

# Understanding Groundwater Modelling: Approaches and Methodology

C. P. Kumar, Former Scientist 'G', National Institute of Hydrology, Roorkee - 247667, India

## Abstract

This article provides an overview of groundwater modelling, a tool used to understand and manage groundwater resources. The article explains the three main types of groundwater models: analytical, numerical, and hybrid models, and outlines the stepwise methodology of groundwater modelling. The components of groundwater models are also discussed, including the geological and hydrogeological framework, boundary conditions, flow equations, contaminant transport, and model calibration and validation. Groundwater modelling is essential for sustainable groundwater use and protection and can provide insights into complex groundwater systems that cannot be easily observed through direct measurements.

## Introduction

Groundwater modelling is a powerful tool for understanding and managing groundwater resources. Groundwater modelling involves the use of mathematical and numerical models to simulate the behaviour of groundwater systems under different conditions. Groundwater modelling can be used for various purposes, including groundwater resource assessment, prediction of groundwater levels and quality, and evaluation of the impacts of human activities and climate change on groundwater resources.

Groundwater modelling can provide insights into the complex behaviour of groundwater systems that cannot be easily observed through direct measurements. Groundwater modelling can help to identify the most effective management strategies for sustainable groundwater use and protection.

## Groundwater Modelling Approaches

Groundwater modelling can be classified into three broad categories: analytical, numerical, and hybrid models.

**Analytical models** are based on mathematical equations that describe the flow of groundwater through porous media. Analytical models can provide fast and accurate solutions for simple groundwater problems, such as steady-state flow and flow in confined aquifers. However, analytical models are limited in their ability to represent complex groundwater systems and processes.

**Numerical models** are based on the discretization of groundwater systems into smaller units, such as cells or nodes. Numerical models solve the flow equations for each unit using iterative methods. Numerical models can represent complex groundwater systems and

processes, including variable aquifer properties, transient flow, and contaminant transport. However, numerical models require significant computational resources and expertise.

**Hybrid models** combine the advantages of analytical and numerical models. Hybrid models use simplified analytical solutions for some parts of the groundwater system and numerical methods for others. Hybrid models can reduce the computational requirements of numerical models while still representing complex groundwater systems and processes.

## **Stepwise Methodology of Groundwater Modelling**

**Develop a conceptual model:** Before beginning the actual modelling process, it is important to develop a clear and comprehensive understanding of the hydrogeological system being modelled. This involves gathering and analyzing data on the geology, hydrology, and other relevant factors, and developing a conceptual model that accurately represents the system.

**Choose an appropriate modelling software:** There are many different groundwater modelling software packages available, each with their own strengths and weaknesses. It is important to choose a software that is appropriate for the specific objectives of the study, and that can handle the complexity and scale of the hydrogeological system being modelled.

**Gather high-quality data:** Accurate data is crucial for developing an accurate model. This includes data on groundwater levels, aquifer properties, hydraulic conductivity, and other relevant parameters. It is important to ensure that the data is collected using appropriate methods and is of high quality.

**Validate the model:** Once the model is developed, it is important to validate it using independent data sets, such as data from monitoring wells. This helps to ensure that the model accurately represents the hydrogeological system being modelled.

**Conduct sensitivity analyses:** Sensitivity analyses can help to identify the most important parameters in the model, and can help to assess the robustness of the model. This involves varying input parameters and observing the effect on the model outputs.

**Communicate the results:** The results of the modelling study should be communicated clearly and effectively to stakeholders, such as regulatory agencies, water resource managers, and the general public. This can involve presenting the results in a visual format, such as maps or graphs, and providing a clear explanation of the implications of the results.

**Update the model as necessary:** As new data becomes available, or as the hydrogeological system changes over time, the model should be updated to ensure that it remains accurate and useful.

## **Groundwater Modelling Components**

Groundwater models consist of several components that represent the different aspects of groundwater systems.

## Geological and Hydrogeological Framework

The geological and hydrogeological framework represents the physical properties of the groundwater system, such as the distribution and properties of aquifers and aquitards. The geological and hydrogeological framework is based on geological maps, borehole data, and geophysical surveys.

The geological and hydrogeological framework is represented in groundwater models using a grid or mesh of cells or nodes. Each cell or node represents a volume of the groundwater system with specific hydraulic properties, such as hydraulic conductivity and porosity.

## Boundary Conditions

Boundary conditions represent the inputs and outputs of groundwater systems, such as recharge, discharge, and water use. Boundary conditions can be either constant or time-varying.

Boundary conditions are essential for predicting the behaviour of groundwater systems under different conditions. Boundary conditions can be based on measurements, such as groundwater levels and streamflow, or estimated using hydrological models.

## Flow Equations

Flow equations represent the flow of groundwater through porous media. The most common flow equations used in groundwater modelling are the Dupuit-Forchheimer equation and the groundwater flow equation.

The Dupuit-Forchheimer equation is a simplified equation that assumes steady-state, horizontal flow in unconfined aquifers. The groundwater flow equation is a more general equation that can represent transient, multidirectional flow in confined and unconfined aquifers.

Flow equations can be solved using analytical or numerical methods. Numerical methods, such as the finite difference and finite element methods, are the most commonly used methods for solving flow equations.

## Contaminant Transport

Contaminant transport represents the movement and fate of contaminants in groundwater systems. Contaminant transport is represented by advection, dispersion, and diffusion processes.

Contaminant transport can be affected by various factors, such as the properties of the contaminants, the hydraulic properties of the aquifer, and the chemical and biological reactions that occur in the groundwater system.

Contaminant transport can be modelled using analytical or numerical methods. Numerical methods, such as the finite difference and finite element methods, are the most commonly used methods for solving contaminant transport equations.

## Model Calibration and Validation

Model calibration and validation are essential components of groundwater modelling. Model calibration involves adjusting the model parameters to match observed data, such as groundwater levels or pumping rates. Model validation involves testing the model's ability to predict the behaviour of groundwater systems under different conditions.

Model calibration and validation are critical for ensuring the accuracy and reliability of groundwater models. Model calibration and validation can be challenging due to the complexity and uncertainty of groundwater systems and the limitations of data.

## Uncertainty and Sensitivity Analysis

Groundwater models are subject to various sources of uncertainty, such as errors in data, model parameters, and conceptual models. Uncertainty and sensitivity analysis are essential components of groundwater modelling that can help to quantify and reduce uncertainty.

Uncertainty analysis involves evaluating the range and probability of outcomes of groundwater models under different scenarios. Sensitivity analysis involves evaluating the sensitivity of groundwater models to different model parameters.

Uncertainty and sensitivity analysis can help to identify the most significant sources of uncertainty and the most critical parameters in groundwater models. Uncertainty and sensitivity analysis can also help to improve the robustness and reliability of groundwater models.

## Applications of Groundwater Modelling

Groundwater modelling has numerous applications in groundwater resource management and environmental protection.

### Groundwater Resource Assessment

Groundwater modelling can be used to assess the quantity and quality of groundwater resources in different regions. Groundwater modelling can provide insights into the potential impacts of human activities and climate change on groundwater resources.

Groundwater modelling can help to identify the most effective management strategies for sustainable groundwater use and protection. Groundwater modelling can also help to evaluate the impacts of groundwater pumping on surface water resources and ecosystems.

### Groundwater Remediation

Groundwater modelling can be used to design and evaluate the effectiveness of groundwater remediation strategies. Groundwater modelling can help to predict the behaviour of contaminants in groundwater systems and the effectiveness of different remediation techniques.

Groundwater modelling can also help to optimize the design and operation of remediation systems, such as pumping and treatment systems.

## Land Use Planning

Groundwater modelling can be used to evaluate the impacts of land use changes on groundwater resources. Groundwater modelling can help to predict the impacts of land use changes, such as urbanization and agricultural intensification, on groundwater recharge, discharge, and quality.

Groundwater modelling can also help to identify the most effective land use management strategies for sustainable groundwater use and protection.

## Groundwater Modelling Codes

There are several modelling codes available for groundwater modelling. Here are some of the most commonly used codes:

**MODFLOW** (MODular Finite-Difference Flow model): MODFLOW is a software package developed by the U.S. Geological Survey (USGS) that is used to simulate groundwater flow in three dimensions. It includes a range of features, such as the ability to simulate variable-density flow and solute transport.

**FEFLOW** (Finite Element subsurface FLOW system): FEFLOW is a software package developed by the German Research Centre for Geosciences that is used to simulate groundwater flow and transport in three dimensions. It includes a range of features, such as the ability to simulate heat transport and the interaction between groundwater and surface water.

**SEAWAT** (SEAwater-intrusion and Tidal effects model): SEAWAT is a software package developed by the USGS that is used to simulate groundwater flow and transport in coastal aquifers. It includes a range of features, such as the ability to simulate saltwater intrusion and the effects of tides on groundwater levels.

**MODPATH** (MODular PATHline analysis): MODPATH is a software package developed by the USGS that is used to simulate the movement of particles in groundwater flow. It is often used in conjunction with MODFLOW to study contaminant transport and other groundwater-related issues.

**PEST** (Parameter ESTimation): PEST is a software package developed by the Watermark Numerical Computing company that is used to calibrate groundwater models. It includes a range of optimization algorithms that can be used to adjust model parameters to better match observed data.

These are just a few examples of the many modelling codes available for groundwater modelling. The choice of code depends on the specific needs and requirements of the modelling project, as well as the expertise and resources available to the modelling team.

## Conclusion

Groundwater modelling is a powerful tool for understanding and managing groundwater resources. Groundwater modelling can provide insights into the complex behaviour of

groundwater systems and the impacts of human activities and climate change on groundwater resources.

Groundwater modelling requires a comprehensive understanding of the physical and chemical processes that occur in groundwater systems, as well as the uncertainties and limitations of data and models. Groundwater modelling also requires collaboration between water managers, policymakers, scientists, and the public to ensure the effective use and protection of groundwater resources.

By adopting a comprehensive and integrated approach to groundwater modelling, we can ensure the sustainable use and protection of groundwater resources for generations to come.