Coupled three-dimensional modelling of groundwater-surface water interactions for management of seawater intrusion in Pingtung Plain, Taiwan

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Student : Li-Yuan Hsu

Advisor: Prof. Jui-Sheng Chen

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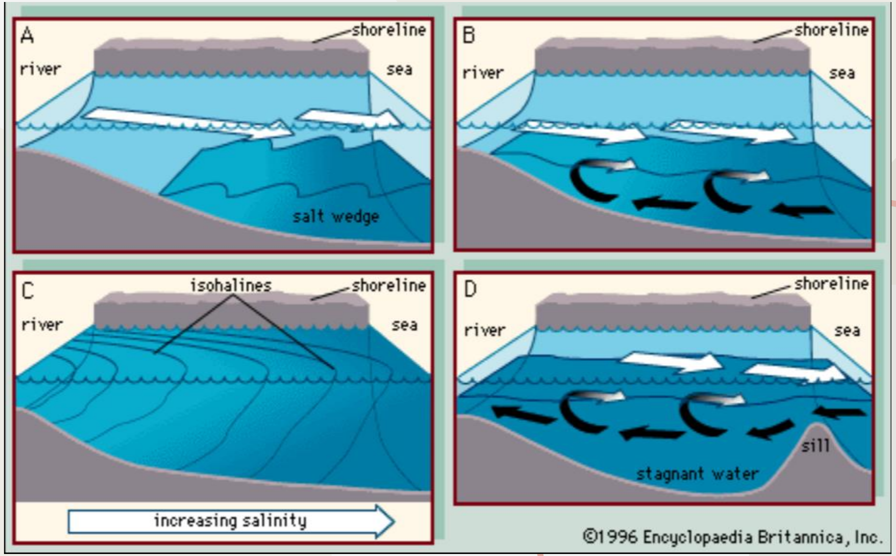
OUTLINE

- Introduction
- Methodology
- Results
- Conclusions

Introduction

- Groundwater play an important role to provide stable water resources.
- Surface and groundwater exchanges are variable and may be affected by changes in hydraulic head due to seasonal rainfall.
- Fresh groundwater in coastal aquifers is vulnerable to salinization by upconing and seawater intrusion (Post, 2005).



Introduction

Objective:

Using FEFLOW and MIKE 11 for simulation, we considered the interaction between surface water and groundwater. The model simulated the occurrence of rainfall and the effects of the lag time in the interaction between groundwater and surface water.

The model can use the results to simulate river flow and flooding, and choose suitable locations to add wells for groundwater recharge.

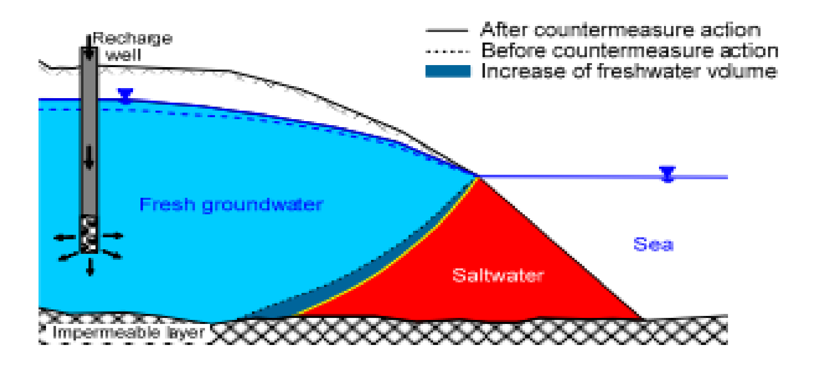
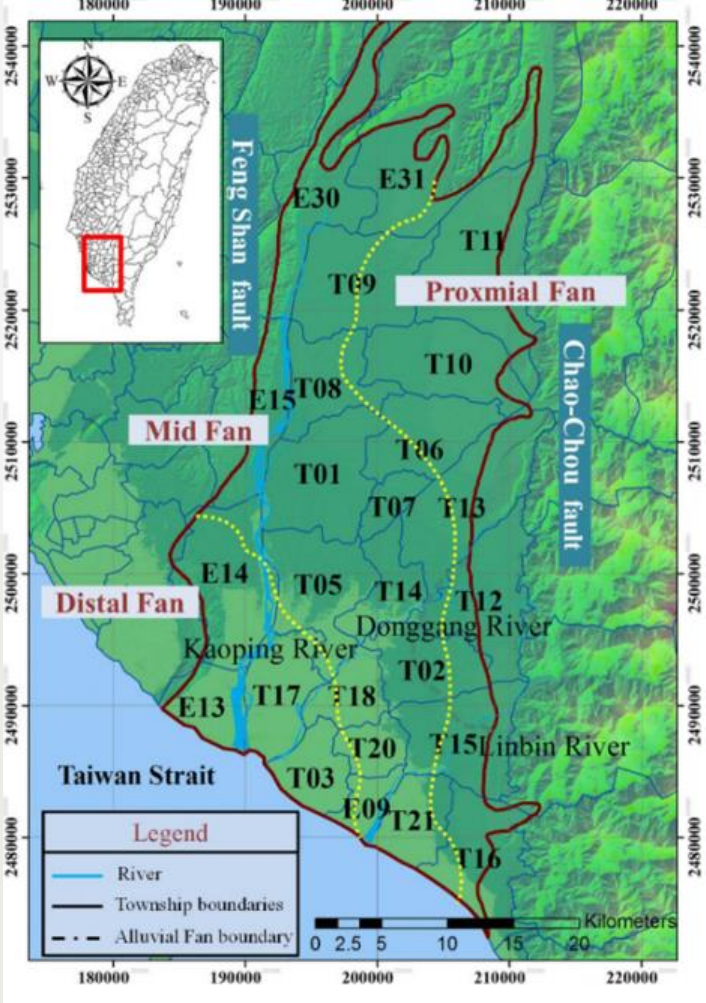


Figure 3. A generalized sketch of a recharge well system.

Introduction

Study area : Pingtung Plain

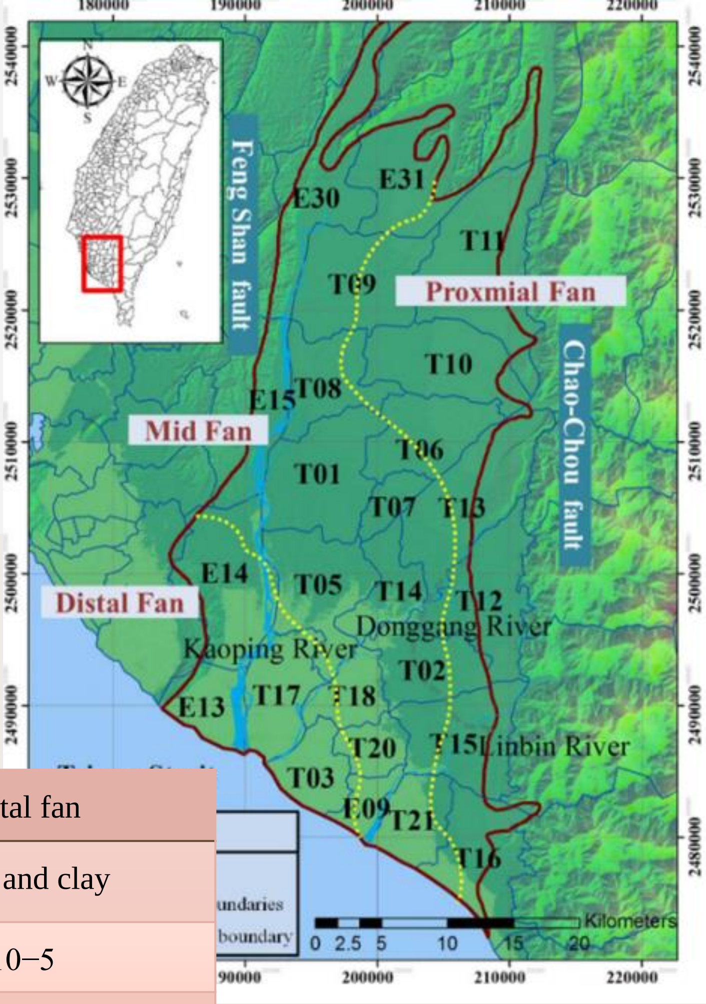
- The boundary conditions of the study area are defined by two faults in the northwest and southeast, named "Feng Shan" and "Chao-Chou" respectively.
- Three main rivers, namely, the Kaoping rivers, Donggang rivers, and Linbian rivers, also divide the region into three areas: proximal fan, mid fan, and distal fan, based on drainage.
- The region experiences an unstable pattern of rainfall, with a ratio of 9:1 between the wet season and the dry season, significantly higher than other areas in Taiwan.
- The distribution of rainfall is a crucial factor influencing the availability of groundwater resources in the Pingtung Plain.



Introduction

Study area : Pingtung Plain

- The aquifer is mainly composed of clay and fine-grained sediments, gradually decreasing from northeast to southwest .
- The heigh of groundwater recharge is determined by the soil permeability. As the proximal fan is composed of gravel and sand, it exhibits higher potential for both recharge from rainfall and infiltration from rivers.
- Surface water in the study area can only meet 20% of demand, and many pumping wells have resulted in over-extraction of groundwater and seawater intrusion.



Parameter	Proximal fan	Mid fan	Distal fan
Soil	20 % sand and 60% gravel	40 % gravel and 40 % sand	silt and clay
Storage factor	6.5×10^{-3}	9.5×10^{-4}	5×10^{-5}
Transmissivity	9000 m^2/day	2300 m^2/day	1200 m^2/day

Methodology

Development three-dimensional model

Finite element modelling

↓

Surface water model development

↓

Coupling of the groundwater and surface water models

↓

Calibration and validation of the model

Methodology

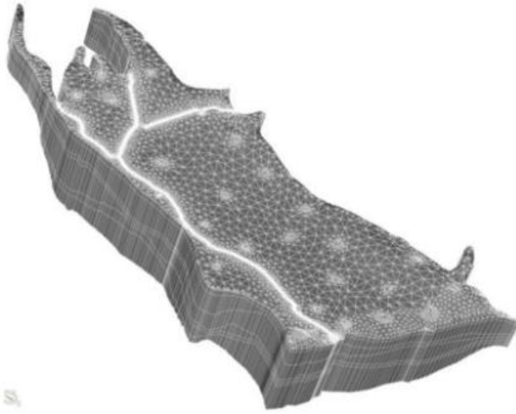
Finite element modelling

ArcGIS → Polygon shapefile → 2D domain

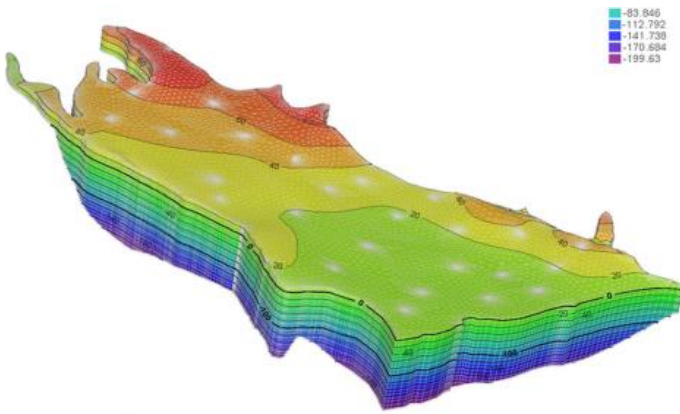
FEFLOW
- 25 pumping wells
- Elevation of 95 observation wells
- Three rivers as polylines
- Mesh + Triangular prism mesh

2D domain → 3D domain → 3D discretise domain

Aquifer with six layers and seven slices	
39,221 elements and 20,352 nodes	
The model total of 43 slices and 42 layers	



(b) 3D layer configuration and Discretising 3D model



BACK

Methodology

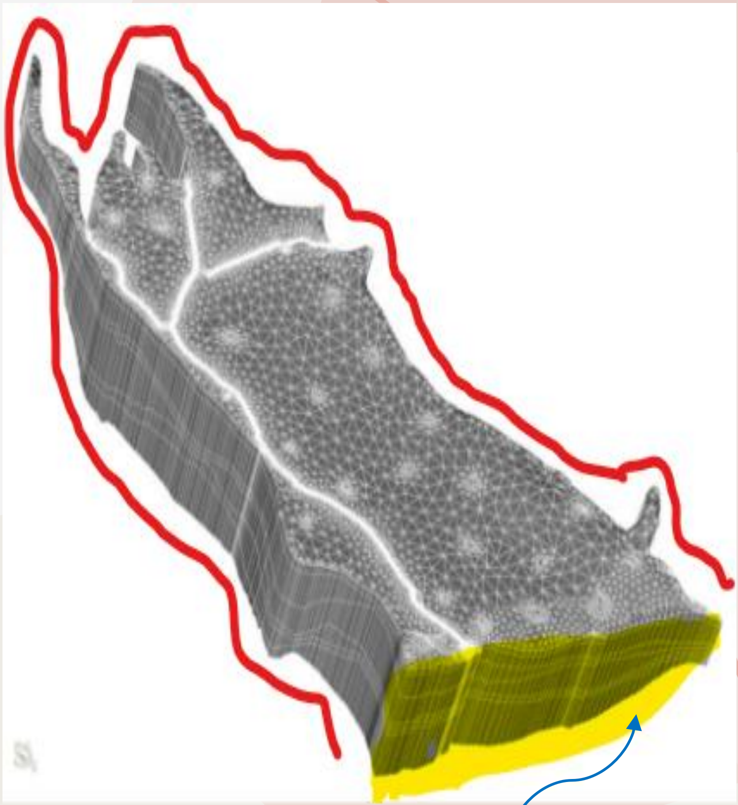
<u>boundary condition</u>

- The yellow area is set as constant head (Dirichlet) boundary condition and the salt concentration of seawater is 35,000 mg/L.
- The red line is set to (Neumann) boundary condition with no fluid flux .
- In this model, salt is the only contaminant.

Saltwater head boundary condition :

$$h_s = \frac{\rho_f}{\rho_s} \times h + \left(1 - \frac{\rho_f}{\rho_s}\right) \times z$$

where
ρ_f = 1,000 kg/m^3: densities of freshwater
ρ_s = 1,025 kg/m^3: densities of saltwater
z is the elevation at each point of the model



The southern the coastal line

Methodology

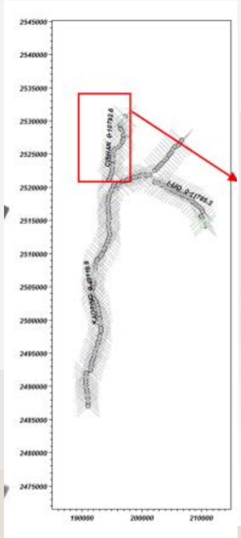
Surface water model development

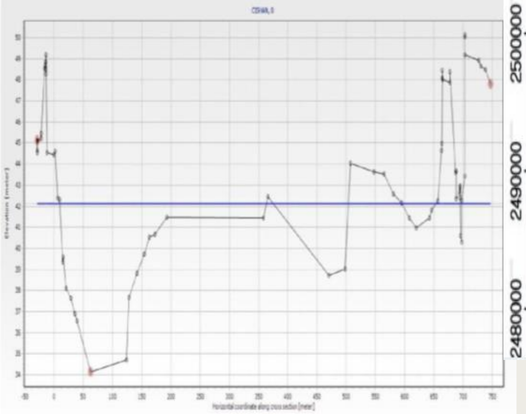
Using point digitisation in MIKE 11 to develop river network
boundary condition: water level at 22 stations in studied area
Input data of water level, streamflow and rainfall from 5 stations
Calibration with data from 4 stations: Qishan, Lilin, Kaoping and Wannta
The actual cross-section data giving the hydraulic head value and flow value through the Manning equation :

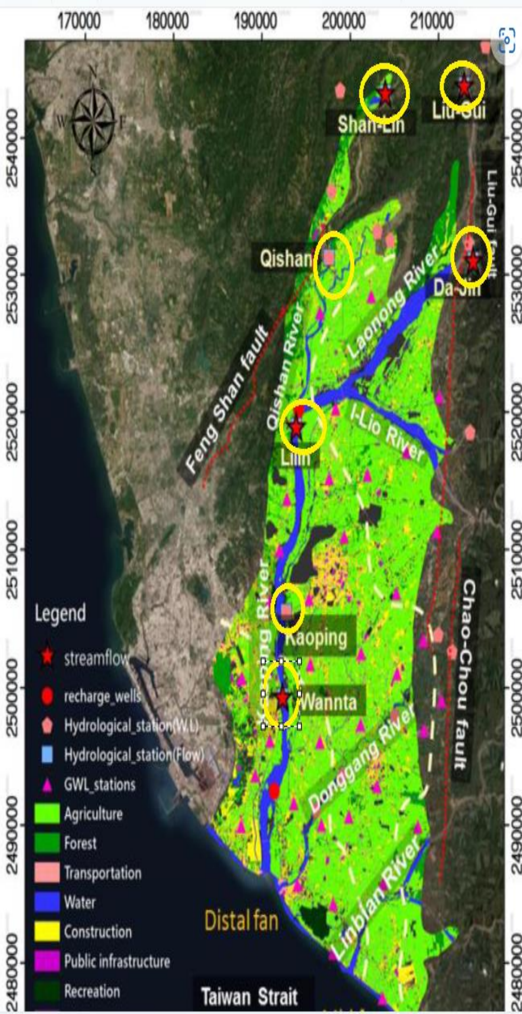
$$Q(h) = \frac{1}{n} A(h) R(h)^{\frac{2}{3}} \sqrt{S}$$

Where:

$Q(h)$:is the discharge amount $(\frac{m^3}{s})$
S: the bed slope
A(h):the level relevant to the area (m^2)
R: the hydraulic radius (m)
n: Manning roughness coefficient







Methodology

Coupling of the groundwater and surface water models

Using FEFLOW calculated the exchange fluxes (q) of each single boundary condition between the surface water and groundwater

$$q = \emptyset_h (h_{ref} - h_{gw})$$

Where:

q: Darcy flux of fluid (m/d)

h_{ref} : river heads (m)

h_{gw} : groundwater head (m)

$\emptyset_h$: transfer coefficient($\frac{1}{d}$)

→ main element for controlling the flux

⇨ The total discharge at each node was calculated by multiplication q at the end of each time step in FEFLOW.

Methodology

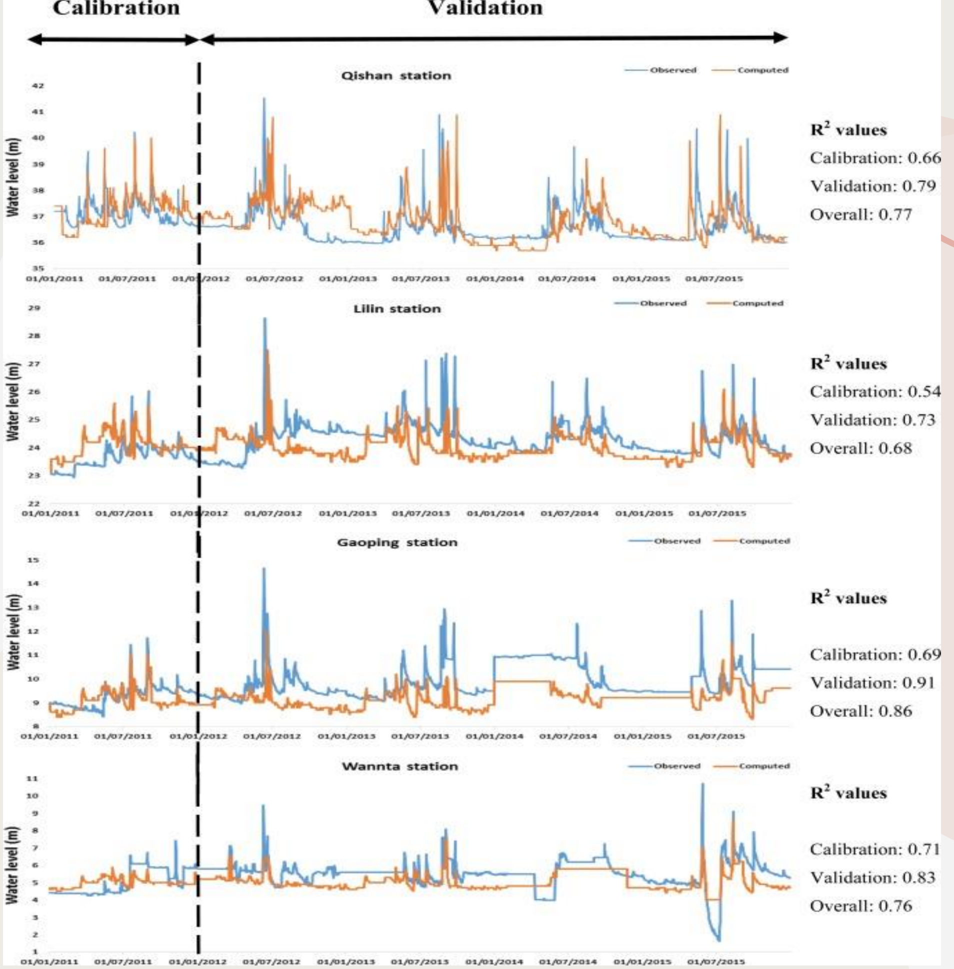
<u>Calibration and validation of the model</u>

- The observed water levels in Qishan Bridge, Lilin Bridge, Kaoping Bridge, and Wannta Bridge in 2011 were used for calibration.

- Analysis was performed using mass concentration hydraulic head, conductivity and rainfall data to validation.

- The Nash-Sutcliffe efficiency coefficient R^2 was used to evaluate the model

The R^2 values of 0.68-0.86 for calibration and validation are consistent with actual conditions.



<u>K&R VALUE</u>

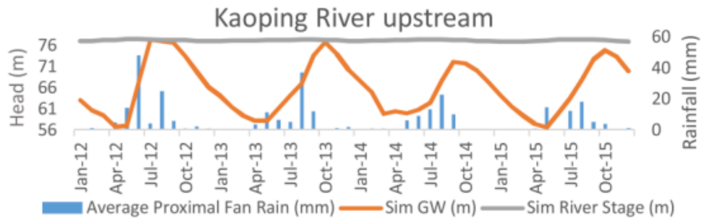
Results

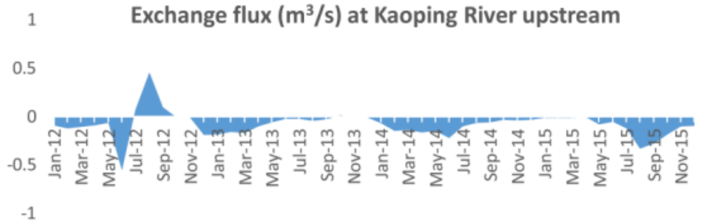
River-precipitation-groundwater interaction

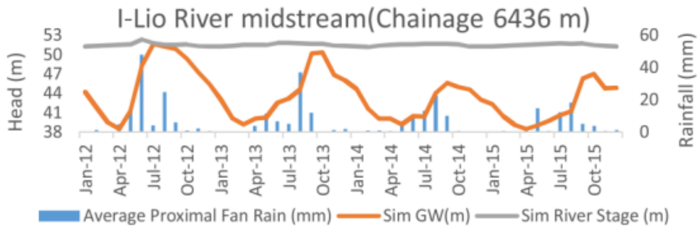
Proximal fan

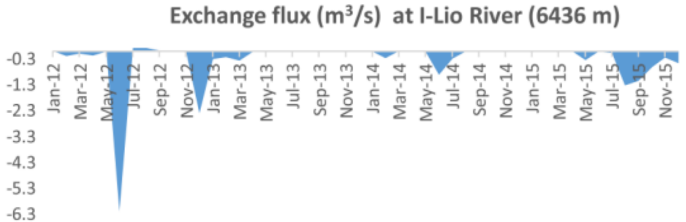
- The soil permeability plays an important role in the recharging pattern

Parameter	Proximal fan
Soil	20 % sand and 60% gravel
Storage factor	6.5×10−3
Transmissivity	9000 $m2 \,/day$









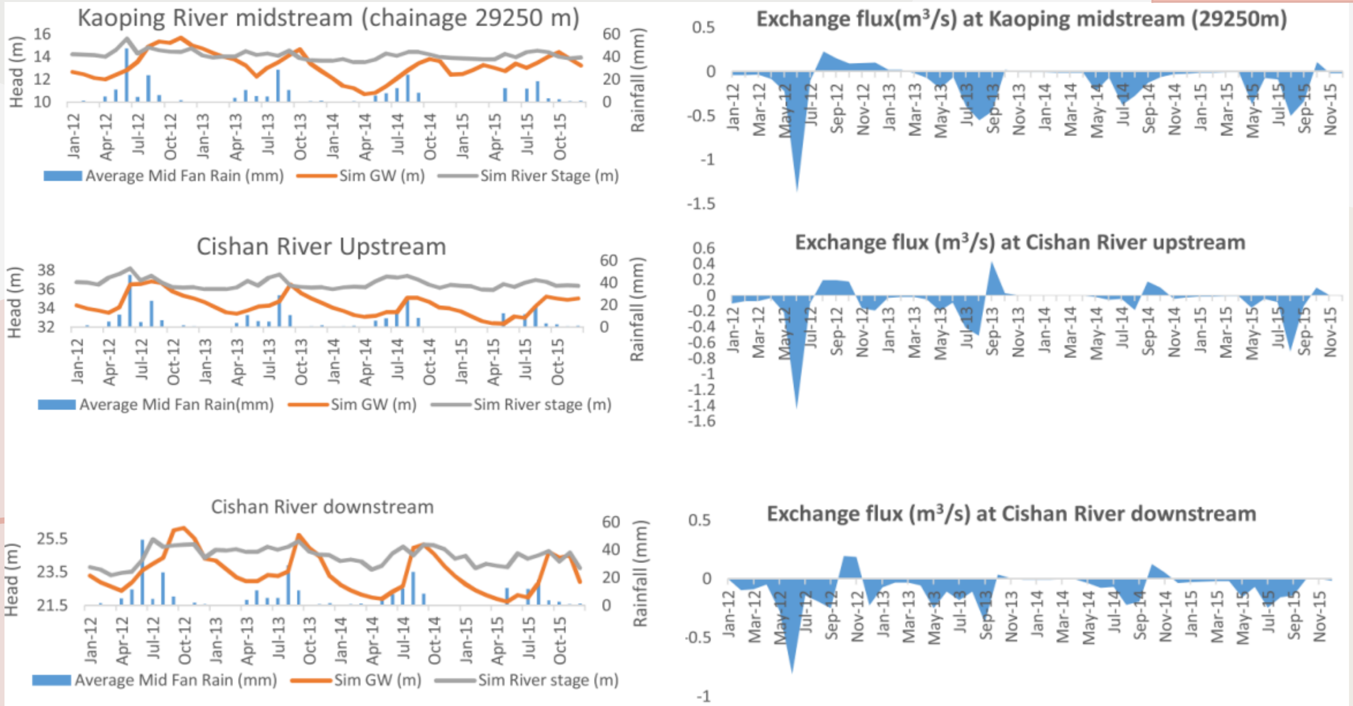
➡ This region has a high potential for groundwater recharge and infiltration due to river flow and precipitation.

Results

River-precipitation-groundwater interaction

Parameter	Mid fan
Soil	40 % gravel and 40 % sand
Storage factor	9.5 ×10−4
Transmissivity	2300 m2 /day

Mid fan



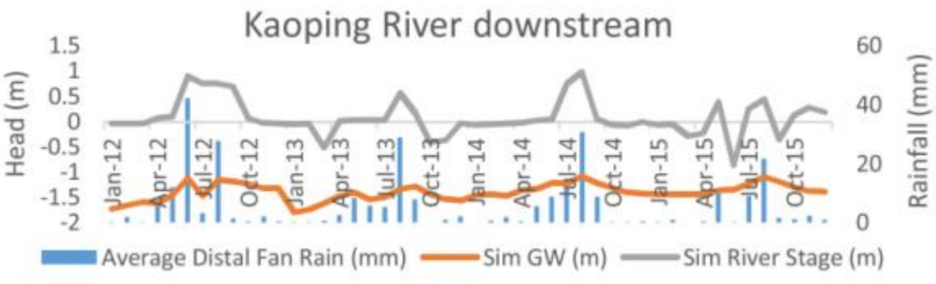
The maximum head difference between groundwater and the river is about 4 meters.

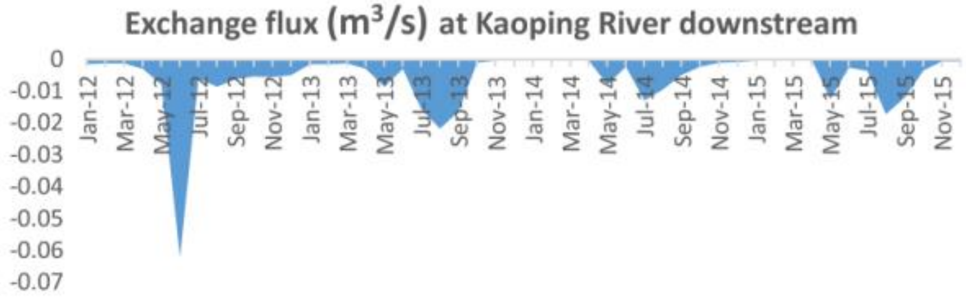
Results

River-precipitation-groundwater interaction

Distal fan

Parameter	Distal fan
Soil	silt and clay
Storage factor	5×10^{-5}
Transmissivity	$1200 m^2/day$



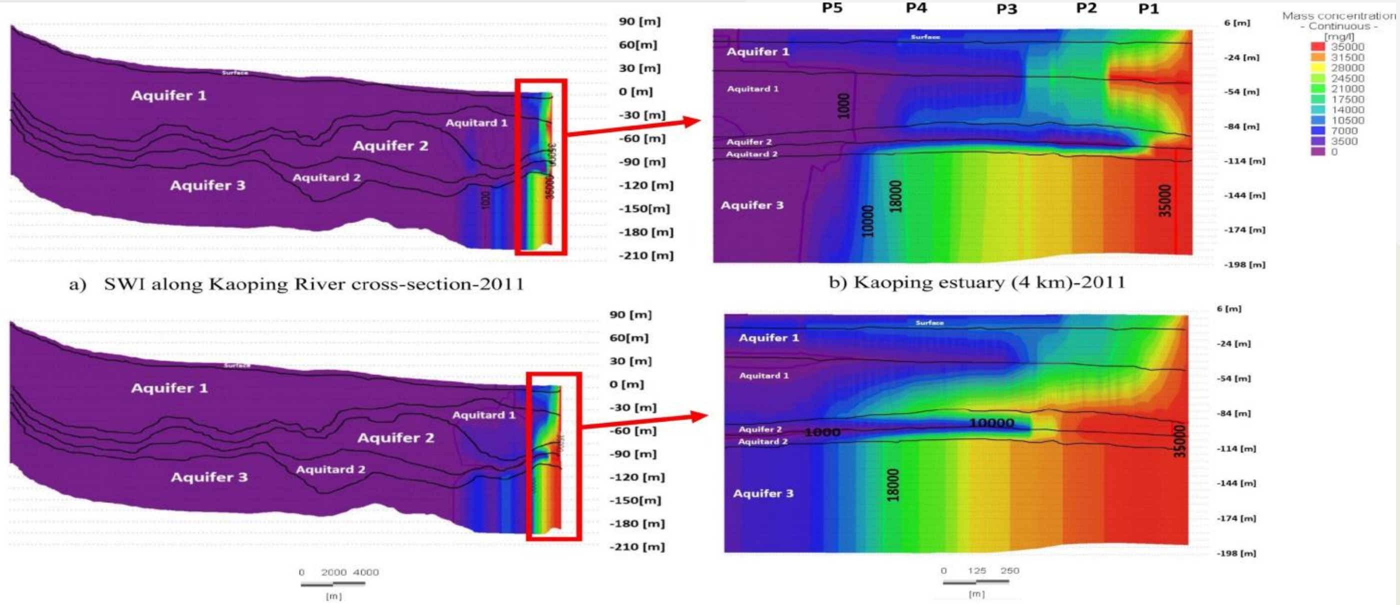


The groundwater reacts rapidly to rainfall events with insignificant head fluctuations.

Results

<u>Seawater intrusion (SWI)</u>

- The effect of river discharge on seawater intrusion illustrate through the cross-section along Kaoping river in 2011-2015.



a) SWI along Kaoping River cross-section-2011
b) Kaoping estuary (4 km)-2011
c) SWI along Kaoping River cross-section-2015
d) Kaoping estuary (4km)-2015

⇨ Seawater intrusion into the entire depth of the aquifer system at different inland distances and in different layers.

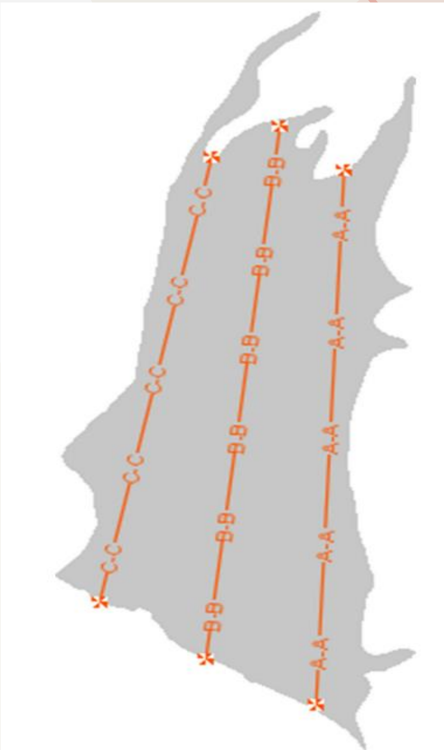
Results

Seawater intrusion (SWI)

Other cross-sections result in domain

Table 1
Inland distance (m) of seawater intrusion along four cross-sections in 2011 and 2015.

10,000<TDS<35,000 mg/l	A-A	B-B	C-C	Kaoping River
	Inland distance (2011)			
First Aquifer	1790	2380	2930	1560
Second Aquifer	1780	2350	2923	1920
Third Aquifer	1790	2400	3014	2320
	Inland distance (2015)			
First Aquifer	1820	2500	3600	2320
Second Aquifer	1822	2442	3060	2540
Third Aquifer	1820	2560	3600	2550



- A-A cross-section, distance inland during the five years of study almost unchanged in all aquifers.
- B-B cross-section, the SWI at all aquifer slightly increase
- C-C cross-section , in 2015, there was 600m inland of seawater along first aquifer and third aquifer

Results

Seawater intrusion mitigation

Artificial recharge of Groundwater is one of the effective methods for SWI mitigation. However, selecting the recharge location is the important

The charging capacity is between $2\times10^5 - 8\times10^5$ m3/d.

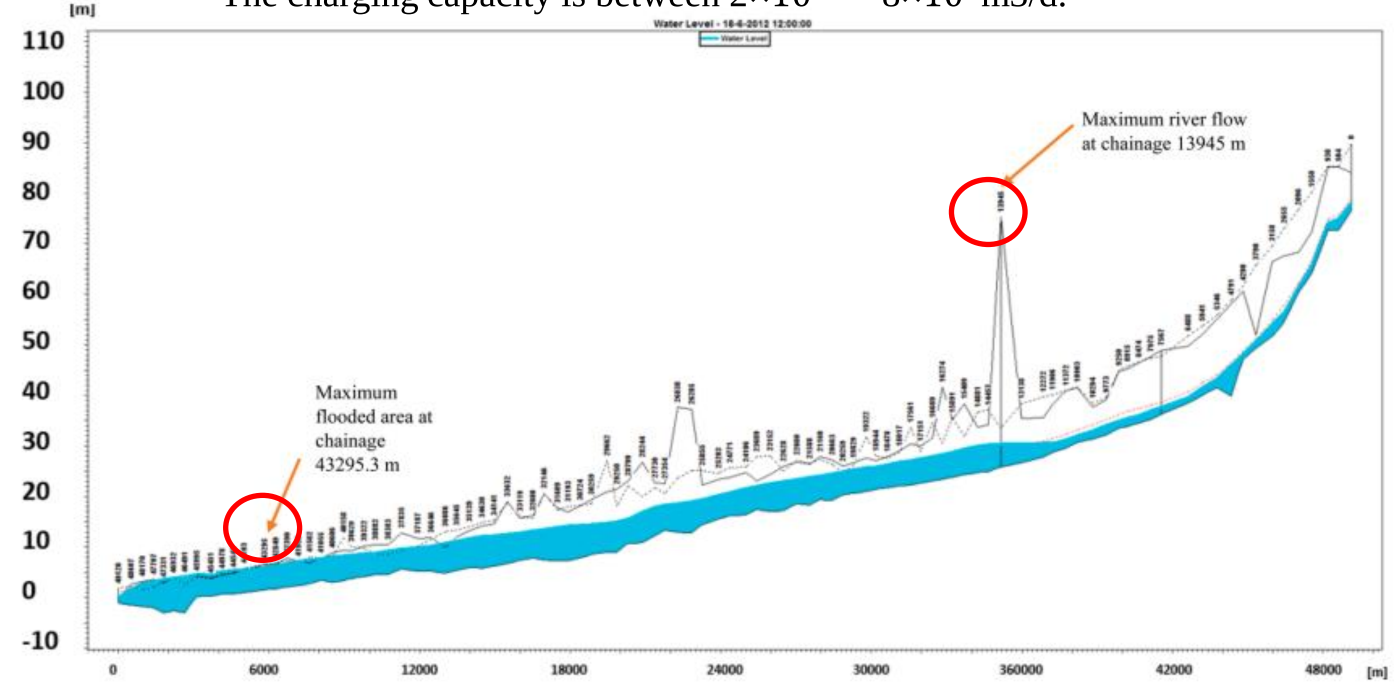


Fig. 11. The water level along Kaoping River profile at heavy rainfall event (18-6-2012).

TABLE

Conclusions

A 3-D transient density-dependent finite element model was developed in combination with a one-dimensional river network model to perform comprehensive simulations of groundwater flow, surface flow, and seawater intrusion in the Pingtung Plain.

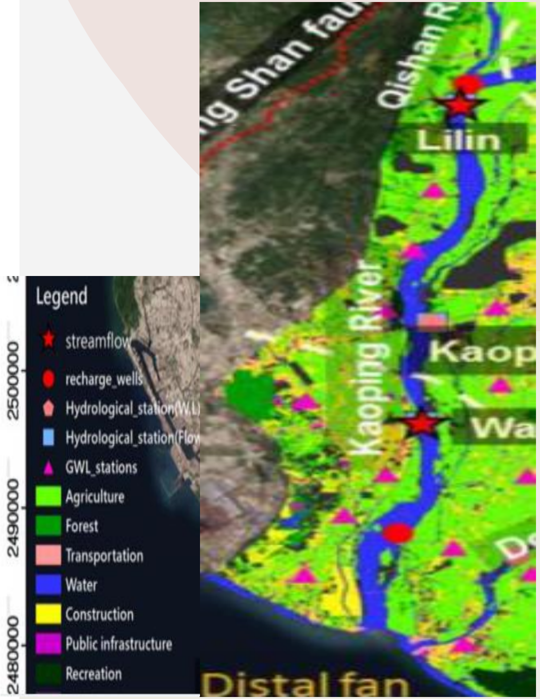
Result showed that:

- Relative to other aquifers, the central aquifer has less intrusion, while the bottom aquifer has more profound seawater intrusion.
- Artificial groundwater recharging can be used to slow seawater intrusion

Thank you for your attention.

Table 2
Inland distance (m) of saline water (10,000 < TDS < 35,000 mg/l) along four cross sections due to different recharge rates at Cishan and Kaopingf River downstream.

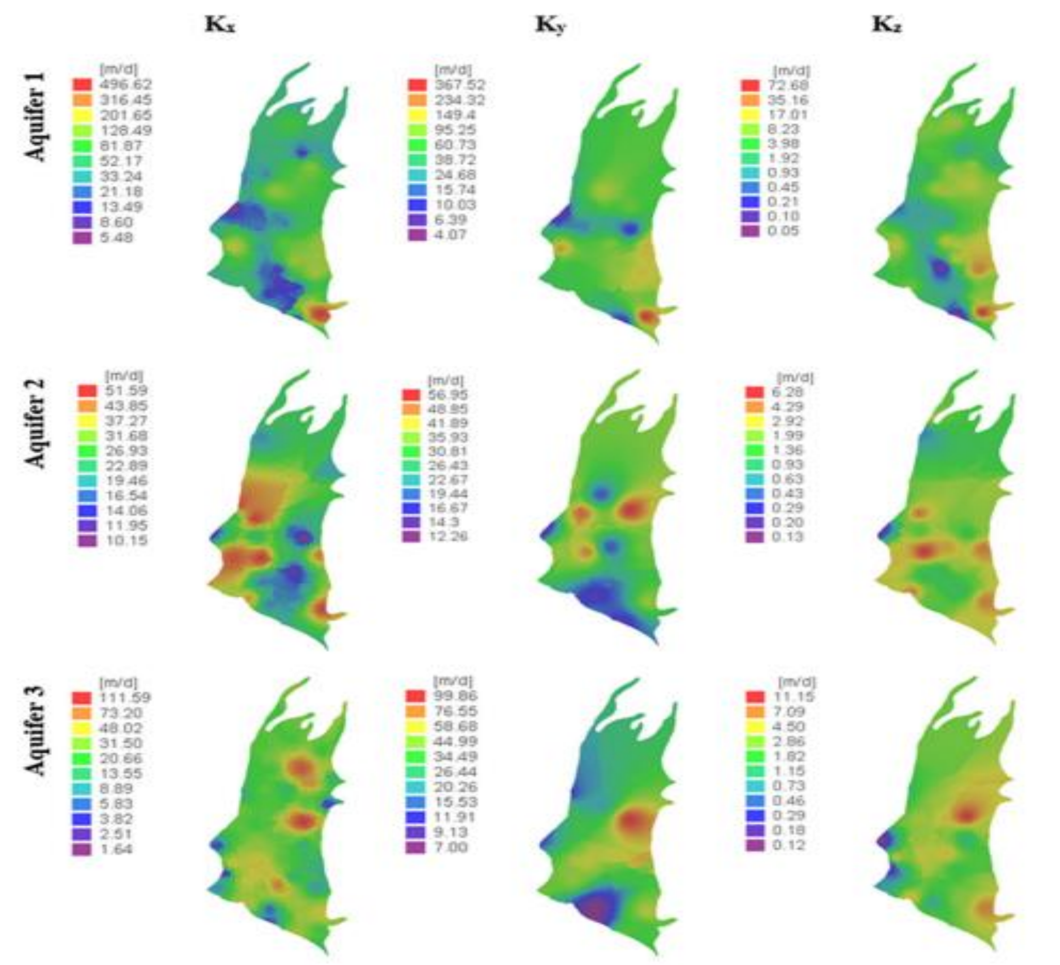
		Cross-Section A-A	Cross-Section B-B	Cross-Section C-C	Cross-Section Kaoping
	Left side of Cishan Downstream				
	Aquifer 1	1818	2450	3550	2260
200 K (m^3/d)	Aquifer 2	1818	2412	2977	2510
	Aquifer 3	1820	2520	3561	2520
	Aquifer 1	1780	2420	3493	2235
400 K (m^3/d)	Aquifer 2	1770	2374	2920	2482
	Aquifer 3	1785	2485	3500	2460
	Aquifer 1	1763	2410	3450	2170
600 K (m^3/d)	Aquifer 2	1758	2359	2887	2420
	Aquifer 3	1765	2460	3455	2419
	Aquifer 1	1750	2403	3420	2135
800 K (m^3/d)	Aquifer 2	1732	2342	2817	2370
	Aquifer 3	1755	2452	3426	2390
	Left side of Kaoping Downstream				
200 K (m^3/d)	Aquifer 1	1800	2400	3460	2180
	Aquifer 2	1793	2362	2885	2420
	Aquifer 3	1812	2460	3480	2430
	Aquifer 1	1790	2350	3400	2140
400 K (m^3/d)	Aquifer 2	1786	2292	2857	2400
	Aquifer 3	1792	2420	3420	2422
	Aquifer 1	1782	2310	3320	2060
600 K (m^3/d)	Aquifer 2	1775	2212	2777	2320
	Aquifer 3	1785	2360	3333	2230
	Aquifer 1	1776	2220	3263	2020
800 K (m^3/d)	Aquifer 2	1770	2142	2710	2300
	Aquifer 3	1776	2260	3300	2200

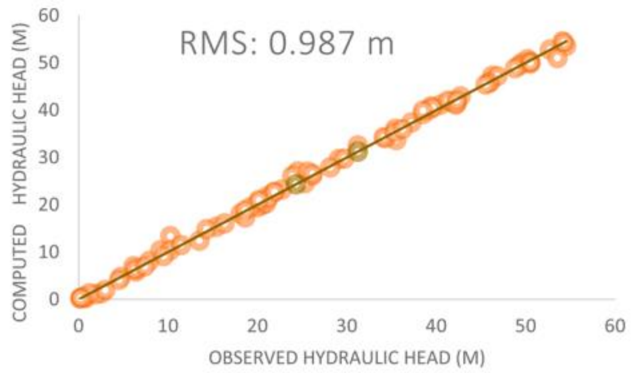


The charging capacity is between 2×10^5 to 8×10^5 m3/d.

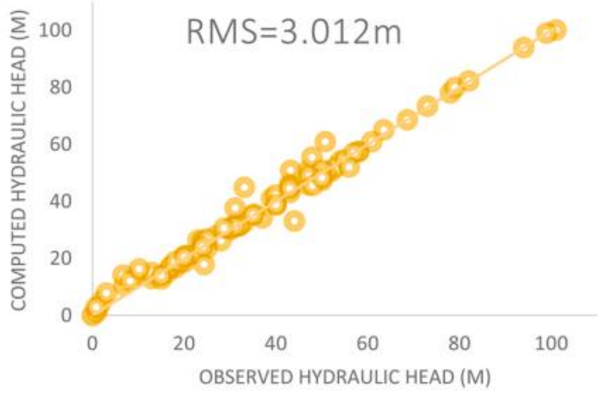
Seawater intrusion can be mitigated by choosing Kaoping River downstream as a recharging source

BACK





a) The calibration process for the groundwater model



b) The validation process for the groundwater model

BACK

Conductivity values	m/day
Aquifer 1	1-520
Aquifer 2	5-90
Aquifer 3	1-100

Methodology