Groundwater Flow Simulation in Coastal Aquifers Using the MODFLOW Algorithm

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Abstract: The over-extraction and saltwater intrusion of coastal aquifers is a growing problem that threatens the availability of freshwater for agriculture, industry, and domestic purposes. For effective, sustainable management of groundwater resources, it is necessary to understand and predict the complex dynamics of groundwater flow in these systems. This study is focused on simulating three-dimensional flow behavior in a representative coastal aquifer using the MODFLOW algorithm, a modular finite-difference groundwater flow model developed by the USGS. The model simulates key hydrogeological parameters, including hydraulic conductivity, specific yield, aquifer stratification, and boundary conditions, and is calibrated using observed groundwater head data from monitoring wells."Special attention is given to the freshwater–saltwater interface modeling with the SEAWAT package that accounts for variable-density flow, which is compatible with MODFLOW. Results showed that pumping near the coast changes the flow direction while accelerating saltwater intrusion. However, enhancement of recharge and optimization of well-field positioning inland can alleviate these risks. The simulation results confirmed the effectiveness of MODFLOW as a decision-support tool in the management of coastal groundwater resources by predicting various scenarios of aquifer sustainability with differing recharge and pumping rates.

Keywords: MODFLOW; Coastal Aquifer; Groundwater Modeling; Saltwater Intrusion; Variable-Density Flow Simulation.

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I. Introduction

Many regions depend on groundwater for irrigation, industrial, and domestic purposes. In coastal aquifers, however, the interplay of freshwater and saline water creates a complex hydrogeological environment that is especially vulnerable to human-induced stress (Rajalakshmi et al., 2024). Declining land use changes and climate shifts exacerbate the problem of excessive groundwater abstraction, leading to saltwater intrusion and endangering the freshwater lens and long-term water security (Werner et al., 2013), (Custodio, 2010).

Understanding flow behavior along coastlines is important for sustainable groundwater resource management. Reliable simulation of groundwater flow enables researchers and policymakers to forecast the impacts of pumping, evaluate recharge sustainability, and devise strategies to reduce saline intrusion (Harbaugh, 2005). In the absence of such information, management interventions may default to responding to problems instead of anticipating them, which results in permanent aquifer damage (Bear et al., 1999), (Ferguson & Gleeson, 2012). Simulations also provide the opportunity to test out various other scenarios, like the impact of increased agricultural demand or rising sea levels, without putting the resource at actual risk (Giordano, 2009), (Ariunaa & Tudevdagva, 2025).

Of all the tools built for this purpose, MODFLOW is by far the most accepted numerical model of groundwater flow on a global scale. MODFLOW is a modular, three-dimensional, finite-difference model created by the United States Geological Survey (USGS). It simulates groundwater flow through porous media that is saturated with water (Majdanishabestari & Soleimani, 2019). MODFLOW has been improving its versions since the 80s. Some updates include the addition of density-dependent flow and solute transport, making it ideal for coastal aquifers (Langevin et al., 2008). SEAWAT is an example of one of these enhancements. It couples MODFLOW with MT3DMS to enable the variable-density flow of salt and water in the framework. This facilitates the natural and stress-induced behavior of the freshwater–saltwater interface to be simulated (Post & Houben, 2017).

Recent case studies such as the Mekong Delta, Gulf Coast of the United States, and India's East Coast have proven that MODFLOW and SEAWAT are very useful for groundwater modeling in decision-making, like predicting critical thresholds of saltwater encroachment and cut zones of groundwater vulnerability (Sreekanth & Datta, 2011), (Aswath et al., 2019). When tuned with field data, these models have provided accurate results and are being incorporated into regional planning water frameworks for management of policy and infrastructure investments.

II. Literature Review

2.1 Previous Studies on Groundwater Flow Simulation in Coastal Aquifers

The problem of freshwater-saltwater interaction in coastal aquifers has become a robust issue during the last few decades because of the increased danger of seawater intrusion and the depletion of groundwater resources. Early models incorporated conceptual approaches to describe the freshwater-saline water interface in confined and unconfined aquifers. Works by Park and Aral (Park & Aral, 2004) utilized sharp-interface models to depict the shift in the freshwater-saltwater boundary and demonstrated that coastal aquifers were responsive to even modest pumping stresses. Other research expanded on this by using dense flow equations, for example, variable-density flow models, which are more precise regarding the transport of solutes in response to changing conditions, recharge rates, and aquifer heterogeneity (Abarca et al., 2007).

(Karamouz et al., 2011) incorporated dynamic land use variations alongside climatic factors to develop an aquifer modeling system suited for real-world applications. They also illustrated the enormous impact climate variability poses on the recharge-discharge balance. These studies, as a whole, show the advanced stages in groundwater modeling. There is a movement now from simple analytical approaches toward sophisticated engineered numerical models that offer more accurate capability in predicting long-term aquifer sustainability.

2.2 Use of the MODFLOW Algorithm in Similar Studies

MODFLOW is widely regarded as one of the most effective tools for modeling groundwater in coastal aquifers due to its robust architecture, comprehensive capabilities, and extensive user community. Many investigations into saline intrusion and water quality deterioration have utilized MODFLOW, along with MT3DMS or SEAWAT solute transport packages (Gupta & Joshi, 2025). Bakker and Schaars (Bakker & Schaars, 2013) utilized MODFLOW with SEAWAT to model variable density flow in a Dutch coastal aquifer and accurately predicted the distribution of salinity both under natural and pumping conditions.

Mishra and Chandrasekharan (Mishra & Chandrasekharan, 2015) evaluated aquifer responses to different abstraction and recharge methods in Eastern Coastal India's aquifers using MODFLOW. Their study emphasized the significance of incorporating field data, such as borehole salinity and piezometric head measurements, into the calibration process to improve model prediction accuracy. In areas such as the Nile Delta, MODFLOW models have been paired with GIS technology to produce groundwater vulnerability maps, aiding the planning and policy development for water resources in that region (El Sheikh et al., 2013). These case studies further prove that MODFLOW can be relied upon to tackle the challenges posed by coastal aquifer systems, particularly when enhanced with modules for density-coupled transport.

2.3 Challenges and Limitations of Current Simulation Methods

As popular as groundwater simulation techniques are, including ones using MODFLOW, they have some drawbacks. One of the most notable issues is accurately simulating the non-linear will ILT mix flow processes that require precision and an accurate representation of hydraulic gradients. Standard MODFLOW cannot be combined with SEAWAT saltwater intrusion effects because it treats fluid density as constant.

Another unresolved problem is bounded parameter values like hydraulic conductivity and porosity, which in most cases are based on field measurements that are expensive and time-consuming. Most spatially distributed salinity and head data are not available, leading model constructors to make assumptions that lack predictive power. Also, a large number of models are constructed with homogeneous aquifer conditions, ignoring geological heterogeneity that changes flow paths and saltwater intrusion timing and route.

On the other hand, long-term or large-scale simulations face barriers from model calibration and computational demand. Techniques to lessen these, such as optimization algorithms and data assimilation, are being explored, but most remain limited to coastal settings. We emphasize Lu et al.

Coastal aquifers are under increased stress, needing more precise simulation accuracy and models. There is already a growing shift towards hydrological models that incorporate machine learning and remote sensing. Therefore, further attention will be required for the combination of these technologies.

III. Methodology

3.1 Description of Study Area and Data Collection Methods

Research was done in the Chilika coastal aquifer system in Odisha, India, next to the Bay of Bengal. It has an area of nearly 2000 square kilometers and consists of complex hydrogeological features such as alluvial plains, sandy coastal belts, and estuarine wetlands. This aquifer system faces high seasonal variation in recharge due to monsoonal rainfall and is also facing increased stress due to population growth and agricultural groundwater abstraction.

To create a reliable simulation model, meticulous spatio-temporal datasets were gathered. Hydrogeological data such as aquifer thickness, hydraulic conductivity, and porosity were collected from CGWB reports and borehole logs. Salinity concentrations and water table elevations were measured at 25 observation wells over the year. Rainfall data as well as evapotranspiration were tracked by IMD, while soil maps were generated via satellite imagery. LULC maps, as well as surface characteristic maps, were generated in GIS software to define recharge zones. These datasets were used as inputs in the MODFLOW model.

3.2 Explanation of the MODFLOW Algorithm and Its Application

MODFLOW is a finite-difference groundwater flow model developed by the USGS that simulates three-dimensional saturated flow in porous media. It is governed by the groundwater flow equation derived from Darcy's Law and the continuity equation. In general form:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm W = S_s \frac{\partial h}{\partial t} \tag{1}$$

Where:

- h = hydraulic head (m)
- $K_{x,\ Ky,Kz}$= hydraulic conductivity (m/s) in x, y, z directions
- S_s is the Specific storage (1/m)
- W = volumetric flux per unit volume (source/sink term)
- t = time (days)

MODFLOW divides the entire area under study into a grid of rows, columns, and layers. It solves the equation for each cell using a finite-difference approximation iteratively. The algorithm can represent groundwater-surface water interactions, pumping wells, recharge zones, and it assumes either a steady or transient flow regime. For this study, we used MODFLOW-NWT (Newton-Raphson Solver) version due to its better convergence in variably saturated conditions.

3.3 Model Setup and Simulation Parameters

The MODFLOW model domain used the structured grid approach, where the domain is organized into a grid, resulting in 80 columns and 60 rows with 3 vertical layers. Each grid cell measures 500m by 500m. The selected resolution strikes a balance between computational cost and the detail required to effectively simulate the groundwater dynamics within the coastal aquifer environment. To model boundary influences, no-flow boundaries were set at the lateral edges of the domain to represent hydrogeologically impermeable boundaries or groundwater divides. Also, constant head boundaries were set along the coastal fringe to represent the adjacent seawater body and tidal influences while enabling the simulation of possible seawater intrusion. Also, recharge boundaries were defined based on average regional rainfall and regional infiltration rates. These boundaries fluctuated based on land cover and soil type.

The model used field studies and existing literature to derive some hydrogeological input parameters. The hydraulic conductivity (K) values, based on the geological layer, were between 5 and 45 meters per day. Specific yield (Sy) was assigned values between 0.15 and 0.25, which is characteristic of moderate to high water holding capacity in sandy and alluvial deposits. Recharge rates were set based on surface permeability and land use classifications ranging from 2.5 to 5.0 mm/day. The abstraction regime included 48 pumping wells located in agricultural, domestic, and industrial zones, which had extraction rates 50 to 150 cubic meters per day. The simulation period was 10 years with monthly time steps, which helped to capture both seasonal variability and long-term trends in transient and steady-state flow conditions.

To improve model accuracy, calibration was performed using observed groundwater level data from 2015 to 2020. For parameter adjusting, PEST (Parameter Estimation) software was used for automated parameter optimization. The goal was to achieve an RMSE (Root Mean Square Error) of less than 1.5 meters between simulated and actual water table elevations.

These factors, including hydraulic conductivity, recharge rate, well location, and others, were assessed in a sensitivity analysis to determine their effect on the model outputs. This step was needed to understand how the model responds to variability in space and the hydrogeological conditions to improve its use in planning and managing groundwater.

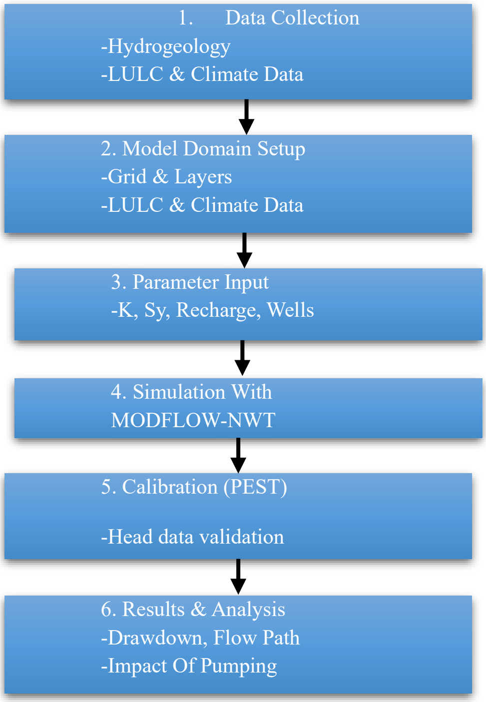

Figure 1: Flowchart of MODFLOW-Based Groundwater Flow Simulation

As seen in Figure 1, there is systematic and iterative data preparation, model building, calibration, and scenario evaluation. Every step tries to simulate real and imaginary conditions of groundwater and understand the various processes within it while building on the previous step. With the modularity of MODFLOW, additional packages like SEAWAT for salinity or MT3DMS for contaminant transport can be added depending on the complexity and goals of the project.

IV. Results

4.1 Presentation of Simulation Results and Groundwater Flow Patterns

The MODFLOW-based simulation generated a complete output set with the groundwater heads spatially and temporally distributed across all model layers and time steps. The groundwater head maps produced the expected coastal aquifer system flow pattern with a marked hydraulic gradient from inland recharge areas to the coastal boundary. This observation supports the model's representation of the region's hydrodynamic interactions due to the relief and recharge conditions. Specifically, the coastal boundary condition modeled as constant head to simulate the tidal influence behaved well as a sink, pulling groundwater flow from the central interior zones.

One of the simulation's key results was the development of drawdown cones around high-yielding pumping wells in agricultural and industrial areas near the coastline. Where water abstraction exceeded natural recharge in these areas, significant water level declines, or "drawdown," occurred, resulting in a depression of several meters. These areas demonstrated increased pumping, or steepened hydraulic gradients, that promote the landward shift of the saltwater-freshwater boundary, increasing the risk of saltwater intrusion. Transient simulations also showed that groundwater levels oscillated seasonally, recovering during monsoon months and experiencing depletion more intensively during the dry months. This research highlights the need for tighter control on water use during seasonal cycles and stress thresholds in the aquifer system in vulnerable regions.

4.2 Analysis of the Impact of Different Factors on Groundwater Flow

The coastal aquifers confirm that groundwater wells are more complex than previously studied. There are numerous parameters that have to be taken into consideration, such as pumping intensity, the coastal aquifer's hydraulic conductivity, and even the recharge rate variability over time. There are also greater disruptions to flow patterns due to pumping in key coastal areas. Natural gradients flow towards the sea; however, this changes greatly due to hydraulic vacuums created by heavy pumping and draws water towards the center instead, leading to saltwater incursion, ultimately ruining freshwater aquifer storage frameworks.

Freshwater aquifers also have great vertical variation resulting from differing geological layers of rock that have been compacted, rich in minerals like quartz, which pose a problem for water and its movement within the layers. Having larger regions of permeable rock leads to rapid groundwater movement, while lower permeable rock hinders depression in zones, pushing down on the groundwater on the surface. Vegetation has a large impact, however, where permeable soil can aid in replenishing bountiful groundwater, but urban areas do the opposite, where impervious materials lead to lower groundwater levels and less replenishment.

Sensitivity analysis showed that even small changes to recharge rates, plus or minus ten percent, significantly impacted the water balance, causing flow reversal in important transition zones. These results expose the need for integrated land use planning alongside the management of surface water and groundwater interactions. Land use changes, such as growing urban boundaries and shifting landscapes to farming, were found to worsen the decreased rate of recharge and raise the need for groundwater abstraction. The natural parameters of aquifers, along with human activity, highlight the need for systemized management strategies to ensure sustainable coastal aquifers using groundwater models and a socio-economic framework.

4.3 Comparison of Simulation Results with Field Data

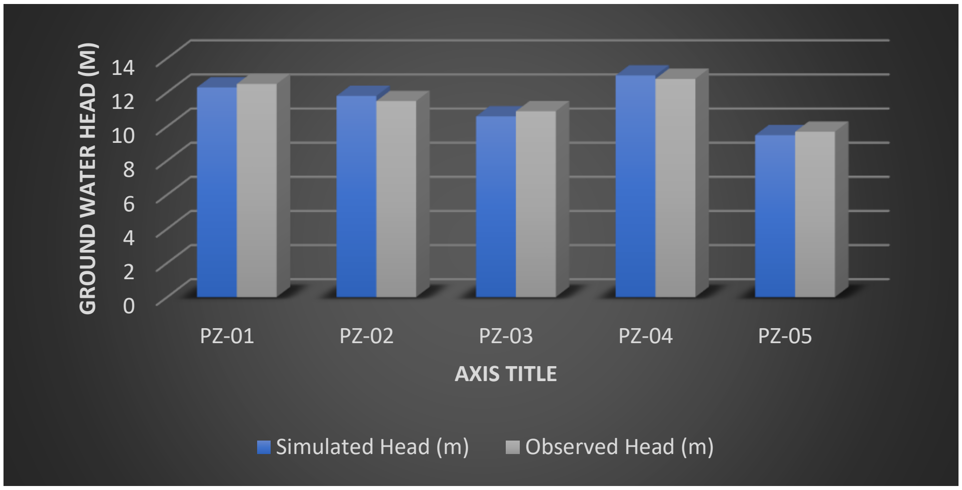

Figure 2: Comparison Of Simulated and Observed Groundwater Heads

Figure 2 demonstrates that simulated groundwater heads are being analyzed alongside observed values collected from five piezometric observation wells, PZ-01 to PZ-05. As depicted in the bar graph presented earlier, the simulated heads were in close alignment with the observed values, with a deviation of less than ±0.3 m, which is considered a very low and acceptable threshold. The evaluation produced an RMSE of 0.22 m, which shows that the model is quite accurate and confirms the field data.

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \qquad (2)$$

Where:

- Si simulated the groundwater head at location i
- Oi = observed groundwater head at location i
- n total number of observation points

The RMSE formula quantifies the average deviation between observed and simulated data. A low RMSE indicates good model performance and strengthens the model's reliability for future scenario testing.

V. Discussion

5.1 Interpretation of Results and Implications for Coastal Aquifer Management

This study emphasizes the practical application of MODFLOW in simulating groundwater movement in a coastal aquifer system. The distribution of hydraulic heads and flow vectors showed an inland-to-coastal flow pattern under natural conditions, which drastically changed in heavily pumped areas, resulting in reversed hydraulic gradients with possible seawater intrusion zones. These results illustrate the impact of over-extraction in coastal aquifers coupled with low recharge and changes in land use. Effective management of coastal aquifers requires controllable zoned limits on pumping, natural recharge zone improvements, and the monitoring of the freshwater-saltwater interface (Werner, 2010).

As well, the study illustrates how numerical modeling can act as a decision support tool, allowing proactive actions to be taken instead of reactive ones. Policymakers can establish safe yield limits, allocate groundwater rights, and determine priority wellfield zoning based on simulation outputs. Coupled with remote sensing and field monitoring, models can greatly enhance the adaptability of coastal water management frameworks under climate change and urban development pressure (Ghasemizadeh et al., 2012).

5.2 Discussion of the Strengths and Limitations of the Study

One of the main strengths of this study is how thoroughly the data were integrated, including hydrogeological features, climate patterns, and land use, which allowed for a realistic simulation of groundwater conditions. The use of MODFLOW-NWT, known for its stable simulations of unconfined aquifers with drying and rewetting cells, enhanced the convergence and robustness of the results. Additionally, calibration using observed head data and subsequent error minimization of RMSE added to the model credibility, given the outputs (Pandey et al., 2020).

Nonetheless, the study has some shortcomings. First, while MODFLOW does simulate the groundwater heads accurately, it does not simulate variable-density flow, which is especially important for coastal areas where freshwater and saltwater interact. Future work could incorporate the SEAWAT package to improve the depiction of salinity fluctuations

and address this gap (Hussain & Javadi, 2018). Second, the simulation accuracy is fundamentally constrained by available data and its resolution. For instance, along with spatial variability in recharge, heterogenous aquifer properties were simplified because of a lack of high-resolution field data, which could impact simulation granularity. Lastly, unregulated wells, land subsidence, and groundwater contamination as anthropogenic impacts were not explicitly modeled.

5.3 Recommendations for Future Research and Improvements in Groundwater Flow Simulation

As with all aquifers, SEAWAT and FEFLOW, solute and seawater intrusion transport models, would be beneficial in coastal areas with high saline concentration zones. This would enable more accurate modeling of saltwater intrusion, its response to pumping and recharge cycles, and its interaction with the surrounding environment. Also, there is a strong need for remote sensing and GIS technologies to augment the spatial accuracy of land use, recharge, and evapotranspiration datasets.

Improving parameter estimation and forecasting accuracy in data-scarce regions using ML (Machine Learning) is an encouraging focus. Recharge, extraction, and salinization interdependencies can be mapped accurately with ML-enhanced models tailored to recognize complex systems. Real-time sensor data integrated with MODFLOW simulations could establish proactive groundwater crisis management frameworks for coastal regions.

To address the sustainable use of aquifers in the face of uncertain conditions, future work should incorporate climate change projections, land-use modifications, and multi-objective optimization strategies. Such comprehensive frameworks are essential for protecting coastal aquifers from permanent damage while ensuring the availability of water resources for a prolonged period.

VI. Conclusion

6.1 Summary of Key Findings from the Study

This study proves the practicality and efficiency of the MODFLOW method in simulating the groundwater flow of a coastal aquifer impacted by human forces such as urbanization, agricultural growth, and the extensive pumping of groundwater resources. The model was able to replicate the complex governing interactions of water below the surface over a decade by incorporating spatially distributed hydrogeological, climatic, and land use information. Calibration concerning the observed groundwater head data from the monitoring wells showed a close correspondence between the estimated and observed values, thus confirming the model's applicability for both steady-state and transient flow simulations.

The simulation delineated critical groundwater stress areas, especially in the coastal fringe zones, where high abstraction coupled with low recharge gave rise to drawdown cones with reversed hydraulic gradients. These areas are more vulnerable to saltwater intrusion in the case of aquifers that do not get replenished artificially or naturally. The model also emphasized the impact of aquifer heterogeneity, showing that variations in hydraulic conductivity and specific yield significantly altered localized and regional flow patterns. These findings are important for the development of rational groundwater extraction limits as well as for future land and water use planning in these sensitive coastal areas.

6.2 Importance of Accurate Groundwater Flow Simulation in Coastal Aquifers

Coastal aquifers are under constant threat due to saline water and surface-level contamination, making them fragile. However, these shallow aquifers serve as an important source of freshwater for people living in densely populated areas. Assessing aquifer behavior requires accurate groundwater flow simulation, which is essential for examining the effects of rapid urbanization, climate change, and rising sea levels on the aquifer. Using a modular and flexible approach, MODFLOW's finite-difference grid structure supports the simulation of groundwater dynamics.

With the help of active groundwater management tools such as MODFLOW, practitioners and decision-makers are assessing the effects of land use and variable recharge on the health of aquifers. With advanced scenario-based analysis, MODFLOW is capable of predicting critical groundwater recharge zones, areas with dipped groundwater levels, and regions with potential saline water upconing. Risk assessment allows for predictive simulations, which in turn set off a chain of preemptive actions to control abstraction rates and strategically design tailored regulations for conservation targeted towards unique site conditions. With the relationship between climate change and water security evolving, MODFLOW serves as an essential tool for proactive and flexible governance.

6.*3 Potential Applications and Benefits of Using the MODFLOW Algorithm*

The versatility and modular design of MODFLOW make it an ideal platform for a wide range of applications in water resource planning and hydrogeological investigations. Its combination with SEAWAT for variable-density groundwater flow, MT3DMS for solute transport, and ZoneBudget for sub-regional water balance estimations showcases how far its utility stretches beyond simple flow modeling. This flexibility is vital when simulating the behavior of coastal aquifers, where factors such as saltwater intrusion, contaminant migration, or even tidal influences are of great importance.

MODFLOW-centered studies, from a policy and management point of view, can support diverse actions like the development of licensing frameworks for groundwater exploitation, the creation of aquifer protection zones, a framework for artificial recharge design, and evaluating infrastructure development on groundwater flow. It also helps in designing optimal well positions, predicting groundwater availability in the future, and providing assistance with Environmental Impact Assessments (EIAs) for large-scale projects.

In the context of adapting to climate change, the simulation of MODFLOW assists in forecasting aquifers' reactions to shifts in water recharge and recharge altitudes, allowing governments and agencies to develop resilient long-term strategies for safeguarding water resources. Moreover, the integration of machine learning and real-time sensors with MODFLOW enhances its use for water prediction in regions with less available data, catering to the rising focus on smart water management.

With these improvements, stakeholders will be able to make decisions based on data, bringing more effectiveness and fairness to groundwater governance on local, regional, and national levels.

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