Modelling Seawater Intrusion in Coastal Aquifers: An Overview of Methods and Approaches

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Abstract

Seawater intrusion is a common phenomenon that occurs in coastal aquifers, leading to degradation of water quality, reduction in water availability, and increased cost of water treatment. Accurate modelling of seawater intrusion is essential for effective management and conservation of coastal aquifers. This article provides an overview of the various methods and approaches used for modelling seawater intrusion, including analytical, semi-analytical, numerical, integrated, and data-driven models. The advantages and disadvantages of each modelling approach are discussed, and recommendations for future research are provided. The article aims to provide a comprehensive understanding of the different methods available for modelling seawater intrusion and help researchers and practitioners in selecting the appropriate approach based on the complexity of the problem, available data, and computational resources.

Introduction

Seawater intrusion is a common phenomenon that occurs in coastal aquifers, where saline water infiltrates the freshwater aquifer due to natural or anthropogenic reasons. This process can result in the degradation of water quality, reduction in water availability, and increase in the cost of water treatment. Therefore, the development of accurate models to predict the behavior of seawater intrusion is essential for effective management and conservation of coastal aquifers. This article provides an overview of the various methods used for modelling seawater intrusion and their advantages and disadvantages.

Analytical models

Analytical models are based on the solution of mathematical equations that describe the physical processes that govern seawater intrusion. These models are simple, fast, and require minimal data input. The most commonly used analytical model for seawater intrusion is the Ghyben-Herzberg model, which assumes a two-layer system, with a freshwater layer overlaying a saltwater layer of constant density. The Ghyben-Herzberg model provides a simple and conservative estimate of the seawater-freshwater interface location, but it has limitations as it does not account for vertical and horizontal heterogeneity, and the effect of groundwater pumping.

- ❖ Ghyben-Herzberg model can be easily implemented using Excel or any other spreadsheet software that can perform simple calculations.

Semi-analytical models

Semi-analytical models are based on the solution of partial differential equations that describe the physical processes that govern seawater intrusion. These models are more complex than analytical models and require more data input, but they provide more accurate predictions. The most commonly used semi-analytical model for seawater intrusion is the Sharp Interface Model (SIM), which assumes a sharp interface between the freshwater and saltwater zones. The SIM model takes into account vertical and horizontal heterogeneity, and the effect of groundwater pumping. However, it has limitations as it does not account for dispersion and mixing.

- Sharp Interface Model (SIM) can be implemented using the SEAWAT code, which is part of the USGS MODFLOW groundwater modelling software package.
- Another option is to use the SEAWAT-MT3DMS package, which includes the SEAWAT code for simulating variable-density flow and transport in porous media.

Numerical models

Numerical models are based on the discretization of the domain into a grid, and the solution of partial differential equations that describe the physical processes that govern seawater intrusion. These models are the most accurate and flexible, but they require a large amount of data input and computational resources. The most commonly used numerical models for seawater intrusion are the Finite Difference Method (FDM), the Finite Element Method (FEM), and the Boundary Element Method (BEM). These models take into account vertical and horizontal heterogeneity, the effect of groundwater pumping, dispersion, and mixing. The choice of the numerical method depends on the complexity of the problem, the available data, and the computational resources.

- Finite Difference Method (FDM) can be implemented using MODFLOW, which is a popular groundwater flow modelling software package.
- Finite Element Method (FEM) can be implemented using FEFLOW, which is a powerful groundwater modelling software that uses the finite element method for simulating groundwater flow and transport.
- Boundary Element Method (BEM) can be implemented using the BEMMOD software, which is a boundary element-based groundwater modelling software package.

Integrated models

Integrated models are combinations of two or more modelling approaches, and they aim to provide a more accurate representation of the physical processes that govern seawater intrusion. Integrated models can be classified into two categories: deterministic and stochastic. Deterministic integrated models use a single set of input data to provide a single output, while stochastic integrated models use multiple sets of input data to provide a range of possible outputs. The most commonly used integrated models for seawater intrusion are the Analytical- Numerical Model (ANM), the Analytical- Stochastic Model (ASM), and the Numerical- Stochastic Model (NSM).

- Analytical-Numerical Model (ANM) can be implemented using a combination of Excel and MODFLOW.
- Analytical-Stochastic Model (ASM) can be implemented using the analytical model in Excel and a stochastic simulation tool such as Monte Carlo simulation in MATLAB.

- ❖ Numerical-Stochastic Model (NSM) can be implemented using FEFLOW and Monte Carlo simulation in MATLAB.

Data-driven models

Data-driven models are based on statistical and machine learning techniques, and they aim to predict the behavior of seawater intrusion based on historical data. Data-driven models require a large amount of data input, but they can provide accurate predictions without the need for detailed knowledge of the physical processes that govern seawater intrusion. The most commonly used data-driven models for seawater intrusion are the Artificial Neural Network (ANN) model and the Support Vector Regression (SVR) model.

- ❖ Artificial Neural Network (ANN) model can be implemented using software packages such as MATLAB, Python (using libraries like Keras or Tensorflow), or commercial software packages like Neural Designer or NeuroSolutions.
- ❖ Support Vector Regression (SVR) model can be implemented using MATLAB or Python (using libraries like scikit-learn).

Conclusion

Seawater intrusion is a complex process that requires accurate modelling for effective management and conservation of coastal aquifers. Various modelling approaches have been developed, ranging from simple analytical models to complex integrated and data-driven models. The choice of modelling approach depends on the complexity of the problem, the available data, and the computational resources. Analytical models provide a simple estimate of the seawater-freshwater interface location, but they have limitations in accounting for vertical and horizontal heterogeneity and the effect of groundwater pumping. Semi-analytical models provide a more accurate estimate of seawater intrusion, but they also have limitations in accounting for dispersion and mixing. Numerical models are the most accurate and flexible, but they require a large amount of data input and computational resources. Integrated models combine two or more modelling approaches and provide a more accurate representation of the physical processes that govern seawater intrusion. Data-driven models are based on statistical and machine learning techniques and require a large amount of data input, but they can provide accurate predictions without the need for detailed knowledge of the physical processes.

In conclusion, modelling of seawater intrusion is a complex process that requires the integration of various modelling approaches. The development of accurate models is essential for effective management and conservation of coastal aquifers. Therefore, it is important to select the appropriate modelling approach based on the complexity of the problem, the available data, and the computational resources. Future research should focus on the development of more accurate and efficient models that can provide reliable predictions of seawater intrusion under different scenarios.