Mechanisms, configuration typology, and vulnerability of pumping-induced seawater intrusion in heterogeneous aquifers

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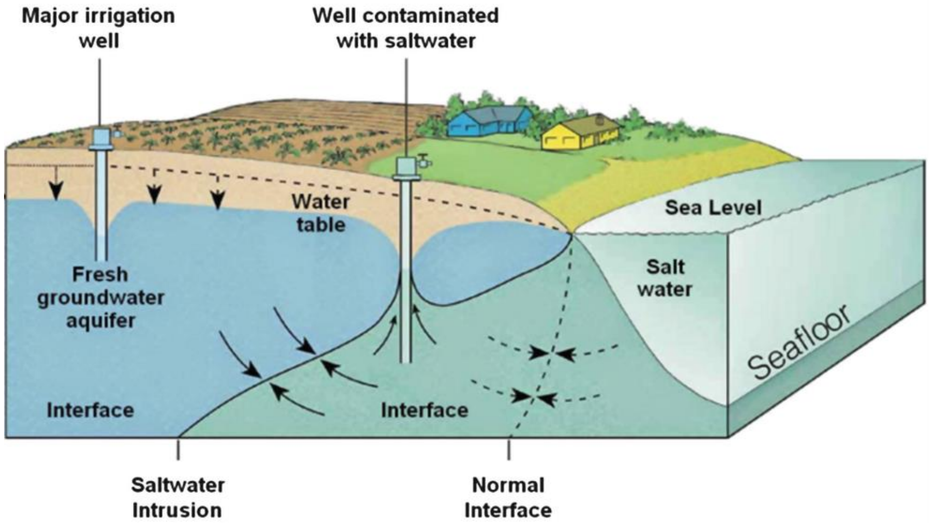
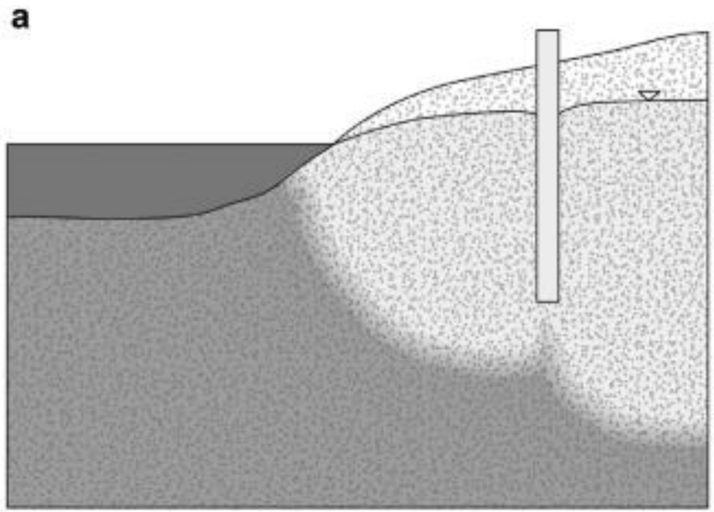


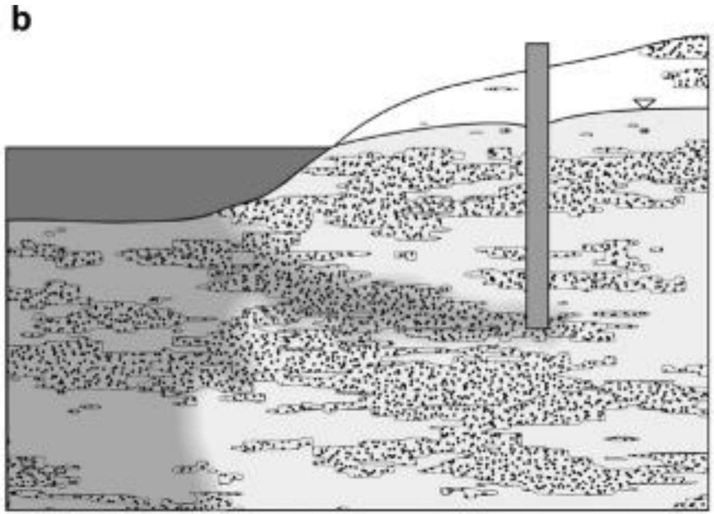
Seawater intrusion phenomenon process in the coastal aquifer ***(Groundwater U, 2021)***

- Freshwater resources in coastal areas are critical to human health and economies, agriculture, and ecosystems ***(e.g. Langston et al., 2017; White and Kaplan, 2017; Xiao et al., 2018)***.
- In many areas, intensive groundwater pumping has resulted in **widespread seawater intrusion (SWI)**, driving aquifers beyond sustainability ***(Werner et al., 2013).***
- **Numerical models** are useful for a more realistic simulation of SWI processes, considering fresh and saline groundwater's nonlinearity, transience, and miscibility.

Introduction



Homogeneous conceptual model



Heterogeneous conceptual model

- Due to the flexibility, most studies on **vulnerability assessment** of SWI assume **homogeneous aquifer** properties or **simplified layered geology**.

- Although much of our understanding of SWI mechanisms and management are derived from homogeneous models, **aquifer heterogeneity has critically affected** both salinity distributions and seawater intrusion processes.

Objective

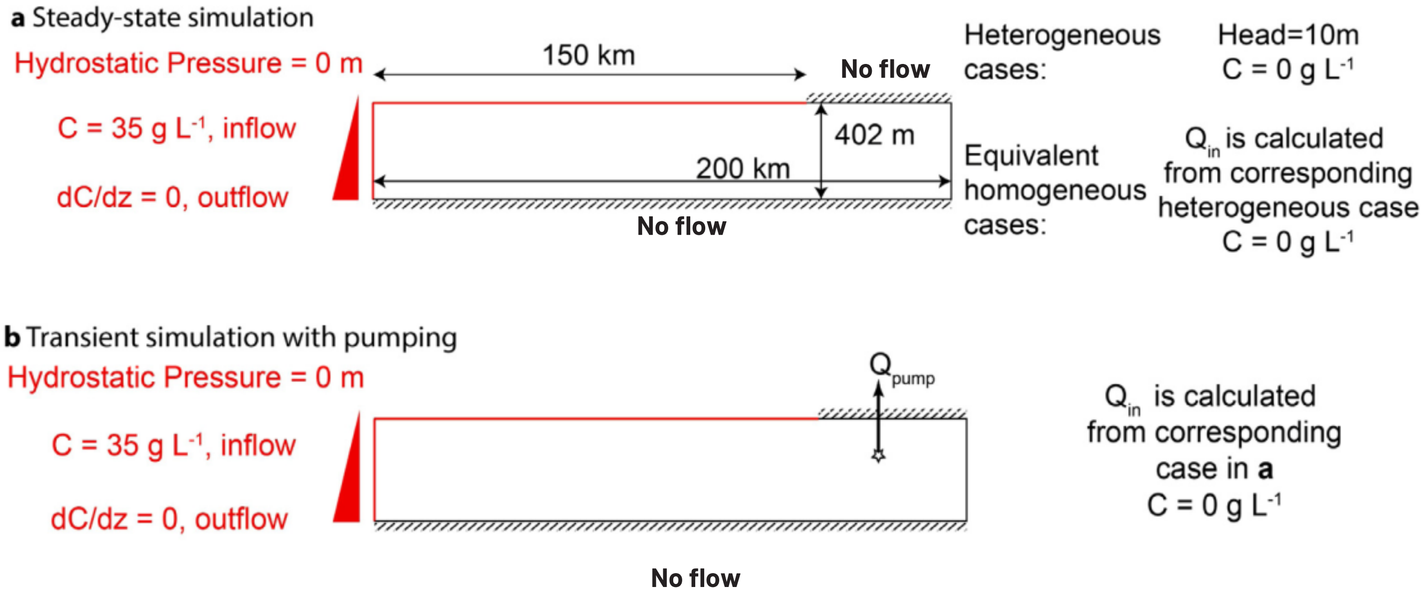
This study investigates the effect of heterogeneity on seawater intrusion due to groundwater pumping with 3 main objectives:

- Show how large-scale **heterogeneities in hydraulic conductivity** may influence **saltwater intrusion** under pumping;
- Develop a configuration framework to identify the influence of different characteristics on intrusion extent, rate, and path;
- Apply the **configuration method** to different types of aquifers and assess groundwater resource vulnerability to coastal pumping;

2. Methodology

Simulation technique, boundary conditions, and model parameters

The model simulated seawater intrusion encompasses both offshore and onshore aquifers by SEAWAT software



- ☐ Grid size 500 m × 3 m
- ☐ Specific storage: $10^{-4}\ m^{-1}$,
- ☐ Effective porosity: 0.2
- ☐ Molecular diffusion coefficient: $10^{-9} m^2/s$.

Pumping well assigned to one cell at 25 km inland and 200 m deep

Simulated scenarios of aquifer heterogeneity

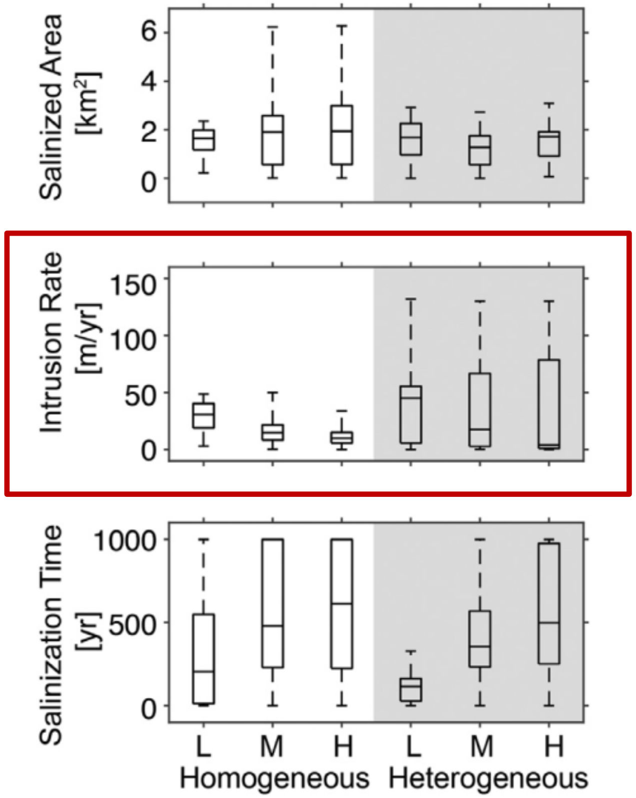
- Four distinct facies, **clay, silt, fine sand, and coarse sand** were distinguished based on the thick stack of highly heterogeneous sediments that comprise the **Lower Bengal Delta aquifer system** *(Alam et al., 2003; Allison et al., 2003)*

- A **variogram model** was developed to capture the spatial correlation of these facies, and the horizontal variogram ranges were 5 km, 25 km, 50km, and vertical ranges 50 m, respectively.

- The variogram model as a basis for a realistic aquifer structure for the simulation of **35 heterogeneous fields** that encompass that of the Bengal Delta and a range of other coastal aquifers (**low, medium, and high geologic continuity**)

3. Results

Influence of aquifer heterogeneity on seawater intrusion



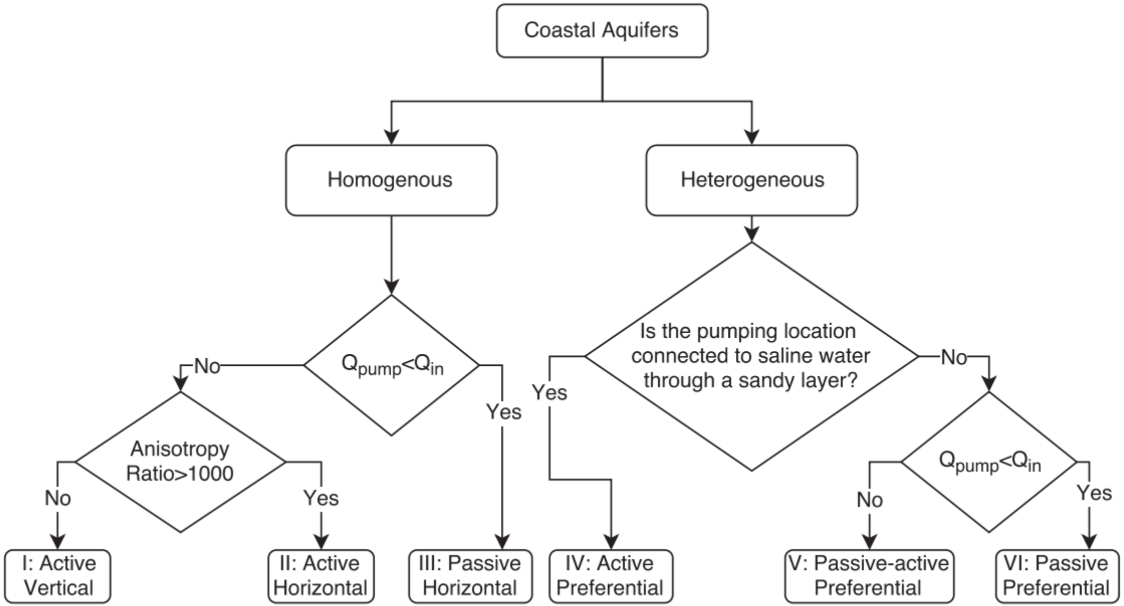
Salinization for each group.
(L, M, H is Low, Medium and high geologic continuity respectively)

- The vulnerability of groundwater to seawater intrusion for simulations with **heterogeneous K distributions** compared to equivalent homogeneous models.

- The average salinized area was not significantly different between the two populations. The average salinized areas was $\mathbf{1.9\ km^2}$ for HM simulations; and **1.4** $\mathbf{km^2}$ for HT simulations.

- Seawater **Intrusion rates** and **Salinization time** (467 years and 311 years) were significantly **greater in heterogeneous** compared to equivalent homogeneous simulations

Configuration of types of seawater intrusion



Coastal Aquifers

Homogenous

Heterogeneous

$Q_{pump}<Q_{in}$

No

Yes

Anisotropy Ratio>1000

No

Yes

Is the pumping location connected to saline water through a sandy layer?

Yes

No

$Q_{pump}<Q_{in}$

No

Yes

I: Active Vertical

II: Active Horizontal

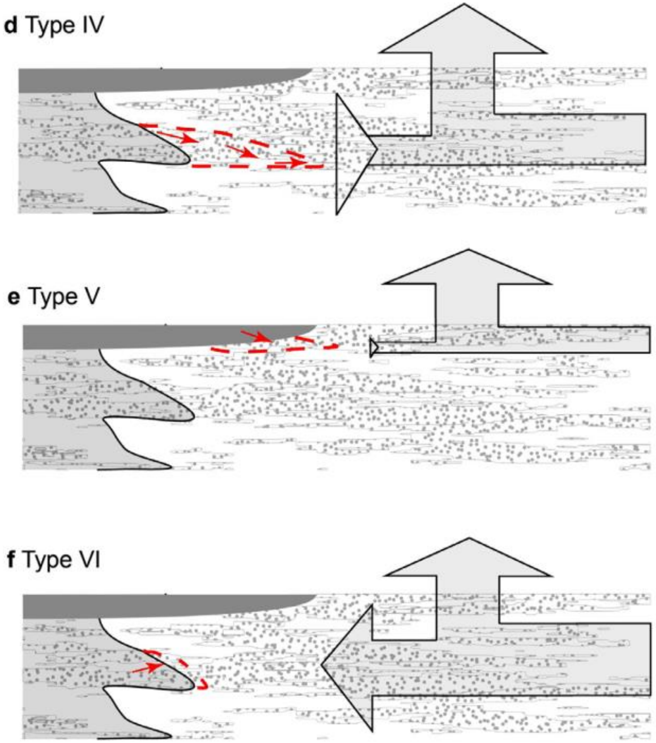
III: Passive Horizontal

IV: Active Preferential

V: Passive-active Preferential

VI: Passive Preferential

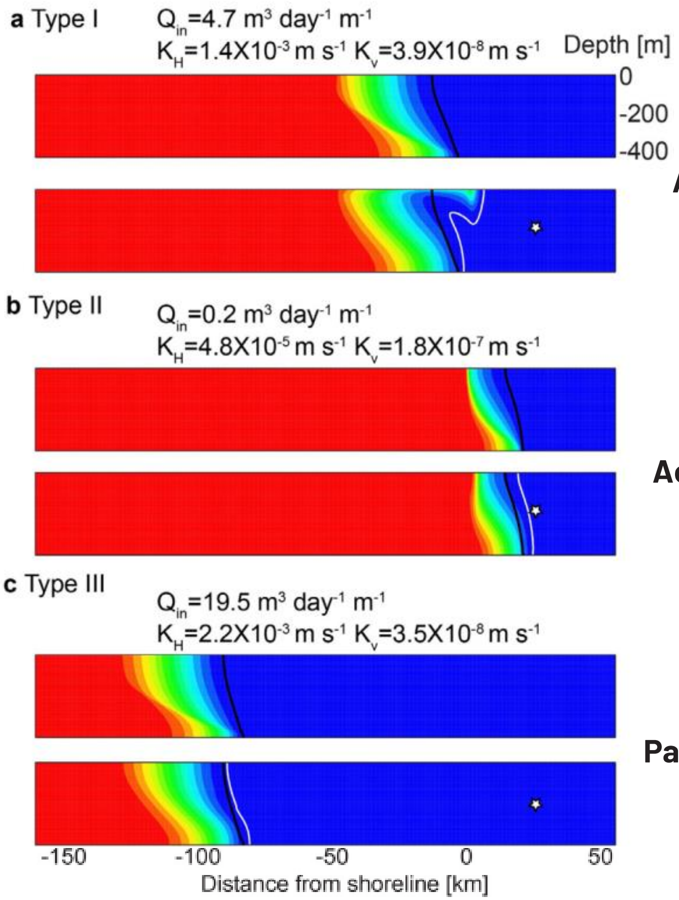
SWI configuration schematic.



- ➢ The **results of the 105 pumping simulations** for homogeneous and heterogeneous aquifers showed 6 configuration of seawater intrusion

3. Results

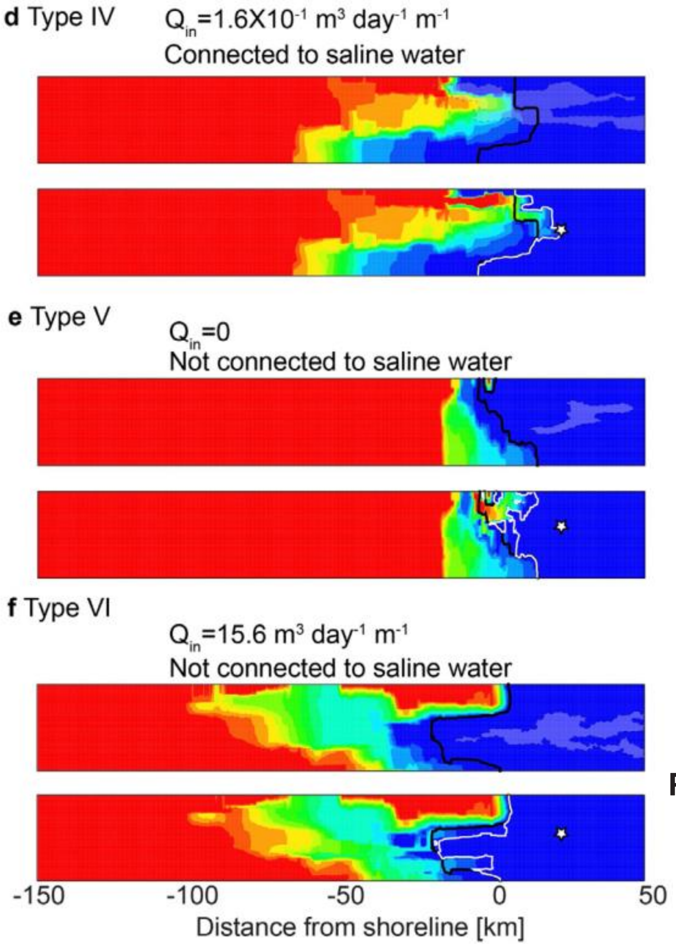
Configuration of types of seawater intrusion



Active vertical intrusion

Active horizontal intrusion

Passive horizontal intrusion



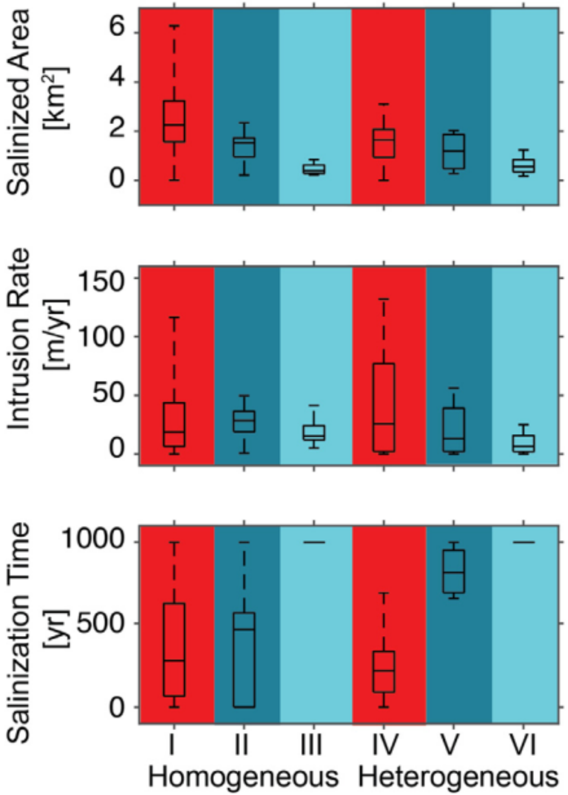
Active preferential intrusion

Passive- active preferential

Passive preferential

3. Results

Vulnerability of SWI types



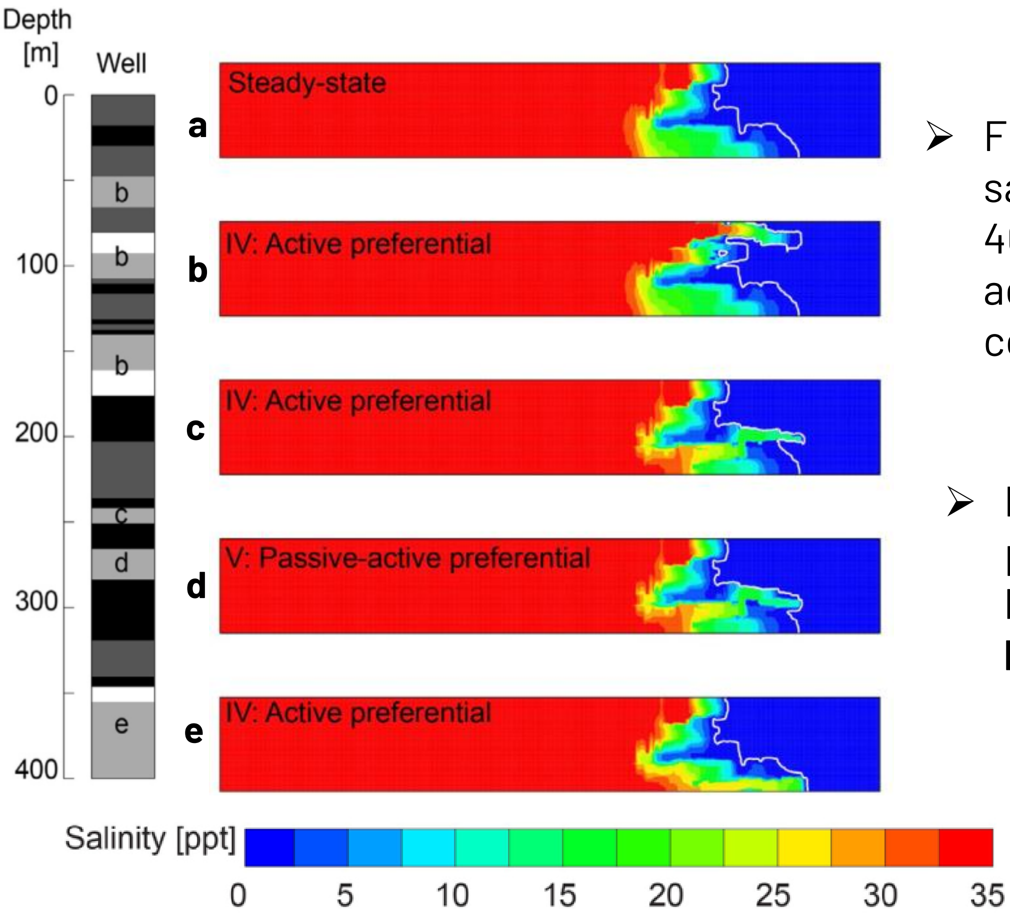
Variability of simulated salinization metrics for different SWI types
(Red to Light Blue mean decreased vulnerably)

- In homogeneous cases, **Type I was the most vulnerable** with large salinized areas, fast intrusion rates, and short salinization times. **Type III was the least vulnerable** due to small salinized areas...

- In heterogeneous cases, **Type IV was most vulnerable** due to high variability in the salinized area, intrusion rate, and short salinization times. **Type VI was the least vulnerable** caused by high Q_{in}.

3. Results

Influence of pumping depth

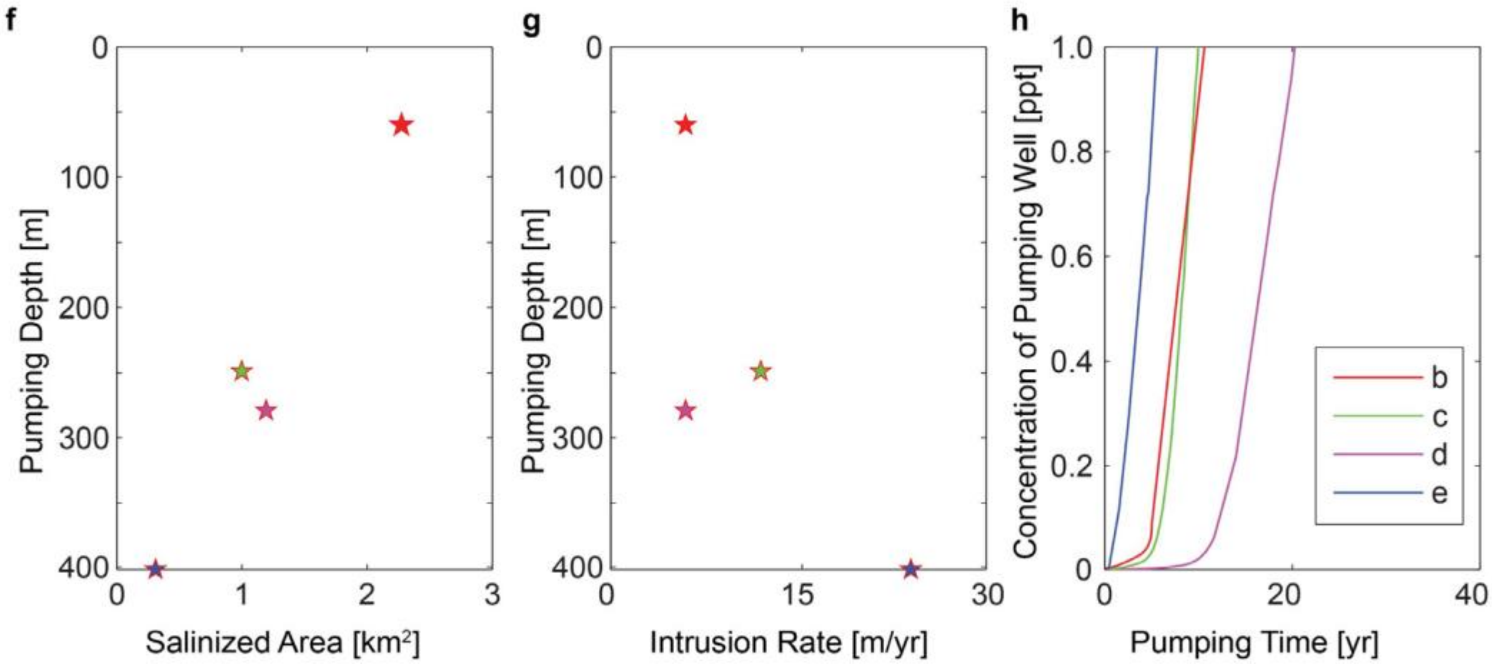


- Four pumping scenarios were created in the sandy layers, with 50 m, 250 m, 280 m, and 400 m depths. In each case, intrusion advanced quickly only in the sandy zone connected to the well

- Pumping depth was **critical** to salinization processes in the **heterogeneous** aquifer but had **negligible** impacts in the equivalent **homogeneous** aquifer.

3. Results

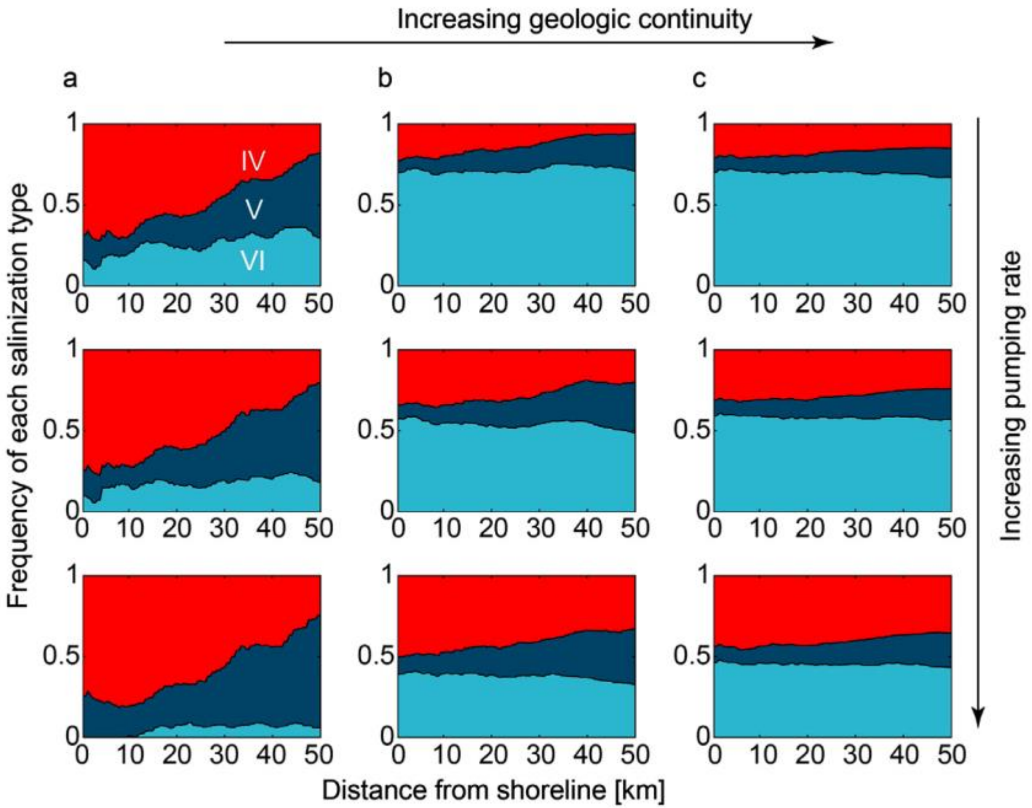
Influence of pumping depth



- The intrusion configuration also depended on the **pumping depth** since it determined the connectedness between the well and saltwater and freshwater zones

3. Results

Probability-based vulnerability assessment



- Geologic continuity decreased groundwater vulnerability to seawater intrusion. However, increasing the **pumping rate increased** the vulnerability in **any geological continuity**.
- The vulnerable intrusion type IV frequency was **0.53, 0.28, and 0.28** in low to high-continuity groups. Respectively type VI was **0.18, 0.54, and 0.58**.

Probability-based vulnerability assessment for heterogeneous aquifers in a) low, (b) medium, and (c) high continuity groups. Top to bottom panels are pumping rates of 5, 10, and 20 m^3/day

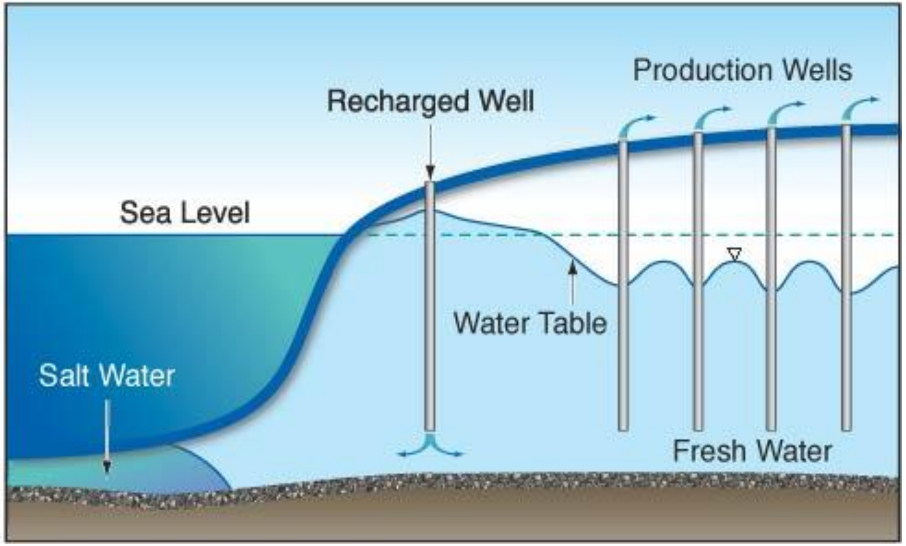
Conclusions

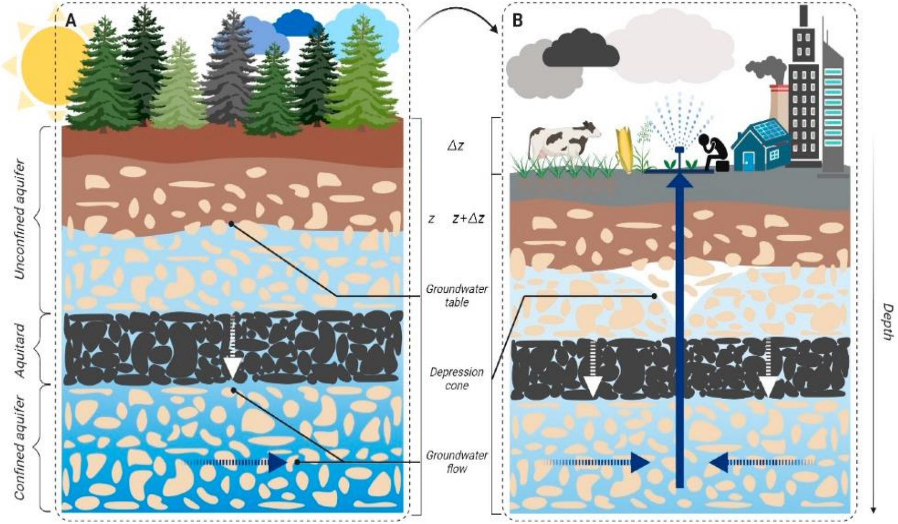
This study highlights the importance of large-scale geologic heterogeneity for pumping induced groundwater salinization.

- **Heterogeneity may create preferential flow paths** that accelerate intrusion processes or barriers that slow SWI. Pumping on this system must be cautious since **a normal pumping rate can also cause active intrusion.**
- The vulnerability was responsive to **pumping distance** to the shoreline for low-continuity aquifers and **pumping depth** for high-continuity aquifers. And the configurations can discriminate critical features of SWI, which are associated with vulnerability levels
- Heterogeneous models are helpful for modeling seawater intrusion and providing **accurate and realistic management scenarios**, particularly for **managed aquifer recharge projects**.

Future works

Applied managed aquifer recharge





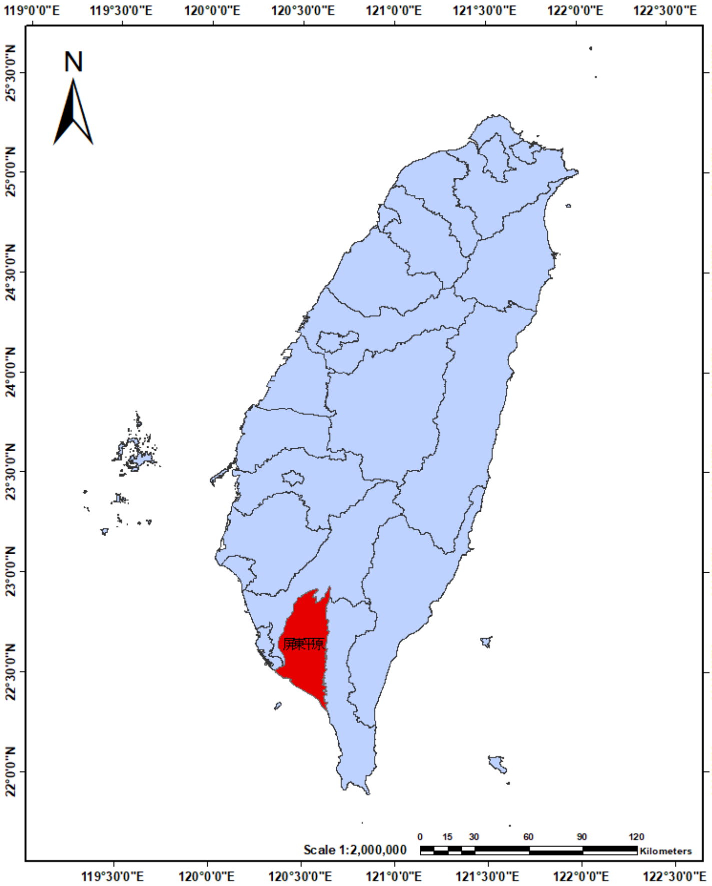
Minimize seawater intrusion

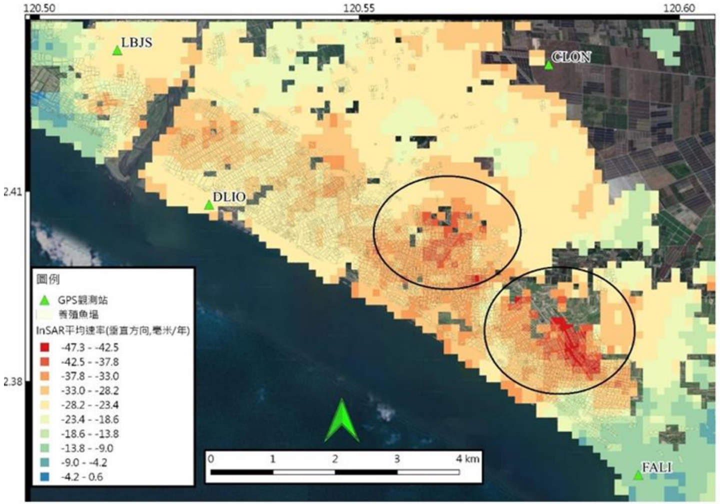
- MAR can reduce the salinity of groundwater by injecting surface water, stormwater, and wastewater ***(ElRawy et al., 2019; Russo et al., 2015)***

Minimizing land subsidence

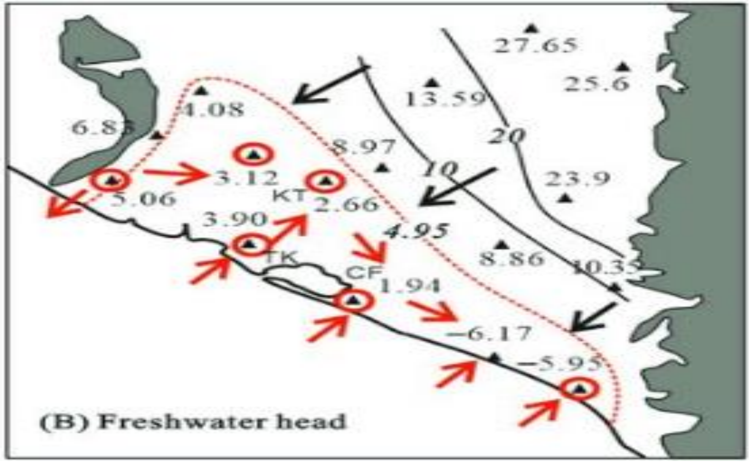
- When groundwater extraction exceeds the natural recharge, the empty pore collapse under stress, irreversibly lowering the storage capacity of the aquifer ***(Smith et al., 2017)***

Research area





(Chein-Way Hwang, 2019)



(Yung-Chia Chiu, 2021)

Thanks for your attention