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

Dibaj, M., Javadi, A.A., Akrami, M., Ke, K.Y., Farmani, R., Tan, Y.C., Chen, A.S., 2021

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OUTLINE

I. Introduction
II. Methodology
III. Result and discussion
IV. Conclusion

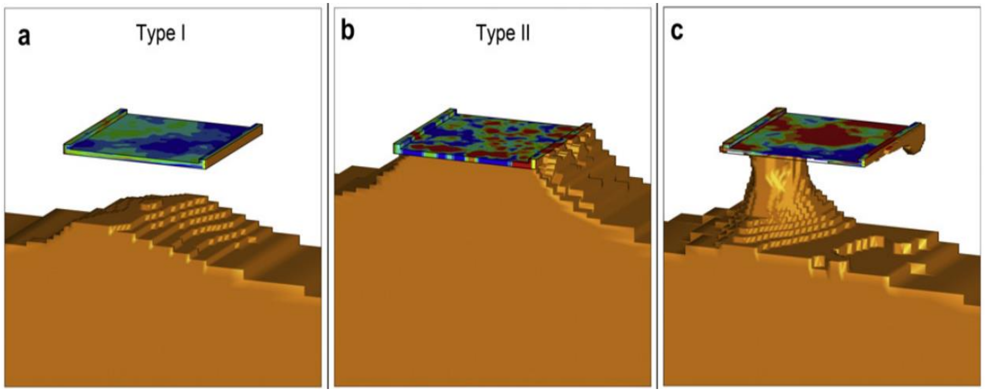
I. INTRODUCTION

Climate change → Instability of Hydrological condition → Water resource vulnerability

Groundwater play an important role to provide stable water resources

➡ Considering surface and subsurface water as a single resource to improve the reliability of water supply

The abstraction of groundwater can cause a local exchange of water between streams and adjacent shallow aquifers (Sophocleous, 2002, Brunner et al., 2011)



Three ways of groundwater interacted with stream:

a) Outflow of groundwater (losing stream)
b) Inflow of ground water (gaining stream)
c) Both losing and gaining stream

Source: (Irvine et al., 2012)

I. INTRODUCTION

➔ Integrated water resource management is one of the cornerstones of the global water framework (Rahaman et al., 2004)

➔ Increasing the demand for modeling tools and methodologies to investigate integrated

Numerical modeling of aquifer-stream interactions has become a mandatory tool for the management of water resources

The coupled models can be used to evaluate the performance of infiltration wells in cutting off the runoff of extreme rainfall and attenuating flood peaks (Sommer et al., 2009)

I. INTRODUCTION

Objective:

Developing an integrated 3-D groundwater model and an 1-D river model for coupled transient analysis of groundwater flow, river flow, and river inundation
→ Considering the interactions between surface water and groundwater

Numerical model that stimulate the effects of rainfall occurrence and duration on groundwater-surface water interaction lag time combine simulates the changes in the salinity of the mixing zone for this specific region

II. METHODOLOGY

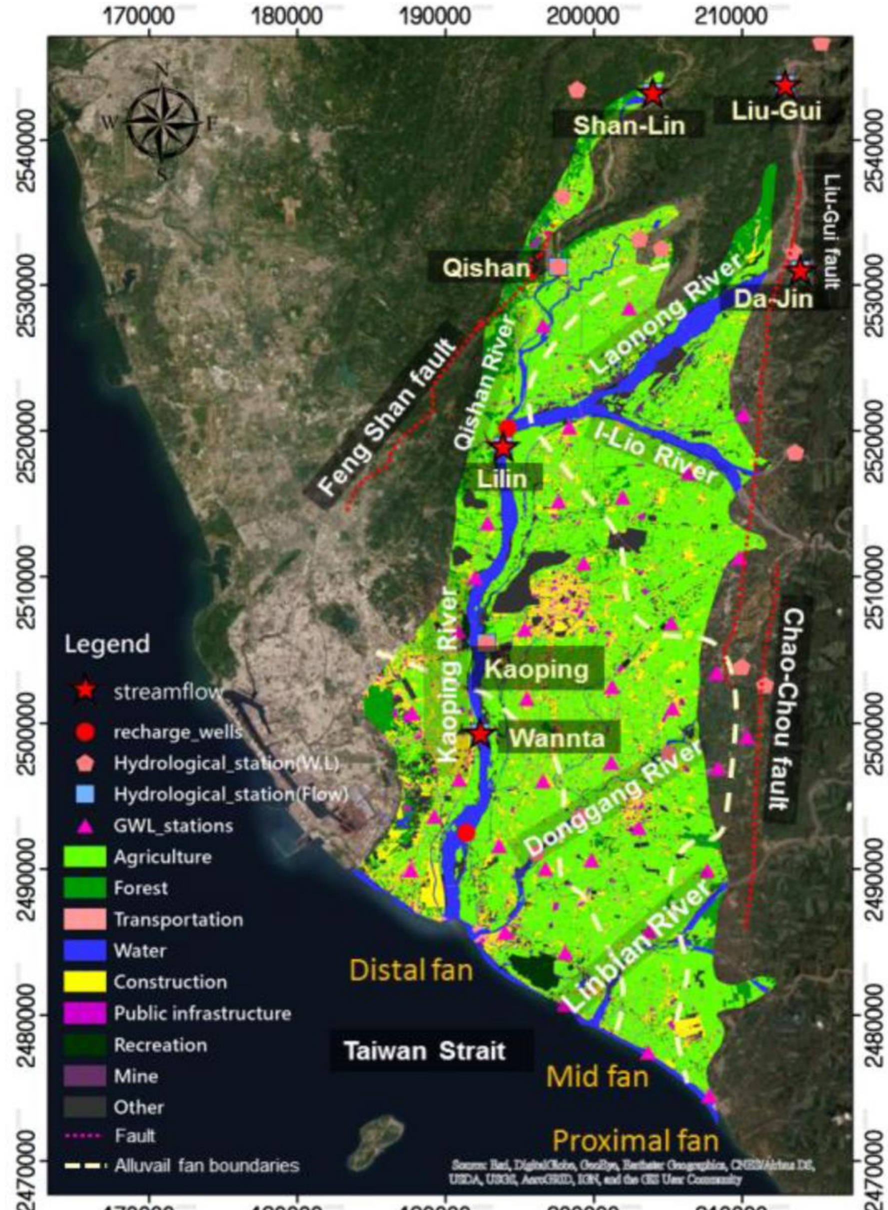
Study area: Pingtung plain

The second largest aquifer providing 60% tap water demand in Taiwan

River network: three rivers divide into three areas of proximal fan, mid fan and distal fan

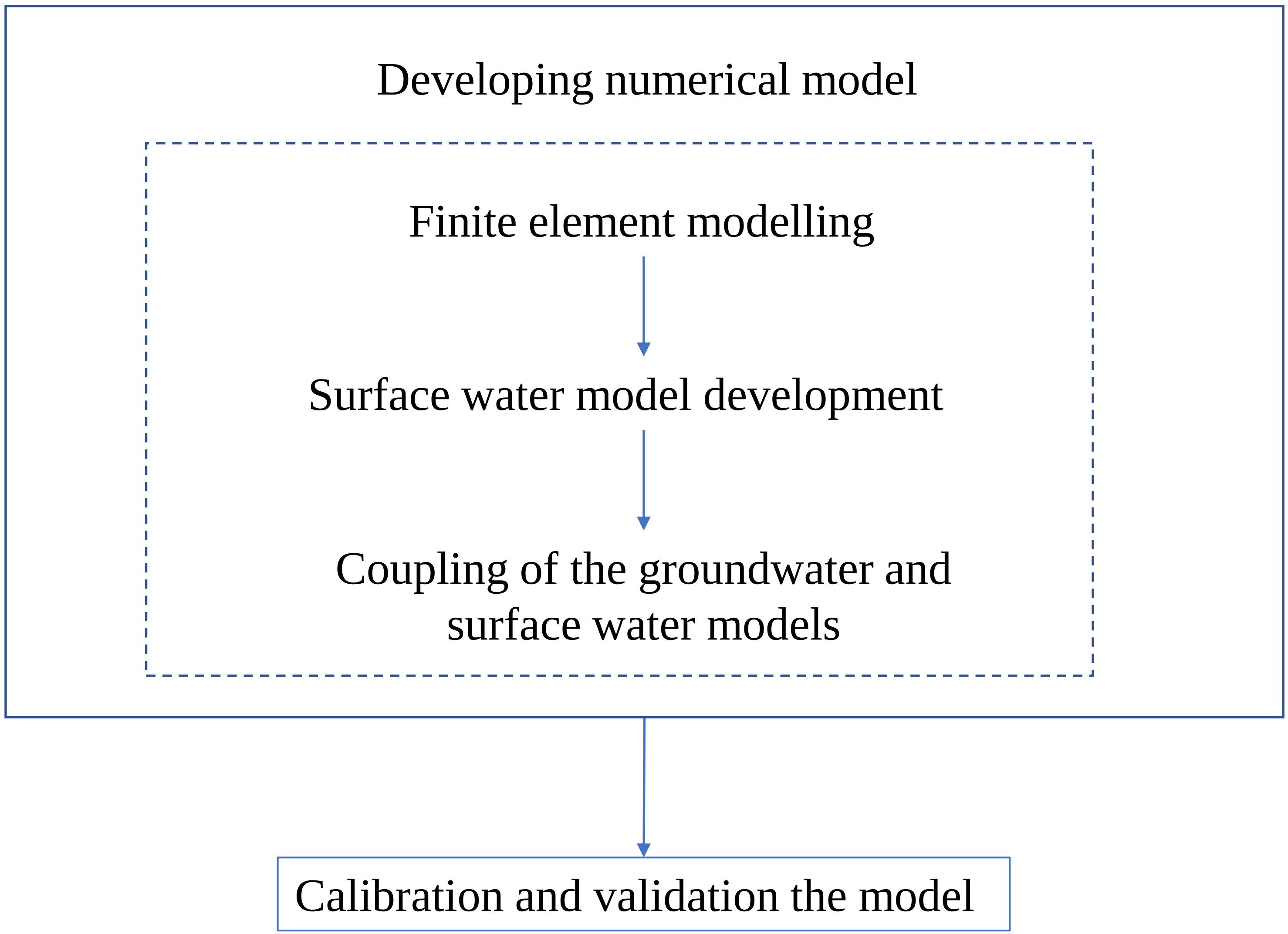
Permeability of soil decrease from the north-east to south-west but there many impervious bedrock at north, east and west → high run-off rate (Dibaj et al., 2020)

Precipitation: monsoon characterized with higher precipitation rate along the north and north east of the plain



Pingtung plain

II. METHODOLOGY



II. METHODOLOGY

Developing numerical model ⇨ Finite element modelling

ArcGIS — Polygon shapefile → 2D domain

FEFLOW:

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

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

3D discretise domain:

- Aquifer with six layers and seven slices
- 39,221 elements per layer and 20,352 nodes per slice

II. METHODOLOGY

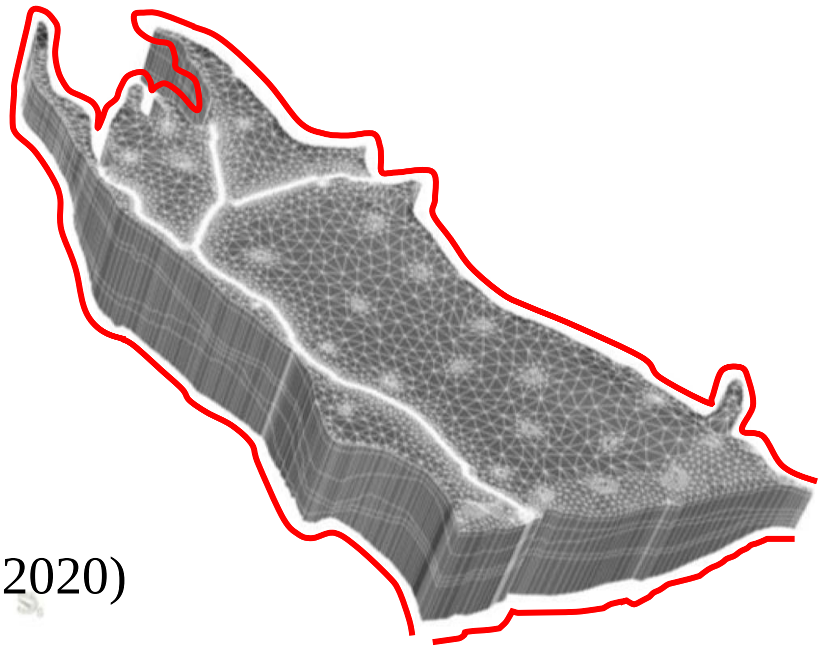
Developing numerical model ⇨ Finite element modelling

Boundary condition (Dibaj et al., 2020)

The first-type constant head (Dirichlet)

The coastal line in the southern boundary was assigned a constant mass concentration of 35,000 mg/L

The second-type (Neumann) boundary remain side of domain as no fluid flux



Saltwater head boundary condition (Dibaj et al., 2020)

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

where

ρ_f = 1,000 kg/m^3: densities of freshwater

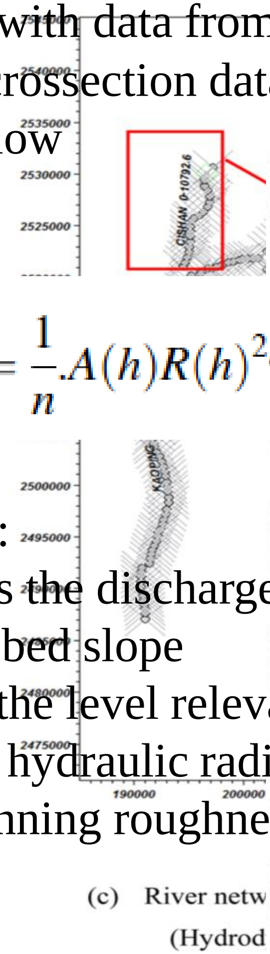
ρ_s = 1,025 kg/m^3: densities of saltwater

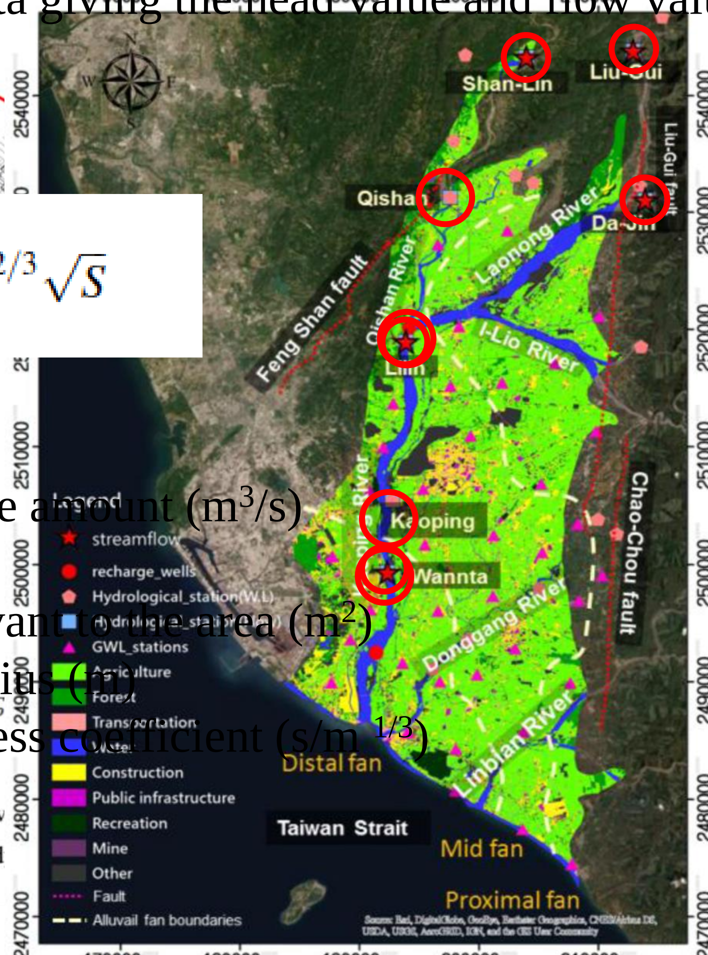
z is the elevation at each point of the model

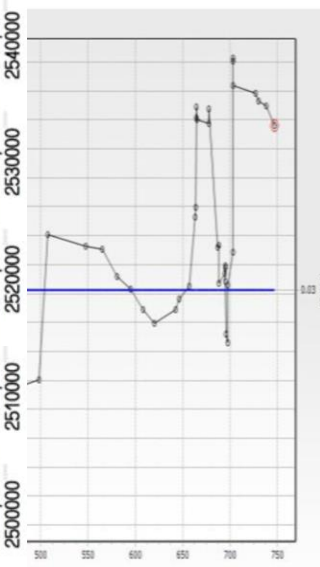
II. METHODOLOGY

Developing numerical model ▷ Surface water model development

- Using point digitisation in MIKE 11 to develop river network
- Open-end river 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 crossection data giving the head value and flow value through the Manning equation below







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

where:

$Q(h)$ is the discharge amount (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 ($s/m^{1/3}$)

II. METHODOLOGY

Developing numerical model ⊏ **Coupling of the groundwater and surface water models**

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

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

where:

q: Darcy flux of fluid (m/d)

h_{gw}: groundwater head (m)

h_{ref}: river heads (m)

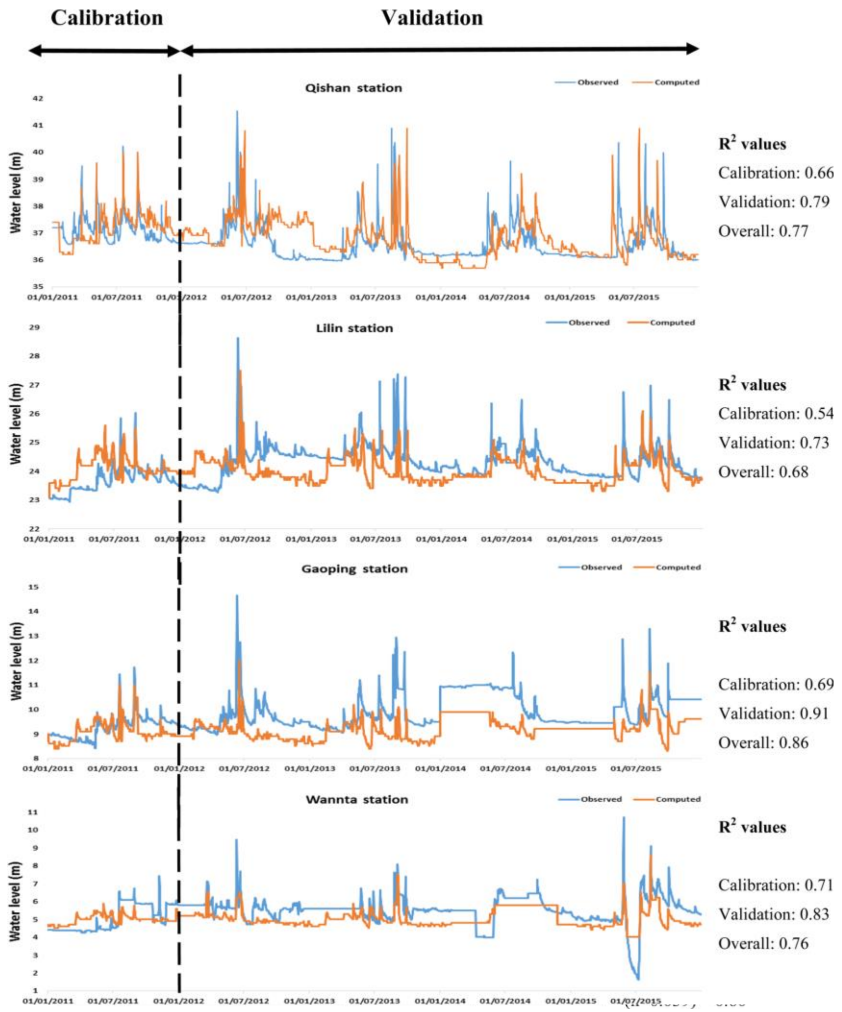
Φ_h: transfer coefficient – main element for controlling the flux (d^{-1})

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

II. METHODOLOGY

Calibration and validation of the model

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



➡ The average R^2 value of Calibration and Validation form 0.68-0.86 is acceptable.

II. METHODOLOGY

Calibration and validation of the model

Mass concentration: 0 mg/L

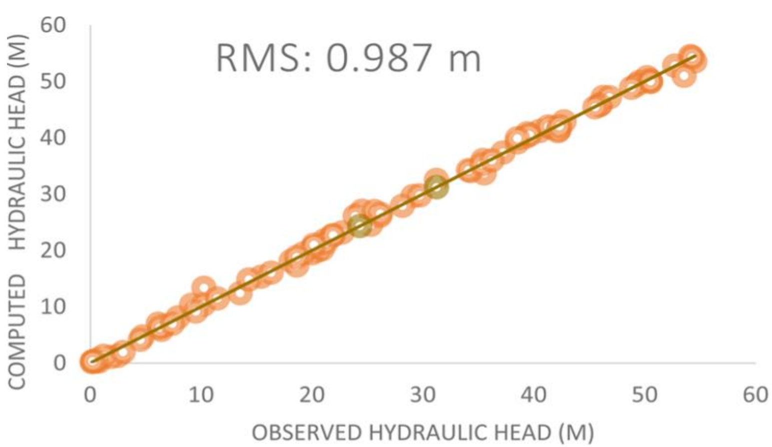
Initial data input

2011 — Calibration → **2012** — Validation → **2015**

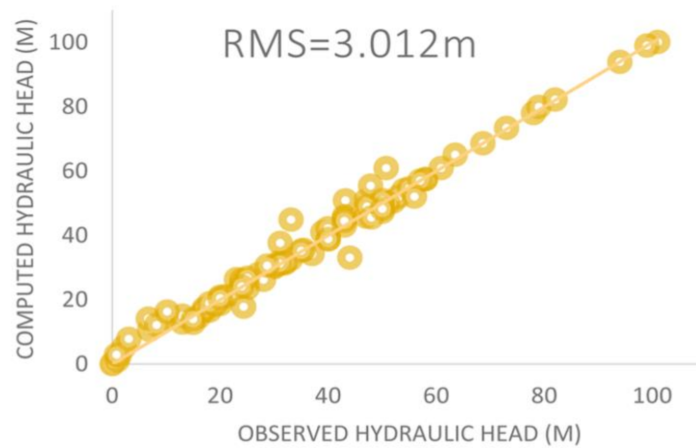
Steady state condition

Transient condition

Resulting mass concentration



The calibration process for the groundwater model

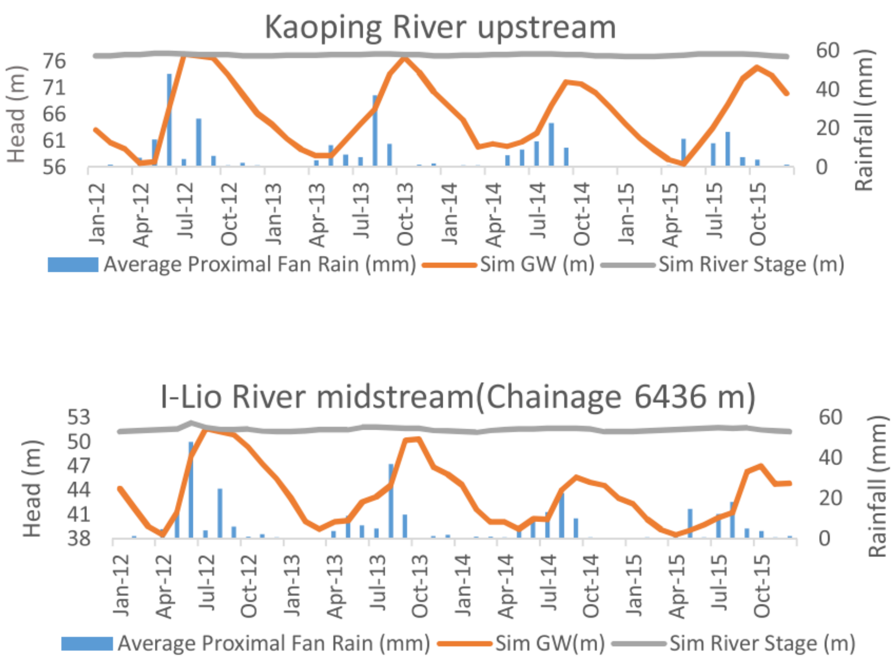


The validation process for the groundwater model

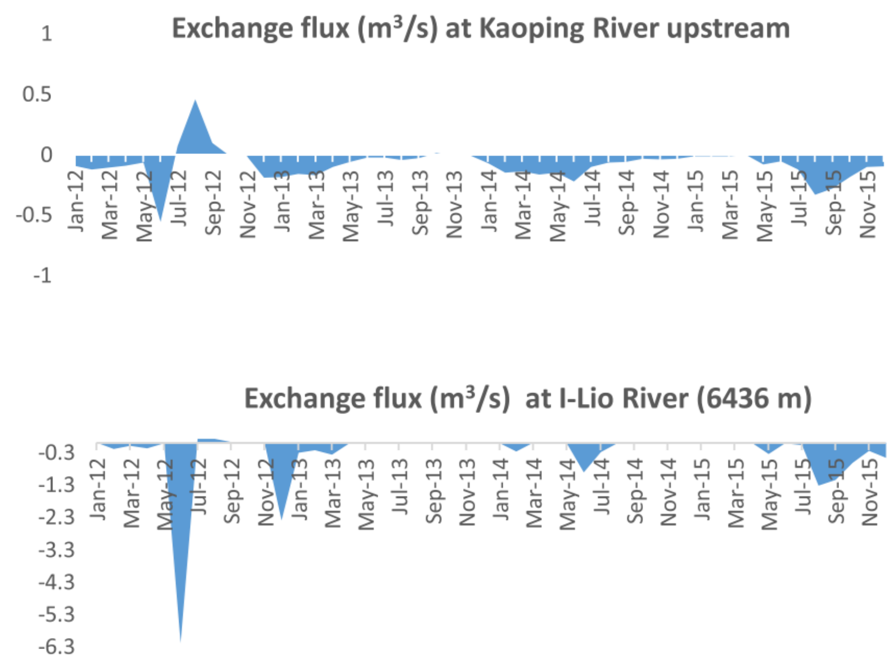
III. RESULT

1. River-precipitation-groundwater interaction

Proximal fan



River and groundwater level after coupling based on average rainfall



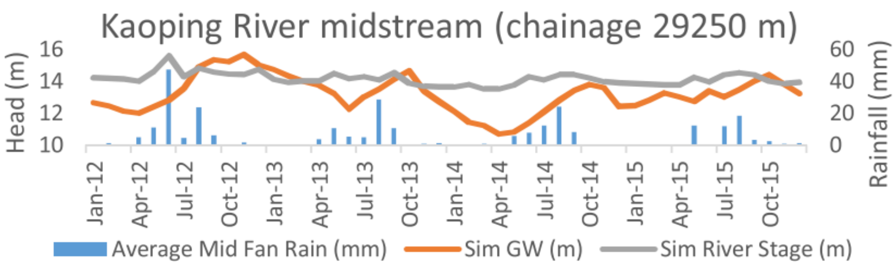
Fluid flux exchange between rivers and groundwater

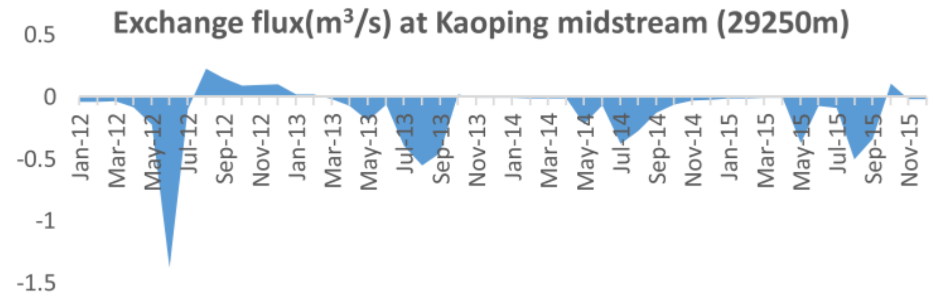
→ Groundwater was highly under the influence of precipitation and abstraction, leading to its fluctuation and interaction with the river water.

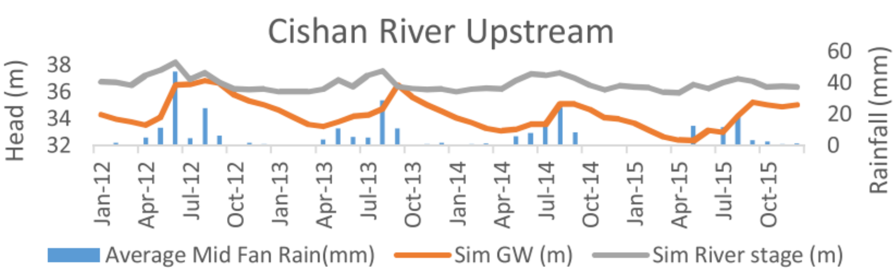
III. RESULT

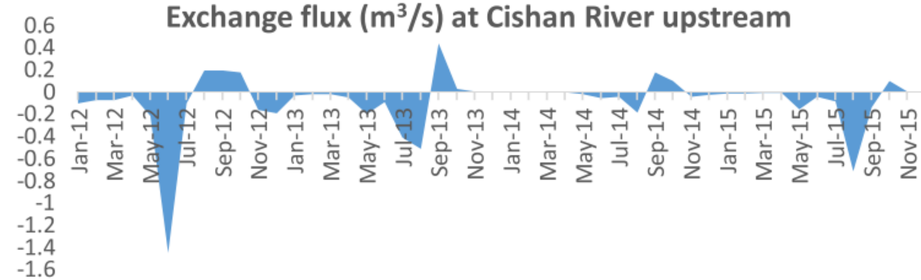
1. River-precipitation-groundwater interaction

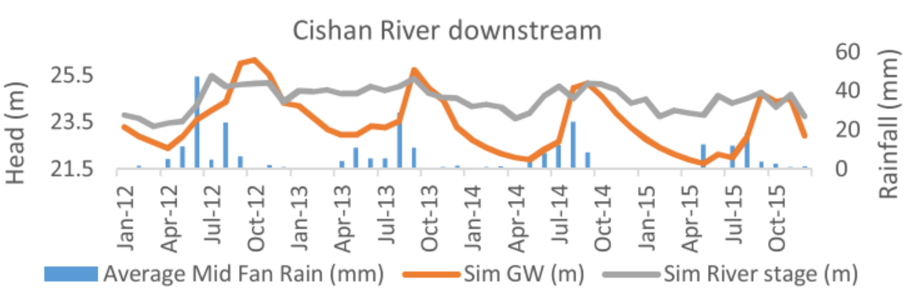
Mid fan

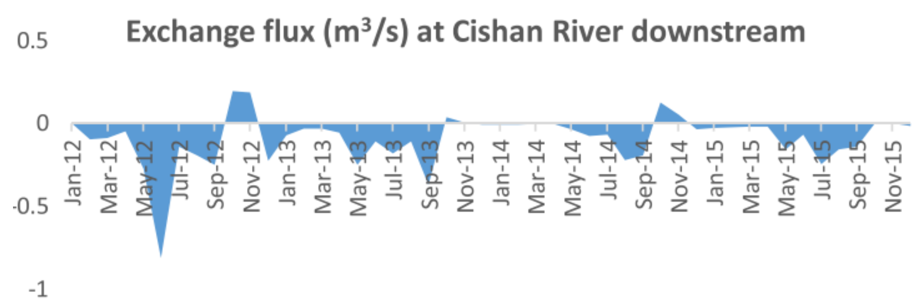












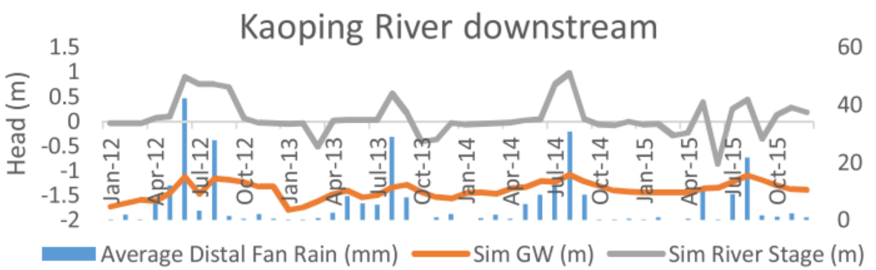
River and groundwater level after coupling based on average rainfall

Fluid flux exchange between rivers and groundwater

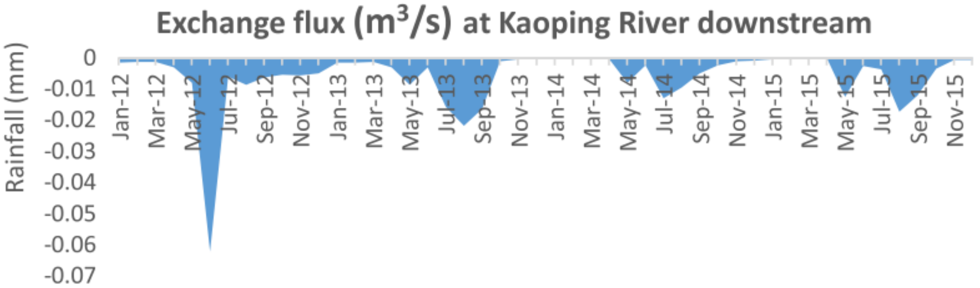
III. RESULT

1. River-precipitation-groundwater interaction

Distal fan



River and groundwater level after coupling based on average rainfall



Fluid flux exchange between rivers and groundwater

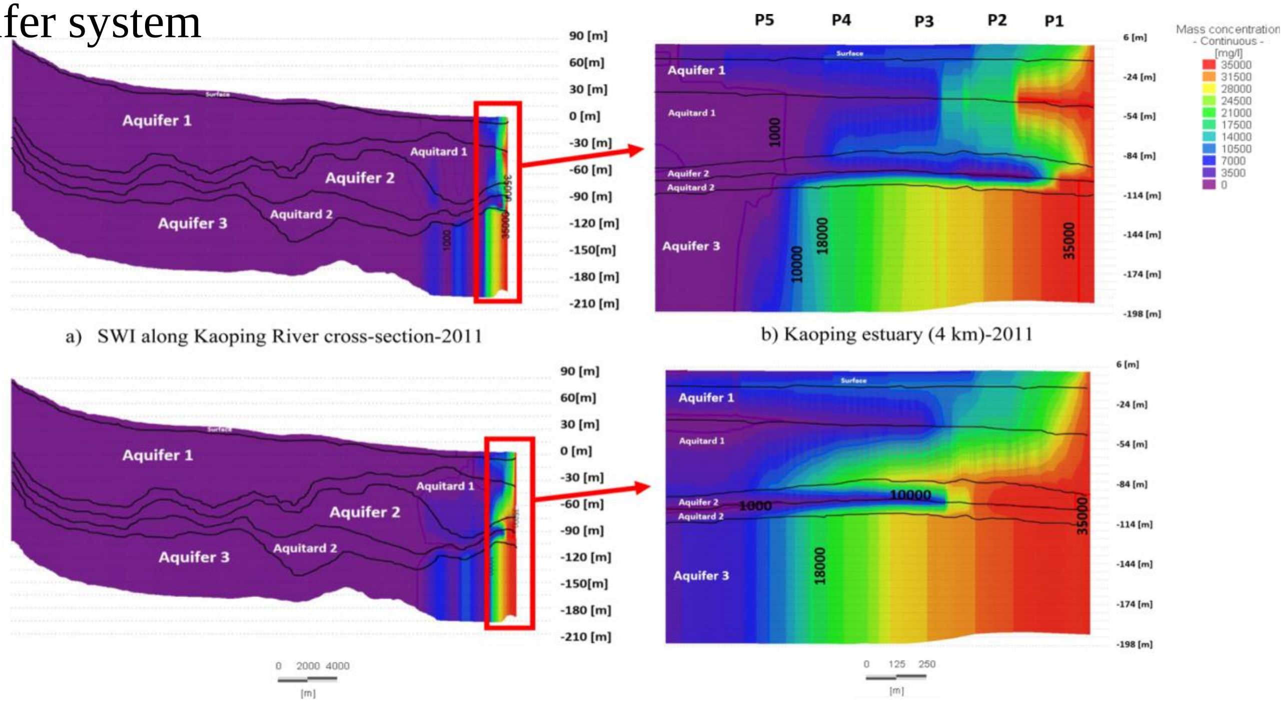
→ Groundwater had a faster reaction (less than one month) to rainfall events with insignificant head fluctuation

III. RESULT

2. Seawater intrusion (SWI)

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

Seawater has intruded in the entire depth of the aquifer at different inland distances in different layers of the aquifer system



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

SWI along Kaoping River cross-section (a&c) and 4 km from the sea (b&d) at the end of 2011 and 2015 with 12 times magnification

→ Effect of groundwater abstraction in this aquifer.

→ Effect of the Kaoping River bed location in the salinization of lower aquifers through the river mouth besides the effect of groundwater abstraction.

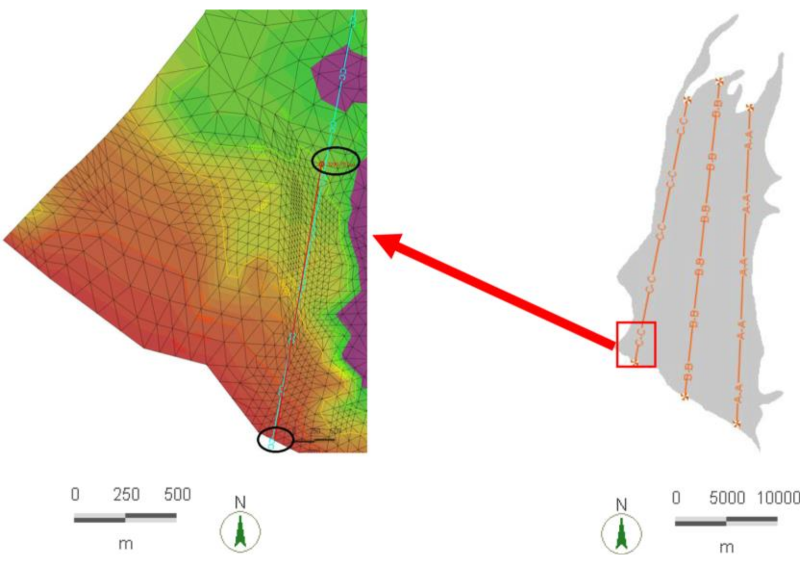
III. RESULT

2. Seawater intrusion (SWI)

Other cross-sections result in the 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, inland distance 2011 - 2015 almost unchanged in all aquifer.
- 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

→ Kaoping river estuary also guiding seawater inland through the river mouth

III. RESULT

3. Seawater intrusion (SWI) mitigation

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

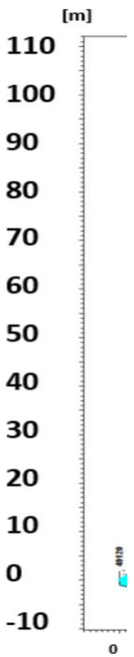


Table 2
Inland distance (m) of saline water (10,000 < TDS < 35,000 mg/l) along four cross sections due to different recharge rates at Cishan and Kaopingf River downstream.

		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				
	Aquifer 1	1800	2400	3460	2180
200 K (m^3/d)	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

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

IV. CONCLUSION

3D transient density-dependent finite element model for groundwater flow and solute transport coupled with 1-D river network model for integrated simulation of groundwater flow, surface water flow and seawater intrusion in Pingtung plain was developed

Result showed that:

- The groundwater in the proximal fan has the slowest reaction time to heavy rainfall whilst the lowest delay was observed in the distal fan
- About seawater intrusion:
  + At the beginning of the simulation, the top layer of the aquifer system was less intruded due to fresh river water discharge pushing back the saline water seaward
  + At the end of the stimulation, increasing seawater inland through river bed towards the top aquifer
- The Kaoping River was selected as the sufficient location for artificial recharge. It resulted seaward movement of seawater highlighted the effectiveness of applying recharge wells near toe location.

THANKS FOR YOUR ATTENTION

2. METHODOLOGY

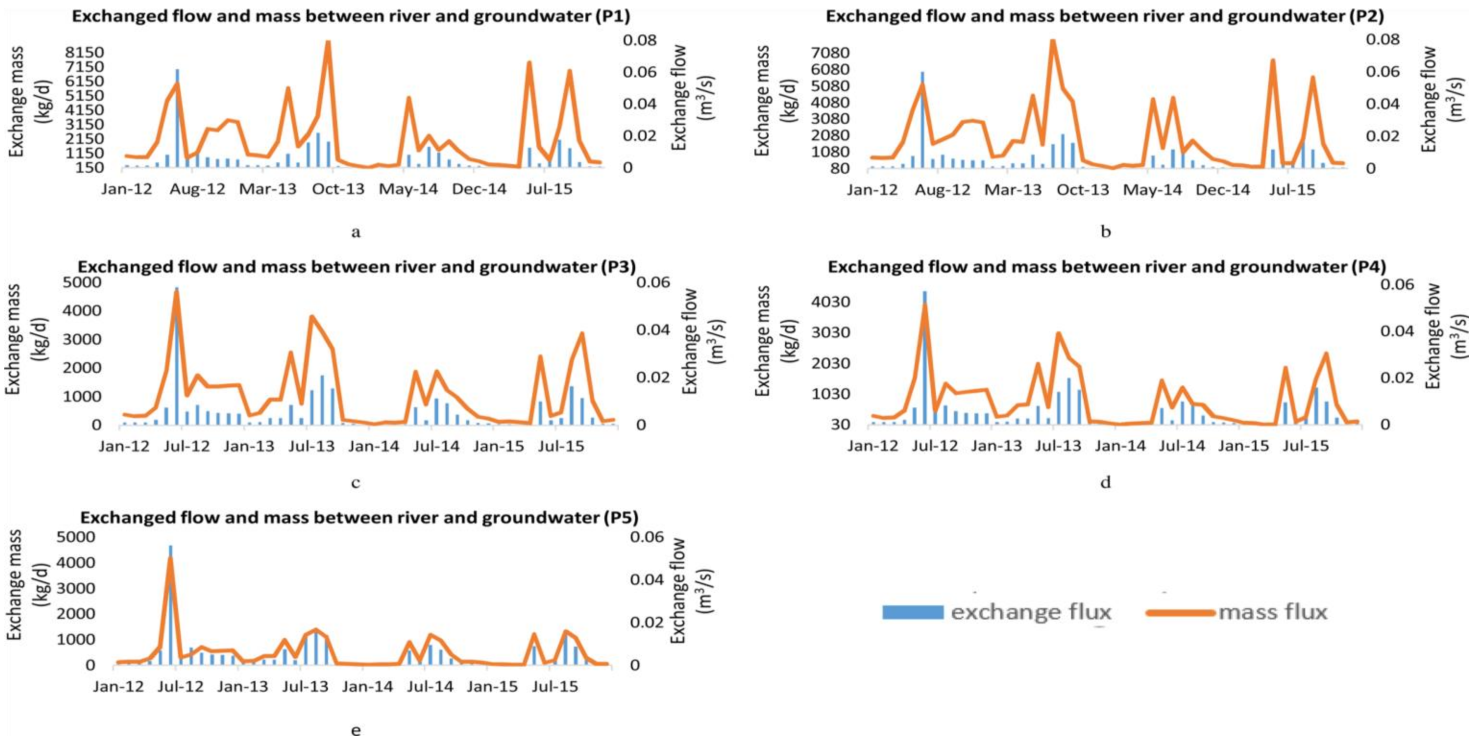
2.1. Study area

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}	0.00005
Transmissivity	9000 m^2/day	2300 m^2/day	1200 m^2/day

III. RESULT

2. Seawater intrusion (SWI) - Mass interaction in Kaoping River estuary

The mass flux between river and seawater was dominated by the changing of fluid flux



Exchange flow and transient mass between Kaoping River and groundwater from P1 to P5

The surface layer and top aquifer under the influence of river effects

- At the first aquifer, 20–30% more salinity than the top surface layer
- The salinity of the underlying layers did not change significantly along the river