Larhyss Journal, ISSN 1112-3680, n°64, Dec 2025, pp. 33-56

A COMPREHENSIVE REVIEW OF PROCESSING MODFLOW APPLICATIONS, ADVANCES AND LIMITATIONS IN GROUNDWATER MODELLING

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Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received October 15, 2024, Received in revised form December 2, 2025, Accepted December 3, 2025

ABSTRACT

Groundwater contamination is an issue of severe concern in any area. Particularly, in areas where groundwater also happens to be a source of potable water in addition to surface water, the threat to the environment becomes even more imminent. In this context, groundwater modelling happens to be the only feasible option to prevent such contamination in future. Out of the various software used MODFLOW stands out tall compared to the others. MODFLOW offers an easy-to-use interface and provides comprehensive analysis of the dispersion pattern of groundwater by offering simplified pre-processing, simulation, and post-processing operations. The present paper presents a thorough review of Processing MODFLOW (PM), including its applications, developments, and limitations. The exhaustive review points to its various applications, ranging from groundwater resource management to contaminant transport modelling, climate change-oriented assessments and urban and agricultural water management. New developments in the form of integration with GIS and remote sensing, enhanced computational efficiency, and better user interfaces are presented and they demonstrate how Processing MODFLOW has been able to adapt to contemporary hydro geological research and also yield highly dependable results with high degree of accuracy. The current paper also makes an attempt to compare Processing MODFLOW with other available groundwater model tools and also highlight its unique combination new advanced technologies such as artificial intelligence and machine learning to produce even more accurate predictions. Through integration of existing knowledge and resolution of major challenges, this review seeks to present a balanced view of the strength and limitations of Processing MODFLOW, including valuable lessons for researchers, practitioners, and policymakers involved in groundwater modelling. The results highlight the need for ongoing innovation and cooperation to further develop the usefulness of Processing MODFLOW in the management of global water resource issues and thus to reduce the effects of groundwater contamination much more.

Keywords: Processing MODFLOW, Groundwater Modelling, Groundwater Management, Numerical Simulation, Contaminant Transport.

INTRODUCTION

Groundwater is among the most critical natural resources, supporting ecosystems, agriculture, industry, and human settlements globally (Belhadj et al., 2017; Zegait et al., 2021; Remini, 2025). It provides about 30% of the global freshwater and acts as a fundamental buffer against drought and climate variability. Nevertheless, the growing water demand, combined with the effects of climate change, pollution, and over-extraction, has put enormous stress on groundwater systems (Kheliel et al., 2015; Aroua, 2018; Sharma, et al., 2021; Aroua, 2022; Aroua, 2023; Lachache et al, 2023). Proper management of such resources is necessary to sustain them as well as protect against the risks involved in their depletion or contamination (Mondal et al., 2022). Groundwater mapping, zoning, and modelling has proved itself to be a useful and valuable tool for deciphering the intricate dynamics of subsurface water systems (Paulo-Monteiro and Costa-Manuel, 2004; Koussa and Berhail, 2021; Jaiswal et al., 2023; Deb, 2024). Through the modelling of groundwater flow and transport, such models can reveal aquifer behaviour, such as level fluctuations (Rajput et al., 2023), forecast the effects of human actions, and support decision-making in the sustainable management of water resources (Boutebba et al., 2014; Bahir et al., 2015; Laghzal et al., 2019; Jayasena et al., 2021; Wali et al., 2024; Kezzar and Souar, 2024). Groundwater models find applications across a broad spectrum, from the determination of its origin, estimation of the recharge (Chibane and Ali-Rahmani, 2015; Bemmoussat et al, 2017), the amount of water available for irrigation and drinking to the estimation of the contamination spread, and remediation design (Saadi et al., 2014; El Moukhayar et al., 2017; Sharma et al., 2020; Later and Labadi, 2024). They also have an important role to play in solving international problems like climate change adaptation, land-use planning, sustainable management (Bahir et al., 2015; Pandey et al., 2022; Kouloughli and Telli, 2023), and protecting ecosystems (Ouis, 2012; Kouassi et al., 2013; Assemian et al, 2021; Qureshi et al., 2024).

Among the tools of groundwater modelling available, the United States Geological Survey (USGS)-developed Modular Finite-Difference Flow Model (MODFLOW) has been one of the most popular and reliable packages (Fadlallah, 2020). Since its release in the 1980s, MODFLOW has been the de facto standard for groundwater flow simulation in porous media (Vellando et al., 2020). Its modular design, open-source code, and ongoing updates have established it as a flexible and strong tool for researchers, engineers, and policymakers. MODFLOW has been used in various hydrogeological conditions, from small-scale local aquifers to large-scale regional systems, and has played a key role in solving intricate water management issues (Wali et al., 2024).

Despite its strengths, MODFLOW has traditionally required significant expertise to use effectively. The preparation of input data, execution of simulations, and interpretation of results can be time-consuming and technically demanding (Ntona et al., 2022). This has limited its accessibility to non-expert users and hindered its broader adoption in some contexts (Banta and Paschke, 2011). To address these challenges, Processing MODFLOW was developed as a user-friendly interface that simplifies and enhances the use of MODFLOW for groundwater modelling (Dongre, 2022). This paper aims to provide a balanced and insightful perspective on Processing MODFLOW, offering valuable guidance for researchers, practitioners, and policymakers involved in groundwater modelling. The findings of this review will contribute to a deeper understanding of the tool's strengths and weaknesses, while also highlighting its potential to address pressing water resource challenges in the future (Dube et al., 2023).

OVERVIEW OF MODFLOW AND PROCESSING MODFLOW

The United States Geological Survey's (USGS) Modular Finite-Difference Flow Model (MODFLOW) has a long and diverse history that traces back to the early 1980s. It was first built to model groundwater flow in porous media through a finite-difference framework (Konikow et al., 2006). MODFLOW has, over the years, become one of the most applied and reliable groundwater modelling software, with regular updates and improvements to respond to new hydrological challenges (Ntona et al., 2022). Its modular design facilitates the addition of new features and functionalities, hence its flexibility across a broad array of applications (Langevin et al., 2024).

The development of MODFLOW was motivated by the necessity of having a flexible and powerful tool capable of accurately simulating groundwater systems. Initial MODFLOW versions aimed to simulate groundwater flow in steady-state and transient conditions within confined and unconfined aquifers (Deyet et al., 2023). More advanced modules have been added with time to represent more intricate processes, including solute transport, variable-density flow, and surface water-groundwater interactions. The open-source status of MODFLOW has facilitated extensive usage and cooperation among the scientific community, resulting in its use across various disciplines such as hydrology, environmental engineering, and water resources management.

Major advantages of MODFLOW include the capability of accommodating large and intricate aquifer systems, multidimensionality to support various boundary conditions, and adaptability in data formats (Langevin et al., 2024). The package system makes the user able to design simulations tailored to the user's needs based on specific selection from packages available, such as River Package, Well Package, and Recharge Package, in line with their research needs (Glass et al., 2022). MODFLOW's versatility and credibility have established it as a staple of groundwater modelling, with applications that span local-scale aquifer studies to regional-scale water resource appraisals.

Introduction to processing MODFLOW

Although it has its advantages, MODFLOW's technical intensity and high learning slope have become daunting to many users, especially those with no prior programming or modelling background (Makhlouf et al., 2024). To overcome these obstacles, Processing MODFLOW was created as a graphical user interface (GUI) that eases the application of MODFLOW in groundwater modelling (Prabhakar, 2023). MODFLOW processing gives an easy-to-use platform for building, executing, and analysing MODFLOW-based models so that it becomes available to everyone, such as students, researchers, and water resource professionals.

It was motivated by the necessity for simplifying the groundwater modelling workflow. Conventional use of MODFLOW involves preparation of input files manually, running simulations via command-line interfaces, and post-processing results with other software tools. Processing MODFLOW packages these steps into an integrated, easy-to-use environment with less time and effort needed to create and analyse groundwater models (Dongre, 2022). With automation of repetitive tasks and visualization tools used for input and output of data, Processing MODFLOW accelerates efficiency and accuracy of MODFLOW-based simulations (Doherty, 2015).

Processing MODFLOW is an extension of MODFLOW that includes additional features and functionalities that the basic version lacks. For instance, it has the capability of integrating geographic information systems (GIS) and remote sensing data to allow users to include spatial datasets within their models directly (Bakker et al., 2016). It also offers capabilities for parameter estimation, sensitivity, and uncertainty, which are all critical for making robust and sound groundwater models (Ntona et al., 2022). Merging the strengths of MODFLOW with the usability of a modern interface, Processing MODFLOW is now an unavoidable tool for groundwater modelling (Ntona et al., 2022). The various timelines of MODFLOW and Processing MODFLOW is depicted as seen in Fig. 1.

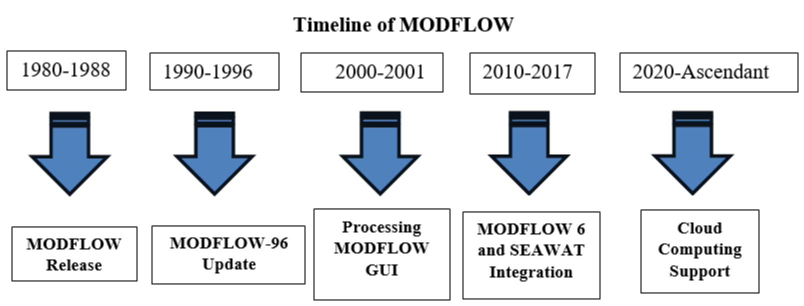

Figure 1: Timeline of MODFLOW and processing MODFLOW evolution

Key components of processing MODFLOW

MODFLOW processing is meant to automate the entire groundwater model workflow, from pre-processing to post-processing. Processing MODFLOW supports preparation of input data, model geometry definition, and hydraulic properties assignment to model layers (Tilahun, 2024). The user can import spatial information like elevation maps and well locations, and set boundary conditions through an easy-to-use graphical interface (Winston, 2009). The software also does grid generation and file formatting automatically, minimizing errors and saving time. MODFLOW can be processed using MODFLOW directly within the GUI by users, which does not require command-line interfaces interface (Winston, 2009). It also supports a large variety of MODFLOW packages such as flow, transport, and surface water-groundwater interaction packages (Ntona et al., 2022). The settings of simulations, including convergence criteria and time steps, may also be controlled by users via an easy-to-use interface (Hughes et al, 2022).

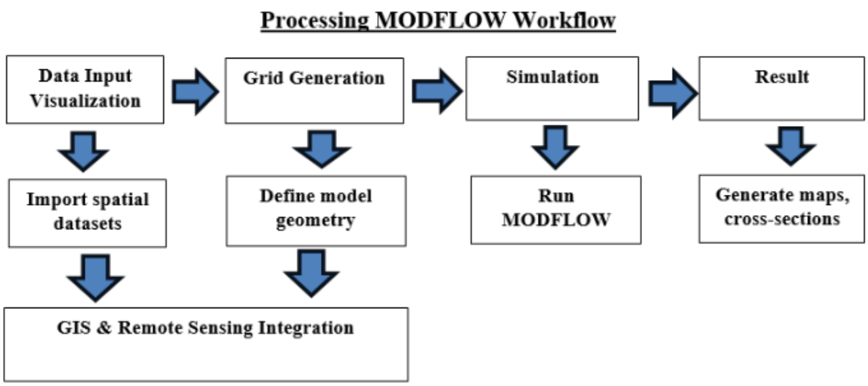

Figure 2: Workflow diagram of processing MODFLOW

Once simulation runs are performed, Processing MODFLOW offers result visualization and analysis tools. It is possible to create maps, cross-sections, and time-series plots for interpreting model outputs (Coxet et al., 2013). The software further allows results to be exported into other formats like GIS files and spreadsheets for additional analysis (Bakker et al., 2016). MODFLOW's user interface can be processed in an intuitive and user-friendly manner, even for inexperienced modellers (Fedra et al., 2020). It also interacts smoothly with other software programs and data sets, including GIS and remote sensing systems, to perform more full and precise simulations (Bakker et al., 2016). MODFLOW also has scripting and automation capabilities, permitting sophisticated users to tailor workflows and enhance its functionality (Pulla, 2024). By integrating these elements, Processing MODFLOW offers a complete solution for groundwater modelling, from data preparation to interpretation of results. Its intuitive interface and sophisticated features make it an essential tool for researchers, practitioners, and policymakers working in water resource management (Grigg, 2023). The complete workflow diagram and key features of Processing MODFLOW is mentioned in Fig. 2 and Table 1 respectively.

Table 1: Key features of Processing MODFLOW

Feature	Description	Example Application
Graphical User Interface	Intuitive GUI for model setup, simulation, and result analysis.	Simplifying aquifer model creation for beginners.
Grid Generation	Automated creation of model grids and boundary condition assignment.	Defining a regional aquifer system layout.
Supported MODFLOW Packages	Compatibility with flow, transport, and interaction packages (e.g., River, MT3DMS).	Simulating river-groundwater interactions.
GIS Integration	Direct incorporation of spatial data from GIS and remote sensing.	Mapping recharge rates using satellite data.
Result Visualization	Tools for generating maps, cross-sections, and time-series plots.	Visualizing contaminant plume spread over time.
Parameter Estimation	Built-in tools for calibration and sensitivity analysis (e.g., PEST module).	Optimizing hydraulic conductivity values.

APPLICATIONS OF PROCESSING MODFLOW

MODFLOW processing has gained extensive usage across several disciplines based on its user-friendly nature, flexibility, and compatibility with other tools. This section discusses its major applications using case studies and literature examples. Fig. 3 illustrate the application of Processing MODFLOW in various field of environmental management.

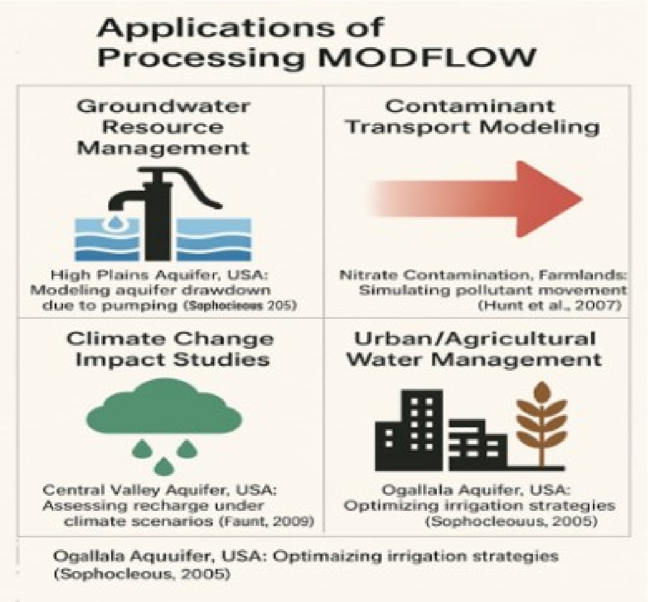

Figure 3: Applications of processing MODFLOW

Groundwater resource management

Groundwater management is one of the major uses of Processing MODFLOW. It allows for the simulation of aquifer response, evaluation of water availability, and formulation of sustainable management practices. For instance, within the High Plains Aquifer of the United States, Processing MODFLOW has been applied to model the effect of groundwater pumping on aquifer drawdown and to design for conservation (Ntona et al., 2022). In the same way, in India, it has been used to simulate groundwater recharge and optimize the rates of extraction in more than exploited aquifers (Kaur et al., 2023). MODFLOW's capacity to handle spatial data like rainfall and land use makes its processing very handy for regional-scale groundwater evaluation (Borzì, 2025). For example, in California, it has been utilized to simulate the impacts of managed aquifer recharge (MAR) on storage of groundwater in an attempt to alleviate the impacts of extreme droughts (Wendt et al., 2021). These are testimonies of how the tool has proven successful in addressing urgent water resource challenges as well as enabling decision-making (Berrezel et al., 2023).

Contaminant transport modelling

Running MODFLOW is extensively applied for contaminant transport simulation and groundwater contamination prediction in the movement of pollutants in groundwater systems. It facilitates users, upon coupling with transport models such as MT3DMS, to evaluate pollutant spreading and formulate remedial approaches (Wali et al., 2024). For instance, to simulate the movement of nitrates through the vadose zone and into groundwater in a study of nitrate contamination in farmlands, Processing MODFLOW was employed to detect sources of contamination and ensure proper prioritization of mitigation strategies (Qurban, 2024). Another significant use is in determining industrial contamination. In a chemical spill case study, Processing MODFLOW was employed to model the contaminant migration in an aquifer and test the efficiency of pump-and-treat remediation systems (Mondal et al., 2022). These illustrations point to the tool's capacity to solve sophisticated contaminant transport issues and assist with environmental protection measures.

Climate change impact studies

Climate change presents major threats to groundwater systems, such as changed recharge patterns, sea-level rise, and more frequent extreme weather events (Remini, 2020; Nakou et al., 2023). MODFLOW processing has played a key role in evaluating these impacts and designing adaptation measures. For example, in coastal aquifers, it has been applied to simulate saltwater intrusion under various climate scenarios to determine vulnerable zones and design mitigation strategies (Basack et al., 2022). Processing MODFLOW was employed in a Central Valley Aquifer study in California to analyze the impacts of diminished snowpack and rising temperature on groundwater recharge (Huang et al., 2024). The findings guided water management planning to sustainably utilize groundwater under projected future conditions. These uses show the tool's capability for incorporating climate information and projecting long-term effects of climate change on groundwater.

Urban and agricultural water management

MODFLOW processing is an essential function in agricultural and urban water management through minimizing the environmental impacts and maximizing water use. For urban settings, it has been utilized to simulate the influence of groundwater pumping on land subsidence and to construct sustainable water supply systems (Chen et al., 2023). For instance, in Mexico City, Processing MODFLOW was employed to model the effects of over-extraction of groundwater on subsidence rates and prompting measures to conserve water (Chepkemoi, 2024). In agriculture, Processing MODFLOW has been employed to maximize irrigation strategies and regulate groundwater resources in water-limited areas. In an analysis of the Ogallala Aquifer in the United States, it was employed to simulate the effects of irrigation on groundwater levels and to devise techniques of sustainable agriculture water use (Sophocleous, 2005). Both examples demonstrate the tool's potential to sustain integrated water resource management in urban and rural environments.

Other applications

MODFLOW processing has also been utilized in various niche areas, such as geothermal research, ecosystem management, and mining. It has been used in mining to simulate dewatering activities and determine the effects of groundwater pumping on adjacent aquifers (Mondal et al., 2022). For instance, in an Australian coal mining district, Processing MODFLOW was applied to model the impacts of dewatering on groundwater systems at the local level and to create mitigation strategies. In geothermal research, Processing MODFLOW has been employed to simulate heat transport within groundwater systems and to determine the feasibility of geothermal energy production. For example, in a model of an Icelandic geothermal reservoir, it was employed to mimic the flow of heated groundwater and to maximize well location for power production (Gómez-Díaz et al., 2022). In ecosystem management, Processing MODFLOW has been utilized to simulate the interactions of groundwater and surface water in wetland systems. For instance, when researching the Everglades of Florida, it was applied to model water management practice effects on wetland hydrology and provide input to assist with ecosystem restoration (Julian et al., 2024). This reveals the utility and capability of the tool in managing sophisticated hydrologic issues in multiple areas of practice. Table 2 highlights some important case studies with the key finding with respect to some specific areas.

Table 2: Case studies of Processing MODFLOW applications

Application Area	Study Location	Objective	Key Findings	Reference
Groundwater Resource Management	High Plains Aquifer, USA	Assess aquifer drawdown from pumping.	Identified sustainable extraction limits.	Sophocleous (2005)
Contaminant Transport Modeling	Farmlands (unspecified)	Simulate nitrate movement in groundwater.	Detected contamination sources effectively.	Hunt et al. (2007)
Climate Change Impact Studies	Central Valley Aquifer, USA	Evaluate recharge under climate scenarios.	Predicted reduced recharge with warming.	Faunt (2009)
Urban/Agricultural Water Management	Ogallala Aquifer, USA	Optimize irrigation strategies.	Improved water use efficiency.	Sophocleous (2005)
Ecosystem Management	Everglades, Florida, USA	Model groundwater-surface water interactions.	Supported wetland restoration strategies.	Harvey et al. (2000)

ADVANCEMENTS IN PROCESSING MODFLOW

MODFLOW processing has made tremendous improvement over the years, with greater capabilities and usability and efficiency in use. The section discusses the major improvements based on references and examples from literature.

Integration with GIS and remote sensing

One of the best developments in MODFLOW in Processing is its interconnection with Geographic Information Systems (GIS) and remote sensing methods. This ensures that users have the ability to include spatial data, including elevation, land use, and rain, into groundwater models directly in order to ensure greater accuracy and realism in their simulations (Bakker et al., 2016). For instance, GIS information can be utilized to delineate model boundaries, attribute hydraulic properties, and display results in a spatial framework (Banta and Paschke, 2011; Saidi et al., 2016; Adja et al., 2021). Remote sensing information, including satellite imagery and LiDAR, can also be incorporated into Processing MODFLOW to offer high-resolution inputs for model calibration and validation (Gangulyet et al., 2023). For example, in a study of groundwater recharge in semi-arid regions, remote sensing estimates of evapotranspiration were used, which were then incorporated into a Processing MODFLOW model to enhance recharge estimates (Babaeiet et al., 2022). Such innovations have rendered Processing MODFLOW a very useful tool for spatially explicit groundwater modeling.

Enhanced user interface and usability

MODFLOW processing has come a long way in enhancing its user interface (UI) and overall user-friendliness, rendering it more user-friendly to non-technical users. The creation of intuitive graphical user interfaces has streamlined activities like model setup, calibration of parameters, and visualization of results (Banta and Paschke, 2011). For instance, users are now able to define model layers, assign boundary conditions, and execute simulations via drag-and-drop tools and interactive menus (Konikow et al., 2006). The addition of wizards and tutorials has also reduced the learning curve, allowing students and professionals in the early stages of their careers to utilize Processing MODFLOW efficiently (Dongre, 2022). All these advances have democratized access to groundwater modeling so that many more users can tap into the capabilities of MODFLOW without needing highly technical skills (Waliet et al., 2024).

Advances in computational efficiency

Improvements in computing efficiency have made it possible for Processing MODFLOW to process larger and more complicated data sets, minimizing processing time and enhancing model performance (Zeydalinejad, 2022). For instance, use of parallel processing methods makes it possible to perform simulation on multi-core processors, greatly accelerating computation time (Bakker et al., 2016). It is especially useful when working with large-scale regional models or models of high spatial and temporal resolution (Deep et al., 2024). Moreover, Processing MODFLOW also accommodates cloud computing, so users can simulate on remote computers and view outcomes from anywhere (Doherty, 2015). With these developments, it is possible to solve more sophisticated hydrologic issues, e.g., simulate the effects of climate change on groundwater systems or model contaminant transport in heterogeneous aquifers (Hughes et al, 2022).

New features and modules

Running MODFLOW has added several new features and modules to improve its performance and meet the needs of developing groundwater modeling. For instance, the integration with MT3DMS for solute transport modeling enables users to model contaminant movement in groundwater systems. In the same way, inclusion of SEAWAT allows variable-density flow to be simulated, which is required for simulating saltwater intrusion in coastal aquifers (Langevin et al., 2024). Newer updates have also brought parameter estimation and uncertainty analysis tools, allowing users to better calibrate models and determine the trustworthiness of their results (Doherty, 2015). For example, the PEST (Parameter ESTimation) module has been added to Processing MODFLOW, making it possible for users to automate model parameter calibration and optimization. These additions have widened the range of Processing MODFLOW, making it a more powerful and flexible tool for groundwater modeling.

Interoperability with other software

Processing MODFLOW has enhanced its compatibility with other hydrological and environmental modeling packages to allow the user to link groundwater models to surface water models (Mehta and Yadav, 2024), climate models (Nassa et al., 2021; Pang and Tan, 2023; Mah et al., 2024), and ecosystem models (Bakker et al., 2016). For instance, compatibility with MODFLOW-NWT enables users to model surface water-groundwater interaction more precisely, which is paramount for water resources management in river basins (Ntona et al., 2022). MODFLOW processing also includes support for data exchange with common GIS packages, including ArcGIS and QGIS, which allows the user to export and import spatial data without any issues (Parket et al., 2023). It also has support for programming languages like Python, which enables expert users to automate workflow and extend its functionality (Bakker et al., 2016). These interoperability capabilities have positioned Processing MODFLOW as the key element in integrated water resource management systems. The advancements in Processing MODFLOW with passage of time are depicted in Table 3.

Table 3: Advancements in Processing MODFLOW

Advancement	Description	Impact	Reference
GIS Integration	Seamless use of spatial data from GIS and remote sensing.	Enhanced model accuracy and spatial analysis.	Bakker et al. (2016)
Enhanced User Interface	Improved GUI with wizards and interactive tools.	Reduced learning curve for new users.	Banta and Paschke (2011)
Computational Efficiency	Parallel processing and cloud computing support.	Faster simulations for large-scale models.	Langevin et al. (2024)
New Modules (MT3DMS)	Integration with MT3DMS for contaminant transport.	Expanded capability for pollution studies.	Zheng and Wang (1999)
SEAWAT Integration	Support for variable-density flow modelling.	Improved coastal aquifer simulations.	Langevin et al. (2024)
Parameter Estimation (PEST)	Automated calibration and optimization tools.	Increased model reliability and precision.	Doherty (2015)

LIMITATIONS OF PROCESSING MODFLOW

Although Processing MODFLOW is a highly capable and common groundwater modeling tool, it does have its own limitations. In this section, the major issues and limitations in using it are presented with the help of literature references and examples.

Technical limitations

Processing MODFLOW is hampered by various technical constraints that limit its performance to simulate complicated geological structures and some hydrological processes. MODFLOW's finite-difference model, for instance, can find it difficult to precisely model very heterogeneous aquifers and complicated geological features like fractures and faults. The limitations can contribute to oversimplification of the representation of subsurface systems, decreasing the accuracy of model predictions (Latrach, et al., 2024). Further, Processing MODFLOW has limited abilities in the simulation of some hydrological processes like unsaturated flow and heat transport, which can only be dealt with using special modules or stand-alone tools (Hughes et al, 2022). For example, although MODFLOW can simulate saturated groundwater flow, it depends on other packages like UZF1 for processes involving the unsaturated zone, which might not necessarily offer the detail needed. These technological limitations may restrict the applicability of the tool in some situations, especially where systems are highly dynamic or complex.

Data requirements and availability

The validity of Processing MODFLOW simulations relies significantly on the quality and availability of input data, including hydraulic conductivity, recharge rates, and boundary conditions (Ntona et al., 2022). In most instances, the acquisition of good-quality data may be difficult, especially in data-poor areas or for large-scale models (Sophocleous, 2005). For instance, in groundwater recharge modeling in arid areas, the unavailability of good rainfall and evapotranspiration data resulted in large uncertainties in model predictions (Banta and Paschke, 2011). Additionally, Processing MODFLOW demands high-resolution spatial and temporal data for model calibration and validation, which is time-consuming and costly to obtain (Doherty, 2015). Poor or faulty data can create poorly calibrated models, making them less reliable and useful for decision-making purposes (Bontempi, 2024). Such data requirements demonstrate the need for investment in monitoring and data collection programs to ensure effective groundwater modeling.

User expertise and learning curve

Although having a friendly interface, Processing MODFLOW also demands a degree of technical proficiency in order to use it effectively, especially when working with complex models or sophisticated applications (Banta et al., 2011). First-time users might have a high learning curve because they would have to comprehend the fundamental concepts of groundwater modeling as well as the software's particular functionalities (Ortega, 2023).

For instance, the installation of a regional-scale model with several layers and boundary conditions may be difficult for new users, resulting in errors or second-best results (Mondalet et al., 2022). To solve this problem, training classes and instructions have been created to assist users in acquiring skills and confidence for working with Processing MODFLOW (Doherty, 2015). Yet, the necessity for continuous training and assistance continues to be a hindrance to most organizations, especially in developing nations or under-resourced environments (Sophocleous, 2005).

Computational constraints

MODFLOW processing can encounter computational limitations when working with large-scale or very detailed models, especially with regards to processing capacity and memory demand. For instance, modeling watersheds and groundwater flow in a regional aquifer at high spatial and temporal resolution may need a lot of computational power, which may not be accessible to everyone (Winston, 2009; Kherde et al., 2024). These limitations may preclude the execution of multiple scenarios or sensitivity analyses, diminishing model prediction robustness (Bontempi, 2024). Advances in recent years in parallel computing and cloud computing have partially mitigated some of these issues, allowing increased speed and efficiency of simulations (Bakker et al., 2016). Yet, such solutions might not be available to everyone, especially those with small budgets or infrastructures (Doherty, 2015).

Comparison with other groundwater modelling tools

MODFLOW processing is usually likened to other groundwater modeling software, including FEFLOW, GMS (Groundwater Modeling System), and OpenGeoSys, each with its own advantages and limitations (Mondal et al., 2022). For instance, FEFLOW is renowned for its capacity to simulate complex geological structures and variable-density flow, thus being a favourite for coastal aquifer research. Nevertheless, FEFLOW's proprietary status and increased cost are a hindrance to some users (Bakker et al., 2016). GMS, however, provides a complete set of tools for modelling groundwater with support for MODFLOW, MT3DMS, and other common models. Its simplicity and high-quality visualization make it a very formidable competitor to Processing MODFLOW, especially for surface water-groundwater integrated modeling (Mondal et al., 2022). Yet, GMS can also be resource-hungry and may need extensive training to utilize effectively (Bontempi, 2024). OpenGeoSys is an open-source option that provides flexibility and customization for experienced users, especially in simulating coupled processes like heat transport and reactive transport. Nevertheless, its high learning curve and absence of a friendly interface may render it less user-friendly for non-specialist users (Bakker et al., 2016). In contrast, Processing MODFLOW is balanced between functionality and accessibility, and thus it is widely used for a broad variety of applications (Banta et al., 2011). Yet, its deficiencies in dealing with intricate processes and geological formations have the potential for it not always being the go-to tool in every situation (Mondal et al., 2022). Comparison of Processing MODFLOW with the other groundwater modelling tools is illustrated in Fig. 4 whereas the limitation and proposed solution for the software is listed in Table 4.

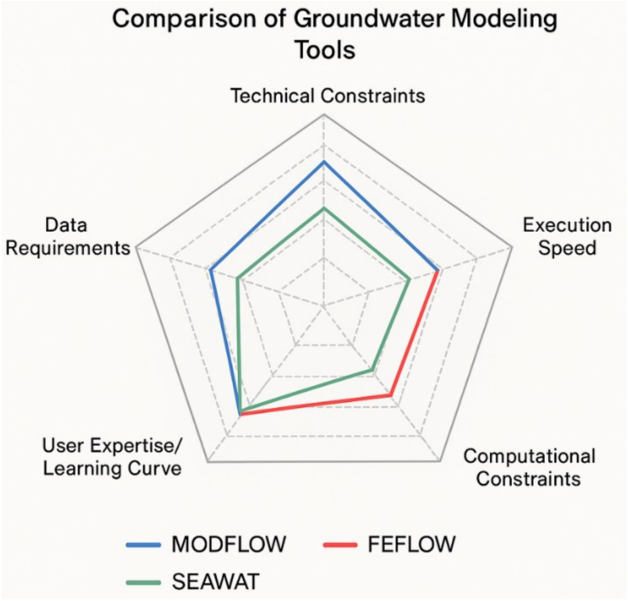

Figure 4: Comparison of processing MODFLOW with other Tools

Table 4: Limitations and proposed solutions

Limitation	Description	Impact	Proposed Solution
Technical Constraints	Limited ability to model complex geological structures.	Reduced accuracy in heterogeneous aquifers.	Integrate finite-element methods.
Data Requirements	High dependency on quality spatial and temporal data.	Uncertainty in data-scarce regions.	Leverage remote sensing and big data.
User Expertise/Learning Curve	Requires technical knowledge despite GUI improvements.	Barrier for novice users.	Expand tutorials and training programs.
Computational Constraints	Resource-intensive for large, high-resolution models.	Limits scenario analysis.	Enhance cloud and parallel computing.
Limited Coupled Process Modeling	Weak support for unsaturated flow and heat transport.	Restricted interdisciplinary use.	Add modules for coupled processes.

FUTURE DIRECTIONS AND OPPORTUNITIES

Processing MODFLOW has become an industry standard and top-of-line groundwater modeling tool, but plenty of opportunities wait in terms of innovation and improvement. This part examines potential changes, new emerging technologies, enlarging applications, and the possible future direction the development of Processing MODFLOW is heading through the contribution of a community-driven perspective. The possible future directions for Processing MODFLOW is shown in the Fig. 5.

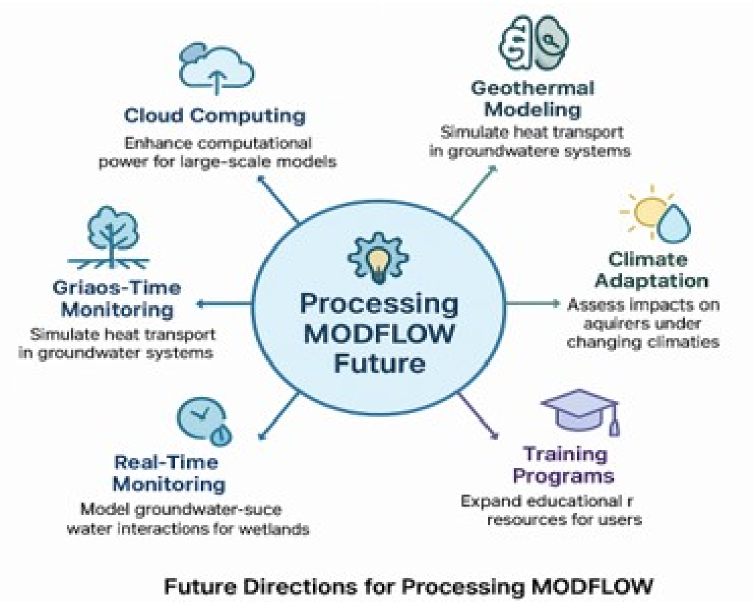

Figure 5: Future directions for processing MODFLOW

Potential improvements

Subsequent versions of Processing MODFLOW may include higher-order numerical solutions, for example, finite-element or finite-volume formulations, to more accurately capture detailed geological structures such as faults, fractures, and heterogeneous aquifers (Mondal et al., 2022). This would enhance the accuracy of simulations in problematic hydrogeological environments. Extending Processing MODFLOW's capabilities to simulate coupled processes, for instance, unsaturated flow, heat transport, and reactive transport, would render it more interdisciplinary for studies. For instance, incorporating modules to simulate geothermal systems or contaminant biodegradation would allow new applications in environmental engineering and energy resource management (Langevin et al., 2024). Additional refinements to the user interface, including drag-and-drop capability, real-time visualization, and interactive tutorials, might further make Processing MODFLOW accessible to inexperienced users (Banta and Paschke, 2011). This would serve to close the gap between sophisticated researchers and practitioners who have little experience with modeling. Utilizing cloud-based systems and high-performance computing (HPC) might allow users to more efficiently execute large-scale, high-resolution models (Bakker et al., 2016). It would be very useful for regional-scale simulations or situations involving large parameter sensitivity studies.

Integration with emerging technologies

Bringing in new technologies like artificial intelligence (AI), machine learning (ML), and big data can really change the future of Processing MODFLOW. We can use AI and ML to set up the models quickly by tuning the settings (Doherty, 2015). For example, neural networks and genetic setups can be used with Processing MODFLOW to make guessing parameters more accurate and faster (Makhlouf et al., 2024). More data from satellite, IoT sensors, and climate models can improve how we input and check data (Borzì, 2025). Like, satellite data on rain and water loss can help guess water refill better in places where data is low (Ntona et al., 2022). If Processing MODFLOW is linked with real-time checks, it would help in guessing and managing water under the ground better (Bakker et al., 2016). Real-time data from water sensors can help update models and predict what will happen next for better decision making.

Expanding applications

Processing MODFLOW is considered as a tool that has the potential to solve different complex problems. Processing MODFLOW could be benefited to forecast the effect of climate change upon the groundwater. By utilizing this software, it would be much easier to analyze the potential impacts of sea level rise on coastal aquifers or to appraise the feasibility of using ground water for food production. Expanding Processing MODFLOW's capabilities for simulating irrigation practices and crop-water interactions could support sustainable agricultural water management. This resource is very critical in water scarce regions which have groundwater as a base for food production. Processing MODFLOW has also been important to model the interactions between groundwater and surface water in wetland ecosystems. Processing MODFLOW could provide insight into how groundwater will interact with surface waters, which is key for restoration of wetland habitat and biodiversity conservation. It could be employed to formulate water management scenarios and strategies to maintain the existence of key habitats in a changing hydrological regime. Increasing urbanization results in barge navigable waterways all over the world similar to Tonle Sap in Cambodia where tree-choking waters cover small creeks and massive rivers which facilitates the export facilities. Urban water management plans to deal with stored runoff (Faye, 2016; Long et al., 2023). Urban land with the infiltration capacity to utilize it, either shallow, flooded groundwater are some stations.

Community and open-source contributions

The future of Processing MODFLOW will involve contributions of the international community of Groundwater Modeling - expanding Open Source as well maybe an additional sentence about why open source is important, encouraging community-driven development which will be more beneficial in terms of implementing the code as new use-cases and best practices/ways of pursuing goals are implemented concurrently rather than having to constantly catch up to each other; for example, user forums, workshops, and collaborative projects are all ways to help identify new features that need development and better ways for our team members to satisfy user needs utilizing Modern Data flow Processing (Bakker et al., 2016). Transparent discussions and collaboration provide important measures on the development of Processing MODFLOW to provide forecasts and training to users and developers. By having a global community of the best research, development and service users in accessible communication, open-source means that we'll always be able to learn - and improve. Open-Source model encourages iterative cooperative learning and contribution, and reduces redundancy in development efforts (Langevin et al., 2024). Facilitative of global research and action, open-source data and programs are frequently updated, self-correcting resources that can enrich the work of everyone involved. Online courses, tutorials, and open-access publications can make the software more accessible to the global population, leading to a more widespread ability to interpret our natural environment (Ntona et al., 2022). Collaboration with experts from areas other than groundwater modelling, such as climate science, ecology, and data science, could result in innovative applications and solutions (Mondal et al., 2022). For instance, working with AI scientists could result in advanced machine learning tools for groundwater models that go even further (theoretical capabilities already/i.e. what they can already do) beyond or like what users want them to expanding training programs and educational resources can help build the capacity of users, particularly in developing countries. By providing a global audience with online courses, tutorials, and publishable publications which use free software Processing MODFLOW more common and widely circulated. Collaboration with experts from other fields such as climate science, ecology, and data science can help to solve many innovative problems leading to the development of advanced machine learning tools for groundwater modeling in some cases.

CONCLUSION

Over the past decades, MODFLOW has become a fundamental piece of modern hydrogeology and its potential to automate workflows, integrate multiple geologic data source and generate reliable simulations make highly effective. MODFLOW has been critical to the advancement of our knowledge on groundwater systems and offers the support for sustainable water resource management because it has enabled users to deal with sophisticated hydrological issues more effectively and confidently. Such technologies as AI and big data can reengineer the groundwater modeling in the form of real time monitoring, predictive analytics, and adaptive management. The use of

MODFLOW flow analysis in addressing interdisciplinary challenges (climate change adaptation and ecosystem restoration) will further strengthen its relevance and impact.

Nevertheless, this potential will have to be realized in the face of some challenges. To enhance the accuracy and versatility of Processing MODFLOW, technical limitations must be overcome, for example, in handling complex geological structures and coupled processes. In addition, continuing adoption and success of the tool will rely on its availability of high-quality data, and training and support for users. In context to this, open-source initiatives will play a pivotal role in the role of the global groundwater modeling community in shaping the future of Processing MODFLOW. The community can help to ensure that Processing MODFLOW continues to be at the frontiers of groundwater modeling for years to come by fostering collaboration, sharing knowledge and promoting innovation. However, processing MODFLOW has made the modeling of groundwater more accessible, efficient, and impactful and even more so important, easy to interpret. Processing MODFLOW thus strives to serve to help us answer these growing challenges regarding water resources and environmental sustainability.

Declaration of competing interest

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

REFERENCES

ADJA M.G., ASSANDE A.A., DJEMIN E.J., SORO S.I., JOURDA J.P. (2021). Contribution of a GIS to mapping and spatial-temporal characterization of rainfall variability: case of the northern part of Ivory Coast, Larhyss Journal, No 47, pp. 119-132.

AROUA N. (2018). Water resources in SNAT 2030. between economic needs and ecological requirements, Larhyss Journal, No 35, pp. 153-168. (In French)

AROUA N. (2022). Long term city development versus water strategy in Al-Maghreb, Larhyss Journal, No 50, pp. 173-197.

AROUA N. (2023). Setting out urban water issues examples from Algeria and worldwide, Larhyss Journal, No 56, pp. 309-327.

ASSEMIAN A.E., DJE BI DOUTIN S., SAMAKÉ Y., (2021). Consequences of the effects of climate change on water resources in a humic tropical zone of central eastern Côte d’Ivoire, Larhyss Journal, No 45, pp. 95-105.

BABAEI M., KETABCHI H. (2022). Determining groundwater recharge rate with a distributed model and remote sensing techniques, Water Resources Management, Vol. 36, Issue 14, pp. 5401-5423.

BAHIR M., EL MOUKHAYAR R., CARREIRA P. SOUHEL A. (2015). Isotopic tools for groundwater management in semi-arid area: case of the wadi Ouazzi basin (Morocco), Larhyss Journal, No 23, pp. 23-39.

BAKKER M., POST V., LANGEVIN C.D. (2016). The Python interface for MODFLOW, Groundwater, Vol. 54, Issue 5, pp. 728-733.

BANTA E.R., PASCHKE S.S. (2011). MODFLOW-2005, the U.S. Geological Survey modular groundwater model - Documentation of the Model Muse graphical user interface for MODFLOW, U.S. Geological Survey Techniques and Methods, Vol. 6, Issue A38.

BASACK S., LOGANATHAN M.K., GOSWAMI G., KHABBAZ H. (2022). Saltwater intrusion into coastal aquifers and associated risk management: Critical review and research directives, Journal of Coastal Research, Vol. 38, Issue 3, pp. 654-672.

BELHADJ M.Z., BOUDOUKHA A., AMROUNE A., GAAGAI A., ZIANI D. (2017). *Statistical characterization of groundwater quality of the northern area of the basin of Hodna, M'Sila, Southeastern Algeria,* **Larhyss Journal**, No 31, pp. 177-194. (In French)

BEMMOUSSAT A., ADJIM M., BENSAOULA F (2017). Use of the ZYGOS model for the estimation of groundwater recharge in Sikkak watershed (Northen west of Algeria), Larhyss Journal, No 30, pp. 105-119. (In French)

BERREZEL Y.A. ABDELBAKI C., ROUISSAT B., BOUMAAZA T., KHALDOON A.M. (2023). Decision support system for the management of water distribution networks a case study of Tourville, Algeria, Larhyss Journal, No 54, pp. 7-24.

BONTEMPI G., 2024, Between accurate prediction and poor decision making: the AI/ML gap, Proceedings of the International Conference on Machine Learning, Optimization, and Data Science, January 15–18, Siena, Italy, pp. 333–343.

BORZÌ I., 2025, Modeling groundwater resources in data-scarce regions for sustainable management: Methodologies and limits, Hydrology, Vol. 12, Issue 1.

BOUTEBBA K., BOUZIANE M.T., BOUAMRANE A. (2014). Decision-making aid for optimizing the management of drinking water supply networks, Larhyss Journal, No 20, pp. 279-296. (In French)

CHEN H., XUE Y., QIU D., 2023, Numerical simulation of the land subsidence induced by groundwater mining, Cluster Computing, Vol. 26, Issue 6, pp. 3647–3656.

CHEPKEMOI A., 2024, Evaluation of the potential of Kericho Aquifer as a source of groundwater, Doctoral dissertation, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya, 256p.

CHIBANE B., ALI-RAHMANI S.E. (2015). Hydrological based model to estimate groundwater recharge, real- evapotranspiration and runoff in semi-arid area, Larhyss Journal, No 23, pp. 231-242.

COX M.E., JAMES A., HAWKE A., RAIBER M., 2013, Groundwater Visualisation System (GVS): A software framework for integrated display and interrogation of conceptual hydrogeological models, data and time-series animation, Journal of Hydrology, Vol. 491, pp. 56–72.

DEEP G., VERMA J., 2024, Deep learning models for fine-scale climate change prediction: Enhancing spatial and temporal resolution using AI, In: Big Data, Artificial Intelligence, and Data Analytics in Climate Change Research, Springer, pp. 81–100.

DEY S., DHAR A., 2023, A reduced-order framework for three-dimensional-equivalent confined groundwater modeling with emphasis on well-boundary implementation, Hydrogeology Journal, Vol. 31, Issue 7, pp. 1883–1902.

DOHERTY J., 2015, Calibration and uncertainty analysis for complex environmental models, Watermark Numerical Computing, Brisbane, Australia, 246p.

DONGRE A. (2022), Groundwater flow modeling of Maleni watershed using Visual MODFLOW, Doctoral dissertation, Banaras Hindu University, Varanasi, India, 172p.

DUBE T., SEATON D., SHOKO C., MBOW C. (2023), Advancements in earth observation for water resources monitoring and management in Africa: a comprehensive review, Journal of Hydrology, Vol. 623, Paper ID 129738.

FADLALLAH J.J. (2020), Modeling of groundwater flow and contaminant transport in a karstic formation using finite difference approach, Doctoral dissertation, Notre Dame University-Louaize, Zouk Mosbeh, Lebanon, 210p.

FAYE C. (2016). Management of water resources in the local of Ndondol: study of community management of water resources and water use conflicts in Mbomboye villages (Senegal), Larhyss Journal, No 25, pp. 219-240. (In French)

FEDRA K., DIERSCH H.J., HÄRIG F. (2020), Interactive modeling of groundwater contamination: Visualization and intelligent user interfaces, In: Grathwohl P., Pankow J.F. Editions, Contamination of Groundwaters, Springer, Berlin, Germany, pp. 189-220.

GANGULY S., BHAN U. (2023), Remote sensing and GIS based monitoring and management of coastal aquifers and ecosystem, In: Shukla S.K. (Ed.), Emerging Technologies for Water Supply, Conservation and Management, Springer, Singapore, pp. 171-193.

GLASS J., JUNGHANNS R., SCHLICK R., STEFAN C. (2022), The INOWAS platform: A web-based numerical groundwater modelling approach for groundwater management applications, Environmental Modelling & Software, Vol. 155, Paper ID 105452.

GÓMEZ-DÍAZ E, SCOTT S, RATOUIS T, NEWSON J (2022), Numerical modeling of reinjection and tracer transport in a shallow aquifer, Nesjavellir Geothermal System, Iceland, Geothermal Energy, Vol. 10, Issue 1, pp. 7.

GRIGG N S (2023), Water Resources Management: Principles, Methods, and Tools, 4th edition, John Wiley & Sons, Hoboken, New Jersey, USA, 648p.

HUGHES J.D., RUSSCHER M.J., LANGEVIN C.D., MORWAY E.D., MCDONALD R.R. (2022), The MODFLOW Application Programming Interface for simulation control and software interoperability, Environmental Modelling & Software, Vol. 148, Paper ID 105257.

JAISWAL T., JHARIYA D., SINGH S. (2023). Identification and mapping of groundwater potential zone using analytical hierarchy process and GIS in lower Kharun basin, Chhattisgarh, India, Larhyss Journal, No 53, pp. 117-143.

JAYASENA H.A.H., RATHNAYAKE R.D.D.P., CHANDRASENA M.G.P.N., RANATHUNGA B.P.D.W. (2021). A classic example of urban-rural linkages through ancient Voda Ela in Sri Lanka - symbiosis of total environment on efficient water management, Larhyss Journal, No 47, pp. 59-82.

JULIAN P, DAVIS S.E (2024), Evaluating water quality change with hydrologic restoration in the Western Everglades (Florida, USA), an application of WAM, Watershed Ecology and the Environment, Vol. 6, pp. 70-83.

KAUR N, KAUR S, TSOLAKIS N, MISHRA N, SRAI J.S (2023), Managing groundwater demand through surface water and reuse strategies in an overexploited aquifer of Indian Punjab, Modeling Earth Systems and Environment, Vol. 9, Issue 2, pp. 2009-2026.

KEZZAR M., SOUAR A. (2024). The water management system in the village of Menades in Algeria between past and present, Larhyss Journal, No 57, pp. 55-79.

KHELIEL O., OUAKOUAK A.E.K., YOUCEF L., ACHOUR S. (2015). Groundwater denitrification by adsorption on activated carbon and by coagulation-flocculation with aluminum sulfate, Larhyss Journal, No 21, pp. 191-200. (In French)

KHERDE R.V., MEHTA D.J., MORE K.C., SAWANT P.H. (2024). Dynamic watershed modelling: HEC-HMS analysis of a tropical watershed, Larhyss Journal, No 60, pp. 87-111.

KONIKOW L.F., REILLY T.E., BARLOW P.M., VOSS C.I. (2006), Groundwater modeling, In: Delleur J.W. (Ed.), The Handbook of Groundwater Engineering, CRC Press, Boca Raton, USA, Chapter 25, pp. 815-866.

KOUASSI A.M., KOUAME K.F., SALEY M.B., BIEMI J. (2013). Impacts of climate change on groundwater of crystalline and Crystalophyllian basement aquifers in west Africa: case of the N'zi-Bandama watershed (Ivory Coast), Larhyss Journal, No 16, pp. 121-138. (In French)

KOULOUGHLI C.E., TELLI A. (2023). Modern water supply management techniques and methods: a review, Larhyss Journal, No 55, pp. 7-23.

KOUSSA M., BERHAIL S. (2021). Evaluation of spatial interpolation techniques for mapping groundwater nitrates concentrations - case study of Ain Elbel-sidi Makhlouf syncline in the Djelfa region (Algeria), Larhyss Journal, No 45, pp. 119-140.

LACHACHE S., DERDOUR A., MAAZOUZI I., AMROUNE A., GUASTALDI E. (2023). Statistical approach of groundwater quality assessment at Naama region, South-West Algeria, Larhyss Journal, No 55, pp. 125-144.

LAGHZAL A., SALMOUN F., BOUDINAR B., ARGAZ A. (2019). Potential impact of anthropogenic activities on groundwater in the Tangier-Tetouan-Alhoceima region (Morocco), Larhyss Journal, No 34, pp. 39-50.

LANGEVIN C.D., HUGHES J.D., PROVOST A.M., RUSSCHER M.J., PANDAY S. (2024). MODFLOW as a configurable multi-model hydrologic simulator. Groundwater, Vol. 62, Issue 1, pp. 111-123.

LATER F., LABADI A.S. (2024). Origin of the alluvial aquifer's groundwater in wadi Biskra (Algeria), Larhyss Journal, No 57, pp. 145-158.

LATRACH A., MALKI M.L., MORALES M., MEHANA M., RABIEI M. (2024), A critical review of physics-informed machine learning applications in subsurface energy systems, Geoenergy Science and Engineering, Paper ID 212938.

LIU H. (2021), Assessment of the usability of OpenGeoSys tools for Aquifer Thermal Energy Storage (ATES) simulations, Doctoral dissertation, TU Delft, 195p.

LONG A., MOKHTAR M., HALIM S., AHMED F. (2023). Fostering inclusive watershed management through Multihelix engagement model on micro hydropower electrification in Sabah, Malaysia, Larhyss Journal, No 56, pp. 7-24.

MAH D.Y.S., ALHADI H.F., BATENI N., TEO F.Y. (2024). Model simulation of dry stormwater detention pond with IPCC AR6 projected climate change scenarios, Larhyss Journal, No 60, pp. 151-169.

MAKHLOUF A., EL-RAWY M., KANAE S., IBRAHIM M.G., SHARAAN M. (2024), Integrating MODFLOW and machine learning for detecting optimum groundwater abstraction considering sustainable drawdown and climate changes, Journal of Hydrology, Vol. 637, Paper ID 131428.

MEHTA D., YADAV S. (2024). Rainfall runoff modelling using HEC-HMS model: case study of Purna river basin, Larhyss Journal, No 59, pp. 101-118.

MONDAL S., PALIT D. (2022), Challenges in natural resource management for ecological sustainability, In the Book titled Natural Resources Conservation and Advances for Sustainability, pp. 29-59.

MORALES ORTEGA L.R. (2023), A Digital Twin for Ground Water Table Monitoring, Master's Thesis, University of Twente, Netherlands.

NAKOU T.R., SENOU L., ELEGBEDE B., CODO F.P. (2023). Climate variability and its impact on water resources in the lower mono river valley in Benin from 1960 to 2018, Larhyss Journal, No 56, pp. 215-234.

NASSA R.A.K., KOUASSI A.M., BOSSA S.J. (2021). Analysis of climate change impact on the statistical adjustment models of extreme rainfall case of Ivory Coast, Larhyss Journal, No 46, pp. 21-48.

NTONA M.M., BUSICO G., MASTROCICCO M., KAZAKIS N. (2022), Modeling groundwater and surface water interaction: An overview of current status and future challenges, Science of the Total Environment, Vol. 846, Paper ID 157355.

OUIS S. (2012). Impact of climatic fluctuations on the quantity and quality of groundwater in a semi-arid region: case of the Ghriss plain (northwest Algeria), Larhyss Journal, No 11, pp. 119-131. (In French)

PANDEY P., MISHRA R., CHAUHAN R.K. (2022). Future prospects in the implementation of a real-time smart water supply management and water quality monitoring system, Larhyss Journal, No 51, pp. 237-252.

PANG J.M., TAN K.W. (2023). Development of regional climate model (RCM) for Cameron highlands based on representative concentration pathways (RCP) 4.5 and 8.5, Larhyss Journal, No 54, pp. 55-70.

PARK S., JEONG J., MOTTER E., BAILEY R.T., GREEN C.H. (2023), Introducing APEXMOD-A QGIS plugin for developing coupled surface-subsurface hydrologic modeling framework of APEX, MODFLOW, and RT3D-Salt, Environmental Modelling & Software, Vol. 165, Paper ID 105723.

PAULO MONTEIRO J., COSTA MANUEL S. (2004). Dams' groundwater modelling and water management at the regional scale in a coastal mediterranean area (the southern Portugal region – Algarve), Larhyss Journal, No 3, pp. 157-169.

PRABHAKAR M. (2023). SWAT-MODFLOW integrated modelling approach for surface water-groundwater interaction-a case study, Doctoral Thesis, Department of Irrigation and Drainage Engineering, 250p.

PULLA S. (2024), Open-Source Frameworks for Groundwater Analytics: Advancing Machine Learning Workflow Development and Deployment, Technical Report, Department of Civil and Environmental Engineering, Indian Institute of Technology, Hyderabad, India, 68p.

QURBAN I.A. (2024), Modeling Nonpoint-Source Uranium Pollution in an Irrigated Stream-Aquifer System: Calibration and Simulation, Doctoral dissertation, Colorado State University, 276p.

QURESHI H.U., ABBAS I., SHAH S.M.H., TEO F.Y. (2024). Hydrologic evaluation of monthly and annual groundwater recharge dynamics for a sustainable groundwater resources management in Quetta city, Pakistan, Larhyss Journal, No 60, pp. 27-53.

RAJPUT D.C., MISTRY K.P., BHORANIYA J.K., UMRIGAR J.N., WAIKHOM S.I. (2023). Assessing the decadal groundwater level fluctuation-a case study of Gujarat, India, Larhyss Journal, No 54, pp. 175-191.

REMINI B. (2020). Algeria: the climate is changing, the water is becoming scarce, what to do? Larhyss Journal, No 41, pp. 181-221. (In French)

REMINI B. (2025). Algeria's groundwater - an untapped strategic resource for water security, Larhyss Journal, No 61, pp. 401-431.

SAADI S., KHATTACH D., EL KHARMOUZ M. (2014). Geophysics and physico-chemical coupled approach of the groundwater contamination. application in a pollution by the landfill leachate of Oujda city (Eastern Morocco), Larhyss Journal, No 19, pp. 7-17.

SAIDI S., AMMAR S., JLASSI F., BOURI S. (2016). Urban expansion and its impact on water resources using remote sensing and GIS: Case of great Tunis, Larhyss Journal, No 28, pp. 87-101. (In French)

SHARMA R., KUMAR R., AGRAWAL P.R., GUPTA G. (2021), Groundwater extractions and climate change, In the Book titled Water Conservation in the Era of Global Climate Change, pp. 23-45.

SOPHOCLEOUS M. (2005), Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA, Hydrogeology Journal, Vol. 13, Issue 2, pp. 351–365.

TILAHUN T. (2024), Groundwater Modeling of the Ogallala Aquifer: Use of Machine Learning for Model Parameterization and Sustainability Assessment, Doctoral dissertation, The University of Nebraska-Lincoln, pp. 258.

VELLANDO P., JUNCOSA R., PADILLA F., GARCÍA-RÁBADE H. (2020), Numerical evaluation of groundwater flows: MODFLOW vs. FE models, Journal of Porous Media, Vol. 23, Issue 6, pp. 579–595.

WALI S.U., USMAN A.A., USMAN A.B. (2024), Resolving challenges of groundwater flow modelling for improved water resources management: a narrative review, International Journal of Hydrology, Vol. 8, Issue 5, pp. 175–193.

WENDT D.E., VAN LOON A.F., SCANLON B.R., HANNAH D.M. (2021), Managed aquifer recharge as a drought mitigation strategy in heavily-stressed aquifers, Environmental Research Letters, Vol. 16, Paper ID 014046.

ZEGAIT R., REMINI B., BENSAHA H. (2021). *Groundwater vulnerability assessment in the M'Zab valley – Southern Algeria,* **Larhyss Journal**, No 48, pp. 211-234.

ZEYDALINEJAD N. (2022). Artificial neural networks vis-à-vis MODFLOW in the simulation of groundwater: A review. Modeling Earth Systems and Environment, Vol. 8, Issue 3, pp. 2911-2932.