al.*, 2023; Mechal *et al.*, 2022; Mihret and Wuletaw, 2025; Nowicki *et al.*, 2023; Takele *et al.*, 2025a; Tola and Deyassa, 2024). Groundwater, in particular, plays a critical role in supporting communities, agriculture and industry, especially in the Ethiopian Rift Valley Basin (ERVB), where its management is fundamental to socio-economic development (Berehanu *et al.*, 2017; Bonetto *et al.*, 2021). However, in this hydrogeologically complex region shaped by Cenozoic volcanism and extensional tectonics – groundwater resources face unprecedented stress from rapid population growth, expanding agricultural demands and climate change (Kebede *et al.*, 2021; Mechal *et al.*, 2016; Truneh *et al.*, 2024; Tufa *et al.*, 2024; Yilma *et al.*, 2023). Recent studies emphasise that climate variability and land-use changes are further intensifying groundwater stress across East African rift systems (Abraham *et al.*, 2018; Ayalew *et al.*, 2023; MacDonald *et al.*, 2021).

Despite a growing body of research, a systematic and holistic synthesis of the current methodological landscape remains absent for

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the ERVB as a whole. While newly available datasets and high-resolution hydrogeological models reveal greater aquifer heterogeneity (Amare *et al*., 2018; Closas and Villholth, 2020; Jibat *et al*., 2024), inconsistencies in method application and limited integration of modern tools such as remote sensing (RS), numerical modelling and machine learning (ML) persist (Tadesse *et al*., 2024).

This systematic review evaluates state-of-the-art methodologies published between 2016 and 2025 with three specific objectives: (i) to systematically categorise and synthesise groundwater assessment methods documented in original research conducted within the ERVB; (ii) to critically evaluate the methodological strengths, limitations and temporal trends in tool application; and (iii) to propose evidence-based, actionable recommendations for improving the technical accuracy and predictive reliability of future hydrogeological assessments in the basin.

The findings of this review have direct implications for the United Nations Sustainable Development Goals (SDGs). Improved groundwater monitoring frameworks inform SDG 6 (Clean Water and Sanitation); quantitative recharge assessments underpin irrigation planning central to SDG 2 (Zero Hunger); and the identification of climate-adaptive assessment tools advances SDG 13 (Climate Action). By bridging methodological gaps in hydrogeological science, this review provides an evidence base for policymakers and water resource managers operating across the ERVB and analogous rift environments globally.

2. Study area description

The ERVB comprises several prominent lakes, including Ziway, Langano, Abijata and Shalla, situated within a tectonically controlled endorheic basin (Street, 1979; Chernet, 1982). Covering approximately 55 000 km^2, the basin lies between latitudes 7°00′56″ and 8°28′8″N and longitudes 38°03′38″ and 39°24′48″E (Figure 1). Annual rainfall varies markedly across the region, ranging from roughly 700 mm in the lowlands to nearly 1200 mm in the surrounding highlands. Due to its strategic location along the seasonal migration path of the Intertropical Convergence Zone, the ERICA Project ("Environmental Research for Intertropical Climate in Africa") has designated the Central Rift Valley (CRV) as a key site for climate studies. Paleoclimatic

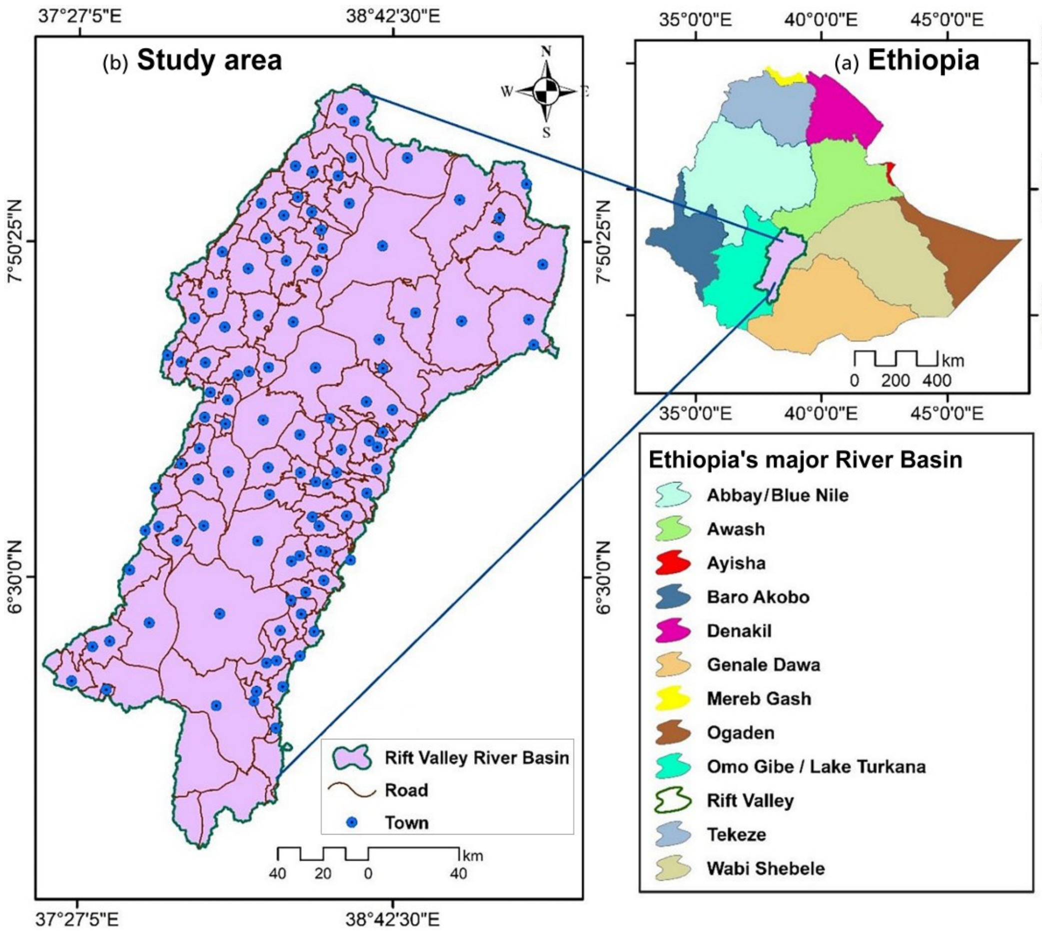

Figure 1. Location map of the Ethiopian Rift Valley River basin (b) with inset map showing major Ethiopian River Basins (a)

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records dating back to the Late Pleistocene indicate significant historical fluctuations in water levels and salinity (Le Turdu *et al*., 1999), with the Ziway–Shalla closed basin serving as a vital reference for regional and global climate reconstructions.

Beyond its geological and climatic significance, the valley supports a diverse range of socio-economic activities and provides essential ecosystem services. Approximately 76.8% of the basin is dedicated to rainfed agriculture, while irrigated farming accounts for less than 3%; of these irrigated areas, roughly 44% depends on surface water from streams, 31% on Lake Ziway and 25% on groundwater. The region experiences a bimodal rainfall pattern, with two main wet seasons the ‘long rains’ (March to May) and the ‘short rains’ (September to November) separated by dry intervals (June to August and December to February). These seasonal cycles are essential for maintaining the basin’s water resources, agriculture, and biodiversity. However, prolonged dry periods often reduce water availability, posing challenges that require adaptive management by the communities dependent on these vital resources.

Hydrogeologically, the ERVB is dominated by Quaternary volcanic rocks – including rhyolites, ignimbrites and basalts interbedded with lacustrine sediments that form the principal productive aquifers. Regional groundwater flow is strongly governed by NNE–SSW-trending border faults and intra-rift faults, which act both as conduits and barriers depending on fault infill mineralogy. Aquifer depth ranges from shallow alluvial systems (<30 m) in the valley floor to deep fractured volcanic units (>150 m) along the escarpments. Geogenic fluoride enrichment attributed to water–rock interaction with fluoride-rich volcanic minerals and hydrothermal inputs is pervasive, with concentrations frequently exceeding the WHO guideline value of 1.5 mg/L. These hydrogeological characteristics fundamentally constrain the selection and applicability of assessment methodologies reviewed herein.

3. Data sources and review methodology

A systematic literature search was conducted in accordance with guidelines the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 reporting guidelines to ensure transparency, consistency and replicability. Peer-reviewed articles published between 01 January 2016 and 31 December 2025, were retrieved from Scopus, Web of Science, GeoRef and Google Scholar using predefined geographic and thematic keywords. Original articles focusing on groundwater assessment within the ERVB were considered. A total of 80 peer-reviewed original research articles constitute the final synthesis dataset used for all analyses, tables, figures and interpretations reported in this review. This approach enables a comprehensive synthesis of groundwater assessment methods applied in the basin, supporting informed recommendations for future research directions. All stages of study identification, title/abstract screening, full-text eligibility assessment and final inclusion were documented in a PRISMA flow diagram (Figure 2).

3.1 Study selection, eligibility criteria and data synthesis approach

3.1.1 Eligibility criteria

This review included original research articles that fulfilled specific eligibility criteria. Eligible studies were required to be published in peer-reviewed academic journals between 01 January 2016 and 31 December 2025. Articles were included if the studies focused on groundwater resource assessment within the ERVB and explicitly incorporated at least one groundwater assessment method (e.g. groundwater potential mapping, hydrochemistry, recharge estimation, flow dynamics or surface–groundwater interaction). All studies were published in English and available as full-text original articles. Grey literature including theses, dissertations, book chapters, conference abstracts and editorials was excluded, as were studies lacking explicit groundwater methodological documentation.

3.1.2 Search strategy and data extraction

For each study, information was extracted regarding the methodological approach, spatial scale, data sources and reported limitations. Studies were grouped into major methodological categories, and emphasis was placed on cross-study comparison and critical synthesis rather than individual case descriptions. A comprehensive literature search was performed across four major academic databases: Scopus, Web of Science (Core Collection), GeoRef and Google Scholar. The search strategy was informed by the 5Ws framework (Who, What, When, Where, Why), aiming to capture all relevant studies. Search terms included combinations of geographic keywords (“Main Ethiopian Rift”, “Ethiopian Rift Valley”, “MER”, “Ethiopia”) and thematic terms such as “groundwater assessment”, “hydrogeological modelling”, “aquifer characterisation”, “groundwater modelling”, “geophysical survey”, “AHP” and “remote sensing”. Boolean operators (AND, OR) were used to formulate optimal queries.

To ensure comprehensiveness, the reference lists of all included articles were imported to Microsoft Excel and manually reviewed for additional relevant publications. A standardised data extraction form was developed, piloted on five randomly selected studies and then applied systematically. Screening and data extraction were conducted by two independent reviewers, with disagreements resolved through discussion; inter-rater agreement was assessed using Cohen’s Kappa ($\kappa \geq 0.80$ was set as the threshold for acceptable reliability). Extracted data included bibliographic information (authors, year, title, journal, DOI), study location (basin or sub-basin within the RVB), research objectives, detailed descriptions of methods used, the spatial or hydrogeological scale of the study, data sources and their origins, significant findings, methodological strengths and limitations, innovations and any reported data gaps or challenges. A PRISMA flow diagram (Figure 2) was

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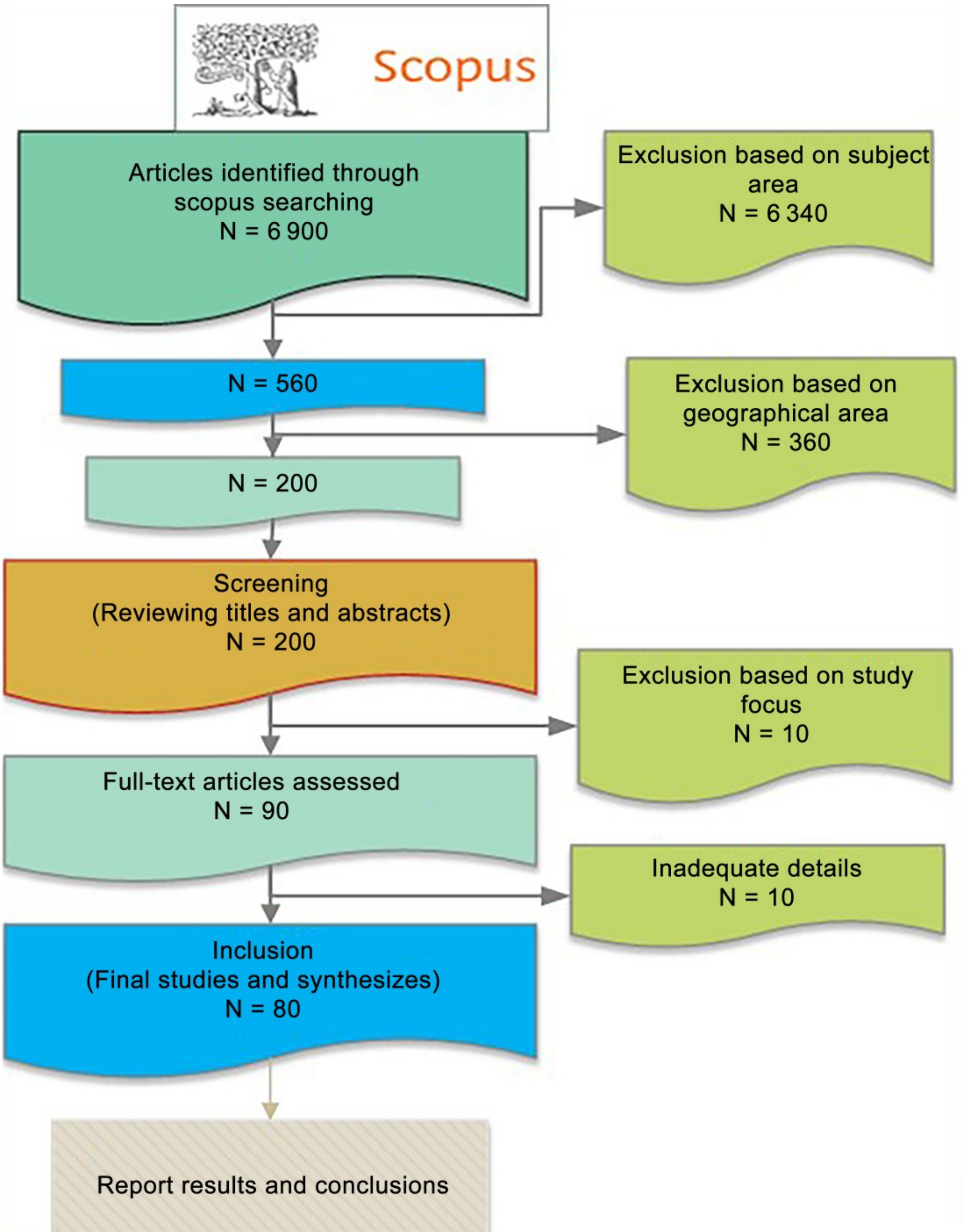

Figure 2. PRISMA flowchart of systematic review, where *N* represents the number of articles

used to document the article selection process, including the number of studies identified, screened, excluded and finally included for synthesis.

3.2 Data synthesis and analysis

A narrative synthesis approach was adopted to analyse the results of the selected studies. The articles were categorised into thematic groups based on the type and application of groundwater assessment methods. The analysis identified trends in methodological application across the 2016–2025 period, as well as patterns in research focus and scale. Of an initial pool of 6900 identified records, 80 studies met all eligibility criteria and were included in the final synthesis (Figure 2). The breakdown by screening stage was: 6900 records identified → 4210 retained after duplicate removal → 1850 screened by title and abstract (1530 excluded:

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reasons: outside geographic scope, non-groundwater focus or non-original research) → 320 assessed for full-text eligibility (240 excluded: reasons detailed in Figure 2) → 80 studies included in the final synthesis. Thematic areas of focus included hydrogeological mapping, geophysical surveying, groundwater modelling, RS applications and the integration of multidisciplinary data. The analysis considered the scale (local, sub-basin or basin-wide) and context of each method's application, as well as the software tools and instrumentation employed. To reduce bias, the review only included original research articles published in reputable journals, and studies were assessed based on research objectives, scope, methodological quality and academic credibility. The resulting synthesis provides a comprehensive overview of current groundwater assessment research in the Main Ethiopian Rift, offering insights into methodological effectiveness and areas requiring further investigation.

3.3 Integrated methodological framework and complementarity of techniques

The methodological strategies identified in the reviewed studies can best be described as part of a complex groundwater assessment framework rather than as a single tool. RS and GIS-based studies, with or without multi-criteria decision analysis (MCDA), are deployed at the basin and sub-basin scales to map groundwater potential zones, recharge potential areas and vulnerability hotspots. These spatial layers combine topography, land use/land cover, soil properties, lithology, lineament density and drainage density. They are therefore a first-order screening tool to guide further field investigations.

Geophysical methods, such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES), are used in areas prioritised by RS-GIS and MCDA to enhance subsurface characterisation. Such techniques are useful for determining the thickness and geometry of aquifers, fractured and weathered horizons, and structural features including faults and lineaments that govern water movement in the ground, as well as the depth to water-bearing formations. Through this, geophysical surveys convert the outputs of the spatial screening process into finer, site-specific information on hydrogeology.

Hydrochemical and, where possible, isotopic investigations complement RS-GIS and geophysics in validating conceptual flow models and describing recharge mechanisms. Major ion chemistry, trace elements and isotopic signatures are applied to discriminate between local and regional recharge, mixing between shallow and deep flow systems, and water-rock interaction processes. These datasets are important constraints for calibrating hydrological and groundwater flow models and for interpreting the temporal and spatial variability of groundwater quality.

Hydrological and groundwater modelling approaches combine spatial and field-based information for capturing recharge, groundwater storage dynamics and groundwater–surface water interactions under current and future boundary conditions. Models such as WetSpass-M and SWAT are used to estimate components of distributed recharge and water balance. In contrast, groundwater flow models and, where applicable, coupled SWAT-MODFLOW systems are used to simulate subsurface flow patterns, hydraulic heads and fluxes. Model inputs are based on RS-GIS products, geophysical interpretations and hydrochemical observations, and model outputs are compared to available monitoring data.

Emerging machine learning (ML) techniques, while not yet widely applied in the ERVB, offer a complementary analytical layer for exploiting heterogeneous multivariate inputs including RS-GIS products, geophysical profiles and hydrochemical data for predictive mapping and classification tasks (Mussa *et al*., 2024). Integration of these tiers RS-GIS/MCDA screening, geophysical validation, hydrochemical constraint and numerical modelling with ML-assisted prediction where training data permit, represents the most robust achievable workflow in this data-sparse region.

4. Results and discussion

The reviewed literature reveals a clear paradigm shift from localised, descriptive groundwater inventories towards integrated, quantitative assessment frameworks. Hydrological and groundwater modelling emerge as the most frequently applied methodologies escalating the academic imperative to quantify recharge dynamics and groundwater–surface water interactions. GIS- and MCDA-based groundwater potential mapping remains widely used as a cost-effective, basin-scale screening tool (Bhowmick *et al*., 2023), while geophysical and hydrochemical methods are primarily employed for subsurface validation and conceptual model refinement. Conversely, machine-learning applications are emerging but remain noticeably sparse. This study systematically evaluated 80 peer-reviewed articles published between 2016 and 2025 leveraging the PRISMA guidelines.

Groundwater assessment methodologies within the ERVB exhibit trade-offs dictated by spatial scale, data availability and hydrogeological complexity. Hydrological and numerical groundwater flow models provide rigorous quantitative estimates of aquifer of recharge, storage dynamicsm and surface–sub-surface interactions. However their predictive reliability depends heavily on the availability of long-term monitoring datasets for calibration and uncertainty quantification (Abraham *et al*., 2018; Ayalew *et al*., 2023). In contrast, RS-GIS and MCDA-based potential mapping facilitate rapid basin-scale screening with minimal data requirements. Nonetheless, these frameworks, but remain inherently qualitative, failing to simulate physical groundwater flow processes and exhibiting high sensitivity to subjective criteria weighting.

Paradigmatic of these hybrid approaches, Bhowmick *et al*. (2023) and Kawo and Karuppannan (2018) integrated RS GIS, RS and water quality index (WQI) techniques to classify groundwater potential zones and characterise hydrochemical profiles in the

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Modjo watershed, located in Ethiopia. The results of this study proved instrumental in delineating the optimal locations for productive well fields and pinpointing geogenic contamination hotspots, specifically fluoride enrichment. Nevertheless, the analytical resolution of both studies was severely constrained by sparse sampling frequencies and a failure to account for critical seasonal fluctuations.

Oyda *et al*. (2025) used geospatial techniques and the frequency ratio (FR) model to delineate groundwater potential zones in the Kulfo-Hamassa watershed of the Ethiopian Rift. By coupling multi-sensor satellite imagery with field-validated borehole data, the study achieved high predictive accuracy.

While the FR framework offers a robust and objective methodology, it introduces an inherently static limitation: it relies on a surface-level approach that omits subsurface hydraulic parameters and temporal factors such as climate change and anthropogenic abstraction. Consequently, such models are highly suited for initial exploratory site selection but offer only a qualitative snapshot rather than the long-term volumetric data needed for sustainable groundwater management.

Geophysical surveys provide high-resolution subsurface characterisation but are costly and difficult to scale. Hydrochemical and isotopic methods help constrain recharge sources and flow connectivity but remain limited by sparse sampling. Emerging machine-learning approaches enhance predictive mapping efficiency but require representative training datasets and may have limited physical interpretability.

The analysis highlights multi-method approaches, including geophysical techniques such as ERT and VES, hydrogeochemical and isotopic methods for tracing recharge and contamination pathways, and advanced tools like RS, GIS and numerical modelling (Mechal *et al*., 2016). Nigussie *et al*. (2019) integrated Sentinel-1 radar and Sentinel-2 optical imagery within the Ethiopian Rift Valley, utilising surface soil moisture as a proxy indicator for shallow groundwater occurrence. Although this innovative method of microwave detection overcame the obstacles of cloud cover and vegetation obstruction achieving a high correlation of $r = 0.93$ with ground-truth measurements; it remains constrained by its inability to resolve deep, multi-layered aquifer geometry. Hydrological modelling has been adopted in the Main Ethiopian Rift area to estimate aquifer sustainability and the movement of pollutants. According to Mechal *et al*. (2016) and Berehanu *et al*. (2017), data scarcity frequently compels researchers to rely on unvalidated or incomplete input datasets, a practice that introduces systematic uncertainty into model outputs. To address some of these shortcomings, Balcha *et al*. (2024) adopted the integration of MODFLOW-NWT with three Regional Climate Models to measure the effects of climate change on groundwater in the CRV. Nonetheless, the approach is limited by the steady-state assumption.

As part of water management in data-sparse Ethiopian basins, scientists have used complementary spatial and hydrological modelling techniques. For instance, Gebremichael and Mechal (2024) and Mechal *et al*. (2022) combined SWAT with CMB parameters to estimate recharge amounts (35–160 mm/year) required to develop sub-watershed conservation zoning, whereas Doyo *et al*. (2022) and Niway *et al*. (2022) used GIS-AHP and WetSpass modelling approaches to determine that physiography, lithology and recharge were dominant factors controlling the groundwater potential in the basin. In a similar vein, Woldu *et al*. (2024) used WetSpass to evaluate artificial recharge check-dam potentials in the Upper Awash Basin. Concerning abstraction hazards, Balcha *et al*. (2022) quantitatively supported irrigation limitations based on the relation between fluctuations in lake levels and withdrawals for agriculture to mitigate the degradation of associated surface water bodies. Despite these methodological advancements, these integrated frameworks continue to face substantial calibration uncertainties. These errors are primarily driven by unquantified atmospheric chloride deposition variations, undetected sub-lacustrine spring discharges and poorly constrained boundary conditions that fail to capture episodic storm pulses (Girma *et al*., 2020).

The issue of addressing water shortages and allocation in Ethiopia's water-scarce basins using data-poor approaches has been studied using the combination of MCDA and more sophisticated hydrological models. The application of GIS-AHP method in the Dijo catchment revealed its potential for groundwater resources mapping with accuracy up to 79.2%, while Molla *et al*. (2019) demonstrated that spatial soil properties and land-use dynamics heavily regulate runoff-evapotranspiration partitioning in the Abaya-Chamo Basin. WEAP was applied by Abdi and Ayenew (2021) to analyse the hydrology of sub-catchments and develop the methodology that can be used by local bureaus to evaluate sector-based water allocation with limitations of water abstraction. However, these frameworks remain vulnerable to institutional vulnerabilities: the subjective assignment of criteria weights within the AHP matrix introduces cognitive bias, while the coarse spatial resolution of the WEAP grid cells limits its capacity to isolate localised hydrogeological anomalies (Table 1).

Concurrently, contemporary, hydrogeological research in the Ethiopian Rift system increasingly combines public health metrics, physical dynamics and advanced spatial modelling. Abera *et al*. (2025) quantified extreme fluoride hazards in Wenji Gefersa, while Mechal *et al*. (2016) used isotopic data to confirm that mountain-block systems supply 35% of aquifer inflows. Anthropogenic stress is highlighted by Mechal *et al*. (2022), who recorded an 87.07% runoff increase due to land conversion, and by Gadissa *et al*. (2018), who modelled sedimentation-driven lake desiccation while omitting sub-lacustrine spring dynamics. To map resource potential, traditional GIS-AHP and hydrogeological modelling (Abegeja and Nedaw, 2024; Gigar *et al*., 2024; Takele *et al*., 2025b) have been effectively deployed alongside

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Table 1. Overview of groundwater studies, methods and major findings in the ERVB

Author(s), year	Aim/objective	Methodology used	Major findings
Abebe *et al*., 2024	Evaluate groundwater quality and suitability	Hydrogeochemical analysis	Some areas are unsuitable for drinking and irrigation
Abegeja and Nedaw, 2024	Identify groundwater potential zones	GIS and geospatial technologies	Potential zones mapped; geospatial method effective
Abera Abdi and Ayenew, 2021	Evaluate WEAP model in subbasin hydrology	WEAP hydrological modelling	Model simulates hydrology; useful for planning
Abera *et al*., 2025	Assess fluoride contamination risk	Probabilistic health risk assessment	Fluoride contamination risk quantified; management implications
Abraham *et al*., 2021	Quantify regional water balance	Water balance modelling with uncertainty	Water balance quantified; uncertainty assessed
Abrar *et al*., 2021	Groundwater potential assessment	GIS + AHP	High potential areas identified; GIS-AHP effective
Alamirew *et al*., 2025	Improve groundwater potential mapping	Integrated validation + aquifer characterisation	Potential zones enhanced; integrated method effective
Alemu *et al*., 2025	Assess industrial impacts on groundwater	Review / SSRN	Industrialisation affects groundwater quality; mitigation is needed
Alemu *et al*., 2025	Groundwater potential mapping	GIS and remote sensing	Potential zones mapped; GIS effective
Aliye *et al*., 2020	Evaluate rainfall-runoff simulation	HEC-HMS and SWAT	Both models effective; HEC-HMS better for data-scarce regions
Amare *et al*., 2018	Groundwater flow modelling	MODFLOW	Flow paths simulated; MODFLOW suitable for rift aquifers
Ayalew *et al*., 2024	Analyse hydrological dynamics in data-scarce regions	Hydrological analysis	Hydrological dynamics unveiled; methods effective in data-scarce regions
Balcha *et al*., 2022	Hydrological simulation under abstraction	Hydrological modelling	Water abstraction impacts quantified; simulation effective
Balcha *et al*., 2024	Groundwater flow modelling under climate change	Numerical groundwater flow modelling	Climate impacts on groundwater quantified
Bedi *et al*., 2018	Geochemical analysis of groundwater	Geochemical analysis	Groundwater chemistry characterised; contamination sources identified
Belihu *et al*., 2020a	Assess hydrologic response to LULC change	Hydrological modelling	Land use impacts on hydrology quantified
Berehanu *et al*., 2017	Inter-basin groundwater transfer and recharge	Recharge estimation + modelling	Recharge estimated; inter-basin transfer potential assessed
Bezabih and Bezabih, 2017	Groundwater potential mapping	GIS + RS	Potential zones delineated; RS-GIS effective
Bonetto *et al*., 2021	Review of groundwater resources	Literature review	Groundwater critical for sustainable development; recharge and quality concerns
Bretzler *et al*., 2011	Groundwater origin and flow	Multi-isotope analysis	Flow paths and sources identified; isotopes effective
Dananto *et al*., 2022	Water resources potential and soil erosion hotspots	GIS + hydrological analysis	Hotspots identified; management recommendations provided
Daniel *et al*., 2022	Groundwater flow modelling under climate change	Numerical groundwater modelling	Flow dynamics under a changing climate quantified
Demissie *et al*., 2024	Groundwater recharge estimation	Hydrological modelling	Recharge quantified; basin management implications
Desta *et al*., 2018	Groundwater recharge	GIS + WetSpass	Recharge zones mapped; WetSpass recommended
Desta and Lemma, 2017	SWAT-based hydrological assessment	SWAT modelling	Hydrological components quantified; SWAT effective
Dinka, 2017	Drainage and groundwater flux	Field study and hydrology	Drainage and recharge areas delineated
Doyo *et al*., 2022	Groundwater prospective mapping	GIS and RS	Potential zones mapped; supports water management

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Table 1. Continued

Author(s), year	Aim/objective	Methodology used	Major findings
Feyissa Negewo and Kumar Sarma, 2021	Sediment yield and sub-basin prioritisation	Hydrological modelling	Variability assessed; HRU prioritisation achieved
Gadissa *et al*., 2018	Climate change impacts on lake volume	Hydrology	Lake volume loss quantified; climate effects significant
Gebremedhin *et al*., 2018	Groundwater potential assessment	GIS + RS	Potential zones identified; RS-GIS effective
Gelete *et al*., 2025	Streamflow modelling	ML + Heuristic algorithms	Accurate streamflow simulation; ML is effective
Getachew and Abdulkadir, 2024	Assess groundwater	Magnetic and electrical surveys	Aquifers mapped; geophysical validation successful
Gigar *et al*., 2024	Aquifer characterisation and budget estimation	Integrated GIS + field data	Groundwater budget quantified; aquifer zones delineated
Girma *et al*., 2020	Watershed attributes evaluation	GIS and hydrology	Watershed characteristics quantified
Girma *et al*., 2023	Land degradation and future management	Integrated modelling	Degradation dynamics evaluated; management insights
Guduru *et al*., 2023	Rainfall-runoff modelling	HEC-HMS	Runoff simulated; model validated
Hailu *et al*., 2023	Groundwater flow characterisation	Multiple approaches	Flow system characterised; volcanic aquifers mapped
Hirko *et al*., 2025	Climate change analysis	ML + satellite data	Impacts quantified; ML effective
Kebede *et al*., 2021	Subsurface depth estimates	2D/3D potential field modelling	Anomalous sources mapped; informs groundwater dynamics
Mamo *et al*., 2018	Groundwater–surface water interactions	Hydrological analysis	Interactions quantified; management implications
Meaza *et al*., 2019	Water balance in agricultural grabens	Hydrological modelling	Components quantified; irrigation potential assessed
Mechal *et al*., 2016	Regional groundwater flow characterisation	Multi-model approach	Flow system mapped; multimodel effective
Mechal *et al*., 2022	LULC impacts on hydrology	Hydrological modelling	Impacts quantified; planning recommendations
Mekonen *et al*., 2023	Recharge estimation	Hydrological modelling	Recharge quantified; water resource planning
Meresa and Taye, 2019	Groundwater recharge estimation	GIS + WetSpass	Recharge zones mapped; WetSpass recommended
Mesay and Mechal, 2024	Groundwater potential mapping	WetSpass-M + GIS-MCDA	Potential zones identified; GIS-MCDA effective
Messene, 2017	Groundwater flow and recharge	Field mapping	Recharge and flow directions identified
Mihret *et al*., 2025	Geological structures impact on groundwater	Review + case examples	Structural impact on groundwater mapped; examples provided
Mitiku *et al*., 2023	LULC and climate impacts on hydrology	Hydrological modelling	Hydrological response analysed; impacts of LULC and climate quantified
Moges *et al*., 2025	Structural analysis for groundwater study	Gravity and magnetic data	Subsurface structures mapped; implications for groundwater
Mohammed and Ayalew, 2016	Inter-basin groundwater transfer modelling	Hydrological modelling	Transfer potential identified; model validated
Molla *et al*., 2019	Surface and shallow groundwater simulation	Spatial water balance model	Water resources quantified; informs management
Moshe *et al*., 2024	Watershed management strategies	SWAT + integrated approach	Strategies developed; sustainable utilisation supported
Musie *et al*., 2019	Precipitation dataset evaluation	Hydrological simulation	Dataset performance assessed; impacts on streamflow
Mussa *et al*., 2024	Groundwater potential evaluation	GIS + ML ensemble	Potential zones mapped; ML improved prediction
Nannawo *et al*., 2022	Groundwater recharge evaluation	WetSpass-M	Recharge quantified; climate change impact analysed
Negasa and Goshime, 2024	Surface runoff and sedimentation evaluation	Hydrological modelling	Runoff and sedimentation quantified; LULC impacts analysed

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Table 1. Continued

Author(s), year	Aim/objective	Methodology used	Major findings
Nigussie *et al*., 2025a	Groundwater recharge and water balance	Hydrological modelling	Recharge and water balance quantified
Nigussie *et al*., 2025b	Groundwater origin and flow	Multi-isotope approach	Flow dynamics mapped; isotopes effective
Nigussie *et al*., 2019	Groundwater potential mapping	Sentinel satellites + AHP	Potential zones delineated; GIS-AHP effective
Niway *et al*., 2022	Groundwater potential evaluation	GIS + MCDA + WetSpass	Potential zones mapped; integrated approach effective
Redda *et al*., 2025	Aquifer characterisation	Geostatistical methods + well-specific capacity	Aquifer zones characterised; geostatistics validated
Serur and Adi, 2022	Multi-site hydrological calibration	Hydrological modelling	Water balance response to LULC change quantified
Tadesse *et al*., 2024	Identify recharge areas	Hydrological modelling	Recharge zones identified; management implications
Takele *et al*., 2025a	Unlock groundwater potential	GIS + AHP + geophysical	Potential zones mapped; multi-method effective/Potential mapped; integrated approach validated
Takele *et al*., 2025b	Assess groundwater potential	GIS + MCDA	Potential zones mapped; informs extraction planning
Takele *et al*., 2025c	Recharge evaluation	GIS + AHP	Recharge potential mapped; GIS-AHP framework validated
Takele *et al*., 2025f	Groundwater potential and quality	GIS + AHP + drinking water index	Potential areas and quality assessed
Takele *et al*., 2025e	Unlock groundwater potential	AHP + geophysical	Potential mapped; integrated approach validated
Tsegaw *et al*., 2025	Groundwater potential comparison	AHP & FR	Potential zones mapped; AHP and FR compared
Tufa *et al*., 2018	Groundwater investigation	Hydrogeological & geophysical	Aquifers characterised; groundwater resources mapped
Woldu *et al*., 2024	Recharge estimation	Hydrological modelling	Recharge variations quantified
Yehualaw *et al*., 2023	Groundwater potential mapping	Geophysical techniques	Potential zones mapped; geophysics effective
Yehualaw *et al*., 2024	Map groundwater	Electrical resistivity and magnetic methods	Potential aquifers delineated; geophysics validated
Yifru *et al*., 2020	Groundwater potential mapping	SWAT + GIS-MCDA	Potential zones identified; GIS-MCDA effective

cutting-edge random forest and SVM ML algorithms (Mussa *et al*., 2024). These ML architectures accurately resolve non-linear aquifer patterns near springs and forests to guide municipal wellfield expansion; however, their practical utility remains constrained by spatial skewing whenever the baseline training datasets are sparse or highly clustered.

Groundwater quality studies focusing on natural contaminants, such as fluoride exceeding WHO limits (Bonetto *et al*., 2021), and spatially explicit recharge assessments using models like WetSpass (Demissie *et al*., 2023), reveal recharge contributions as low as 7% of annual rainfall in some watersheds. Conceptual water budget modelling in the northern Ethiopian Rift's Raya and Ashenge grabens highlights substantial evap.

5. Synthesis of the results

A critical analysis of the systematic review database (n = 80 primary studies, 2016–2025) confirms a methodological paradigm shift within the hydrogeological domain of the ERVB (Table 1). The research designs have fundamentally transitioned from localised, descriptive groundwater inventories towards integrated multi-parameter modelling and predictive simulations. This scientific synthesis isolates the operational strengths, critical data gaps and scalable applicability of the dominant methodologies documented in the literature. Recent hydrological and hydrogeological research in the ERVB demonstrates a clear shift towards integrated, data-driven methodologies (Figure 3). Research studies that have used the SWAT, HEC-HMS and SWAT-MODFLOW hydrological models have shown declining streamflow trends and increased seasonal variability in the hydrological system (Aliye *et al*., 2020). Aliye *et al*. (2020) utilised two different hydrological models in the Katar River Basin by analysing rainfall, soil, digital elevation model (DEM) and land-use information over the long term for model calibration and validation. The models proved highly effective for predictive flood routing and macro-scale watershed analysis, achieving robust statistical validation metrics. Nonetheless, the investigation focused primarily on streamflow

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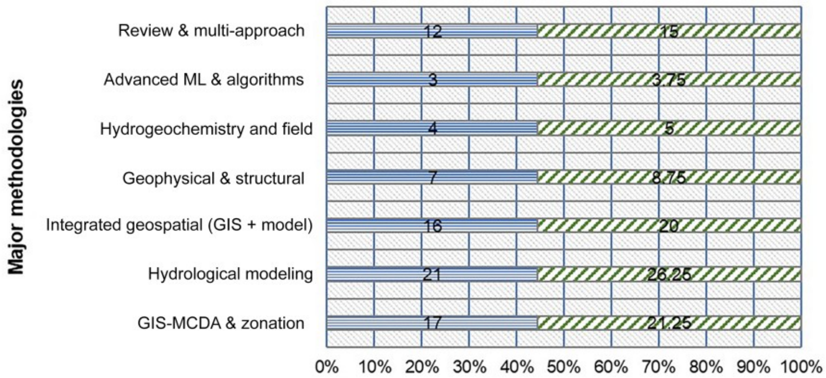

	GIS-MCDA & zonation	Hydrological modeling	Integrated geospatial (GIS + model)	Geophysical & structural	Hydrogeochemistry & field	Advanced ML & algorithms	Review & multi-approach
Count	17	21	16	7	4	3	12
Percentage	21.25	26.25	20	8.75	5	3.75	15

Frequency and percentage of original article

Figure 3. Summary of major methodologies used in groundwater studies in the ERVB (2016–2025)

simulation, dedicating minimal emphasis to deep aquifer percolation or groundwater-surface water exchange loops. Additional structural limitations included reliance on statistical infilling for missing gauge data, omission of temporal land-use trajectories and an absence of comprehensive parameter uncertainty analysis. To circumvent the limitations of sparse gauge networks, Ayalew *et al*. (2024) deployed a distributed water balance framework driven by multi-sensor satellite RS data, substituting continuous gridded climatic datasets for missing observational records. This methodology successfully isolated the impacts of climate variability from anthropogenic land-use land-cover (LULC) changes. However, the coarse spatial and temporal resolution of the pixel-based inputs introduced systematic uncertainties into their actual evapotranspiration calculations. Concurrently, Moshe *et al*. (2024) applied distributed watershed modelling to evaluate integrated water resource management strategies and sediment transport dynamics. Their model accurately tracked catchment sediment pathways and quantified the impacts of physical land-management interventions on basin-wide water yields, offering actionable insights for targeted afforestation to mitigate downstream reservoir siltation. However, the performance of this framework was highly sensitive to localised soil structural parameters, forcing reliance on coarse global datasets that compromised local model precision. Furthermore, Belihu *et al*. (2020) and Mechal *et al*. (2022) quantified LULC conversion impacts on water balance configurations by integrating multi-temporal satellite imagery with SWAT and SWAT-CUP algorithms. This approach effectively isolated long-term environmental trends and quantified seasonal flow variations, though its absolute accuracy remained constrained by regional data scarcity and missing hydrological records. Addressing the intersection of physical availability and socio-agricultural demand, Taye *et al*. (2022) simulated sustainable agricultural intensification scenarios. This research coupled human land-use patterns and crop-specific water requirements with catchment flow loops, yielding operational decision-support tools for water utility executives managing competing demands between agricultural expansion and aquifer conservation.

In addition, hybrid and ML models have been increasingly applied in the ERVB, improving prediction accuracy under data-limited conditions (Amare *et al*., 2018; Gelete *et al*., 2025). Climate-impact assessments project reduced groundwater recharge and elevated flood risk, underscoring the need for adaptive basin management strategies. Synthesising these dynamics, Alamirew *et al*. (2025) integrated digital potential mapping with empirical field observations to clarify groundwater zonation, hydrodynamic behaviour and hydrochemical variations – a particularly valuable contribution for engineers and regional planners. The framework's primary limitation lies in its prioritisation of instantaneous water availability over long-term qualitative sustainability indicators, limiting its direct utility for adaptive management under projected climate change scenarios. The application of Geospatial tools alongside the analytical hierarchy process (AHP) within the Meki watershed (Abegeja and Nedaw, 2024) highlights an efficient way to estimate the suitability of groundwater with 91.26% validity. Although thorough in its integration of eight distinct environmental parameters, the model's utility is limited by its reliance on static datasets and its total omission of water quality variables.

Gebremedhin *et al*. (2018) studied groundwater potential zones through RS and multicriteria grids, successfully combining

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regional data (lithology, lineaments, drainage, slope), although the lack of validated and weighted layers might be a source of institutional bias. In their recent study conducted in the Kulfo-Hamassa Watershed, Oyda *et al*. (2025) utilised geospatial analysis with the application of the FR model, including the use of satellite images and boreholes with validation in field work, resulting in a highly accurate prediction. The FR is capable of identifying landscapes associated with groundwater occurrence, though predictive power is significantly reduced in sub-catchments where boreholes are unavailable. Takele *et al*. (2025a–d) used GIS and AHP models to estimate the recharge potential of the region without quantifying absolute groundwater storage and seasonal infiltration, though the results can help with sustainable groundwater management. Finally, Kawo and Karuppannan (2018) used the WQI in combination with GIS for groundwater quality evaluation in the Modjo River Basin, distinguishing between safe drinking water and water fit for irrigation and finding the origins of groundwater pollution.

Geophysical and geological analyses repeatedly indicate fault and fracture systems as major factors in determining aquifer shape (Wolde *et al*., 2021; Getachew and Abdulkadir, 2024). Geological surveys conducted using multiple electrodes geophysical profiling and resistivity measurements have proven very efficient in detecting rift faults and sediment-buried fracture networks that dictate groundwater movement. Nevertheless, these techniques are difficult to conduct because of their high cost and logistical problems associated with their use in expansive terrain. These tools are used by drilling engineers for site surveys in guiding heavy machinery through productive fracture routes. GIS-based AHP mapping shows that high-potential groundwater zones coincide with fault intersections and weathered volcanic terrains. These findings are reinforced by isotopic analyses, which reveal mixed recharge sources and deep structural connectivity. Water quality investigations indicate widespread fluoride enrichment (Demelash *et al*., 2019; Alemu *et al*., 2025), while erosion studies highlight hotspots linked to deforestation. Such integrated approaches provide highly reliable tools for regional planning, significantly reducing the costs and risks associated with trial-and-error drilling. With validation accuracies reaching 81%, these prioritisation maps remain valuable, though on-site geophysical confirmation is recommended before drilling. According to Nigussie *et al*. (2019), groundwater potential zones were identified using the combination of Sentinel-1 and Sentinel-2 imagery in an AHP model that included subjective weighting. Despite this, the research showed very good correlation (0.93) with real borehole data and helped the technicians pinpoint their target zones even in distant locations. Berehanu *et al*. (2017) analysed groundwater transfer between basins and several methods of recharge for the Upper Awash Aquifer System. However, there were shortcomings associated with the lack of long-term monitoring systems.

Inter-basin groundwater flow studies, such as those by Mebruk Mohammed and Ayalew (2016), reveal flow across surface divides, reducing discharge in the Rift Valley Lakes Basin while increasing it in the Awash Basin. These findings underscore the necessity of integrated basin-scale management.

A systematic review of 80 publications indicates a pronounced increase in research between 2023 and 2025. Methodological preferences include hydrological modelling (26.25%), GIS-MCDA and zonation (21.25%) and integrated geospatial approaches (20.0%), collectively representing nearly half (46.25%) of the research output this decade (Figure 4).

The combined use of hydrological modelling and geospatial technology reflects a paradigm shift towards dynamic, process-based quantification, addressing the complex hydrogeological heterogeneity imposed by the Rift Valley's tectonic setting. Geophysical surveys (8.75%) and hydro-geochemical analyses (5%) remain indispensable for subsurface validation, while ML approaches (3.75%) highlight emerging directions for predictive modelling. Effective groundwater assessment in the region requires coordinated, multi-strategy approaches. RS-GIS and MCDA first define high-potential zones, minimising the scope of resource-intensive investigations. Geophysical techniques then refine subsurface characterisation, facilitating accurate well placement and model parameterisation. Independent hydrochemical and isotopic data provide additional validation for conceptual and numerical models, while the comparative purpose, data requirements and limitations of the major assessment methods are summarised in Table 2.

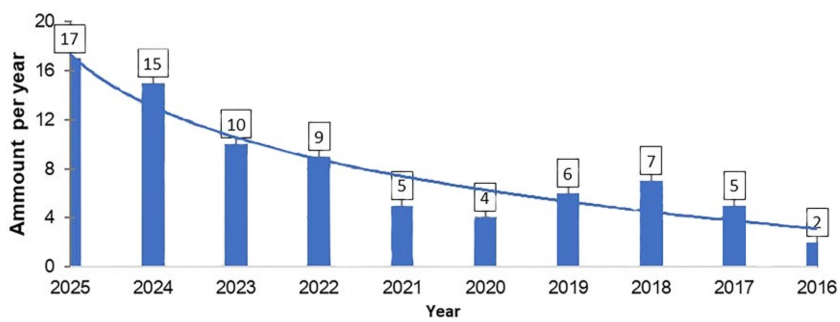

Figure 4. Summary of the frequency of the original paper plotted against year (2016–2025)

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The literature shows that ERVB methodologies are complementary with hydrological models offering dynamic insights but are sensitive to data availability. GIS-based approaches provide broad spatial coverage but rely on subjective weighting. Geophysical methods deliver high-resolution subsurface information but are difficult to scale. Hydrological models provide dynamic insights but are sensitive to data; GIS-based approaches offer broad coverage but rely on subjective weighting; and geophysical methods deliver high-resolution info but are difficult to upscale. ML techniques enhance performance but lack physical interpretability. Robust assessments in the ERVB employ coordinated workflows: RS-GIS for screening, geophysics for refinement, isotopic analysis for flow mechanisms and numerical models for integration. The methodological categories along with their application purpose, scale and principal drawback were summarised in Table 3.

The methodological landscape of groundwater research in the ERVB is characterised by a strategic challenges between broad-scale efficiency and site-specific precision. In this regard, RS GIS- and RS-based MCDA have become foundational for regional prioritisation due to their cost-effectiveness and rapid execution; these tools are inherently limited by their semi-quantitative nature and

Table 2. Comparative summary of groundwater assessment method categories in the ERVB: purpose, spatial scale, data requirements and principal limitations

Method category	Context	Typical data requirements	Principal limitations	References
Hydrological modelling (SWAT, WetSpass/ WetSpass-M, HEC-HMS)	Quantify water balance components and distributed recharge; evaluate climate/LULC impacts on runoff and recharge	Climate time series (P, T), DEM, LULC, soils; streamflow/runoff for evaluation	Calibration/validation sensitive to monitoring gaps; uncertainty increases with short records	Desta and Lemma (2017); Aliye *et al*. (2020); Demissie *et al*. (2023)
Groundwater flow modelling (MODFLOW, FEFLOW; coupled SWAT–MODFLOW; TAGSAC)	Simulate heads/fluxes and groundwater–surface water exchange; assess climate/stress scenarios and regional connectivity	Aquifer geometry; hydraulic parameters; recharge inputs; boundary conditions; groundwater heads/fluxes for comparison	Data-intensive; parameter non-uniqueness; limited validation where long-term head/flux data are sparse	Daniel *et al*. (2022); Amare *et al*. (2018); Meresa and Taye (2019); Mohammed and Ayalew (2016)
RS–GIS and MCDA zonation (AHP-based mapping; zonation of potential/ recharge/ vulnerability)	Basin-scale screening and prioritisation of groundwater potential/ recharge/vulnerability; guide field targeting	DEM/topography; LULC; soils; lithology; lineament and drainage density; rainfall proxies	Primarily relative/qualitative; subjective weighting; requires field validation	Diriba *et al*. (2024); Bezabih and Bezabih Bashe (2017); Doyo *et al*. (2022); Niway *et al*. (2022)
Integrated geospatial approach (explicit modelling and spatial analysis)	Combine geospatial screening with modelling and/or field evidence for a more robust distributed assessment	RS–GIS layers plus modelling inputs/parameters; supporting field/ monitoring observations	Reliability constrained by monitoring gaps; sensitive to the consistency of inputs and validation data.	Abera Abdi and Ayenew (2021); Yifru *et al*. (2020)
Geophysical and structural surveys (ERT, VES, gravity, magnetic)	Subsurface validation: aquifer thickness/geometry; fractured/weathered zones; faults/lineaments controlling flow; support well siting and conceptual models	Field geophysical measurements; survey layout; borehole/log control, where available	Cost/logistics limit coverage; difficult to upscale; interpretation uncertainty without ground truth	Kebede *et al*. (2021); Getachew and Abdulkadir (2024); Moges *et al.* (2025)
Hydrogeochemistry and isotopes	Constrain recharge sources and mixing; infer flow connectivity and water–rock interaction; support conceptual/model calibration and quality assessment (e.g. fluoride)	Sampling network; lab analyses (major ions/trace elements/isotopes); hydrogeologic context	Sampling density/cost limit coverage; interpretation depends on conceptual model quality	Bretzler *et al*. (2011); Bonetto *et al*. (2021); Tadesse *et al*. (2024)
Advanced machine learning (e.g. random forest, SVM; hybrid ML)	Predictive mapping/ classification (e.g. groundwater potential); improve prediction efficiency under sparse monitoring	Training labels (e.g. well yields/springs); RS–GIS predictors; validation dataset	Dependent on representative training/validation; limited physical interpretability; transferability/overfitting risk	Mussa *et al*. (2024); Gelete *et al*. (2025)

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Table 3. Comparative summary of groundwater assessment method categories in the ERVB

Methodological category	Purposes/applications	Major limitations identified
Hydrological modelling	Distributed recharge and water balance	Calibration sensitivity to data gaps
RS-GIS and MCDA	Potential zone screening	Subjective weighting; requires validation
Geophysics	Subsurface/aquifer geometry	High cost; difficult to upscale
Hydrochemistry	Recharge sources/connectivity	Limited sampling density
Machine learning	Predictive mapping efficiency	Low physical interpretability

failure to simulate physical subsurface flow linked to persistent gap between methodological sophistication and data availability in the region. While advanced numerical models, ML algorithms and integrated geospatial techniques are increasingly applied, their predictive reliability remains constrained by limited monitoring networks, sparse hydrochemical datasets, inadequate long-term observations and uncertainty in model parameterisation. Furthermore, relatively few studies explicitly quantify uncertainty or integrate climate-change projections into groundwater assessments. Addressing these limitations should constitute a central priority for future groundwater research and policy development in the basin.

To address these quantitative gaps, researchers frequently use numerical flow and hydrological models that offer rigorous estimations of storage and recharge dynamics, yet the reliability of such models is often compromised by parameter non-uniqueness and the pervasive lack of long-term observational data required for robust calibration.

Subsurface complexity of the hydrogeological systems in the study areas was also cross-examined through geophysical techniques, most notably ERT and VES which yield high-resolution data regarding aquifer geometry. However, the intensive logistical and economic demands of these surveys typically restrict their application to localised scales, preventing easy upscaling for basin-wide analysis. Consequently, a paradigm shift has occurred towards integrated coordinated workflows that capitalise on the strengths of each individual method while neutralising their weaknesses. By adopting a structured sequence beginning with RS-GIS for macro-level screening, proceeding to geophysical validation and isotopic analysis for process confirmation, and culminating in numerical modelling researchers can develop comprehensive, decision-ready frameworks that support the sustainable management of groundwater within the intricate hydrogeological environment of the rift.

6. Recommendations for future research

To overcome the persistent data scarcity, parameter non-uniqueness and methodological inconsistencies identified across the original articles reviewed (*n* = 80, 2016–2025), the following strategic priorities are proposed for future research and institutional policy:

- **Prioritisation of integrated coupled simulations:** Future investigations must transition from isolated surface or groundwater models to fully coupled modelling frameworks, such as SWAT-MODFLOW to accurately simulate the complex surface-groundwater interactions and profound inter-basin subsurface transfers that characterise the tectonically fractured Rift Valley Basin.
- **Data-driven subsurface validation:** Studies using numerical flow and predictive simulation models must be explicitly constrained by empirical hydrochemical and environmental isotopic data. This validation step is required to independently verify modelled recharge mechanisms, mixing ratios and groundwater residence times, thereby mitigating the risk of the 'calibration trap'.
- **Targeted contaminant pathway analysis:** Given the widespread geogenic fluoride enrichment throughout the ERVB, research should prioritise mapping specific structural fault networks, caldera boundaries and volcanic lithologies. Quantifying these controls is essential for understanding how mineralised, high-temperature hydrothermal fluids migrate into shallow, potable aquifer systems.
- **Establishment of a unified hydrogeological database:** Institutional efforts must prioritise developing a centralised, open-source national hydrogeological database. This platform should house standardised groundwater level time-series, hydro-meteorological data, borehole lithological logs and water chemistry profiles (specifically fluoride concentrations) to enhance model reproducibility and support evidence-based policy decisions.
- **Integration of ground-truthing in volcanic terrains:** While advanced spatial and RS tools are highly efficient at the macro-scale, they must remain securely tethered to conventional hydrogeological validation methods, including exploratory drilling, pumping tests and physical field-based characterisation, to ensure accuracy within the highly heterogeneous volcanic formations in the region.
- **Advancing predictive analytics via machine learning:** Where representative training datasets exist, researchers should leverage ML algorithms specifically random forests, SVMs and deep neural networks to resolve non-linear aquifer patterns. In data-sparse sub-basins, semi-supervised learning and transfer learning architectures warrant exploration to maximise predictive efficiency from limited labelled observations.
- **Interdisciplinary and socio-economic alignment:** Future hydrogeological studies must incorporate transdisciplinary approaches that align advanced technical, geophysical and data science models with localised socio-economic contexts, water governance structures and climate adaptation policies.

7. Conclusion

This systematic review synthesised 80 peer-reviewed primary studies (2016–2025) on groundwater assessment in the ERVB,

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following PRISMA 2020 guidelines. Four principal conclusions emerge from this evidence base. First, the methodological landscape has undergone a clear paradigm shift: from localised, descriptive inventories towards integrated, quantitative, multi-method simulation frameworks. Hydrological modelling (26.25%), GIS-MCDA approaches (21.25%) and integrated geospatial techniques (20.0%) now dominate the literature. Second, methodological advancement notwithstanding, persistent data scarcity characterised by sparse monitoring networks, short hydrological records and limited calibration datasets remains the overriding constraint on model reliability and predictive accuracy. Third, geophysical methods (ERT, VES), hydrochemical analyses and isotopic investigations have proven indispensable for subsurface validation and conceptual model refinement, particularly in characterising the structurally complex, volcanically heterogeneous aquifer systems of the Rift. Fourth, ML approaches, though representing only 3.75% of the reviewed studies, demonstrate emerging but promising capacity to resolve non-linear aquifer patterns and improve predictive mapping efficiency under data-limited conditions. To realise the full potential of these advances, future research must prioritise integrated, multi-tier methodological workflows; the establishment of a centralised, open-source hydrogeological database; and strengthened interdisciplinary collaboration across the hydrogeological, public health and policy communities. Bridging the persistent gap between advanced simulation tools and field-scale monitoring infrastructure is not merely a technical aspiration; it is a scientific and governance necessity.

Author contributions

Tariku Takele: conceptualisation, data curation, formal analysis, methodology, software, supervision, visualisation, validation, writing – original draft, writing – review and editing, funding acquisition. Demise Tadessa: methodology, data curation, funding acquisition, visualisation, writing – original draft. Muralitharan Jothimani: data curation, visualisation, writing – review and editing. Shankar Karuppannan: visualisation, writing – review and editing. Mekonnen Beyene: assisted visualisation, writing – reviewand editing. Awol Mohammed: writing – review and editing.

Data availability

Data related to this paper will be made available upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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