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Comprehensive Review of Hydrogeological Assessments and Modeling Approaches for Groundwater Flow Dynamics and Sustainable Management

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REVIEW PAPER

ABSTRACT

This review synthesizes recent advances in hydrogeological assessment and groundwater flow modeling, emphasizing their role in sustainable water resource management. Drawing from studies published between 1992 and 2024, this analysis emphasized the progression from analytical models to numerical and hybrid approaches, including tools that are enhanced by geospatial data and artificial intelligence. Methods for recharge estimation, aquifer characterization, and model calibration are evaluated, along with the application of sensitivity and uncertainty analyses. The review also explores how modeling practices intersect with governance, particularly through integrated water resource frameworks and stakeholder participation. Persistent challenges include limited data availability, underutilized stakeholder engagement, and difficulties in translating model outputs into policy decisions. Recommendations for future research focus on improving model accessibility, integrating socio-environmental variables, and developing adaptive platforms that can support decision-making under uncertainty. By consolidating key developments, limitations, and opportunities, this review provides a critical reference for researchers, practitioners, and policymakers working to improve the application and impact of groundwater modeling.

Keywords: *climate change adaptation, management of water resources, modelling groundwater flows, artificial intelligence applications in hydrology*

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INTRODUCTION

Groundwater is a critical component of the global freshwater supply, providing essential resources for domestic, agricultural, and industrial use, particularly in regions with limited access to surface water. It is estimated that nearly 97% of the Earth's freshwater lies underground, highlighting its importance for both human development and ecosystem stability (*Mishra 2023*). In developing regions, groundwater supports more than 60% of irrigation needs, making it indispensable to food production and rural livelihoods (*Pena et al. 2020*). The growing reliance on groundwater has spurred advancements in hydrological science, with modern flow modeling increasingly supported by developments in mathematics and computational techniques (*Mustafa and Mawlood 2024*). These trends are driven by mounting pressure from urbanization, population growth, and the escalating impacts of climate change, all of which demand more resilient and data-driven water resource planning.

Despite its widespread use, groundwater remains one of the least understood natural resources due to its hidden nature and the complexity of aquifer systems. Effective management is hindered by challenges such as pollution, overuse, insufficient hydrogeological data, and outdated modeling approaches (*Khorrami and Malekmohammadi 2021; Gorelick and Zheng 2015*). These issues are particularly pronounced in many parts of the Global South, where data scarcity and limited technical capacity hinder the reliable monitoring and management of aquifer systems (*Gaffoor et al. 2020; Chopra et al. 2009*). Advances in groundwater modeling such as those focused on climate-responsive systems and AI-based simulations delineate promising tools to address these challenges (*Esiri et al. 2024; Tavakoli et al. 2024*). However, realizing their full potential requires better integration of local data, interdisciplinary collaboration, and context-specific adaptation of models.

In many developing countries, the management of groundwater resources is undermined by systemic challenges, including inadequate data collection, insufficient monitoring infrastructure, and the continued reliance on outdated modeling frameworks. Aquifer degradation from industrial discharge, chemical-intensive agriculture, and poor waste management practices remain widespread and often undetected until serious environmental consequences emerge (*Chopra et al. 2009*). These issues are exacerbated by the use of obsolete models that do not accurately reflect current hydrogeological realities, particularly in complex environments such as those found in Southern Africa (*Gaffoor et al. 2020*). Historically, analytical models based on simplified mathematical representations of groundwater behavior have been applied to understand localized flow systems and aquifer responses (*Ibragimov 2009*). While valuable for conceptual analysis, these models are often too limited to address the variability and spatial complexity of real-world aquifers. In response, the field has seen a growing shift toward more robust numerical models that use computational methods, such as finite element and finite difference approaches, to simulate groundwater flow and contaminant transport with greater precision (*Di Salvo 2022*). These tools have significantly improved the capacity to model complex subsurface conditions and project the impacts of human and climatic pressures. However, their effectiveness still hinges on the availability of reliable input data and rigorous model calibration, conditions not always present in many parts of the world. Addressing these limitations requires not only methodological advancement but also stronger integration of field observations, stakeholder engagement, and institutional support for adaptive groundwater governance.

The primary obstacle to advancing groundwater modeling is in the persistent scarcity of high-resolution, site-specific hydrogeological data. These data gaps especially concerning subsurface structure, recharge rates, and aquifer properties are particularly troubling in regions where geological complexity, climatic variability, and land use change interact in unpredictable ways (*Rodriguez et al. 2013*). The challenge of accurately simulating such systems is compounded when models are based on porous media flow, where small variations in hydraulic parameters can significantly alter predicted outcomes (*Amanambu et al. 2020*). Although sensitivity analysis is commonly employed to evaluate how changes in input parameters affect model performance, its practical utility is often limited by insufficient calibration data. As a result, models may remain under-validated or poorly constrained, reducing their reliability and undermining their value for real-world water management decisions. Beyond technical limitations, model uncertainty is a broader governance issue, particularly when stakeholders ranging from local communities to policymakers and businesses must rely on these outputs for planning and regulation (*Sepúlveda and Doherty 2015*). Yet, engaging diverse stakeholders in model development remains a challenge, especially in areas where awareness or understanding of groundwater dynamics is limited (*Sepúlveda et al. 2022*). Addressing this disconnect calls for more inclusive, participatory approaches and improvements in data collection infrastructure. Recent efforts to integrate citizen science and remote sensing technologies have shown promise in enhancing data accessibility and public involvement (*Njue et al. 2019*). Tailoring models to reflect local aquifer conditions, supported by collaboration between community actors, scientists, and water managers, can strengthen both model precision and policy relevance (*Hojberg et al. 2013*). Emerging technologies, such as machine learning and automated calibration tools, also present opportunities to reduce human intervention and enhance model responsiveness. However, navigating model uncertainty particularly in the face of worst-case projections requires not just technical adjustments but a coordinated response from government agencies, civil society, and the scientific community. Without such collective engagement, efforts to achieve sustainable groundwater use may fall short of their potential.

Considering these persistent challenges and knowledge gaps, this review aims to synthesize current approaches to hydrogeological assessment and groundwater flow modeling, with a focus on their relevance to sustainable groundwater management. It draws on a broad range of scientific literature, technical case studies, and modeling frameworks to evaluate how groundwater systems are characterized, simulated, and managed under various environmental and socio-economic conditions. Special attention is given to the integration of advanced tools, including artificial artificial intelligence, remote sensing, and uncertainty analysis techniques, alongside traditional field-based assessments. By consolidating recent developments and identifying areas of methodological and practical deficiency, this review provides a comprehensive resource for researchers, practitioners, and policymakers seeking to enhance groundwater resilience. Ultimately, the goal is to support more informed decision-making and promote adaptive, data-driven strategies for groundwater sustainability in diverse hydrogeological settings.

MATERIALS AND METHODS

This review was conducted to synthesize key developments, challenges, and innovations in hydrogeological assessments and groundwater flow modeling within the context of sustainable water resource management. Rather than presenting original experimental results, the study adopts a narrative review approach, focusing on consolidating and interpreting findings from a broad selection of peer-reviewed literature, case studies, and technical reports. The reviewed works encompass a range of hydrogeological contexts, modeling techniques, and sustainability frameworks. Emphasis was placed on identifying recurring methodological patterns, evaluating the applicability of different modeling approaches, and highlighting research gaps that affect model performance and decision-making. The organization of this review reflects several major thematic areas observed across the literature, including aquifer characterization methods, groundwater modeling strategies, data analysis techniques, and integrated management frameworks.

Review Scope and Literature Selection Process

To ensure a comprehensive and demonstrative synthesis of current knowledge, this review considered a broad selection of peer-reviewed studies, technical reports, and modeling-based research articles published between 1992 and 2024. The selection was guided by relevance to hydrogeological assessments, groundwater flow modeling, and sustainable water resource management across diverse hydrogeological and socio-environmental contexts. Particular emphasis was placed on studies employing both conventional methods such as analytical and numerical modeling, as well as emerging approaches that incorporate geospatial tools and remote sensing technologies (*Scanlon et al. 2002; Taylor et al. 2013*).

Relevant literature was identified through keyword-driven searches in academic databases including Scopus, Web of Science, and Google Scholar. Keywords and Boolean combinations such as “groundwater flow modeling,” “hydrogeological assessment,” “aquifer properties,” “numerical simulation,” and “sustainable groundwater management” were used to filter studies. Inclusion criteria prioritized methodological rigor, clarity of model application, and contributions to the broader understanding of groundwater dynamics. Both global overviews and region-specific case studies were considered to reflect the variability in aquifer behavior, management practices, and modeling requirements (*Taylor et al. 2013*). To further contextualize the scope of literature analyzed in this review, a timeline illustrating key methodological developments in groundwater modeling and hydrogeological assessment over the past three decades were presented (**Figure 1**). The timeline features the field’s progression from early analytical frameworks in the 1990s to the current integration of numerical simulation, artificial intelligence, and sustainability frameworks. This visualization emphasizes the temporal span and thematic breadth of the reviewed literature, supporting the review’s objective to capture both historical foundations and contemporary innovations.

The final body of literature emphasized interdisciplinary perspectives, integrating hydrological modeling with socio-environmental frameworks relevant to integrated water resource management (IWRM) and adaptive governance. The selected works offer a balanced perspective on theoretical development, technological advancements, and policy-driven applications supporting this review’s aim to link scientific knowledge with practical groundwater management and planning needs (*Scanlon et al. 2002; Taylor et al. 2013*).

Thematic Structure of the Review

The reviewed literature was grouped into two major thematic categories that capture the methodological scope and scientific focus of recent advances in groundwater research: hydrogeological assessments and groundwater modeling approaches. These themes emerged from a synthesis of case studies, technical methodologies, and modeling innovations aimed at improving the understanding, prediction, and sustainable management of aquifer systems.

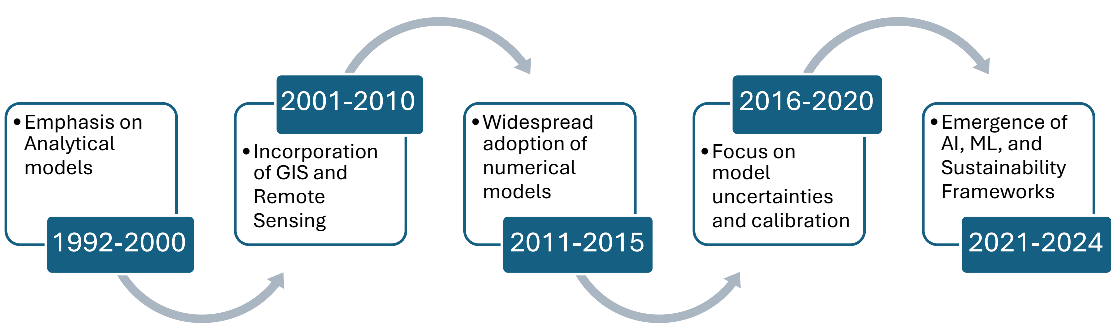

Figure 1. Timeline of major methodological developments in groundwater flow modeling and hydrogeological assessments from 1992 to 2024.

Hydrogeological Assessment. Hydrogeological assessments form the foundation of any groundwater modeling or management strategy, as they provide essential comprehensions of the behavior, capacity, and vulnerability of aquifer systems. Among the core areas reviewed are methods used for recharge estimation, aquifer characterization, and analysis of surface–groundwater interactions, each of which is critical for informing conceptual models and supporting the accurate simulation of flow dynamics.

a) Recharge estimation techniques vary by climatic region and geological setting but commonly involve the use of water table fluctuation data, chloride mass balance methods, and hydrological modeling. These approaches aim to quantify the rate and spatial distribution of water entering the aquifer, which directly influences storage, sustainability, and resource planning (*Scanlon et al. 2002; Taylor et al. 2013*). In many reviewed studies, recharge estimates are constrained by the availability of long-term climatic and hydrometric records, often requiring indirect or proxy-based methods to compensate for data gaps.

b) Aquifer characterization is another essential component, focusing on defining hydraulic properties such as transmissivity, storativity, and hydraulic conductivity. Field-based techniques such as pumping tests, slug tests, and geophysical surveys are commonly used to measure these parameters at various scales. The reviewed literature frequently highlights the importance of integrating physical data with geological mapping and sedimentological analysis to enhance the spatial accuracy of aquifer models (*Hojberg et al. 2013; Amanambu et al. 2020*).

c) Identifying surface–groundwater interactions is also essential, particularly in basins influenced by seasonal variability, anthropogenic pressures, or climate extremes. These interactions affect not only recharge processes but also water quality and ecosystem health. Several reviewed studies utilize isotopic analysis and hydrochemical profiling to trace the origin and mixing of water sources, assess residence times, and detect contamination pathways (*Njue et al. 2019; Rodriguez et al. 2013*). These techniques are especially effective in complex or data-poor environments, posing qualitative and quantitative indicators of hydrological connectivity. Largely, hydrogeological assessment methods continue to evolve, increasingly blending field observations with advanced analytical and geochemical tools. These developments enhance the capacity to characterize subsurface conditions and reduce uncertainties in groundwater modeling, particularly in areas where data scarcity and hydrogeological complexity present ongoing challenges.

Groundwater Flow Modeling Approaches. Groundwater flow modeling plays a critical role in predicting aquifer behavior, evaluating management strategies, and informing policy under conditions of uncertainty and environmental change. The reviewed literature includes a wide range of modeling approaches, each selected based on system complexity, data availability, and the specific objectives of the study. These models fall into four broad categories: analytical models, numerical simulations, hybrid frameworks, and computational techniques based on finite methods. Table 1 below presents a comparative overview of the modeling types discussed in this subsection. This framework helps clarify the distinctions in complexity, applicability, and underlying assumptions across the modeling spectrum.

Analytical models, such as those derived from the Theis and Jacob solutions, represent some of the earliest tools used to simulate groundwater flow. These models are based on idealized assumptions, typically assuming homogeneity, isotropy, and steady-state flow conditions and are often applied to relatively simple or conceptual aquifer systems (*Ibragimov 2009*). Despite their limitations, they remain valuable for preliminary assessments, validation benchmarks, and instructional purposes due to their mathematical simplicity and transparent assumptions. In contrast, numerical models offer greater flexibility for simulating real-world aquifer conditions, especially where heterogeneity, transient flows, or complex boundary conditions are present. Among the most widely used tools in the reviewed studies are MODFLOW, developed by the U.S. Geological Survey, and FEFLOW, which supports advanced hydrogeological simulations involving heat and solute transport (*Anderson et al. 2015; Refsgaard et al. 2010*). These models rely on discretizing the study domain into a computational grid and solving flow equations iteratively over time and space.

A growing number of studies employ hybrid models, which integrate traditional simulation tools with spatial datasets obtained through GIS and remote sensing. These frameworks enable modelers to incorporate land cover, elevation, soil type, and other spatially distributed variables into groundwater flow simulations. This integration enhances both the spatial resolution and environmental realism of groundwater models, particularly in regions where direct field data are scarce or incomplete.

Table 1. Summary of Groundwater Flow Modeling Approaches Reviewed in the Literature.

Model Type	Examples	Key Features	Typical Applications	Limitations
Analytical	Theis, Jacob	Closed-form solutions, rapid results	Pumping tests, simple systems	Assumes homogeneity; lacks spatial precision
Numerical	MODFLOW, FEFLOW	Grid-based, time-variable modeling	Multi-layer aquifers, transient conditions	High data needs; computational load
Hybrid	GIS + MODFLOW/ FEM	Integrated spatial datasets with simulations	Land use impact, recharge mapping	Dependent on spatial data availability
FDM / FEM	MODFLOW (FDM), FEFLOW (FEM)	Structured vs. flexible grid solvers	Complex flow and transport modeling	Requires technical expertise and calibration

Underlying many of the modeling systems are numerical solvers based on the finite difference method (FDM) and the finite element method (FEM). FDM is commonly applied in structured-grid models, suc as MODFLOW and is favored for its simplicity and computational efficiency in layered systems. FEM, on the other hand, offers greater geometric flexibility and is better suited for irregular domains or anisotropic conditions, as often implemented in tools like FEFLOW (*Di Salvo 2022*). Both methods have been extensively reviewed for their strengths and limitations in representing groundwater flow and transport under varying hydrogeological conditions.

Field-Based Techniques Reviewed

Field-based investigations remain a crucial component of groundwater studies, providing direct measurements that support aquifer characterization and model calibration. Among the techniques frequently cited in the reviewed literature are centrifugal pump tests, which are widely used to assess aquifer properties under controlled extraction conditions. These tests involve pumping water from a well at a constant rate while monitoring drawdown in both the pumped and observation wells. When properly designed and interpreted, they provide valuable data for estimating key parameters such as transmissivity and storativity, which are fundamental inputs in most groundwater flow models (*Kruseman and de Ridder 1970; Butler 2019*). The reviewed studies emphasize the importance of conducting these tests under stable hydraulic conditions and over sufficient time periods to ensure reliability. In many cases, analytical methods such as the Theis solution are used in combination with drawdown data to estimate transmissivity, particularly in confined aquifers. Where observation wells are available, storativity can also be inferred by comparing drawdowns across multiple monitoring points (*Ibragimov 2009; Hojberg et al. 2013*). A typical application of centrifugal pump testing as illustrated in the study of *Kruseman and de Ridder* (*2000*), involves plotting drawdown versus time curves, which are then analyzed using type-curve matching or derivative-based methods to infer aquifer behavior.

It is important to note that this review presents pump testing as a synthesis of established field-testing methods, not as an account of original experimental work. The discussion draws from published literature that evaluates the design, interpretation, and application of these tests in various hydrogeological settings. In particular, studies reviewed underscore the role of pump testing in validating conceptual models, supporting calibration of numerical simulations, and informing sustainable groundwater extraction strategies. The continued relevance of centrifugal pump testing lies in its ability to generate site-specific data that are otherwise difficult to obtain, especially in data-scarce or geologically complex regions. As modeling tools become more sophisticated, the integration of high-quality field data through methods like pump testing will remain a crucial element of robust groundwater system analysis.

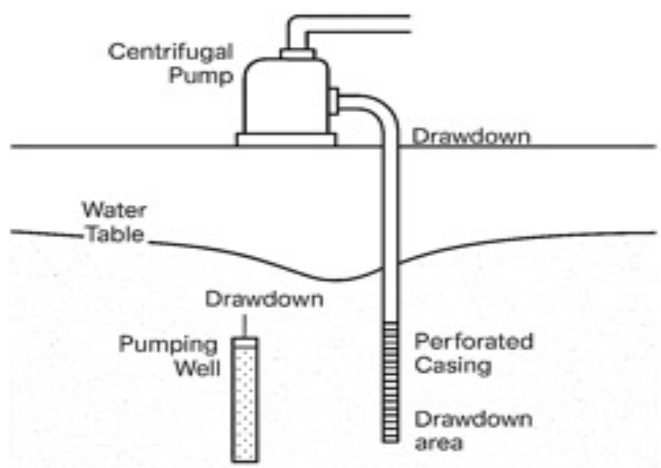

Figure 2. Conceptual diagram of a centrifugal pump test showing drawdown measurement from pumping and observation wells (*adapted from Kruseman and de Ridder 2000*).

Data Processing and Model Calibration

Accurate simulation of groundwater systems requires not only a solid conceptual model but also a robust process for data handling, parameter estimation, and model calibration. Across the reviewed literature, considerable emphasis is placed on the selection, preprocessing, and integration of hydrological and hydrogeological datasets to reduce uncertainty and improve model reliability.

a) Calibration is a recurring methodological focus, with most reviewed studies applying either manual trial-and-error techniques or automated calibration tools to align model outputs with observed field data. Parameters such as transmissivity, hydraulic conductivity, and recharge rates are typically adjusted within defined limits to minimize the difference between simulated and observed values, often using statistical indicators like root mean square error (RMSE) or Nash-Sutcliffe efficiency. The importance of calibration is especially pronounced in data-scarce regions, where even slight parameter inaccuracies can lead to a significant misrepresentation of aquifer behavior (*EPA Victoria 2004; Kumar et al. 2023*).

b) Sensitivity analysis is also widely applied to identify parameters that most influence model outputs and to prioritize data collection efforts. Reviewed studies use both local (one-at-a-time) and global (variance-based) sensitivity methods, depending on model complexity and data availability. These techniques help establish the range within which predictions can be considered reliable and provide information on which variables most affect system performance under different scenarios (S*epúlveda and Doherty, 2015; Amanambu et al. 2020*).

c) The validation of models, although often constrained by limited long-term monitoring data, is addressed in several reviewed works through cross-checking with independent datasets or using temporal subsets for testing. The reviewed literature stresses that models should not be viewed as deterministic forecasting tools, but rather as decision-support frameworks that reflect the best-available understanding within recognized limits of uncertainty.

Lastly, reviewed studies show increasing interest in data assimilation techniques, automated calibration platforms, and machine learning tools that can streamline model setup and improve predictive performance. While still emerging, these approaches offer promise in reducing human error and enabling more frequent updates to reflect changing hydrogeological conditions.

Integration into Sustainability Frameworks

An increasing number of studies emphasize that groundwater models should not function in isolation as technical tools but rather be integrated within broader sustainability frameworks that account for social, ecological, and institutional dynamics. This trend is reflected in the reviewed literature, which demonstrates how hydrogeological modeling supports not only water balance assessments but also long-term resource planning, climate resilience, and policy formulation.

Many studies align model outputs with the goals of Integrated Water Resources Management (IWRM), where modeling is used to evaluate trade-offs among competing water uses, identify priority recharge zones, and assess the impacts of land use or abstraction changes on aquifer sustainability (*EPA Victoria 2004*). These applications often involve coupling physical groundwater models with decision-support tools, such as multi-criteria analysis, scenario planning, and stakeholder input frameworks. Moreover, the reviewed literature shows that sustainability-oriented modeling increasingly draws from interdisciplinary data sources, incorporating socioeconomic indicators, institutional constraints, and climate projections into hydrological simulations. This allows models to serve as platforms for adaptive management, where policies can evolve in response to updated model scenarios and monitoring feedback (*Kumar et al. 2023*).

In data-scarce or resource-constrained contexts, several reviewed studies emphasize the importance of stakeholder engagement and the use of simplified, participatory models to inform local decision-making and build trust among users. These approaches help bridge the gap between technical modeling and governance, enabling more inclusive and transparent planning processes. Thus, the growing convergence of hydrogeological modeling with sustainability science reflects a shift toward more holistic water governance that values not only technical accuracy but also practical usability, transparency, and institutional alignment. This integration highlights the evolving role of models as decision-making tools, supporting equitable and resilient groundwater management in the face of complex and uncertain environmental futures.

RESULTS AND DISCUSSION

The following section presents a thematic synthesis of key findings derived from the literature reviewed, organized to reflect the methodological categories outlined earlier. Rather than presenting experimental results, this discussion evaluates patterns, strengths, limitations, and emerging directions in hydrogeological assessments, groundwater modeling techniques, and their integration into sustainability frameworks. Each thematic area is examined through a comparative lens to highlight how different approaches perform across varying environmental, technical, and policy contexts. Figures included in this section serve to illustrate conceptual frameworks and support critical interpretation, aligning with the review's aim to consolidate current practices and inform future groundwater management strategies.

Overview of Global Groundwater Modeling Trends

Over the past three decades, groundwater flow modeling has undergone a transformation, shifting from the the use of simplified analytical equations to the development of sophisticated numerical and hybrid systems capable of capturing spatial, temporal, and environmental complexity. Early models, such as those based on Theis and Jacob solutions, were foundational in estimating aquifer parameters under controlled conditions but were limited in their ability to represent heterogeneity, boundary fluxes, and variable recharge conditions (*Ibragimov 2009*). The limitations of these models prompted a transition toward numerical tools like MODFLOW and FEFLOW, which offered greater flexibility in simulating multi-layered, transient groundwater systems using finite difference and finite element methods (*Anderson et al. 2015*). As illustrated in the timeline presented in the Methods section (**Figure 1**), this shift has not been static but progressive. Between the early 1990s and mid-2000s, the focus of modeling remained largely deterministic, with greater attention given to solving flow equations under specific boundary conditions. From 2010 onward, however, studies increasingly began to incorporate geospatial technologies such as GIS and remote sensing, expanding the capability to model complex surface–groundwater interactions across diverse terrains (*Taylor et al. 2013*). More recently, the adoption of hybrid and machine learning-based tools has expanded modeling functionality, allowing for automated calibration, real-time updates, and improved handling of uncertainty in data-poor environments (*Di Salvo 2022; Tavakoli et al. 2024*).

Geographically, the reviewed literature reveals an uneven distribution of groundwater modeling research, with notable concentrations in South Asia, Sub-Saharan Africa, North America, and select regions of the Middle East. These studies vary widely in scale from small catchments and agricultural sub-basins to regional aquifer systems and national-level water balance assessments. For instance, some localized models focus on village-scale recharge and abstraction analysis, while others, like the work of *Khorrami and Malekmohammadi* (*2021*), evaluate groundwater dynamics in complex basin systems over decadal timescales. This variability in spatial and temporal scope underscores the adaptability of groundwater models but also highlights a need for more harmonized frameworks to ensure comparability and policy relevance across regions. Hence, the trajectory of groundwater modeling reflects a shift from simplified, static tools to dynamic, integrated platforms that support both scientific inquiry and policy decision-making. As modeling technologies continue to evolve, their utility in addressing global water challenges is expected to expand particularly where integration with socio-environmental datasets enables more holistic planning.

Evaluation of Hydrogeological Assessment Techniques

Hydrogeological assessment forms the foundation of groundwater modeling, as it provides the physical and conceptual understanding needed to define aquifer behavior, recharge dynamics, and flow boundaries. The reviewed studies highlight a range of assessment methods, each offering distinct advantages and limitations depending on the hydrogeological context, data availability, and spatial scale.

Recharge estimation methods vary widely in complexity and applicability. In humid regions or areas with significant monitoring infrastructure, techniques such as the water table fluctuation (WTF) method or chloride mass balance (CMB) approach are frequently used. These approaches rely on the availability of long-term observational data and hydrochemical profiles to quantify recharge rates (*Scanlon et al. 2002*). In more arid or data-scarce environments, however, indirect methods such as remote sensing-based rainfall-runoff modeling and isotopic tracing are more commonly applied. The latter is particularly useful in delineating recharge zones, estimating residence time, and identifying the contribution of various sources to aquifer replenishment (*Taylor et al. 2013; Njue et al. 2019*).

Aquifer characterization also varies across studies, ranging from localized pumping and slug tests to regional geophysical surveys and stratigraphic profiling. In many cases, transmissivity and storativity are derived through pumping test interpretation or geostatistical extrapolation. However, the configuration of the basin itself plays a crucial role in defining the direction and behavior of subsurface flow. Groundwater systems within sedimentary terrains, for example, often follow gravity-driven pathways influenced by structural gradients and confining layers. The two major basin types, unit and composite, govern how groundwater circulates and discharges within these systems (**Figure 3**). In unit basins, flow is typically constrained within a single topographic feature, resulting in localized recharge-discharge zones with relatively short flow paths. In contrast, composite basins may host overlapping or nested flow systems that extend across sub-basins and interact with deeper geological structures. This configuration gives rise to longer residence times, more complex hydrogeochemical evolution, and often more pronounced uncertainty in flow boundaries and recharge sources (*Czauner et al. 2022*).

In addition, many reviewed studies assess surface–groundwater interactions using a combination of isotopic analysis, hydrochemical fingerprinting, and remote sensing. These methods are instrumental in identifying areas of connectivity between rivers, wetlands, and aquifers, an important consideration in integrated water resource planning. Such interdisciplinary approaches are especially relevant in landscapes undergoing land use change, where natural recharge processes may be disrupted or redirected. In general, the literature underscores that no single assessment method is universally applicable. Instead, combinations of field-based, geochemical, and spatial tools are often required to construct reliable conceptual models. The choice of method must be carefully aligned with site conditions, data limitations, and the intended application of the model whether for recharge estimation, contamination risk analysis, or long-term planning.

Performance and Categorization of Groundwater Flow Models

Groundwater flow models vary widely in complexity, structure, and intended application, ranging from simplified analytical equations to hybrid platforms combining physical and data-driven techniques. The reviewed literature consistently highlights that model selection depends not only on the hydrogeological setting and data availability, but also on the management objectives and spatial scale of interest. This section synthesizes the strengths, limitations, and performance characteristics of different model categories while drawing from practical examples and conceptual frameworks.

Analytical models such as those based on the Theis and Jacob solutions represent the earliest tools developed for estimating aquifer parameters. Their mathematical simplicity and closed-form structure make them ideal for use in homogeneous, confined systems, particularly in

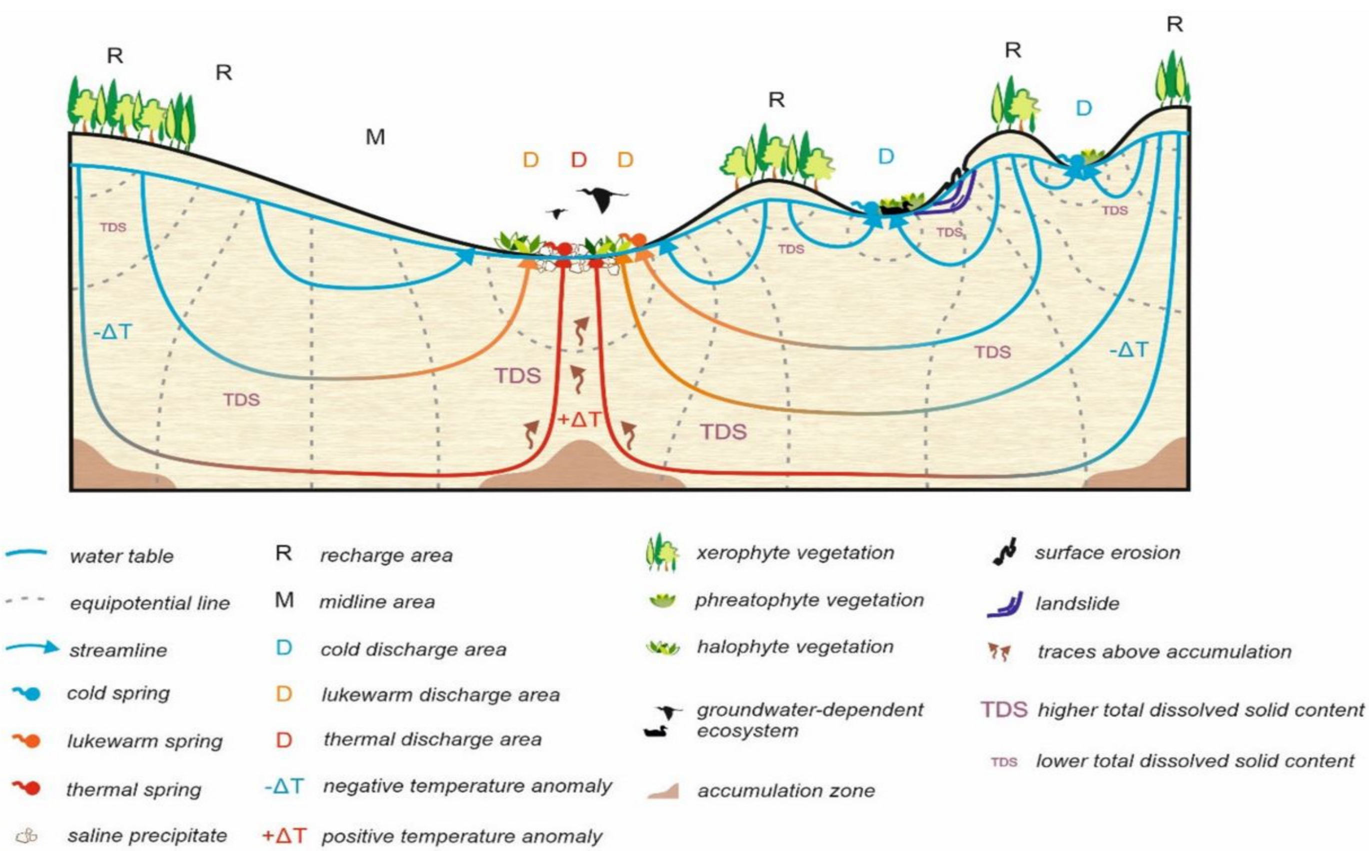

Figure 3. Conceptual diagram of groundwater flow systems in sedimentary basins, illustrating unit and composite basin types and gravity-driven flow behavior (*Czauner et al. 2022*).

applications involving pumping tests and short-term drawdown analysis (*Ibragimov 2009; Kruseman and de Ridder 2000*). However, their inherent assumptions, such as infinite areal extent, isotropy, and steady-state conditions, render them unsuitable for most real-world applications involving spatial or temporal variability. As hydrogeological investigations have become more sophisticated, numerical models have emerged as the standard in most practical groundwater studies. Tools like MODFLOW and FEFLOW use finite difference and finite element methods, respectively, to discretize the flow domain and simulate conditions ranging from multi-layer aquifers to transient, unconfined systems (*Anderson et al. 2015; Refsgaard et al., 2010*). MODFLOW remains widely adopted due to its modular structure and community support, whereas FEFLOW is often used in more advanced simulations involving heat or solute transport. While both platforms offer significant flexibility, they also demand careful calibration and are often data-intensive.

The reviewed studies also point to a growing use of hybrid and integrated models, particularly in regions with uneven data availability or where socio-environmental variables need to be considered. These models combine physical groundwater equations with spatial data derive from GIS and remote sensing, and in some cases, are enhanced with machine learning techniques to optimize calibration or identify patterns in groundwater response (*Gorelick and Zheng 2015; Di Salvo 2022*). For instance, models that couple MODFLOW with GIS-based land cover data or AI-based recharge estimation can simulate scenarios where conventional models may struggle due to data gaps or dynamic surface interactions (*Tavakoli et al. 2024*). These diverse approaches are synthesized, which categorizes groundwater models based on level of complexity, data requirements, and decision-support utility (**Figure 4**). Analytical models, positioned at the conceptual end of the spectrum, are best suited for initial assessments. Numerical models form the core of technical investigations, while decision-support and hybrid models span a range of uses, including stakeholder engagement, sustainability planning, and scenario testing (*Kumar et al. 2023*).

The usefulness of a given model is not determined solely by its sophistication but by how well it matches the needs and constraints of a specific setting. For example, high-resolution numerical models may yield precise outputs but are of limited value in areas lacking adequate input data. Conversely, hybrid models incorporating stakeholder input and socio-economic drivers may offer broader utility in integrated water resource management, even if physically simplified. Moreover, studies from

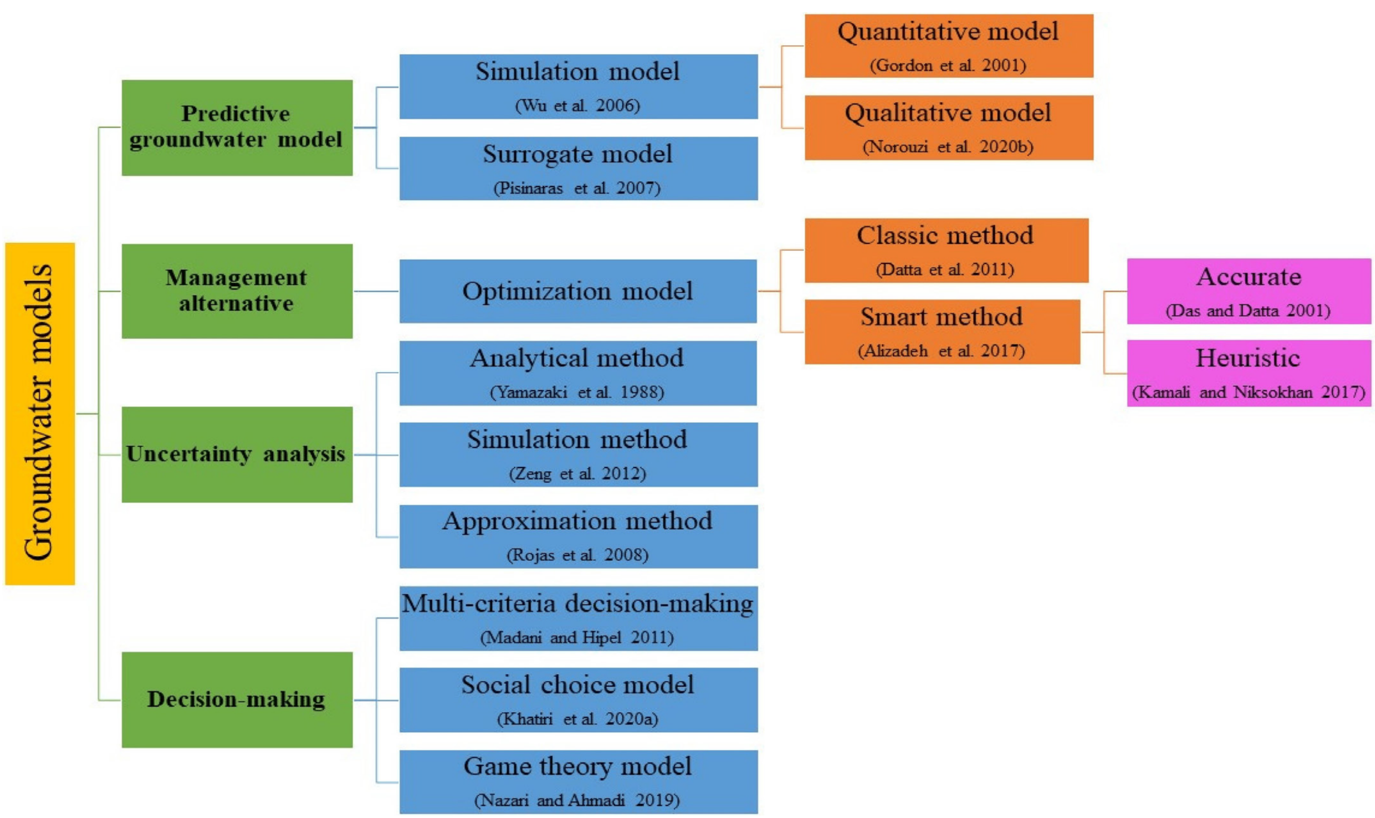

Figure 4. Categorization of groundwater management models based on complexity, data requirements, and decision-support integration (*Norouzi Khatiri et al. 2023*).

various regions underscore the importance of model transparency and stakeholder accessibility. In low-resource settings, simpler models with open-source platforms are often preferred over complex commercial software. Conversely, institutional and technical capacity in more developed regions allows for greater adoption of coupled models that integrate groundwater-surface water interaction, land use dynamics, and climate scenarios (*Taylor et al. 2013; Khorrami and Malekmohammadi 2021*). Ultimately, the performance of groundwater models is not only a technical question but also a function of their fit-for-purpose design, user accessibility, and integration into decision-making frameworks. The literature reflects a growing consensus that model utility must be evaluated not just by precision, but by its ability to support adaptive management in complex, data-variable, and policy-driven contexts.

Calibration, Sensitivity and Uncertainty Handling

A consistent theme across the reviewed literature is the importance of model calibration and sensitivity analysis in enhancing the reliability and decision-support value of groundwater simulations. Calibration is not merely a technical process but a critical step in building stakeholder confidence and ensuring that modeled scenarios reflect field conditions within acceptable margins of error. Most reviewed studies apply either manual (trial-and-error) or automated calibration routines to align simulated outputs such as water levels or hydraulic heads with observed data. Manual calibration, while flexible and often guided by expert knowledge, is time-consuming and susceptible to bias, particularly when dealing with multi-parameter models or limited data (*EPA Victoria 2004*). Automated methods, by contrast, utilize optimization algorithms such as PEST or genetic algorithms to systematically minimize error and reduce subjective adjustments (*Sepúlveda and Doherty 2015*). While these tools improve consistency and reproducibility, they also require robust datasets and careful control of parameter constraints to avoid overfitting.

Sensitivity analysis plays a complementary role in identifying the parameters that most significantly influence model outcomes. This allows modelers to prioritize data collection around the most impactful variables and focus validation efforts where uncertainty poses the highest risk. The literature reflects a spectrum of approaches, from simple one-at-a-time (OAT) local sensitivity methods to more advanced global variance-based techniques. For example, *Amanambu et al.* (*2020*) applied global sensitivity techniques to assess the influence of recharge rate, hydraulic conductivity, and evapotranspiration on model output in data-limited contexts. These techniques revealed not only parameter ranking but also non-linear interactions among variables understandings that are crucial when developing models for planning and resource allocation. To consolidate these methodologies, the key calibration, sensitivity, and uncertainty analysis approaches used across the reviewed literature were summarized (**Table 2**). It compares their respective strengths, limitations, and appropriate application contexts.

The table emphasizes that no single method dominates across all modeling contexts. Instead, the reviewed studies demonstrate that effective modeling often involves blending multiple techniques depending on system complexity, stakeholder needs, and resource availability. For example, manual calibration remains prevalent in data-scarce or localized studies, where hydrogeologists rely on domain expertise. In contrast, automated methods are increasingly used in regional or national assessments due to their scalability and

Table 2. Comparison of calibration, sensitivity, and uncertainty analysis methods commonly used in groundwater modeling, based on reviewed studies (e.g., *EPA Victoria 2004; Sepúlveda and Doherty 2015; Amanambu et al. 2020; Kumar et al. 2023*).

Technique	Common Tools/ Examples	Strengths	Limitations	Best Used When
Manual Calibration	Visual fit, expert judgment	Intuitive, site-specific insights	Time-consuming, subjective	Small-scale or conceptual models
Automated Calibration	PEST, UCODE, genetic algorithms	Reproducible, scalable, minimizes bias	Data-intensive, risk of overfitting	Multi-parameter or regional models
Local Sensitivity Analysis	OAT (One-at-a-time)	Simple, low computation	Ignores parameter interactions	Preliminary screening or small models
Global Sensitivity Analysis	Sobol, FAST, Morris methods	Captures interactions, ranks importance	Computationally demanding	Complex or highly uncertain systems
Uncertainty Quantification	Monte Carlo, Bayesian methods	Informs risk, presents model confidence	Requires large datasets and computation	Risk assessment and decision-making models

consistency. Similarly, local sensitivity analysis is suitable for early-stage investigations, while global techniques offer more robust insights in multi-parameter systems where variable interactions are non-linear or uncertain (*Amanambu et al. 2020*).

Uncertainty quantification, though less frequently implemented, is gaining attention particularly in studies concerned with long-term management, climate resilience, or where decisions must be made under variable conditions. *Kumar et al.* (*2023*) emphasize that embracing probabilistic outputs, rather than deterministic ones, allows for more adaptive, risk-informed planning especially when linked to sustainability frameworks. Therefore, the reviewed literature reflects a trend toward integrated workflows, where calibration, sensitivity, and uncertainty tools are used in combination, not isolation. This allows models to serve as more reliable platforms for both scientific exploration and policy guidance.

Integration into Sustainability and Water Governance Frameworks

A growing segment of groundwater modeling literature moves beyond technical simulation and emphasizes integration with sustainability planning, stakeholder engagement, and multi-sectoral policy frameworks. The reviewed studies reflect a paradigm shift: models are no longer viewed merely as computational tools, but as platforms to support adaptive management and resilient groundwater governance.

One of the most cited frameworks is Integrated Water Resources Management (IWRM), which promotes coordinated planning across hydrological, ecological, and institutional systems. Several studies reviewed particularly those in highly stressed or water-scarce regions use groundwater models to evaluate the effects of land use changes, agricultural withdrawals, and climate variability on aquifer health (*EPA Victoria 2004; Kumar et al. 2023*). In these cases, models inform decisions about zoning, allocation, and recharge interventions by simulating long-term impacts under alternative scenarios. A conceptual view of the interacting sectors that influence groundwater sustainability adapted from *Norouzi Khatiri et al.* (*2023*) shows how environmental, agricultural, technological, political, and social dimensions intersect in shaping groundwater dynamics and management outcomes (**Figure 5**).

The reviewed literature supports this systems view. For instance, *Sepúlveda et al.* (*2022*) highlight the need for stakeholder involvement during model development, particularly when dealing with competing demands or culturally sensitive water practices. Similarly, *Hojberg et al.* (*2013*) document how community-driven data collection and collaborative scenario building improve the acceptance and applicability of model results, especially when planning for long-term sustainability. In lower-income or data-scarce settings, several studies point to the value of participatory modeling using simplified tools or decision-support systems. These approaches enable non-technical users such as local farmers, water authorities,

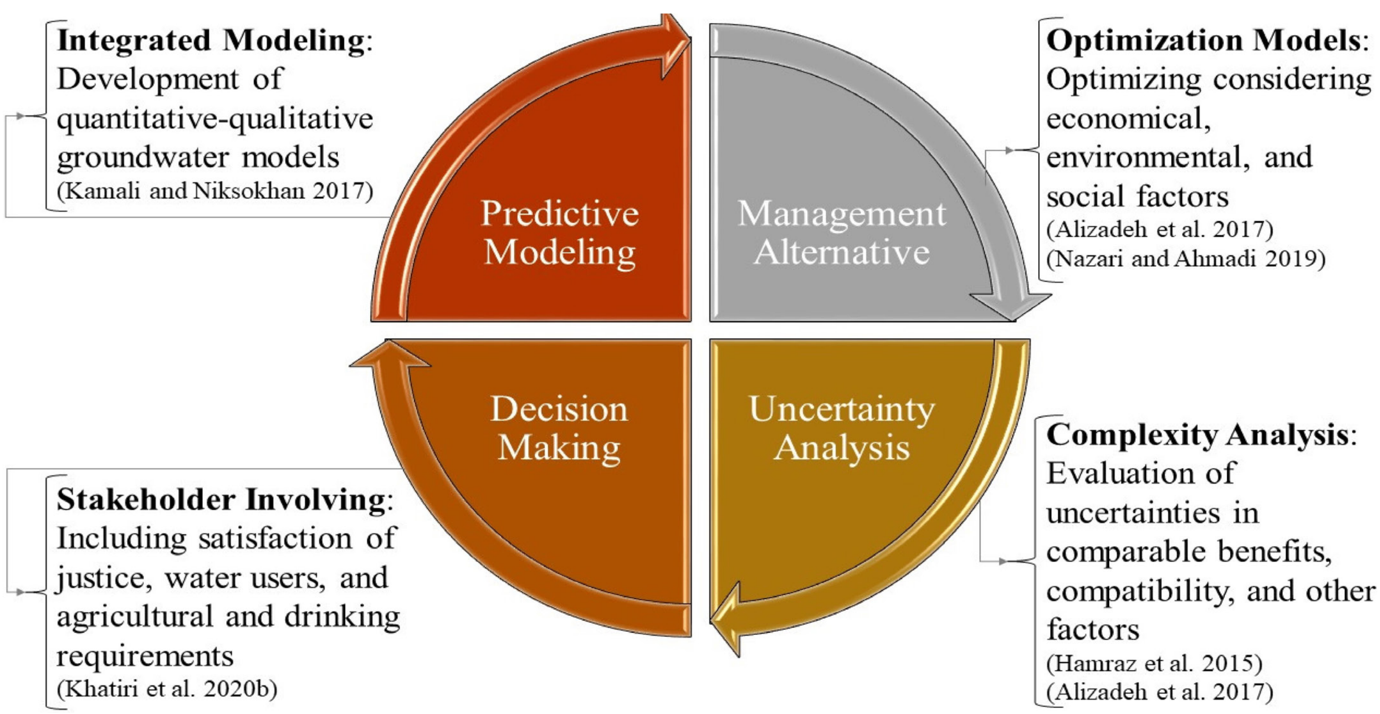

Figure 5. Interacting sectors of groundwater management and their interdependencies (*Norouzi Khatiri et al. 2023*).

or village councils to visualize trade-offs and explore adaptive responses. For example, *Njue et al.* (*2019*) emphasize the use of citizen science and remote sensing to compensate for the lack of institutional monitoring capacity, making groundwater modeling more inclusive and actionable.

Likewise, the integration of model outputs with policy cycles is becoming increasingly prominent. *Kumar et al.* (*2023*) argue that models should not operate in isolation from real-world governance processes. They advocate for embedding models within feedback loops that include periodic recalibration, stakeholder review, and scenario updates. This adaptive approach ensures that groundwater management remains responsive to changing environmental and socio-political conditions. In synthesizing these findings, the reviewed literature makes clear that the effectiveness of groundwater modeling in sustainability contexts depends not only on computational accuracy, but also on how well models are aligned with governance realities. This includes ensuring transparency, supporting communication among sectors, and prioritizing flexibility over technical perfection especially when dealing with long-term water security under uncertainty.

In addition to participatory and interdisciplinary modeling approaches, several studies underscore the value of integrating field-based hydrogeological investigations such as borehole drilling and stratigraphic logging with numerical modeling platforms like MODFLOW. This combination provides a robust framework for characterizing aquifer behavior, simulating flow under varying stress conditions, and designing site-specific strategies for Managed Aquifer Recharge (MAR). By aligning conceptual understanding with predictive modeling, such approaches support long-term planning and enable more resilient and adaptive groundwater management practices, particularly in vulnerable or over-extracted aquifer systems.

Challenges and Future Research Directions

Despite considerable advances in groundwater modeling, the reviewed literature reveals several persistent challenges that limit the effectiveness, transferability, and decision-making value of these tools. These challenges span technical, data-related, and institutional dimensions and must be addressed to improve the contribution of groundwater models to sustainable water resource management.

A recurring obstacle in many studies is the lack of high-resolution, long-term monitoring data, particularly in regions with limited hydrogeological infrastructure. Without sufficient data, even the most advanced models face difficulties in calibration, validation, and long-term reliability. This issue is especially critical in fractured or heterogeneous aquifers, where subsurface complexity complicates model parameterization and increases structural uncertainty (*Rodriguez et al. 2013; Amanambu et al., 2020*). Future research should focus on developing techniques that improve model robustness under uncertainty, including methods for downscaling or synthesizing data from remote sensing, citizen science, and proxy indicators (*Njue et al. 2019*). Another challenge lies in the limited uptake of models in governance and policy settings, particularly in areas where technical capacity or institutional continuity is weak. Although many models demonstrate technical rigor, their outputs often fail to influence actual planning decisions due to a lack of stakeholder engagement, poor communication of uncertainty, or overly complex platforms (*Sepúlveda et al. 2022*). To address this, future groundwater modeling efforts should emphasize co-design processes, where stakeholders are involved from the beginning of model development, and where outputs are framed in formats accessible to non-technical users.

There is also a need to address the fragmentation of modeling efforts across disciplines. Many groundwater models are still developed in isolation from broader hydrological, ecological, or socio-economic systems. This reduces their relevance in contexts where groundwater interacts closely with land use, energy policy, or climate resilience planning. Emerging research should therefore pursue integrated socio-hydro models that account for feedbacks between human activity and groundwater behavior, particularly under stress scenarios such as drought or contamination events (*Kumar et al. 2023*). In addition, while machine learning and data-driven tools are gaining attention, their interpretability and integration with physical models remain limited. Research is needed to develop hybrid approaches that combine the predictive power of AI with the mechanistic clarity of physically based simulations. Such models could streamline calibration, improve forecasting, and allow for faster scenario analysis especially useful in dynamic or emergency-response contexts.

Future research would benefit from advancing integrated workflows that combine borehole-based aquifer characterization with physically based simulation tools such as MODFLOW. This methodology allows for high-resolution, location-specific modeling of subsurface conditions and supports the design of intervention strategies like Managed Aquifer Recharge (MAR). When informed by local hydrostratigraphy and calibrated through reliable field data, such models can offer powerful decision-support capabilities for sustainable groundwater development, especially in data-scarce or climate-sensitive regions. Lastly, efforts should be directed toward developing simplified, open-access modeling platforms that support capacity building in low-resource settings. These tools must balance usability with scientific credibility and should be accompanied by training modules and decision-support templates to enhance adoption at the community and institutional levels. Hence, addressing these challenges will require not only technical innovation, but also a commitment to inclusivity, transparency, and interdisciplinarity in groundwater research. Future modeling must go beyond predictive accuracy and become more adaptable, collaborative, and policy-relevant.

CONCLUSION AND RECOMMENDATION

This review has synthesized three decades of scholarly efforts in groundwater flow modeling, with a focus on hydrogeological assessments, simulation approaches, calibration techniques, and their integration into sustainability and governance frameworks. The literature reveals a clear evolution from early analytical models rooted in homogeneous assumptions to hybrid platforms that incorporate geospatial data, machine learning, and socio-environmental dynamics. While progress has been substantial, key challenges persist, particularly in data availability, model scalability, and policy relevance.

Hydrogeological assessments remain foundational, yet their effectiveness depends on robust conceptualization of basin-scale flow systems, recharge variability, and aquifer heterogeneity. Modeling approaches continue to diversify, with numerical tools like MODFLOW and FEFLOW remaining widely used, while integrated and hybrid models gain traction in complex or data-scarce settings. Calibration and sensitivity analysis practices have also matured, with growing use of automated techniques and global uncertainty frameworks. However, the transfer of modeling results into actionable decision-making remains uneven, especially where institutional capacity or stakeholder involvement is limited.

To improve the effectiveness of groundwater modeling in sustainable resource management, the following recommendations are offered:

Ensuring transparency in modeling and maintaining detailed documentation is crucial, particularly when working with incomplete or uncertain data, as it builds trust with both policymakers and the general public. Involving stakeholders from the outset through collaborative methods and tools specific to local needs can improve both the relevance and effectiveness of modeling efforts. To broaden the use of these tools, especially in areas with limited resources, it is important to support the development of user-friendly, open-access platforms that integrate physical modeling. Encouraging the use of interdisciplinary approaches that connect groundwater behavior with factors such as land management, ecosystem functions, and economic conditions can also lead to more comprehensive outcomes. Advancing hydrogeological assessments by combining borehole-based aquifer characterization with physically based simulation tools, such as MODFLOW, enhances the accuracy and applicability of groundwater models in diverse settings. Moreover, continued innovation in hybrid modeling, blending traditional simulations with artificial intelligence and remote sensing, can support more flexible and timely decision-making processes.

Groundwater systems are inherently complex and modeling them effectively requires not only technical precision but also institutional alignment, local relevance, and the flexibility to adapt to evolving environmental pressures. As water scarcity, contamination, and climate variability intensify, groundwater models must continue to evolve—not only as scientific tools, but as enablers of more informed, inclusive, and sustainable water governance.

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