Simulation and Sensitivity Analysis of Seawater Intrusion Using FEFLOW in a Confined Coastal Aquifer

Abstract

Seawater intrusion (SWI) is a critical problem for coastal aquifers subject to over-extraction, climate variability, and reduced recharge. This study presents a two-dimensional density-dependent groundwater flow and solute transport simulation of a Henry-type coastal aquifer using FEFLOW. A simplified vertical confined aquifer (2 m × 1 m) with a constant freshwater inflow boundary and a hydrostatic seawater boundary was modeled. Sensitivity analysis was performed on hydraulic conductivity, porosity, molecular diffusion coefficient, longitudinal and transverse dispersivity, and freshwater inflow. Results show a classic interface pattern consistent with the Henry benchmark, with saltwater intrusion strongly influenced by hydraulic properties and dispersion parameters. Higher hydraulic conductivity, diffusion, and dispersivity increase mixing and intrusion, while higher freshwater inflow reduces intrusion significantly. The model confirms the suitability of FEFLOW for density-dependent flow analysis and provides insights into controlling factors governing SWI in coastal aquifers.

Keywords

Seawater intrusion; FEFLOW; Henry problem; density-dependent flow; solute transport; coastal aquifer; dispersivity; diffusion.

1. Introduction

Coastal aquifers are vital freshwater sources for domestic, agricultural, and industrial uses. However, they are vulnerable to seawater intrusion (SWI), particularly in arid and semi-arid regions where groundwater demand is high and natural recharge is limited. SWI occurs when the hydraulic gradient toward the sea is reversed or weakened, allowing dense saline water to migrate into freshwater zones (Barlow, 2016; Werner et al., 2013). This process compromises the quality of groundwater resources and poses long-term risks to water sustainability.

Understanding SWI requires simulating coupled flow and transport processes, as the movement of saline water depends on density-driven flow interactions. Numerical models offer the most reliable approach to represent these nonlinear processes under controlled conditions.

This study focuses on the classical Henry problem, a widely used benchmark for evaluating density-dependent numerical models. Using FEFLOW, we simulate SWI in a simplified coastal confined aquifer and evaluate the sensitivity of intrusion to key hydrogeological parameters. The outcomes provide valuable insights into the mechanisms driving SWI and the impact of aquifer properties.

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2. Literature Review

2.1 Seawater Intrusion in Coastal Aquifers

SWI has been extensively studied using analytical, experimental, and numerical approaches. Early analytical solutions such as the Ghyben–Herzberg relation provided simplified approximations of the freshwater–saltwater interface but ignored critical factors such as dispersion, transient dynamics, and density effects (Cooper, 1959). Numerical models allow simulation of the full density-coupled flow field and have become essential tools for SWI assessment (Bear, 1979).

2.2 The Henry Problem

The Henry problem (Henry, 1964) is the standard benchmark for evaluating variable-density groundwater models. It consists of a rectangular domain with freshwater inflow on one boundary and hydrostatic seawater boundary conditions on the opposite boundary, leading to a characteristic interface shape influenced by advection, dispersion, and diffusion. Numerous studies have extended the Henry problem using finite element and finite difference models (Voss & Souza, 1987; Ackerer et al., 2004).

2.3 Numerical Modeling Tools

Common numerical codes for SWI include:

- **SUTRA** (Voss, 1984): Saturated–unsaturated variable-density flow.
- **SEAWAT** (Langevin et al., 2008): MODFLOW-based density-coupled flow and transport.
- **FEFLOW** (Diersch, 2014): Finite element code with strong coupling capabilities.

FEFLOW stands out for its flexibility in mesh design, strong coupling algorithms, and capability to handle nonlinear density effects efficiently.

2.4 Sensitivity of SWI to Aquifer Properties

Previous studies have demonstrated that SWI is highly sensitive to aquifer parameters such as hydraulic conductivity, porosity, diffusion, dispersivity, and recharge. Higher hydraulic conductivity promotes intrusion due to weaker inland gradients (Werner et al., 2013). Diffusion and dispersivity expand the mixing zone (Zhang et al., 2002). Recharge acts as the primary counter-intrusion mechanism.

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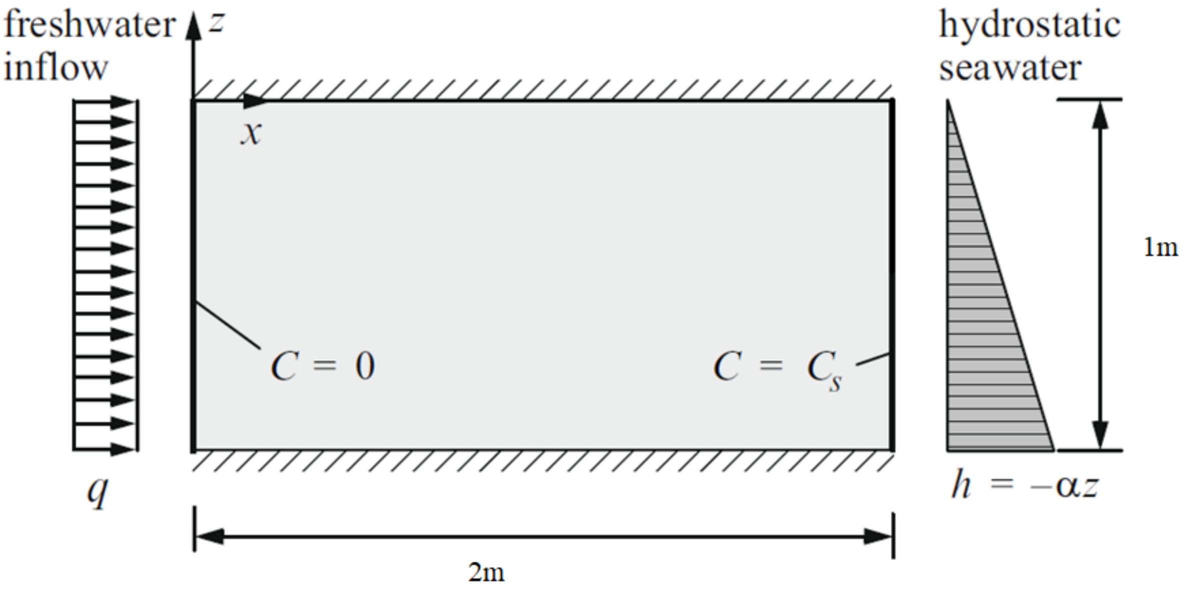
3. Conceptual Model and Governing Equations

3.1 Conceptual Model

The conceptual model represents a simplified two-dimensional vertical cross-section of a coastal confined aquifer with a total length of 2 m and a depth of 1 m. The domain is assumed to be fully saturated, homogeneous, isotropic, and rectangular, allowing for controlled examination of density-dependent flow processes. A constant freshwater inflow is applied along the left vertical boundary, where the solute concentration is fixed at C=0 mg/L, representing inland recharge. The right vertical boundary is subjected to hydrostatic seawater pressure, with a prescribed concentration of C=3500 mg/L to represent saline ocean water. The upper and lower boundaries are treated as impermeable no-flow boundaries, preventing both fluid and solute exchange across these limits.

The initial condition assumes a uniform freshwater concentration throughout the domain, with hydraulic head subsequently evolving according to the imposed boundary gradients. Hydrogeological properties are assigned uniformly, including hydraulic conductivity K=864 m/d, porosity n=0.35, molecular diffusion coefficient D=6.6 x 10^{-6} m²/s, and zero longitudinal and transverse dispersivities ($\alpha_L = \alpha_T = 0$) in the base case. This conceptual configuration captures the key physical processes governing seawater intrusion, including freshwater–seawater interface formation, density-driven circulation, and development of the transition (mixing) zone.



A two-dimensional vertical cross-section (2 m long and 1 m high) was constructed to represent a simplified confined coastal aquifer. The left vertical boundary serves as a freshwater inflow boundary, while the right boundary represents seawater with hydrostatic pressure distribution:

$$h = -0.025z$$

3.2 Steady-State Governing Equations

Under steady-state conditions, the system is in hydraulic and chemical equilibrium**,** meaning that no changes occur with time**.** All head and concentration gradients remain constant. Therefore, the storage terms in both flow and transport equations vanish.

3.2.1 Steady-State Flow Equation

$$\boldsymbol{\nabla} . (\boldsymbol{\rho q}) = \boldsymbol{\rho Q}$$

This equation expresses conservation of mass for groundwater under equilibrium conditions.

- q is the Darcy flux (m/s), describing groundwater flow through the porous medium.
- ρ is the fluid density**,** which may vary with solute concentration.
- Q is sources or sinks (e.g., injection wells, pumping wells, recharge).

In steady state, the amount of water entering any part of the aquifer equals the amount leaving it; therefore, no accumulation term appears.

3.2.2 Steady-State Solute Transport Equation

$$\nabla . \left(nD_{eff}\, \nabla C\right) - \nabla . (Cq) + R = 0$$

This equation describes the steady distribution of solute concentration in the aquifer.

- n is porosity, representing the fraction of void space available for fluid and solute storage.
- D_{eff} is the effective diffusion–dispersion tensor, incorporating both:
    - molecular diffusion, and
    - mechanical dispersion due to velocity variations.
- C is the solute concentration (e.g., salt concentration).
- R represents sources or reactions, such as salt injection or decay.

Since the system is at equilibrium, concentration does not change with time. The balance between diffusion, dispersion, and advective transport creates a stable saltwater wedge typical of coastal aquifers.

3.3 Transient-State Governing Equations

In transient simulations, both hydraulic head and solute concentration change with time. Storage terms are included to describe the time-dependent evolution of the system.

3.3.1 Transient Flow Equation

$$\frac{\partial}{\partial t}(\rho S_s h) + \nabla.(\rho q) = \rho Q$$

This equation incorporates time-dependent groundwater storage.

- The term

  $$\frac{\partial}{\partial t}(\rho S_s h)$$

  represents water storage changes in confined aquifers.

  It arises from:

    - elastic compression of the porous matrix, and
    - expansion/compression of the fluid.
- The term

  $$\nabla.(\rho q)$$

  accounts for flow divergence, identical to the steady-state form.

Transient flow is necessary to simulate how the system evolves from initial conditions toward equilibrium.

3.3.2 Transient Solute Transport Equation

The transient solute transport equation solved in FEFLOW is written as:

$$\frac{\partial\,(nC)}{\partial t} = \nabla\,.\left(nD_{eff}\,\nabla C\right) - \nabla\,.(Cq) + R$$

This equation describes the time-dependent evolution of solute concentration within the groundwater system and incorporates the effects of accumulation, diffusion, mechanical dispersion, advection, and external sources or sinks.

This equation represents time-dependent solute movement controlled by:

- **Advection**: movement of solutes with flowing groundwater

$$\nabla\,.(Cq)$$

This term represents solute transport by bulk groundwater flow.

- Solutes move with the Darcy flux q
- Controls the direction and rate of solute transport
- In seawater intrusion, advection drives saltwater landward along hydraulic gradients

Advection is often the dominant transport mechanism in coastal aquifers.

2. Diffusion and Mechanical Dispersion Term

$$\boldsymbol{\nabla\,.\left(nD_{eff}\,\nabla C\right)}$$

The effective dispersion tensor combines:

- **Molecular diffusion:**
  Spreading of solute from regions of high to low concentration due to thermal motion.
- **Mechanical dispersion:**
  Spreading caused by variations in groundwater velocity at the pore scale.

For this study's base case:

$$\alpha_L = \alpha_T = 0$$

which means dispersion is negligible, and spreading is controlled primarily by molecular diffusion.

This term governs the broadening of the mixing zone between freshwater and seawater.

4. Reaction / Source–Sink Term

$$R$$

This term accounts for:

- external solute injection
- solute removal
- chemical reactions (if present)

In the Henry problem (and in your model), R=0, but the term is included for completeness.

4. Numerical Model Setup (FEFLOW)

- Mesh: 1185 triangular elements
- Hydraulic conductivity K=864K = 864K=864 m/d
- Porosity n=0.35n = 0.35n=0.35
- Molecular diffusion D=6.6×10−6 m2/sD = 6.6 \times 10^{-6} \, \mathrm{m^2/s}D=6.6×10−6m2/s
- Dispersivity (base): αL=0\alpha_L = 0αL=0, αT=0\alpha_T = 0αT=0
- Freshwater inflow q=5.7024q = 5.7024q=5.7024 m/d

Sensitivity analyses varied each parameter individually.

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5. Results and Discussion

5.1 Hydraulic Head Distribution

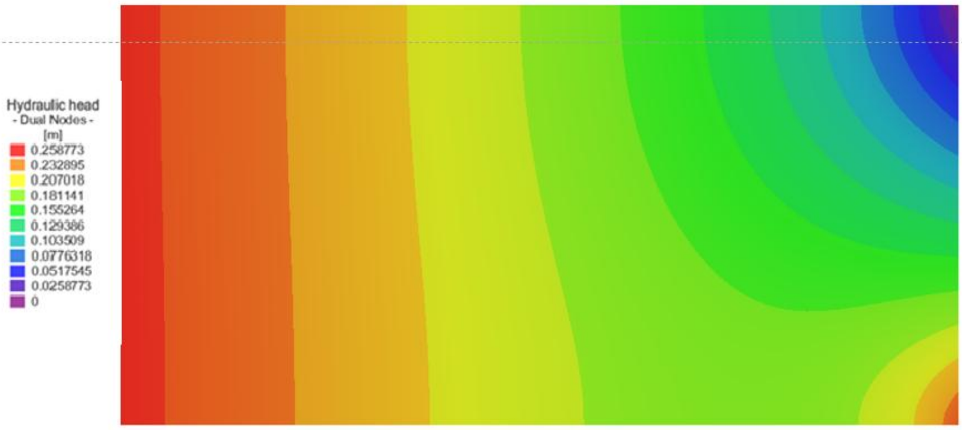


Figure 1. Hydraulic head distribution.
The hydraulic head field demonstrates a downward-curving pattern typical of density-driven systems, where hydraulic gradients are influenced by spatial density variations. The freshwater head decreases toward the seawater boundary.

5.2 Salt Concentration Distribution

Figure 2. Salt concentration distribution.

A stable freshwater–seawater interface develops, with a characteristic diffusion-dominated mixing zone. Higher concentrations occur near the coastal boundary, gradually diffusing inward. Results resemble classical Henry profiles, confirming model validity.

5.3 Sensitivity Analysis

5.3.1 Hydraulic Conductivity

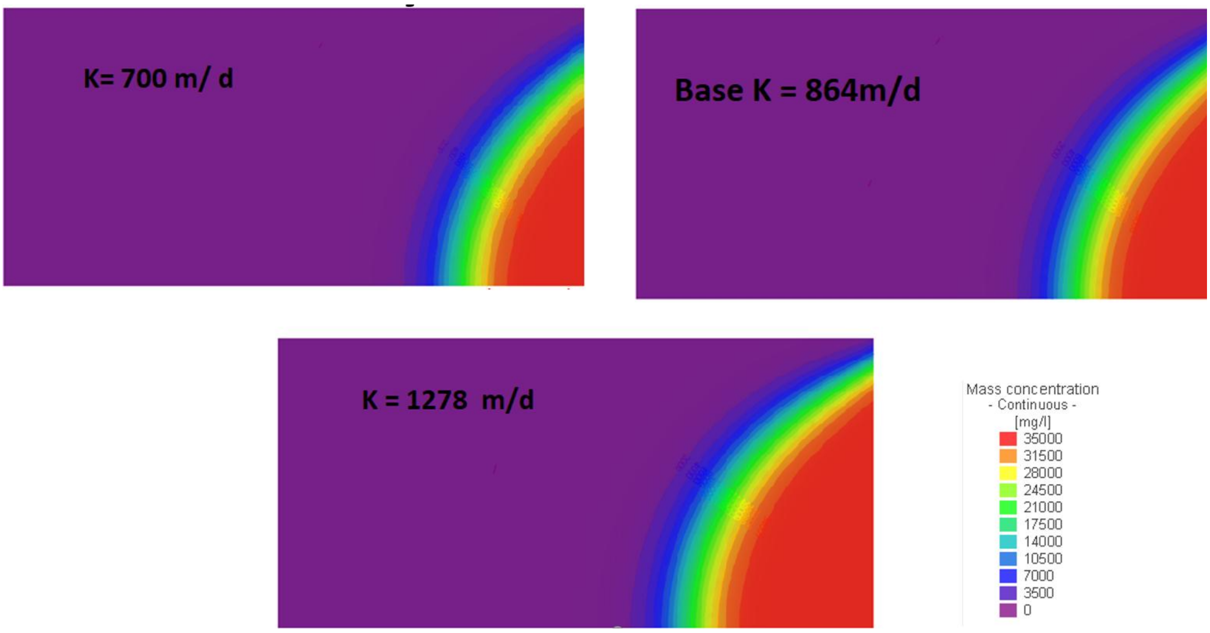


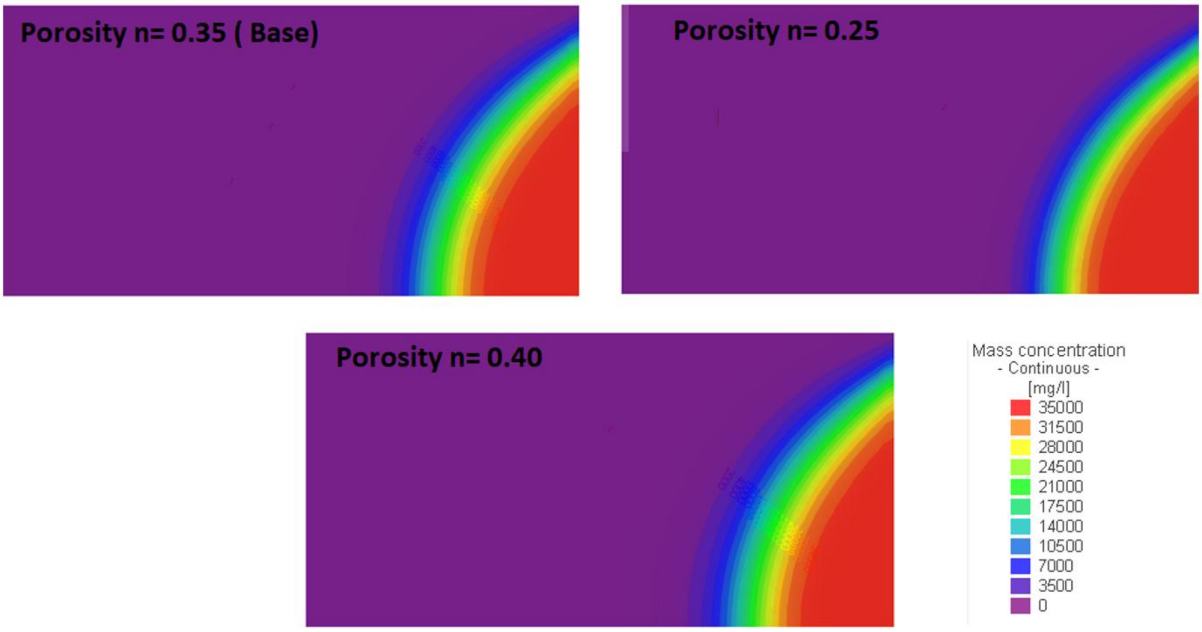
Figure 3. Sensitivity to hydraulic conductivity.

Higher conductivity increases intrusion length and widens the interface due to lower hydraulic resistance.

- Lower K (700 m/d): Intrusion decreases; mixing zone shrinks.
- Higher K (1278 m/d): Intrusion increases; interface moves landward.

Interpretation:
Higher K increases saltwater penetration due to reduced hydraulic gradient, consistent with studies by Werner et al. (2013).

5.3.2 Porosity



Porosity n= 0.35 (Base)

Porosity n= 0.25

Porosity n= 0.40

Figure 4. Sensitivity to porosity.

Higher porosity increases the mixing zone thickness due to enhanced storage and slower advection.

- Lower n = 0.25 → sharper interface (less mixing).
- Higher n = 0.40 → wider mixing zone.

Interpretation:
Higher porosity increases storage and diffusion path length, broadening the mixing zone.

5.3.3 Diffusion Coefficient

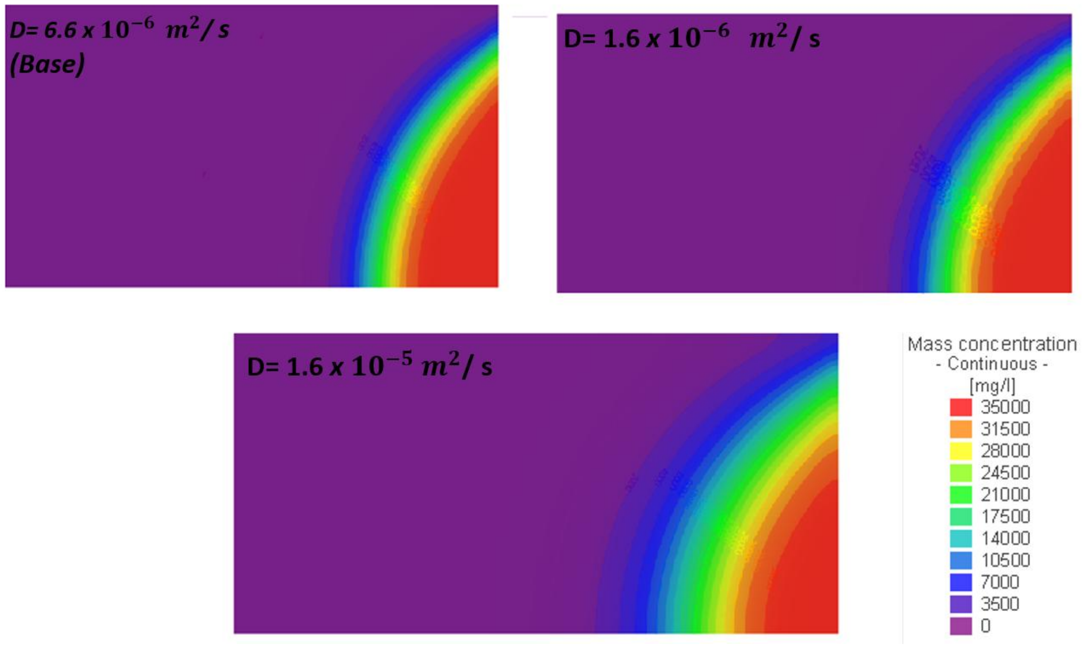


Figure 5. Effect of molecular diffusion.

Increasing molecular diffusion significantly broadens the mixing zone, confirming its role in smoothing sharp concentration gradients.

- Lower $D = 1.6\times10^{-6}$ → steep interface.
- Higher $D = 1.6\times10^{-5}$ → large mixing zone.

Interpretation:
Diffusion strongly enhances smoothing of the concentration gradient.

5.3.4 Longitudinal and Transverse Dispersivity

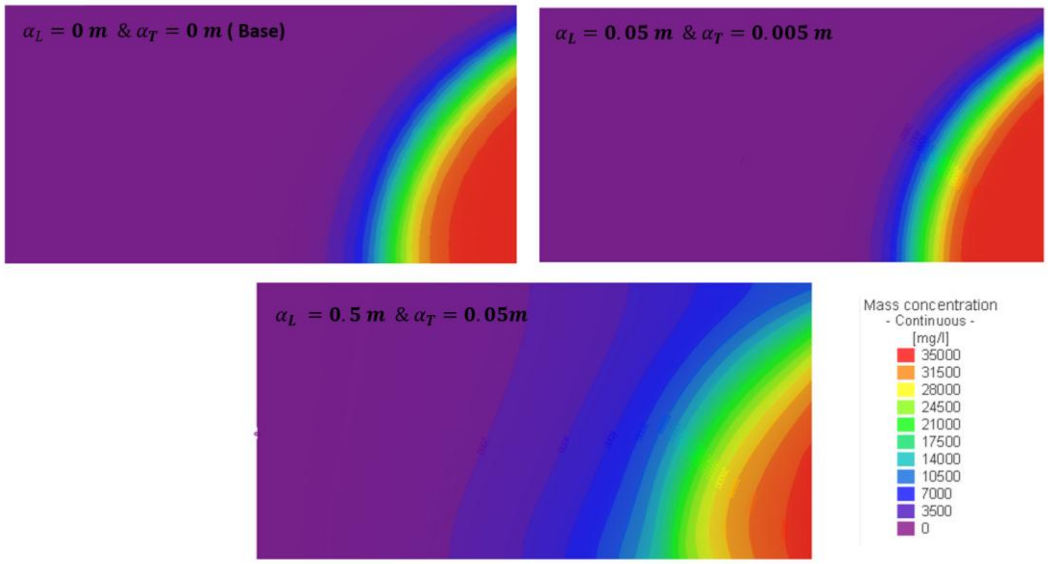


Figure 6. Sensitivity to dispersivity.

Dispersivity strongly affects interface spread. Large dispersivities lead to extensive mixing and less distinct interfaces. Increasing dispersivity magnifies mixing, especially in the lower part of the domain where velocities increase.

- αL = 0.5 m, αT = 0.05 m → thickest mixing zone.

Interpretation:
Mechanical dispersion plays a dominant role in interface development.

5.3.5 Freshwater Inflow

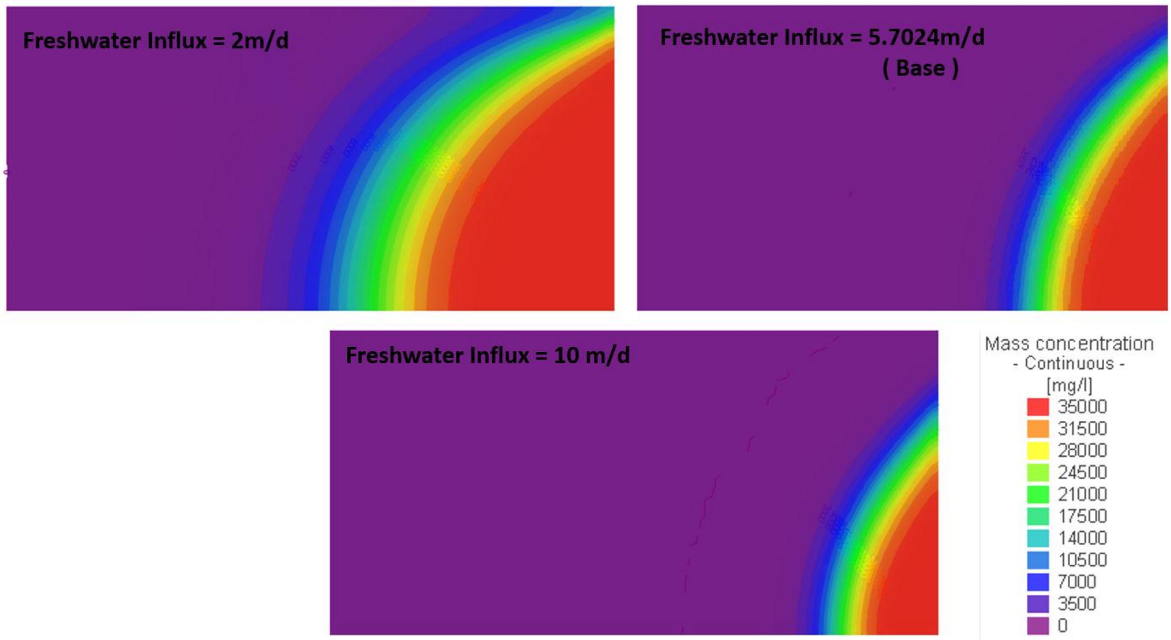


Figure 7. Effect of freshwater inflow.

Enhancing freshwater inflow dramatically pushes the seawater interface seaward, confirming inflow as the dominant control factor.

- q = 2 m/d → large intrusion
- q = 5.7 m/d → base case
- q = 10 m/d → intrusion toe moves seaward significantly

Interpretation:
Freshwater inflow is the strongest counter-intrusion mechanism

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6. Conclusions

This study used FEFLOW to model density-driven groundwater flow and solute transport in a Henry-type coastal aquifer. The simulation successfully reproduced the freshwater–saltwater interface and matched benchmark SWI behavior.

Key findings:

1. Hydraulic conductivity and freshwater inflow have the strongest influence on intrusion extent.

2. Diffusion and dispersivity control mixing zone thickness.
3. Porosity affects solute spread by altering storage capacity.
4. FEFLOW is reliable for density-dependent flow simulations.

The results enhance understanding of key parameters affecting SWI and can support groundwater management decisions.

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