SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I5P122

Volume 12 Issue 5, 275-283, May 2025

Review Article

Integrating Groundwater Modelling System Software and QGIS for Spring Water Delineation and Management: Comprehensive Review

Mudang Tamer[1], R K Prasad[2], Yamem Tamut[3]

[1,2,3]*Department of Civil Engineering, North Eastern Regional Institute of Science and Technology, Arunachal Pradesh, India.*

[1]*Corresponding Author : mudangtamer@gmail.com*

Received: 17 March 2025 Revised: 19 April 2025 Accepted: 18 May 2025 Published: 31 May 2025

Abstract *- In order to protect the ecosystem and ensure that there is always access to the required amount of fresh water, it is crucial to arrange the management of spring water in a proper manner. Regarding the characteristics of the spring water sources, it must be emphasized that specialized equipment and techniques must be applied. The next document describes the specifics of the software GMS's integration with QGIS to enhance spring water management and division. The groundwater modelling capabilities of GMS and the spatial analysis and spring water resource display capabilities of QGIS would be complementary in the suggested framework. The paper illustrates the methodology, the positive aspects, and the drawbacks of the integration process and provides examples of its use in work.*

Keywords *- Groundwater Modelling System (GMS), QGIS, Spring, Water resource, Integration.*

1. Introduction

Springs are integral components of the hydrological cycle and serve as vital freshwater sources for ecosystems and human populations. As natural outlets of groundwater, they play a central role in sustaining water supplies. Nevertheless, springs are captivating to buffs and are sensitive to environmental changes or human activities like urbanization because they contribute to pollution and alter groundwater recharge patterns. Springs are very under-studied and poorly managed; hence, there is a huge research gap in understanding their dynamic and vulnerability conditions. This has created a big data and analysis deficit in managing springs effectively or conserving them amid increasing water and environmental degradation demands. Dealing with such issues will require advanced modeling tools and spatial analysis methods. Among the best tools are MODFLOW, used for groundwater flow modeling; MT3DMS, which evaluates contaminant transport; and MODPATH, which is designed for particle tracking. Most of these modeling tools are combined with the Groundwater Modeling System (GMS), a platform for the building, analysis, and visualization of groundwater systems. This allows research and water resources managers to get deeper insights into how groundwater behaves, thus making better-informed decisions.

Apart from GMS, Quantum GIS, apart from Geo-mapping, comprises critical components for space data analysis and visualization required in water resource management. QGIS is an open-source GIS tool for managing, analysing, and visualising geospatial data. Besides, integrating data from GMS and QGIS would allow researchers to create comprehensive maps of aquifer systems, migration directions of groundwater, spring locations, and potential pollutant sources. Such balanced action between advanced modeling and geographic information systems would greatly enable springs to be effectively evaluated and managed.

The coupling of GMS and QGIS gives much-needed enhancement to groundwater modeling and sustainable planning and management of freshwater resources. Using such platforms will allow stakeholders to make smart decisions balancing the environment's health and human needs, which is critical in keeping springs healthy and available for generations to come in the face of the challenges of water scarcity and environmental sustainability.

2. Materials and Methods

2.1. QGIS's role & GMS

Quantum GIS, commonly referred to as QGIS, is an open-source system that transforms GMS handling and analyzing spatial data into fine art. The program can design elaborate mapping and perform high-end spatial processing, which provides a strong platform for the visualization and interpretation of geographic information. QGIS's main strength is integrating various types of spatial data, which allows the user to overlay different data sets for a thorough analysis. During groundwater management, these spatial relationship qualities are most useful, with different environmental factors. Using QGIS could help visualize the groundwater flow patterns, identify the recharge area, and localize potential contaminant sites, especially during decision-making.

Groundwater modeling with GMS, in conjunction with QGIS, is thus taken to another level. The complementarity between spatial analytic tools from QGIS used in GMS provides the users with better modeling tools. Thus the groundwater management system is made much more functional and efficient. This collaborative effort leads to the capture of intricate model results that could better inform hydrological understandings for various stakeholders.

Furthermore, QGIS operates with a range of data formats, while the capacity to integrate with other software tools ensures its efficiency as a versatile and convenient environment for groundwater analysis.

As open source, QGIS is highly extensible and has many custom plugins and extensive tutorials built into the software, extending the tools and capabilities of the software even more.

In general, GMS, along with QGIS, provides a very strong support system for efficient groundwater management. Besides advancing modeling skills, it facilitates spatial data visualization and analysis to properly plan and manage groundwater resources sustainably [1]. Through these improved methods, therefore, researchers and policymakers can better tackle the problems facing freshwater resources.

2.2. Collection of the Data

The measurements from collective hydraulic testing and experiments are hydraulic conductivity, porosity, and storability in hydrogeology. On the calibration of the model, the following data should be collected: each day's average flow rate and also water table recorded from the monitoring wells with the location of the springs.

Remote sensing and geophysics, including Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT), are the studies that enhance data accuracy [2].

2.3. Building the Model in GMS

A model domain in GMS is established by first specifying the research area's border and then creating a computational grid. The grid resolution is a similar idea; the higher the grid, the more details there are, but the higher the processing power requirements. The models have embedded hydrogeological parameters, and model calibration entails modifying these parameters to match empirical data. In order to assess the model's accuracy in representation, validation entails evaluating its predictive power on other datasets [3, 4].

2.4. Spatial Analysis in QGIS

Watershed, flow direction, and visualization are a few techniques that come under the category of spatial analysis in QGIS. The groundwater flow pattern is designated by net water movement within the watershed, but the demarcation of recharge zones based on topographical and hydrological criteria constitutes watershed demarcation [5]. The visualization features in QGIS provide frightening-themed maps and three-dimensional models that enhance understanding of groundwater systems [6].

2.5. Integration of GMS and QGIS

There are two methods for transferring data between QGIS and GMS: The geographic aspect is made possible by bringing the output data into QGIS. In contrast, the spatial data is taken out of the GMS in order to update the model. The compatibility of data, the appropriate format of the data, and future predictions are also required for integration [7]. As mentioned by Prosper et al., 2022, integrated analysis is defined as the combination of GM's results and QGIS data, which is more useful in the global evaluation of groundwater systems and in evaluating outcomes and model calibration [8].

3. Advantages of Integration

By combining the positive features of both tools, integrating Quantum GIS (QGIS) and Groundwater Modelling System (GMS) software provides many benefits for managing groundwater resources. The main advantages of this integrated strategy are described in this section.

3.1. Enhance Visualisation

It is particularly important to link GMS with QGIS because of the striking increase in the presentation of groundwater models from a groundwater perspective. In addition, QGIS offers enhanced visualization features that complement mapping the flow of water in the sub-surface, recharge areas and contamination areas. This spatial representation is useful and aids in comprehending various hydrogeological procedures. For example, if one was only working with GMS outputs, there may be cases where one would not distinguish which areas are vital to groundwater replenishment. However, when using QGIS, there are possibilities to map these zones as well [9]. Using analytical tools and programs like QGIS, more dynamic and often informative thematic maps and three-dimensional models are created to facilitate better engagements with stakeholders, and using maps to represent groundwater domains is quite common. All of these enhance the presentation of technical information to make it easier to explain to people who may not have a technical background and policymakers [10]. Sophisticated GIS operation also extends to options for adding multiple layers to the map and comparing different conditions, which can help to predict effects in these fields of groundwater management, which is extremely important to prevent problems while they are still developing [5, 11].

3.2. Improve Accuracy

Most importantly, the integration of advanced spatial analysis with well-proven methods of groundwater simulation makes the combined use of both Groundwater Modelling System (GMS) and QGIS more accurate. The GMS is particularly useful in the fields of groundwater, stream, and solute transport simulations, as well as particle tracking. However, the accuracy that is realized in models is, to a great extent, dependent on the quality of input data and model calibration [12]. To this effect, QGIS has available high-resolution spatial data, including but not limited to land use maps and Digital Elevation Models (DEMs), that can help enhance calibration precision and generally refine inputs into the models [13]. Using spatial analysis from QGIS, one can differentiate disparities in the GMS model outputs. Using GIS, water users can augment what has already been modelled in GM's simulation results and tweak the models further to increase their precision and precision [14]. It also makes the embedding of features of real-time data into the model possible, which is highly essential for the proper management of groundwater [15].

3.3. Improved Decision Making

It is stated that the appropriate decision on groundwater management can be made when GMS and QGIS are combined. Through integrating QGIS, which employs groundwater analysis and GMS, which simulates the management scenarios, users can gauge the impact of different management situations on freshwater resources, such as groundwater [16]. This integrated aquifer management approach enables accurate assessment of policy measures or modifications in land use and impacts of climate change since details of groundwater systems are well provided. For instance, QGIS scenario analysis will help to identify the effect of various land use practices on groundwater quality and availability [17]. Some benefits of transparent communication with stakeholders include using the scenarios to create sustainable water management policies due to the capacity to create maps and detailed representations of the scenarios [11].

4. Challenges and Restriction

Despite its benefits, there are a number of issues and restrictions with GMS and QGIS integration that must be resolved. These difficulties are covered in detail in this section.

4.1. Issues with Data Compatibility

The compatibility of QGIS and GMS data is a huge challenge. Switching between data in GMS and QGIS can be more difficult due to differences in the coordinate reference systems and data structures [19]. For instance, there may be a need to change the outputs of the GMS model to some form that is friendly to QGIS. This may result in data transform methods, and this may sometimes cause some errors or loss of data. To address all these problems, users need to adopt standard formats and reference systems for both systems. It can also be useful to refine data translation and projection using QGIS capabilities and such plugins. Even methods in using QGIS tools and plugins in making projection alterations and data conversion is an intricate process that requires proper direction to avoid data distortions. Additionally, integration and analysis require high consistency between the two systems and the data in each system [20].

4.2. Complexity and Skill Requirements

In this paper, an overview of the integration of GMS and QGIS has been presented, where several activities and big data handling processes, as well as multiple-level models, need to be addressed and automated for different scenarios of groundwater modelling using GIS expertise while having the essential knowledge in GMS software. The specialization of the two software packages requires practitioners to have the knowledge of both in order to harness their interrelated usefulness [21]. This can create a challenge, especially for people who do not have any prior experience in handling GMS and QGIS.

To that end, the following approaches can be used. The routine training must become more stringent to address this particular problem. There is a need for institutions to undertake capacity building as a way of empowering the human resources within institutions. However, the user-specific interfaces and the availability of technical details and materials can make integration less complicated and enable experts in various fields to incorporate it [22].

4.3. Processes using a Lot of Resources

There are times when one can spend a lot of time and effort trying to link GMS and QGIS due to the model's complexity and the data's size. High-definition geographic data and complex groundwater networks require considerable computing power, extended computational time, and costly cost overheads [23, 24]. The solution for such demands for resources is to optimise computing performance. Different strategies presented the reduction of computational load using methods such as data aggregation, parallel processing, and simplicity of models [25]. Moreover, tapping on cloud computing resources could lead to solutions for the effective large-scale modelling and analysis of groundwater resources.

4.4. Data Quality and Availability

A significant advantage that can determine the effectiveness of integrated GMS and QGIS techniques is the quality and availability of the input information. A lack of data may compromise the credibility of the integrated analysis, and the data may be old or of low quality in many areas, including developing nations, as stated by Matia et al. (2022) [26]. This limitation can reduce the accuracy of geographical assessment and models for groundwater. The challenge requires improvement in data gathering and surveillance efforts. The penetration of regional organizations, academic circles, and communities can contribute to augmenting both data access and data quality [27]. Additionally, integrating geophysical surveys with remote sensing allows for acquiring additional crucial information to enable a more comprehensive groundwater modelling.

4.5. Updating and Maintenance

Since groundwater systems and LU circumstances constantly change, models and spatial data must be updated and kept current. Using old-fashioned models or geographic databases could lead to ineffective prediction and management approaches through many inaccurate forecasts and ineffective use of resources [28]. The validity and the currency of the integrated approach are best ensured by updating the QGIS database and the GMS model as often as possible. The study stresses the necessity of utilising a systematic approach to groundwater management to involve dynamic update and verification of data and models [29].

5. Case Studies

5.1. Managing Spring Water in the Himalayan Area

The advancement in studying water resources in the Himalayan region has also shaped over the years through contribution. Further, in 2015, the calibration and validation process of the groundwater models was described by Abbaspour et al., where the field data were compared with GMS and QGIS [30]. This was followed by Jay Krishna et al., 2016 [31], who added more problems encountered regarding data resolution and handling the same while doing GMS and QGIS analyses of mountainous regions. It came to 2022 when Ruchi Verma and Priyanka Jamwal effectively used these tools to understand the management of spring waters in the Himalayan foothills area and address issues of groundwater recharge simulation and the effects of land use change [32]. In the same year, 2022 (Horthing et al., 2022), implementing GIS-integrated tools for watershed analysis and recharge prediction increased understanding of spring water management [33]. More recently, Himanshu et al. extended the knowledge in 2024 through offering enhanced GIS tools for evaluating spatial information about springs and their discharge area and, thereby, enhancing the study of the water bodies of the region [34]. Combined, these works demonstrate a dynamic yet coordinated research process to face the multifaceted issues of water resource development in the Himalayas.

5.2. Urban Springwater Delineation in Indian Cities

GIS and modeling tools in managing water, especially in the urban sector, have evolved over the years. In 2007, this integration was further elevated by Madan et al.,2007 [35], who noted that GIS data was used to show how changes in land use affected spring sources. Subsequently, Tamer et al. (2015) employed the GMS Q-GIS tools to assess the effects of urbanization on the rates of groundwater recharge as it is important for increasing water supply capacities in urban India [36]. Arthur S. Guarino, in 2017, elaborated on the problems connected with urban spring water in Indian cities and focused on the questions of the connection between GMS and QGIS [37]. His study evaluated the effects of urbanization water and used QGIS in mapping the potential recharge areas, contributing positively to water resources management in growing urban complexes [37]. This was followed by further computational detail by Michele et al. (2019) concerning the specifics of GMS integration with QGIS for water quality, which highlighted challenges in calibration and validation in highly populated urban areas. More recently, Sreechanth et al. (2021) introduced or revisited the role of high-resolution GIS data in managing urban groundwater, and they highlighted problems for the development of spring resources in India’s Tier 1 megacities; they also refined the approaches that can be used for the calculation of an element of spring discharge called spring water area [38, 39]. Altogether, these studies have pointed out the need to incorporate sophisticated instruments for optimal optimization of urban water supply, given the fact that urbanization is inevitable in most regions across the globe.

5.3. Groundwater Management in the Deccan Plateau

The area of groundwater management as an area of research on the Deccan Plateau has developed with enhanced progression with different research initiatives. In 2004, Thomas E. Reilly and Arlen W. Harbaugh wrote an article that focused on the steps of calibrating and validating groundwater models, including field and spatial data, as instruments in the management of GBR in the future [40]. Another study conducted by Shrikant Daji Limaye in 2010 to capture a subsequent update of the map incorporated GMS and QGIS to obtain data on groundwater accessibility and its quality revealed vital probabilities of water scarcity and quality crises [41].

In 2019, Arulbalaji et al. used remote sensing data and GIS to assess the status of groundwater resources in the Deccan Plateau and to understand the groundwater regime and future management issues [42]. Subsequently, Chaitanya et al. (2021), together with GMS and QGIS for enhancing water source used in the region, GMS was used for the groundwater flow and recharge modeling and QGIS for the analysis of Changes in land use and Water availability assessments. The combined approach provided important data for decision-making towards sustainable growth and appropriate utilization of water from underground sources in this part of the world [43].

More recently, Rajarshi et al. (2023) added to this line of research by evaluating the groundwater recharge and discharge system in the Deccan Plateau using the subsurface modeling with GMS and QGIS analysis. They, with other scholars, were more concerned with the rational management of the available groundwater resources, especially under conditions of land use change and /or climatic variations [44].

Altogether, these studies depict the integrated way to manage the groundwater resources in the region concerned: the Deccan Plateau removing the environmental barriers and fulfilling the developmental requirements.

5.4. Springwater Management in the Western Ghats

The present study involving micro-level research on groundwater management in the Western Ghats has provided significant information with the help of GMS and QGIS tools. MD Subash Chandran and TV Ramachandra investigated the occurrence and movement of groundwater in this hydro-geologically distinctive region in 2014, centred on the scope of GMS for the simulation of groundwater movement and recharge, coupled with QGIS for land-and-water-use change analyses. They also advanced their knowledge further regarding the continuing pattern of groundwater and the changes in land use due to spring water [45].

Sandeep Mahajan and R. Sivakumar, in their study conducted on GIS tools for visualizing GWM and carried out in the Western Ghats in 2018, called for the creation of detailed spatial analysis and 3D visualization of the groundwater flow and recharge system in the region. Following this train of thought, Bhowmick et al. (2014) conducted a study that combined geospatial mapping under GMS and Geographical Information System or GIS using QGIS to assess the dispersion of spring water by calculating the probable rates of groundwater recharge and discharge within the hydrogeological setting of the region and called for a relevant evaluation of reported topography and vegetation regimes while determining groundwater management strategies [46]

In 2024, Maya et al. assisted in the calibration and validation of the groundwater models for the Western Ghats by comparing the field data with GM's simulation results and QGIS analysis, which improved water resource management [47]. In the same year, 2024, Veeraswamy and his group started examining the impacts of climate change on water availability in the groundwater and recharge rates using integrated GMS and QGIS methods to accurately appraise these dynamics [48]. Altogether, the present papers underscore the imperative of high-end modeling and spatial analysis in controlling groundwater resources in the Western Ghats and solving environmental and hydrological issues.

5.5. Groundwater Management in the Indo-Gangetic Plain

The use of GMS and QGIS to study groundwater management in the Indo-Gangetic Plain has expanded the research in recent years. Similarly, in 2021, Jain et al. employed these tools to assess the groundwater flow and recharge in this highly populated study area; they also focused on using QGIS for spatial analysis of land use and water availability. In the same year, Singh et al. discussed several significant facets of GIS regarding the underground models that exist in the Indo-Gangetic Plain region and its flow procession and recharge procedure through separate means of geographic interface tools [49].

Subsequently, Asadi et al. (2024) extended this field by integrating GMS and QGIS in order to outline the conditions of groundwater supply, which include important environmental issues involving water scarcity and quality, as well as the demand for water in the future [50]. Based on this, Kumar et al. (2022) delved into groundwater recharge and discharge processes in the IGP basins, spurring advancement in the interrelation of GMS and GIS with QGIS to address issues of water scarcity and quality [51]. Singh et al. (2023) work provides a glance at the calibration and validation of the groundwater models pertaining to the Indo-Gangetic Plain, wherein they appropriately correlated geographical information and field data for improving the quantitative and qualitative approach to water resources management [52]. Altogether, these papers reveal a systematic and holistic framework for resolving groundwater management concerns in the IGP, emphasising the role of up-to-date technological applications.

6. Conclusion

The integration between GMS and QGIS can be considered a strong concept in managing groundwater resources due to the development of effective numerical simulations, powerful GIS, and spatial analysis. This integration also helps to increase the reliability of the developed models, as well as in the visualization of the results and conclusions drawn about hydrogeological relations, decisions based on which will be more effective. This integrated methodology is powerful because the numbers generated from QGIS's high-resolution spatial data can be easily incorporated into and simulated within GMS for dynamic modeling and quantitative determination of groundwater recharge, flow, and contamination for various landscapes.

Both GMS and QGIS provide valuable knowledge on groundwater systems and give tangible recommendations for sustaining the use of water resources, especially in areas characterized by composite hydrogeologic configurations. Research from different geopolitical zones of the world like the Himalayan region, Indian cities, Deccan plateau, and Indo-Gangetic Plain show that integration of the proposed parameters can effectively be used in real-life management of groundwater with varying effects of urbanisation, changes in land use, and fluctuations in climate. In addition, the portrayal of the various scenarios, the probable consequences, and the involvement of stakeholders are key factors when it comes to the formulation of long-lasting policies on water management. As much as there are strengths, weaknesses arise from the compatibility of data in 2 or more models, the computational requirements that may be required, and the technical know-how of the team handling the integration. To overcome these hurdles, new improvements in software functionalities, data compilation, and capacity enhancements must be made to ensure maximum utilization of integrated groundwater modeling by researchers, policymakers, and stakeholders.

Therefore, the utilization of GMS and QGIS suggests a framework for enhancing the effectiveness of groundwater management strategies. As the tools and datasets are further developed and improved and the linkages between different components are strengthened, this integrated approach can provide improved decision support for managing alternative water resources and promote better water sustainability and preparedness for future challenges in the groundwater in various hydrological conditions.

6.1. Challenges and Future Direction

The integration of advanced technologies such as Machine Learning (ML), remote sensing, and software tools like Groundwater Modeling System (GMS) and Quantum Geographic Information System (QGIS) into groundwater modeling and management has revolutionized the field, offering unprecedented opportunities to address complex hydrological challenges. These technologies enable more accurate predictions, efficient resource management, and scalable solutions for groundwater systems. However, their adoption is accompanied by significant challenges that must be addressed to fully realize their potential. These challenges span technical, operational, and interdisciplinary domains, requiring innovative solutions and collaborative efforts to overcome.

Problems related to data quality and availability are very critical. For groundwater modeling, the most effective data in terms of applicability for modeling should be reliable, consistent, and expansive; however, for many regions, especially the developing countries in the world, having sparse monitoring networks and incomplete datasets causes huge gaps for such analysis. Inconsistent measurement techniques and very limited historical records amplify uncertainties in model outputs. Therefore, robust frameworks for data collection must be developed, and data must be made transparent. Methods such as satellite imagery and IoT-based sensors should be utilized to fill or endorse data gaps and real-time monitoring provisions. At the same time, governments, research institutions, and private entities need to join forces in standardizing procedures relating to data collection and sharing to make certain that all models are being developed with reliable and comprehensive datasets.

Another big limitation is the computation complexity of advanced groundwater models. Coupling machine learning algorithms and/or high-resolution remote sensing data is computationally expensive and generally requires a long time to process, making it highly cost-relevant and unrealistic for real-time applications or large-scale studies. The focus, therefore, should shift to optimizing the algorithms to achieve an outlet of results within reasonable times and at low costs, as well as leveraging the available cloud computing and HPC infrastructure. Parallel and distributed computing techniques can go beyond computational efficiency, thus making these high-end modeling tools more accessible and usable across a broader range of applications and in different settings.

Interdisciplinary collaboration is yet another major challenge. By nature, groundwater modeling and management are interdisciplinary, requiring skills from hydrology, data science, software engineering, environmental policy, and other disciplines. Different vocabulary, rules of engagement, methods, and end goals often hinder effective communication and eventual integration. Interdisciplinary training courses and partnered research endeavors would beef up efforts towards closing these gaps. By developing shared frameworks and promoting a collaborative culture, the disciplines' different goals and approaches can be aligned, thereby facilitating completely holistic and effective solutions.

Of course, the advanced modeling tools remain a barrier user friendly and so readily accessible. The majority of the software platforms, such as GMS, for example, and QGIS, require specialized knowledge and technical skills to use, given that they are available only for use by trained experts, excluding non-technical stakeholders such as policymakers and local water managers. Improve interfaces, intelligent dashboards, full tutorials, and training materials can open access even to open-source platforms and community-generated support to democratize access to these tools and enable even wider ranges of users to leverage these capabilities. Validation and uncertainty quantification usually go unnoticed, but they are very important in terms of making the failure rates of groundwater models acceptable. Models are created after simplification and, in most cases, assume normal conditions; thus, their output undergoes uncertainties due to data limitations and computational constraints. Stringent validation protocols, ensemble modeling approaches, and uncertainty quantification techniques such as Monte Carlo simulations hold ways to increase the reliability of models. Further, transparency with which model boundaries and uncertainties are reported is important for trust in those predictions and, thus, their application in practice.

In years to come, some key areas will propel a field forward. Data integration is going to be focused on immediately. Remote sensing, in-situ measurements, and climate model records can all be combined and will thus add considerable value to the model. Their joint harmonization and analysis through machine learning algorithms will make the most powerful predictive models possible. Scalability and adaptability are equally necessary, since groundwater models are to be applied within diverse hydrological environments-from arid to humid climates. However, developing modular and flexible modeling frameworks that are customizable to a specific context will certainly improve the productivity and relevance at which they can be deployed. The development of real-time monitoring and decision support systems represents another important future direction. Integrating IoT-based sensors, satellite data, and advanced analytics can enable dynamic groundwater management, providing timely insights for decision-makers. These systems can facilitate proactive interventions, such as optimizing extraction rates or mitigating contamination risks, ensuring sustainable groundwater use. Additionally, incorporating sustainability and climate change considerations into models is essential for long-term resilience. Simulating scenarios such as changing precipitation patterns, sea-level rise, and increased groundwater extraction can help stakeholders prepare for future challenges and develop adaptive management strategies.

Aligning technological advancements with policy and governance frameworks is equally important. Effective groundwater management requires not only advanced tools but also supportive policies and regulations. Developing frameworks that promote sustainable groundwater use, incentivize data sharing, and foster stakeholder collaboration can ensure that technological innovations are effectively implemented. Finally, capacity building and education are critical for empowering stakeholders to leverage advanced modeling tools. Training programs, workshops, and online courses can bridge the knowledge gap, enabling water managers, policymakers, and researchers to harness the full potential of these technologies. While integrating advanced technologies into groundwater modeling and management presents significant challenges, it also offers immense opportunities to improve groundwater systems' accuracy, efficiency, and scalability. By addressing issues related to data quality, computational complexity, interdisciplinary collaboration, accessibility, and model validation, and pursuing future directions such as enhanced data integration, real-time monitoring, sustainability considerations, and policy alignment, the field can advance toward more effective and sustainable groundwater management. Collaborative efforts, capacity building, and a commitment to innovation will be key to achieving these goals, ensuring the sustainable use of groundwater resources for future generations.

Acknowledgement

The authors would like to acknowledge and sincerely thank the organizing committee of the International Conference on Computer-Aided Modeling for the Sustainable Development of Smart Cities (CAMSSC), sponsored by the Anusandhan National Research Foundation (ANRF), held at the Department of Civil Engineering, North Eastern Regional Institute of Science and Technology (NERIST), Nirjuli, Arunachal Pradesh, India, during November 27–30, 2024, for allowing us to present the paper and sponsoring the paper for publication.

References

[1] Mohammad N. Almasri, and Jagath J. Kaluarachchi, "Modeling Nitrate Contamination of Groundwater in Agricultural Watersheds," *Journal of Hydrology*, vol. 343, no. 3-4, pp. 211-229, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[2] Jeffry M. Flenniken, Steven Stuglik, and Basil V. Iannone, "Quantum GIS (QGIS): An Introduction to a Free Alternative to More Costly GIS Platforms," *UF IFAS Extension University of Florida*, vol. 2020, no. 2, pp. 1-6, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Markus Hirsch, Laurence R. Bentley, and Peter Dietrich, "A Comparison of Electrical Resistivity, Ground Penetrating Radar and Seismic Refraction Results at a River Terrace Site," *Journal of Environmental & Engineering Geophysics*, vol. 13, no. 4, pp. 313-364, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[4] Rita Deiana, Jacopo Bonetto, and Alessandro Mazzariol, "Integrated Electrical Resistivity Tomography and Ground Penetrating Radar Measurements Applied to Tomb Detection," *Surveys in Geophysics*, vol. 39, pp. 1081-1105, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[5] Giovanna De Filippis et al., "Spatial Data Management and Numerical Modelling: Demonstrating the Application of the QGIS-Integrated FREEWAT platform at 13 Case Studies for Tackling Groundwater Resource Management," *Water*, vol. 12, no. 1, pp. 1-31, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ankita P. Dadhich, Rohit Goyal, and Pran N. Dadhich, "Assessment and Prediction of Groundwater using Geospatial and ANN Modeling," *Water Resources Management*, vol. 35, pp. 2879-2893, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Apoorv Verma, Brijesh Kumar Yadav, and N.B. Singh, "Data on the Assessment of Groundwater Quality in Gomti-Ganga Alluvial Plain of Northern India," *Data in Brief*, vol. 30, pp. 1-11, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Prosper Kpiebaya et al., "Spatial Assessment of Groundwater Potential using Quantum GIS and Multi-Criteria Decision Analysis (QGIS-AHP) in the Sawla-Tuna-Kalba District of Ghana," *Journal of Hydrology: Regional Studies*, vol. 43, pp. 1-22, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hemlata Goyal, Chilka Sharma, and Nisheeth Joshi, "An Integrated Approach of GIS and Spatial Data Mining in Big Data," *International Journal of Computer Applications*, vol. 169, no. 11, pp. 1-6, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] G.P. OBI Reddy et al., "Evaluation of Ground Water Potential Zones Using Remote Sensing Data -A Case Study of Gaimukh Watershed, Bhandara District, Maharashtra," *Journal of the Indian Society of Remote Sensing*, vol. 28, pp. 19-32, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[11] Massimiliano Cannata, Jakob Neumann, and Rudy Rossetto, "Open Source GIS Platform for Water Resource Modelling: FREEWAT Approach in the Lugano Lake," *Spatial Information Research*, vol. 26, pp. 241-251, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[12] V. Pisinaras et al., "Integrated Modeling as a Decision-Aiding Tool for Groundwater Management in a Mediterranean Agricultural Watershed," *Hydrological Processes*, vol. 27, no. 14, pp. 1973-1987, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[13] Khabat Star Mohammed et al., "Prediction of Groundwater Level Fluctuations Using Artificial Intelligence-Based Models and GMS," *Applied Water Science*, vol. 13, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[14] M. Perdikaki et al., "Free and Open-Source GIS-Integrated Hydrogeological Analysis Tool: An Application for Coastal Aquifer Systems," *Environmental Earth Sciences*, vol. 79, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] G. Tziatzios et al., "The Use of the Pilot Points Method on Groundwater Modelling for a Degraded Aquifer with Limited Field Data: The Case of Lake Karla Aquifer," *Water Supply*, vol. 21, no. 6, pp. 2633-2645, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] Denis Obura, David Kimera, and Derrick Dadebo, "Application of GIS and Hydraulic Modeling for Sustainable Management of Water Supply Networks: A Pathway for Achieving Sustainable Development Goal (SDG) 6," *Process Integration and Optimization for Sustainability*, vol. 8, pp. 1017-1034, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Evgenia Koltsida, and Andreas Kallioras, "Groundwater Flow Simulation through the Application of the FREEWAT Modeling Platform," *Journal of Hydroinformatics*, vol. 21, no. 5, pp. 812-833, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[18] Rudy Rossetto, Iacopo Borsi, and Laura Foglia, "FREEWAT: FREE and Open Source Software Tools for Water Resource Management," Rendiconti Online Delta Societa Geologica Italiana, vol. 35, pp. 252-255, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[19] Michele M Tobias, and Alex I Mandel, "Literature Mapper: A QGIS Plugin for Georeferencing Citations in Zotero," *Air, Soil and Water Research*, vol. 14, pp. 1-8, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[20] Sukhjit Singh Sehra, Jaiteg Singh, and Hardeep Singh Rai, "Assessing OpenStreetmap Data Using Intrinsic Quality Indicators: An Extension to the QGIS Processing Toolbox," *Future Internet*, vol. 9, no. 2, pp. 1-22, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[21] Anita Graser, and Victor Olaya, "Processing: A Python Framework for the Seamless Integration of Geoprocessing Tools in QGIS," *ISPRS International Journal of Geo-Information*, vol. 4, no. 4, pp. 2219-2245, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[22] S.V. Sabale et al., "Review Paper on Applications of Q-GIS Software," *International Research Journal of Engineering and Technology*, vol. 8, no. 5, pp. 1-6, 2021. [Google Scholar] [Publisher Link]

[23] Chun-Wei Tsai et al., "Big Data Analytics: A Survey," *Journal of Big Data*, vol. 2, pp. 1-32, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[24] Reihaneh H. Hariri, Erik M. Fredericks, and Kate M. Bowers, "Uncertainty in Big Data Analytics: Survey, Opportunities, and Challenges," *Journal of Big Data*, vol. 6, pp. 1-16, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[25] K.U. Jasenna, and Julie M. David, "Issues, Challenges and Solutions : Big Data Mining," *CS & IT-CSCP*, pp. 131-140, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[26] Matia Menichini et al., "Groundwater Modeling with Process-Based and Data-Driven Approaches in the Context of Climate Change," *Water*, vol. 14, no. 23, pp. 1-25, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Pedro Henrique Jandreice Magnoni, César de Oliveira Ferreira Silva, and Rodrigo Lilla Manzione, "Groundwater Recharge and Water Table Levels Modelling Using Remotely Sensed Data and Cloud-Computing," *Sustainable Water Resources Management*, vol. 6, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[28] Husam Musa Baalousha, and Christopher S. Lowry, "Applied Groundwater Modelling for Water Resource Management and Protection," *Water*, vol. 14, no. 7, pp. 1-2, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[29] Laura E. Condon et al., "Global Groundwater Modeling and Monitoring: Opportunities and Challenges," *Water Resources Research*, vol. 57, no. 12, pp. 1-27, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[30] K.C. Abbaspour et al., "A Continental-Scale Hydrology and Water Quality Model for Europe: Calibration and Uncertainty of a High-Resolution Large-Scale SWAT Model," *Journal of Hydrology*, vol. 524, pp. 733-752, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[31] Jay Krishna Thakur, Sudhir Kumar Singh, and Vicky Shettigondahalli Ekanthalu, "Integrating Remote Sensing, Geographic Information Systems and Global Positioning System Techniques with Hydrological Modeling," *Applied Water Science*, vol. 7, pp. 1595-1608, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[32] Ruchi Verma, and Priyanka Jamwal, "Sustenance of Himalayan Springs in an Emerging Water Crisis," *Environmental Monitoring and Assessment*, vol. 194, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Horthing V. Zimik et al., "GIS-Based Identification of Potential Watershed Recharge Zones Using Analytic Hierarchy Process in Sikkim Himalayan Region," *Applied Water Science*, vol. 12, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[34] Himanshu Joshi et al., "Groundwater Recharge Potentiality Mapping for Opportune Augmentation Following Two MCDMs for a Western Himalayan Watershed," *Discover Water*, vol. 4, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[35] Madan K. Jha et al., "Groundwater Management and Development by Integrated Remote Sensing and Geographic Information Systems: Prospects and Constraints," *Water Resources Management*, vol. 21, pp. 427-467, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[36] Tamer Eshtawi, Mariele Evers, and Bernhard Tischbein, "Potential Impacts of Urban Area Expansion on Groundwater Level in the Gaza Strip: A Spatial-Temporal Assessment," *Arabian Journal of Geosciences*, vol. 8, pp. 10565-10584, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[37] Arthur S. Guarino, "The Economic Implications of Global Water Scarcity," *Research in Economics and Management*, vol. 2, no. 1, pp. 1-13, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[38] Michele Lancia et al., "Analysis of Groundwater Resources in Densely Populated Urban Watersheds with a Complex Tectonic Setting: Shenzhen, Southern China," *Hydrogeology Journal*, vol. 127, pp. 183-194, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[39] Sreechanth Sundaram, Suresh Devaraj, and Kiran Yarrakula, "Modeling, Mapping and Analysis of Urban Floods in India-a Review on Geospatial Methodologies," *Environmental Science and Pollution Research*, vol. 28, pp. 67940-67956, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[40] Thomas E. Reilly, and Arlen W. Harbaugh, *Guidelines for Evaluating Ground-Water Flow Models*, U.S. Department of the Interior, U.S. Geological Survey, pp. 1-30, 2004. [Google Scholar] [Publisher Link]

[41] Shrikant Daji Limaye, "Review: Groundwater Development and Management in the Deccan Traps (basalts) of Western India," *Hydrogeology Journal*, vol. 18, pp. 543-558, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[42] P. Arulbalaji, D. Padmalal, and K. Sreelash, "GIS and AHP Techniques Based Delineation of Groundwater Potential Zones: A Case Study from Southern Western Ghats, India," *Scientific Reports*, vol. 9, pp. 1-17, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[43] Chaitanya B. Pande, Kanak N. Moharir, *Groundwater Resources Development and Planning in the Semi-Arid Region*, Springer Cham, pp. 1-571, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[44] Rajarshi Saha et al., "Geospatial Delineation of Groundwater Recharge Potential Zones in the Deccan Basaltic Province, India," *Arabian Journal of Geosciences*, vol. 16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[45] Subash Chandran, and T.V. Ramachandra, "Towards Integrated Management of Western Ghats," *Lake 2014: Conference on Conservation and Sustainable Management of Wetland Ecosystems in Western Ghats*, pp. 1-2, 2014. [Google Scholar] [Publisher Link]

[46] Prasenjit Bhowmick, S. Mukhopadhyay, and V. Sivakumar, "A Review on GIS Based Fuzzy and Boolean Logic Modelling Approach to Identify the Suitable Sites for Artificial Recharge of Groundwater," *Scholars Journal of Engineering and Technology*, vol. 2, no. 3A, pp. 316-319, 2014. [Google Scholar] [Publisher Link]

[47] K. Maya et al., "Hydrogeochemical Signatures of Spring Water in Geologically Diverse Terrains: A Case Study of Southern Western Ghats, India," *Environmental Monitoring and Assessment*, vol. 196, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[48] Veeraswamy Davamani et al., "A Critical Review of Climate Change Impacts on Groundwater Resources: A Focus on the Current Status, Future Possibilities, and Role of Simulation Models," *Atmosphere*, vol. 15, no. 1, pp. 1-22, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[49] Arjun Ram et al., "Groundwater Quality Assessment Using Water Quality Index (WQI) under GIS Framework," *Applied Water Science*, vol. 11, pp. 1-20, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[50] Sara Asadi et al., "Analyzing Hydrological Alteration and Environmental Flows in a Highly Anthropized Agricultural River Basin System Using SWAT+, WEAP and IAHRIS," *Journal of Hydrology: Regional Studies*, vol. 52, pp. 1-16, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[51] Mukesh Kumar et al., "Understanding Land Use/Land Cover and Climate Change Impacts on Hydrological Components of Usri Watershed, India," *Applied Water Science*, vol. 12, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[52] Atar Singh et al., "Delineation of Groundwater Potential Zone Using geospatial tools and Analytical Hierarchy Process (AHP) in the State of Uttarakhand, India," *Advances in Space Research*, vol. 73, no. 6, pp. 2939-2954, 2024. [CrossRef] [Google Scholar] [Publisher Link]