APPLYING THE VARIABLY SATURATED FLOW MODEL TO SIMULATE GROUNDWATER FLOW IN PINGTUNG PLAIN BY USING THMC

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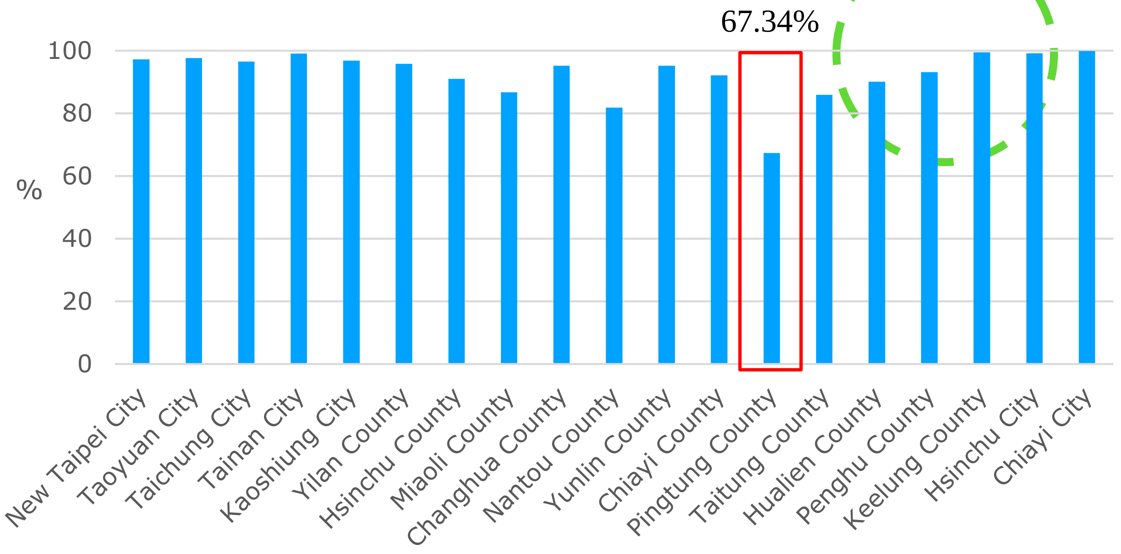
Outline

- In 2023, tap water coverage average rate in Taiwan is 94.74 %

Pingtung county

- Limited surface water
- Lowest ratio of tap water use (67.34%)
- Agriculture water demand large (85%)

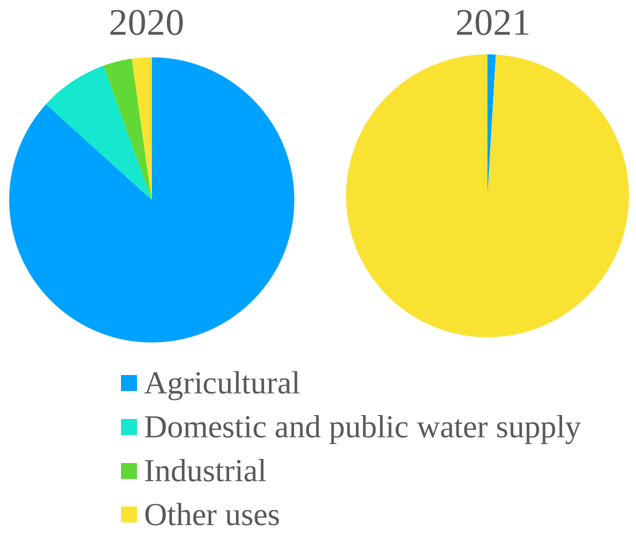


The coverage of the tap water in main city in Taiwan in the first half of 2023 (water.gov.tw)

Over-exploitation groundwater

Seawater intrusion affects about 30% of the Pingtung area. With climate change and rising sea levels, the problem has become more serious.

Land subsidence has been occurring over several decades. In 2022, the subsidence area covered approximately 68.5 km^2, with a subsidence rate ranging from 4 to 6 cm/year. It extends 8 km parallel to the coastline and averages about 3 cm/year inland.



Literature Review

Jang et al. (2016) use MODFLOW to create a numerical flow model combined with groundwater quality to establish utilization strategies for groundwater and surface water in the Pingtung Plain.

Gao et al. (2017) use MODFLOW and the groundwater fluctuation method to determine the accuracy of groundwater recharge estimates in the Donggang River and Linbian River basins.

Vu et al. (2021) utilize the MODFLOW model to simulate the physical response of the groundwater system and calculate its vulnerability under different climate change scenarios.

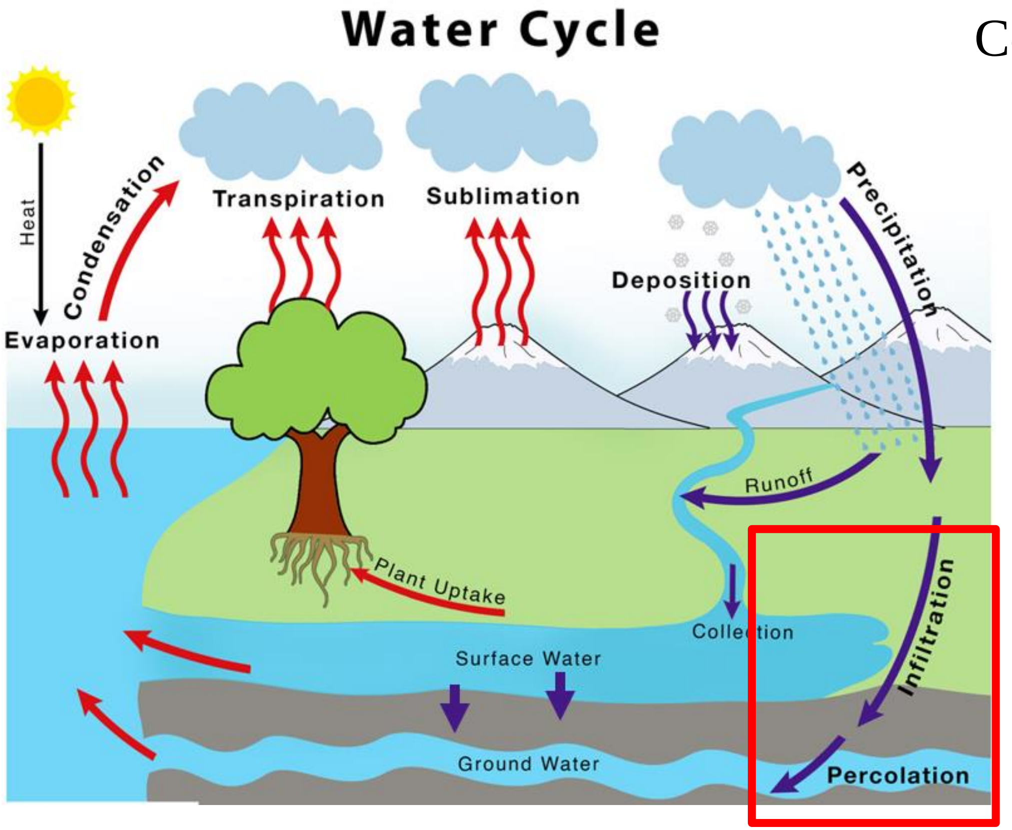
Dibaj et al., 2021 use FEFLOW in conjunction with MIKE11 to model 3D groundwater-surface water interactions for managing seawater intrusion in the Pingtung Plain.

- ✓ Research focus on the relationship between surface and groundwater interaction.
- ✓ Using the combination of difference model and software to reach research purpose.

Motivation

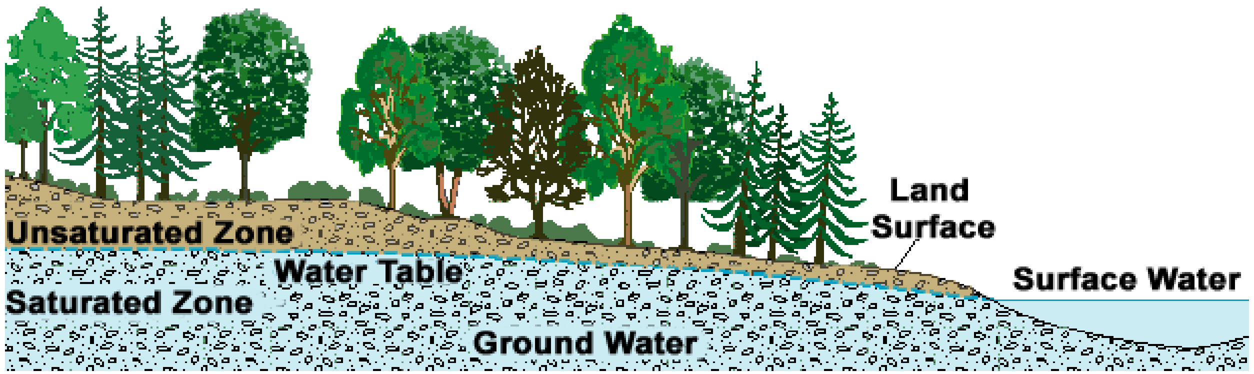
Rainfall has a significant effect on the agriculture water demand of Pingtung Plain.

The main water recharge source of groundwater in Pingtung plain is the accumulation of rainfall.



Controlling water movement from the land surface to the aquifer

Affects the rate of aquifer recharge



❖ Currently, numerical models are simulating in saturated mode, and for further purposes, they need to be combined with other models.

Model selection: THMC

PART 1

Developed by Hydroscience Chair Professor Gour-Tsyh Yeh

Saturated groundwater model

Properties of soil and behavior of flow in unsaturated zone are neglected. Assumed amount of percolation is assigned.

MODFLOW
flow only

2013

1991

1981

Consider properties of soil in unsaturated zone, and evaluate amount of infiltration and percolation based on rainfall.

FEMWATER
a.flow
b.solute transport

code revised

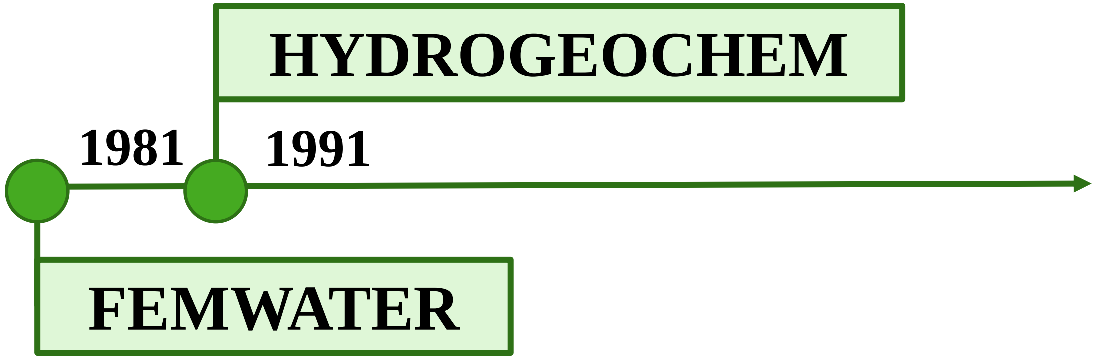
HYDROGEOCHEM
a.flow
b.solute transport
+chemical reaction
c.heat transfer

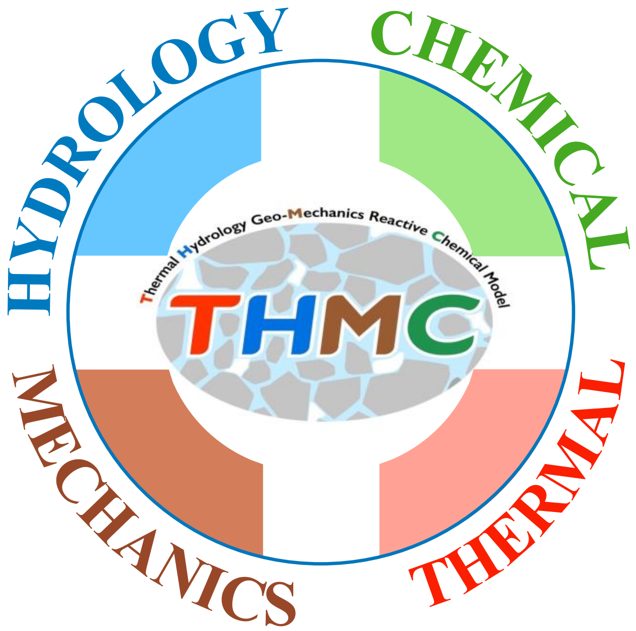
code revised

THMC
a.flow
b.solute transport
+chemical reaction
c.heat transfer
d.geomechanics

Variably saturated groundwater model

THMC software (Thermal – Hydrology – Mechanic – Chemical)





THMC is the groundwater numerical model using Finite Element Method simulation through Saturated-Unsaturated Media. The software is continuity developed by CAMRDA team with a user-friendly interface platform.

- ➢ Applying under saturated and unsaturated mode
- ➢ Precipitation is used to calculate infiltration and percolation
- ➢ Combine with the soil characteristic of unsaturated layer in the subsurface media

Objective

Applying the variably saturated flow model to simulate groundwater flow in Pingtung plain by using THMC software

- The accumulation of rainfall is the main recharge factor for groundwater in the model.
- The model simulates under both saturated and unsaturated mode.
- Impermeable surfaces are determined based on roads and buildings in the study area.

II METHODOLOGY

Study area - Pingtung plain

1210 km^2

Natural boundary with fault, foothills and river valley and the elevation gradually reduce from North to South

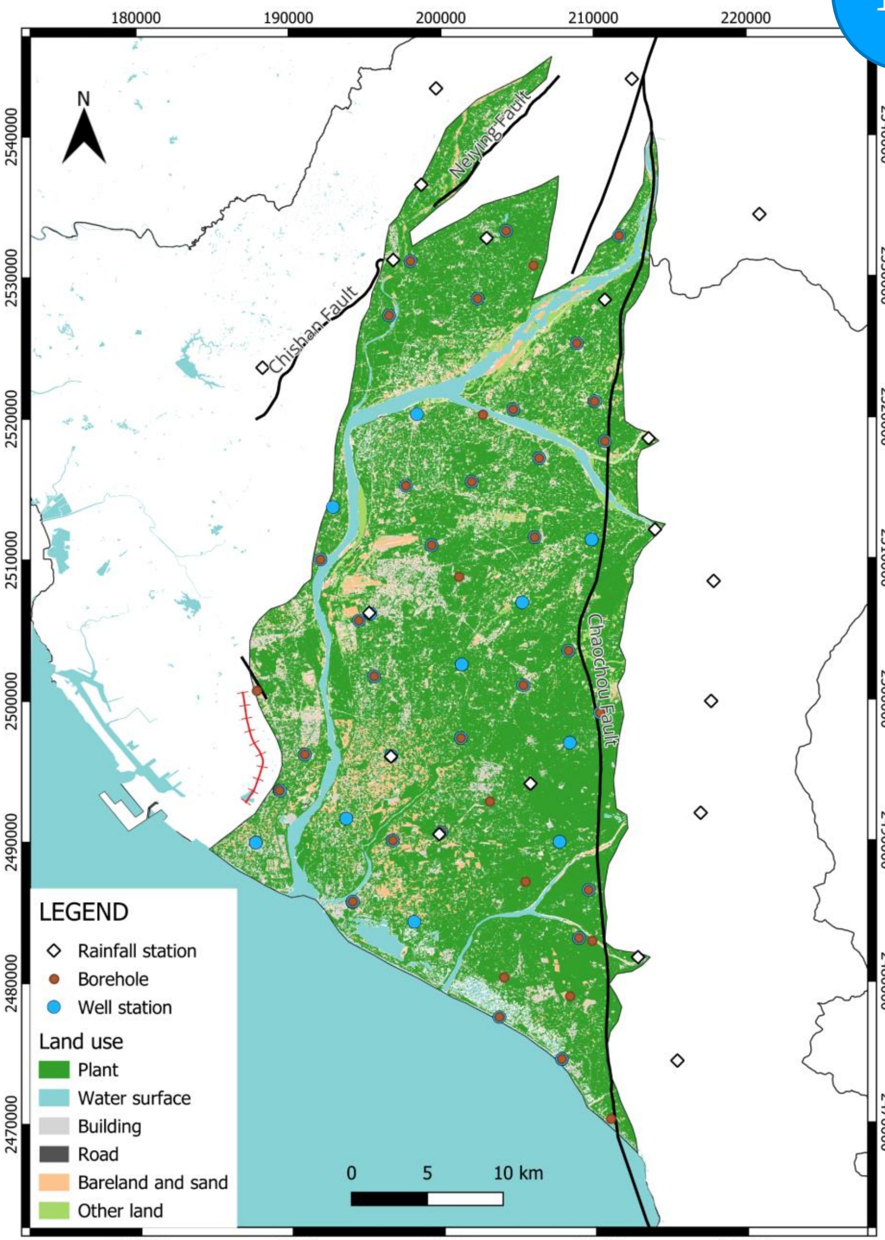
The weather is influenced by the monsoon climate with high annual rainfall rate

- ✓ Water from heavy rainfall in wet season
- ✓ Lacking of water in dry season

About 62% land use for agriculture

- ✓ Rely on weather
- ✓ High demand for irrigation purpose with large number of private pumping wells

Manage groundwater and establish sustainable use plans is an essential issue.



Study area

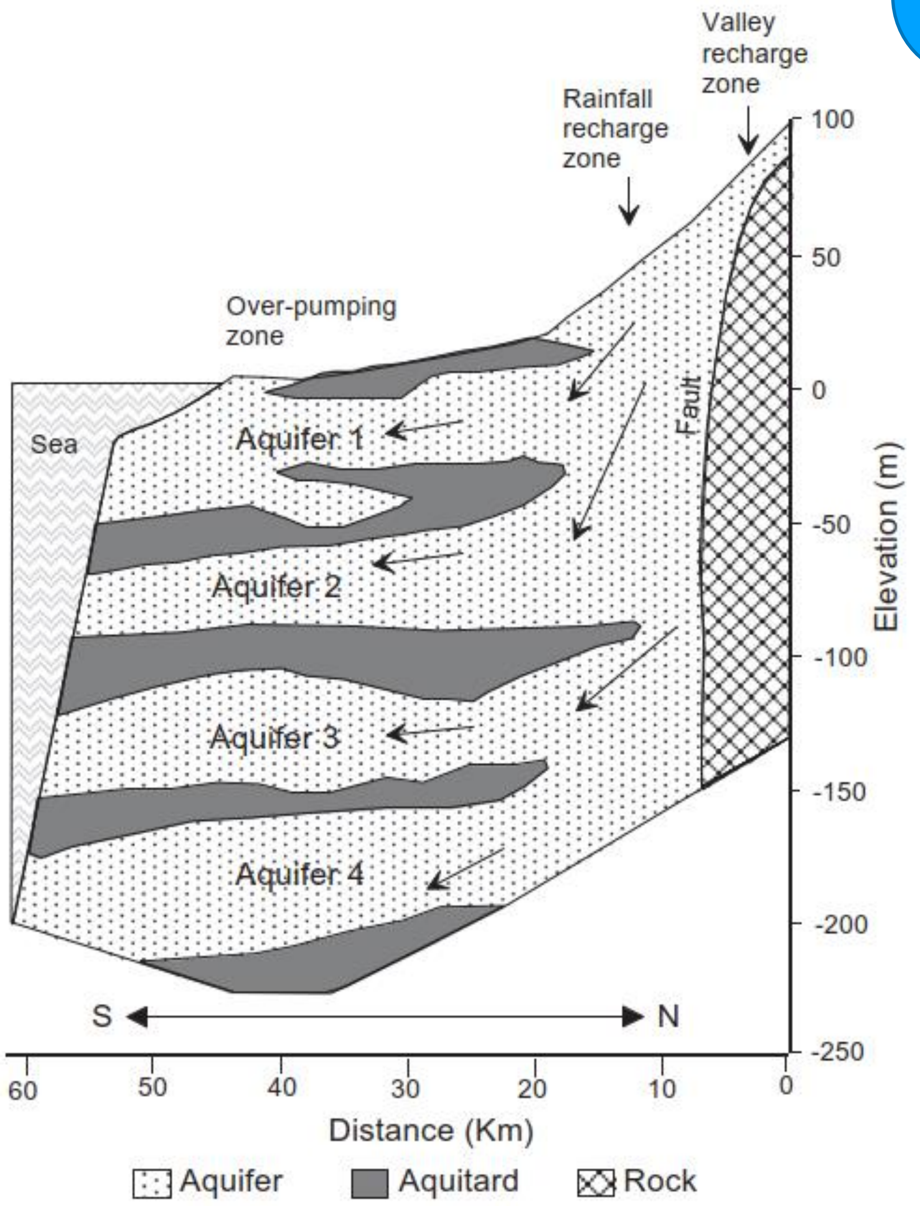
Study area - Pingtung plain

Hydrogeological

- Aquifer: high permeable coarse sediment ranging from medium sand - gravel
- Aquitard: low permeable fine sediments like fine sand, silt.

Aquitard layers only appear in the southern part of the study area and divide the aquifer into four layers.

The recharge area mostly consists of aquifer layers, with almost no aquitard appearance.
→ Water from rainfall can pass through the recharge area to reach all aquifer layers in the southern part.



A conceptual hydrogeological profile of the Pingtung Plain (CGS)

Governing equation

Data input

Boundary Conditions

Governing equation for flow through saturated-unsaturated media using in THMC software follow below equation:

$$\frac{\rho}{\rho_0}F\frac{\partial h}{\partial t} = \nabla.\left[\boldsymbol{K}.\left(\nabla h + \frac{\rho}{\rho_0}\nabla z\right)\right] + \frac{\rho^*}{\rho_0}q$$

(Yeh et al., 1994a, 1994b)

θ: effective moisture content (L^3/L^3)
h: pressure head (L)
t: time (T)
z: potential head (L)
q: source/sink of fluid $[(L^3/L^3)/T]$
ρ_0: referenced fluid density at zero chemical concentration (M/L^3)
ρ: fluid density with dissolved chemical concentrations (M/L^3)
ρ^*: fluid density of either injection (ρ^*) or withdraw $(=\rho)$
μ_0: fluid dynamic viscosity at zero chemical concentration $[(M/L)/T]$
μ: fluid dynamic viscosity with dissolved chemical concentrations $[(M/L)/T]$
α': modified compressibility of the soil matrix (1/L)
β': modified compressibility of the liquid (1/L)
n_e: effective porosity (L^3/L^3)
S: degree of effective saturation of water
g: gravity (L/T^2)
k: permeability tensor (L^2)
$\boldsymbol{k_s}$: saturated permeability tensor (L^2)
$\boldsymbol{K_{so}}$: referenced saturated hydraulic conductivity tensor (L/T)
k_r: relative permeability or relative hydraulic conductivity (dimensionless)

F: generalized storage coefficient (1/L)

$$F = \alpha'\frac{\theta}{n_e} + \beta'\theta + n_e\frac{dS}{dh}$$

K : hydraulic conductivity tensor (L/T)

$$\mathbf{K} = \frac{\rho g}{\mu}\boldsymbol{k} = \frac{\rho/\rho_0}{\mu/\mu_0}\frac{\rho_0 g}{\mu_0}\boldsymbol{k_s}k_r = \frac{\rho/\rho_0}{\mu/\mu_0}\boldsymbol{K_{so}}k_r$$

Darcy's velocity (L/T)

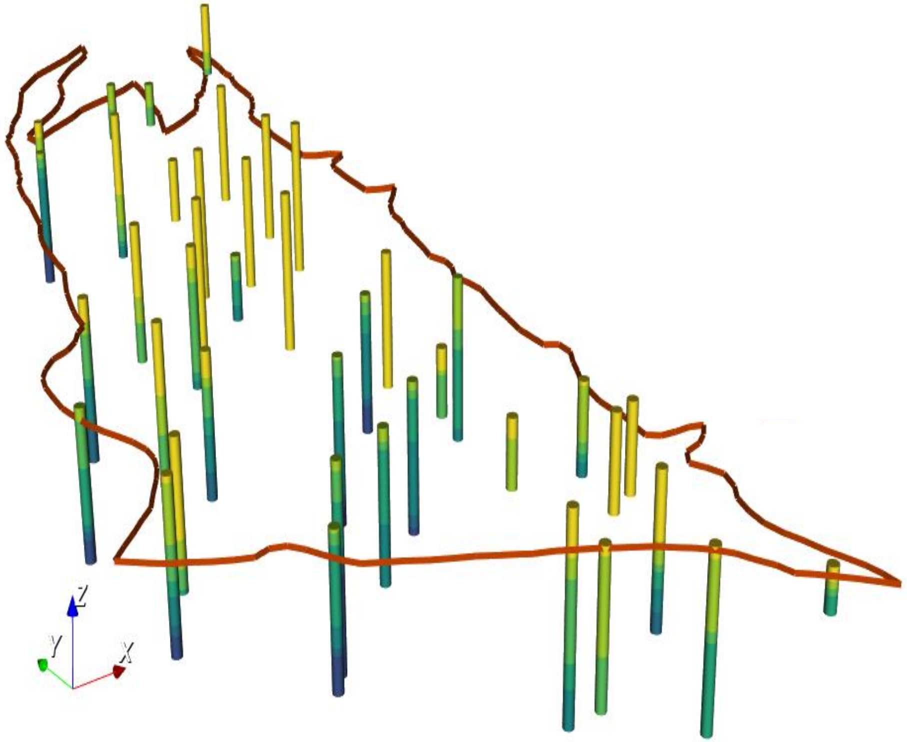
$$V = -\boldsymbol{K}.\left(\frac{\rho_0}{\rho}\nabla h + \nabla z\right)$$

Governing equation

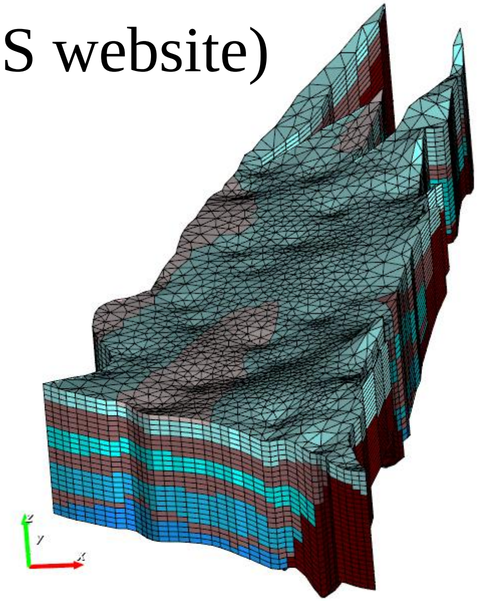
Data input

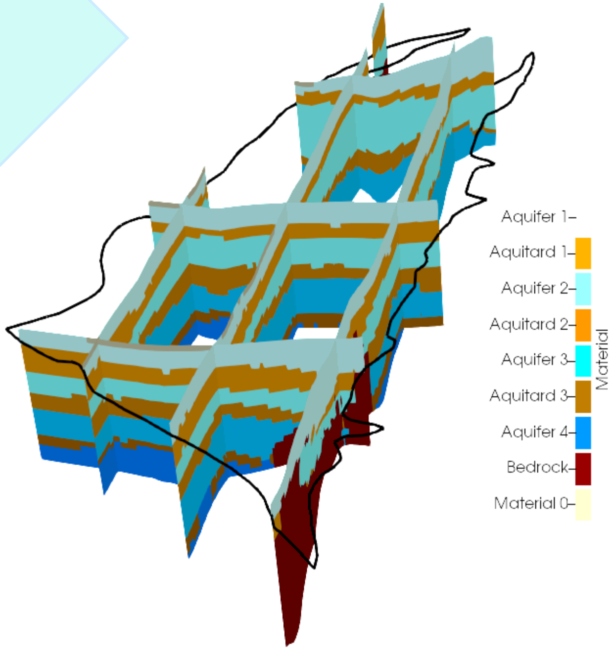
Boundary Condition

- Conceptual hydrological: build up from 42 borehole cores (CGS website)



Triangular column grid system with 33,358 nodes and 10,257 elements





Governing equation

Data input

Boundary Condition

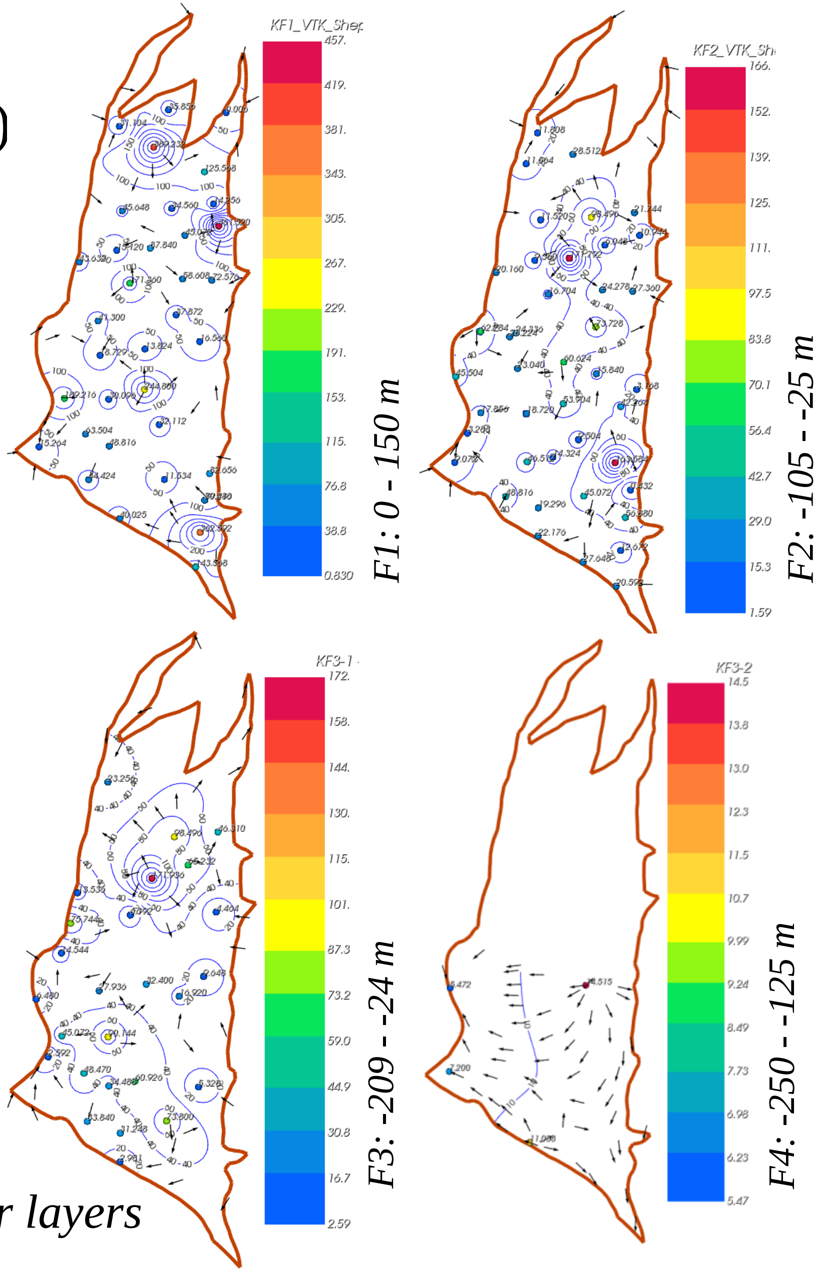
- K value reference:

  Aquifer: 148 wells pumping test result (CGS report)

  Aquitard: According to type of rock and giving K value base on reference table of Domenico and Schwartz (1998).

Unit: m/day

Layer	Material	Kxx	Kyy	Kzz
1	Material 0	1.719	1.719	0.172
2	Aquifer1	89.682	89.682	8.968
3	Aquitard1	1.239	1.239	0.124
4	Aquifer2	44.438	44.438	4.444
5	Aquitard2	0.874	0.874	0.087
6	Aquifer3	25.027	25.027	2.503
7	Aquitard3	1.816	1.816	0.182
8	Aquifer4	43.027	43.027	4.303
9	Bedrock	0.124	0.124	0.012



Hydraulic conductivity distribution in 4 aquifer layers

Governing equation

Data input

Boundary Condition

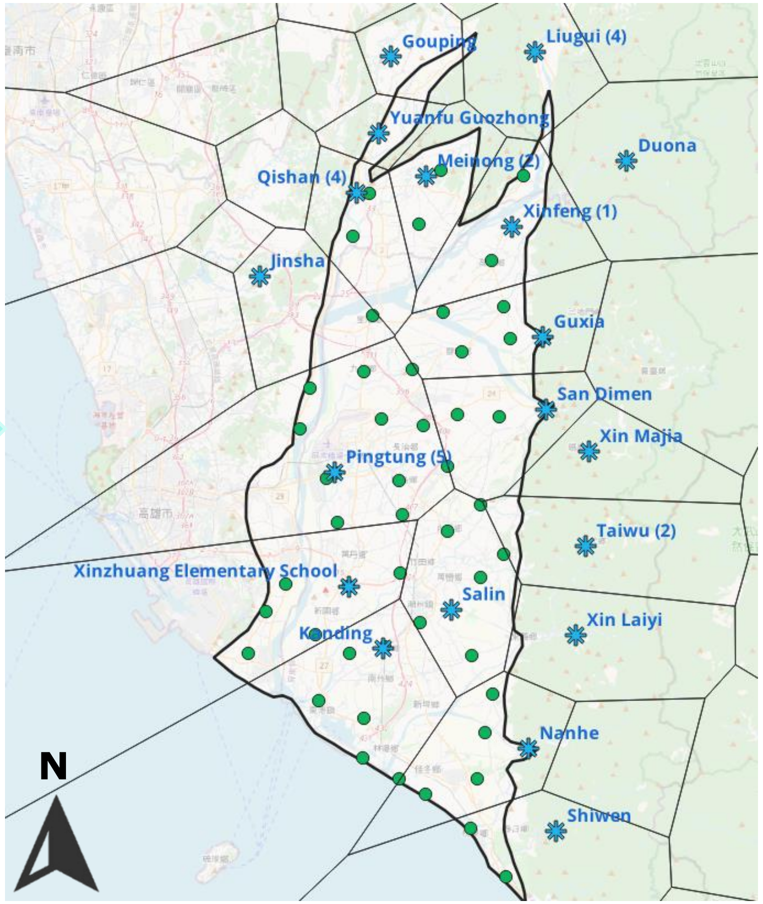
Groundwater level: daily data 2020 – 2022 of 90 stations (WRA)

Rainfall rate: daily data 2020 – 2022 of 19 stations (WRA)

Unit: mm/year

Station ID	Station name	2020	2021	2022
1670P001	Jinsha	2192	3255	1244
1730P021	Guxia	2286	3698	1350
1730P060	Pingtung (5)	1996	3536	1241
1730P081	Meinong (2)	1744	3976	1580
1730P147	Duona	2171	4373	1474
1730P148	Xinfeng (1)	2094	4279	1803
1730P150	Gouping	1797	3975	1437
1730P151	Yuanfu Guozhong	1631	3616	1522
1730P152	Xinzhuang School	2118	3141	1077
1740P049	Salin	2136	3737	1413
1740P050	Kanding	1941	3447	1182
1740P051	Taiwu (2)	3270	5658	1762
1760P011	Nanhe	2123	3453	1117
1760P013	Xin Laiyi	2694	4962	1447
1790P002	Shiwen	2439	3521	1161

Using Thiessen method to determine rainfall distribution zone



GW level station

Rainfall station

Pumping rate: using groundwater usage right of Pingtung county (WRA) to represent for pumping rate

Unit: $10^6 m^3$

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2020	77.89	70.40	78.00	75.27	77.64	71.99	77.58	77.12	74.62	77.29	75.14	75.34	908.26
2021	0.108	0.097	0.108	0.105	0.108	0.104	0.107	0.107	0.104	0.108	0.104	0.108	1.268
2022	94.58	85.52	94.23	91.72	94.74	81.17	95.15	95.43	92.79	96.13	93.13	85.47	1100.06

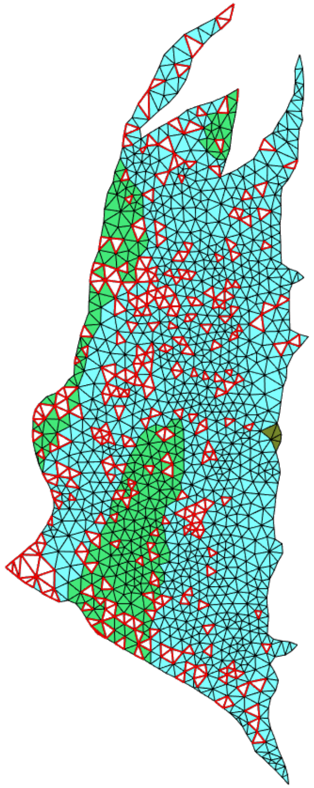
Permeable surface:

Satellite image

Land cover classify

Road and building distribution

Point distribution



Impermeable surface

Governing equation

Data input

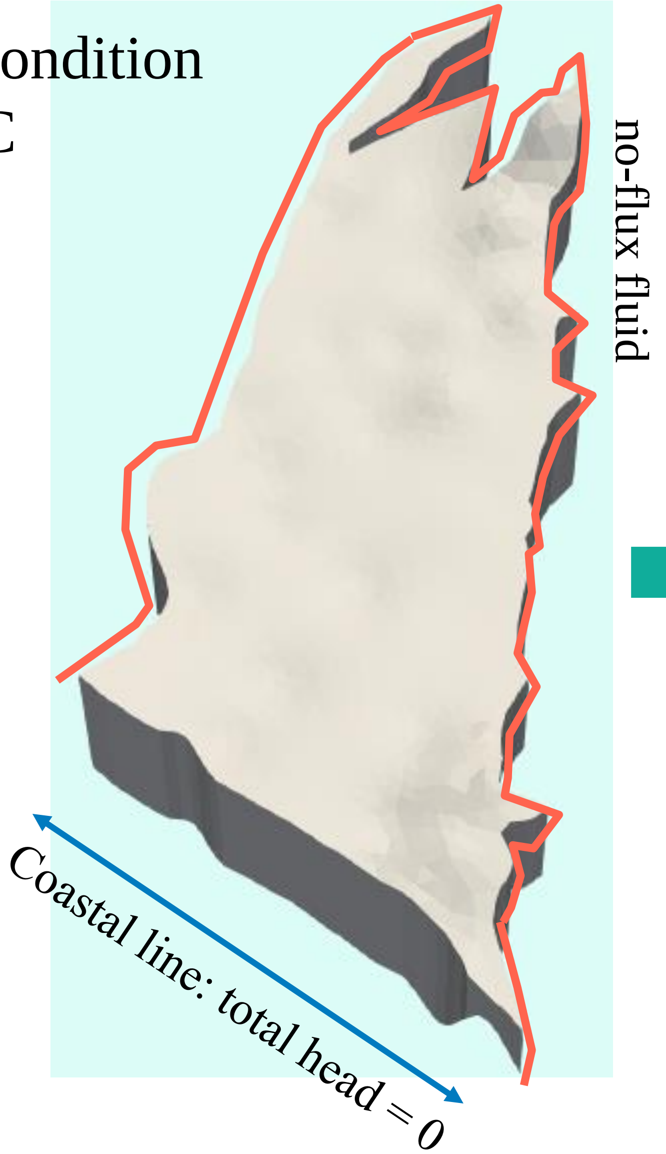
Boundary Condition

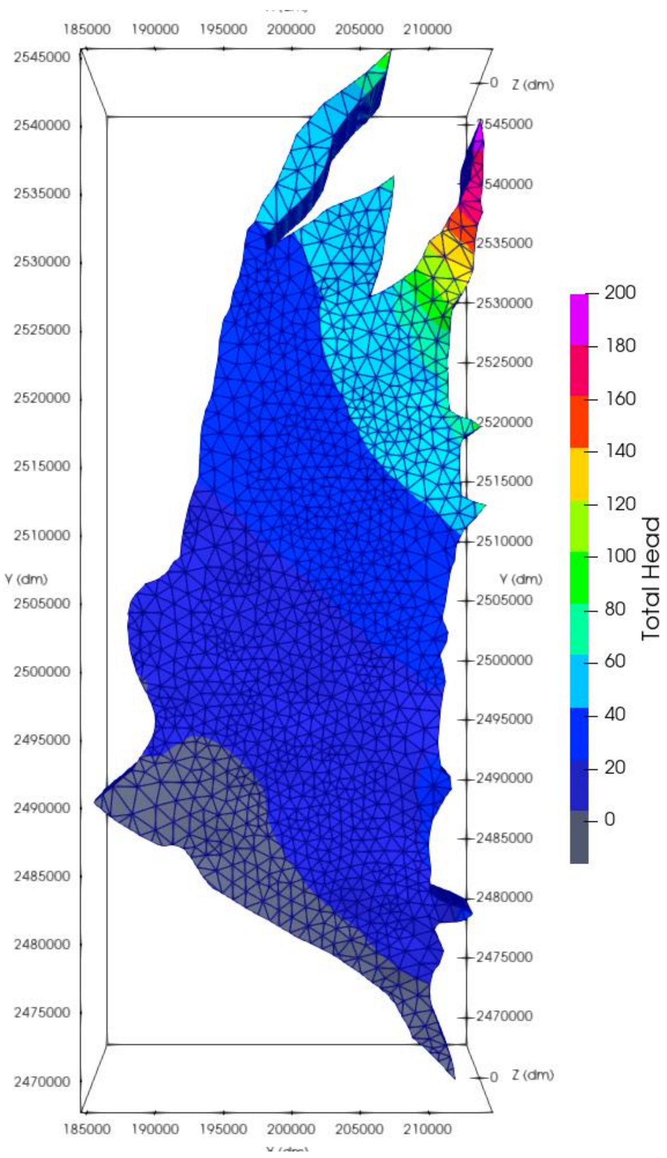
Steady-state simulation for Initial condition

- ✓ Dirichlet boundary condition
- ✓ Rainfall: variable BC

Initial result

Transient simulation

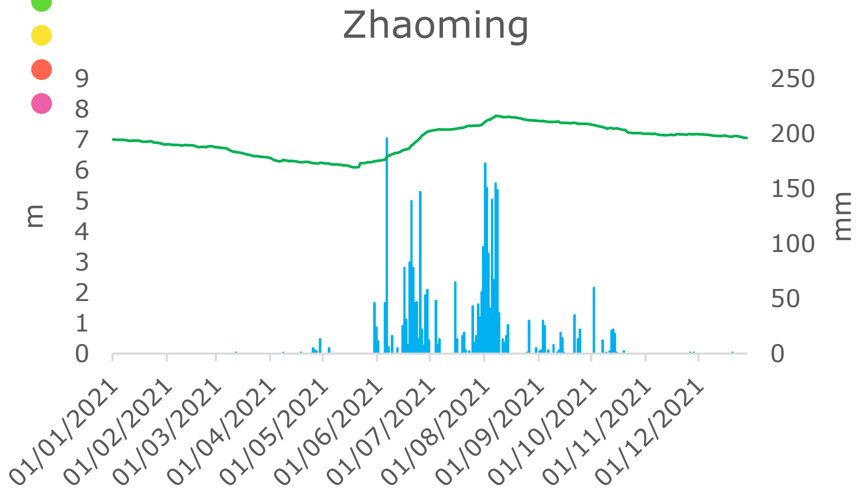


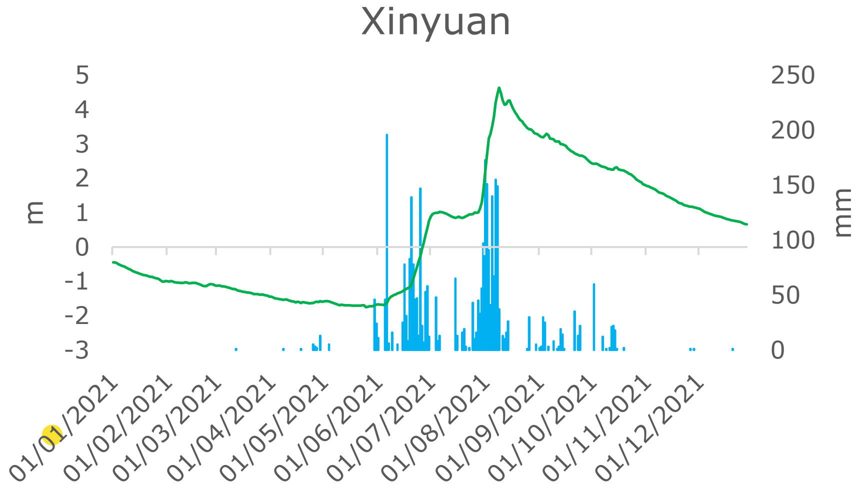


Initial data distribution

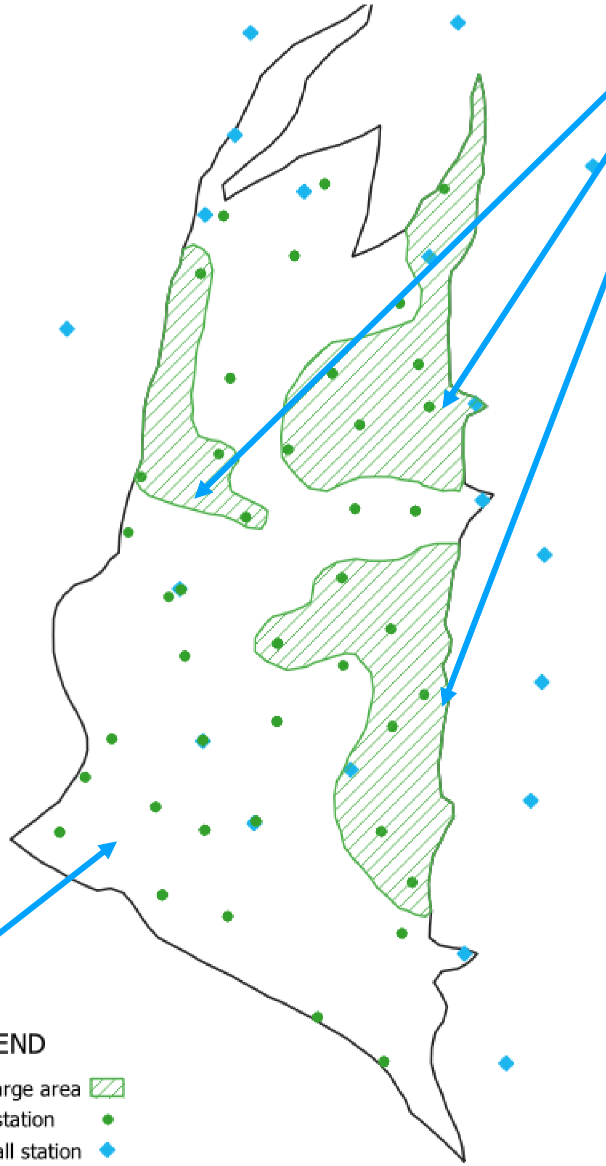
III PRELIMINARY RESULT

Recharge area distribution

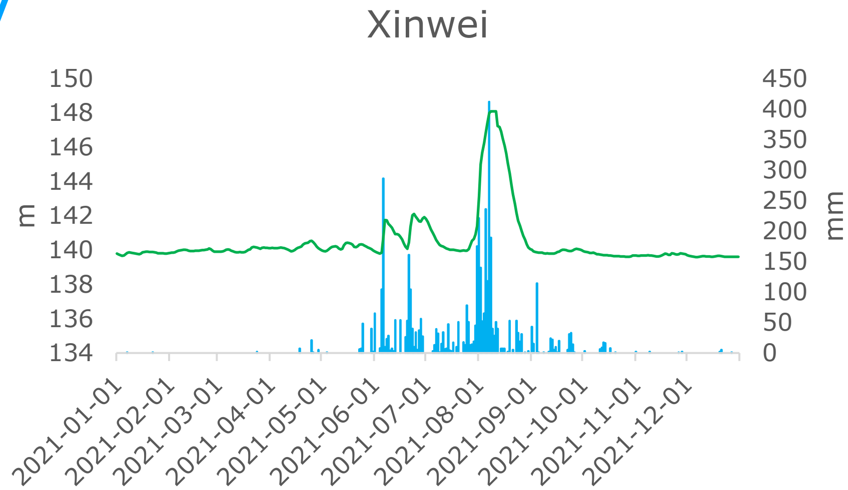


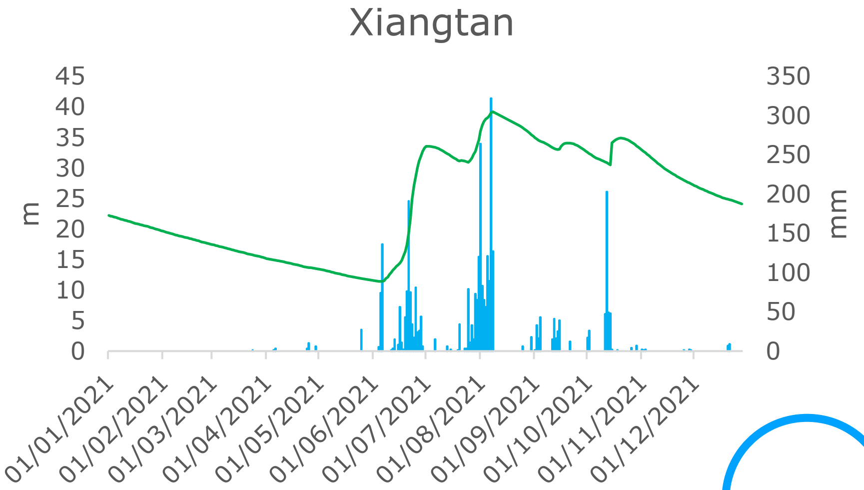


Groundwater level have long time response after rainfall event, from 3 – 30 days

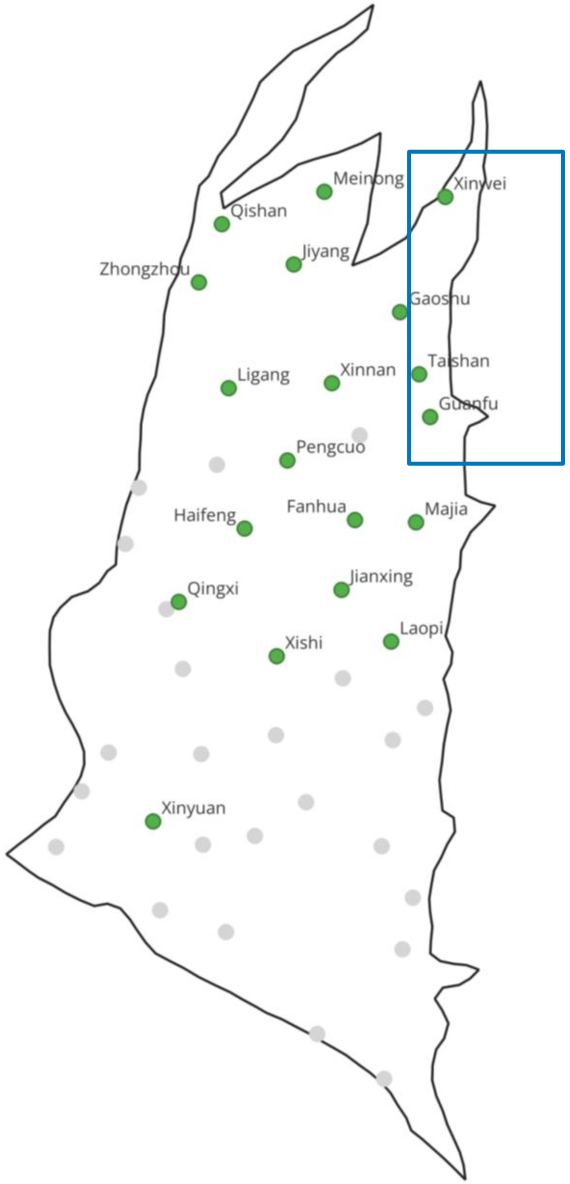


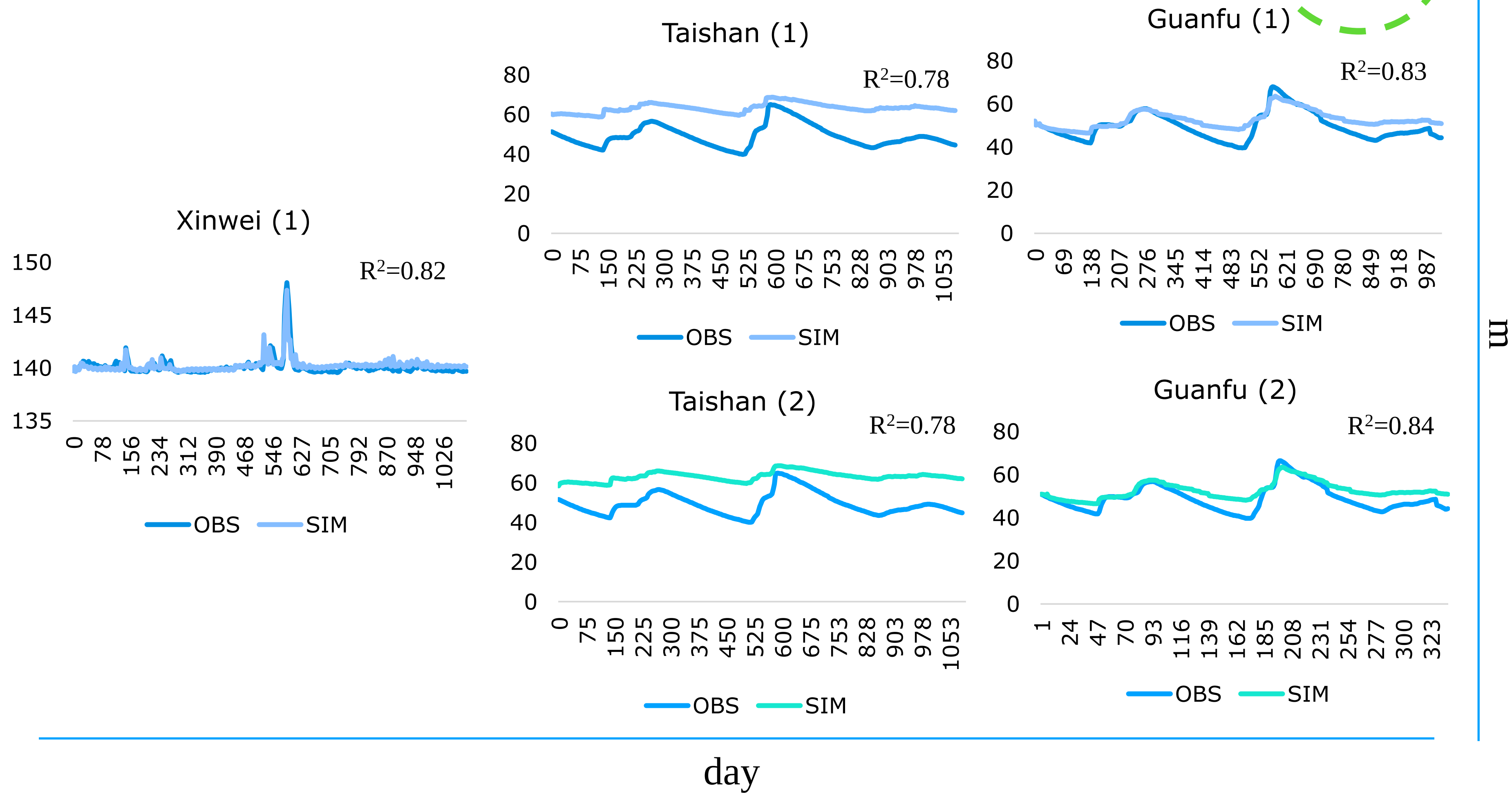
Groundwater level response within 1 day after rainfall event





Comparison between observation data and simulation data from 2020 – 2022





The simulation yielded better results in the recharge area, with almost the same accuracy of simulation at stations with different depths.

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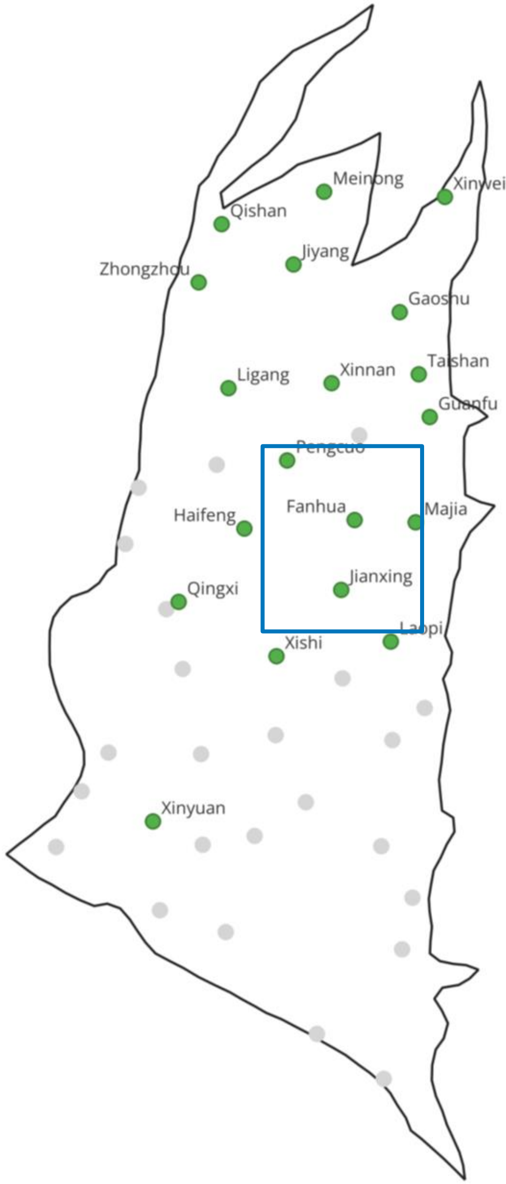

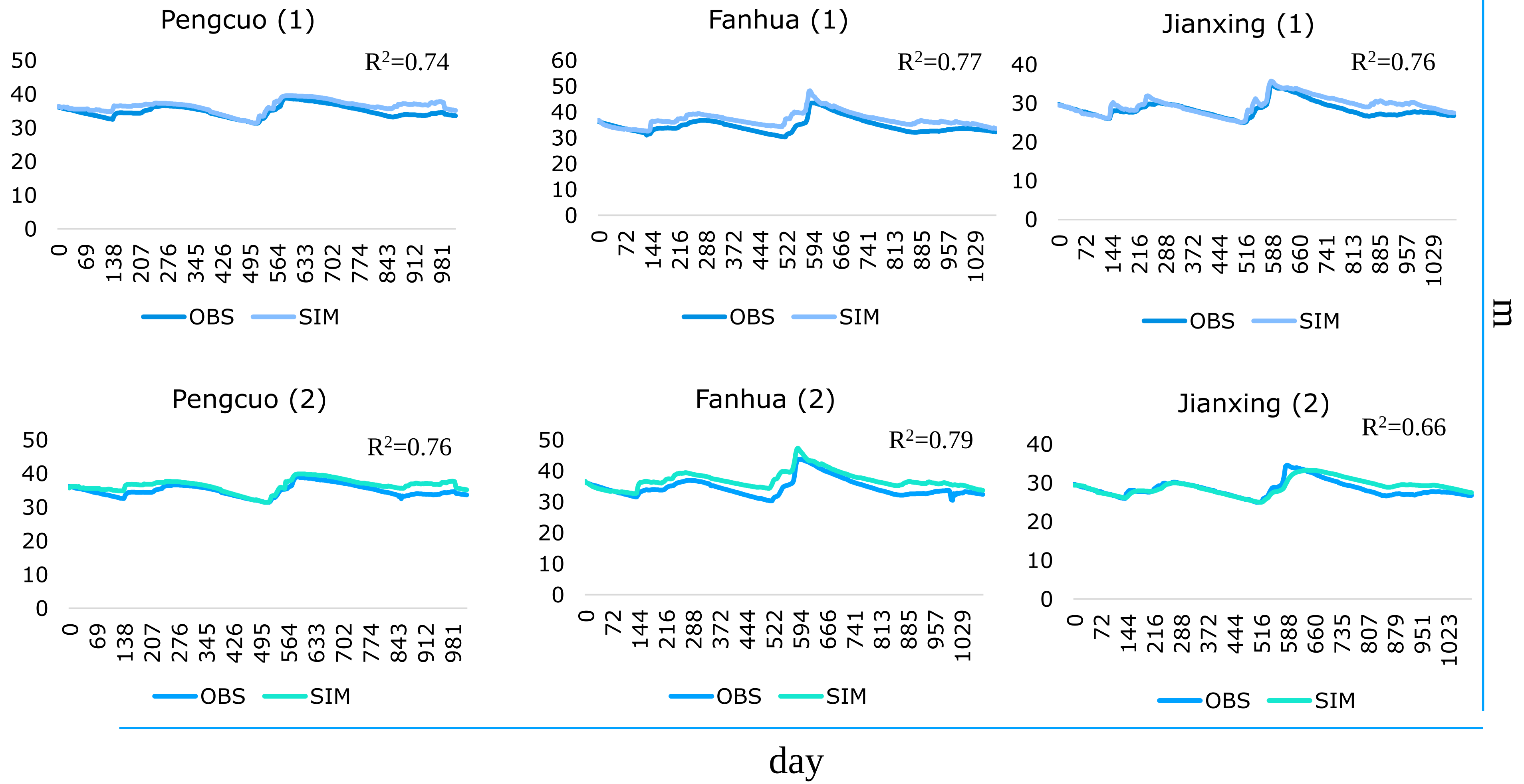

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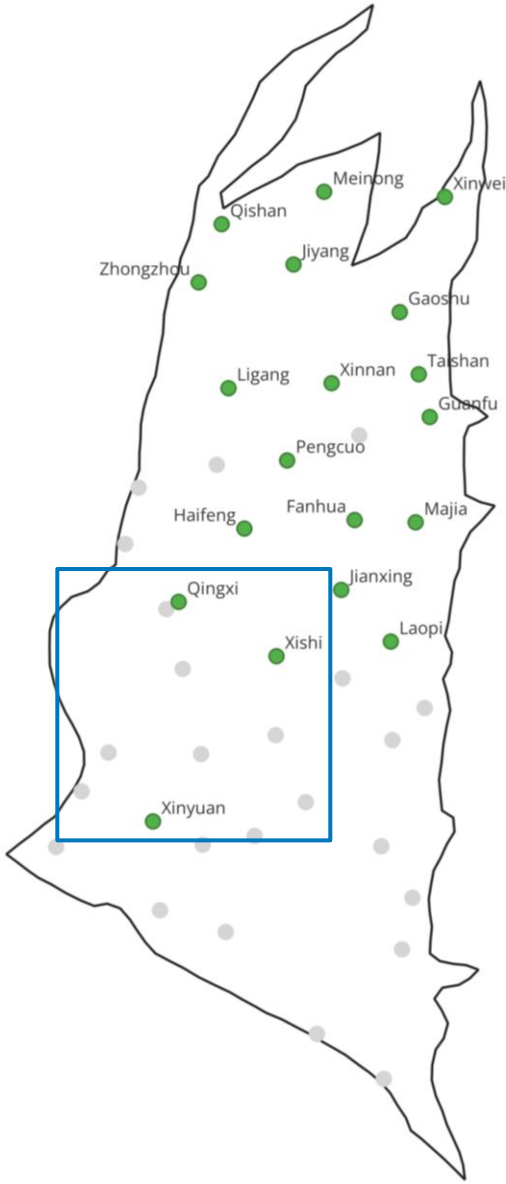
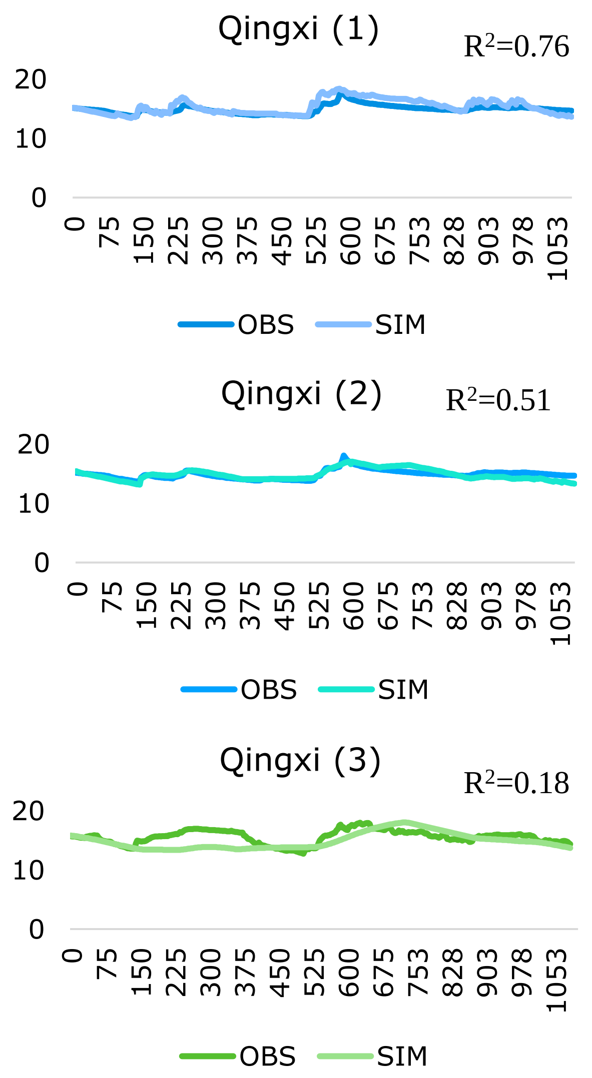
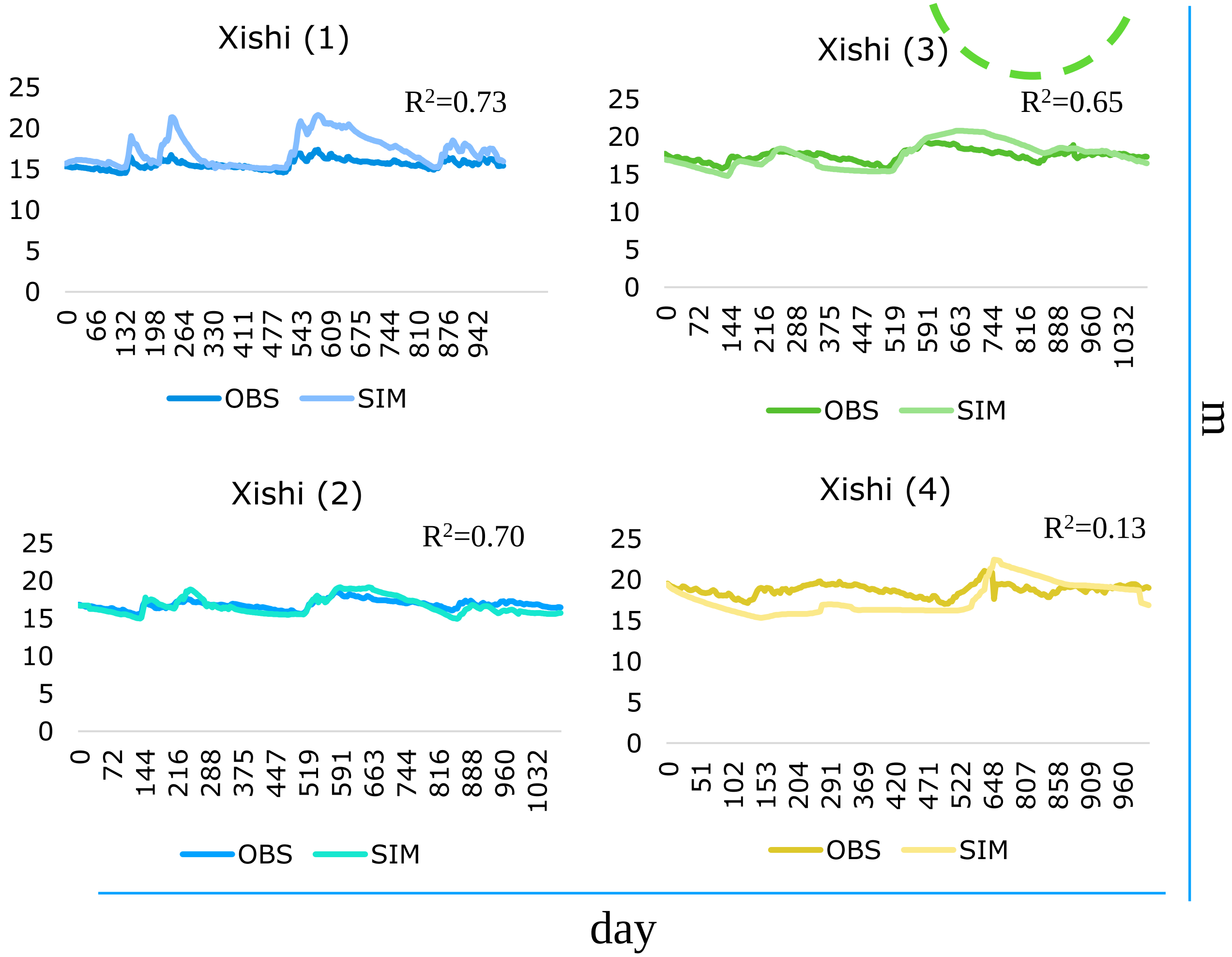






The obstruction of aquitard make the simulation in the deeper aquifer have the worse performance.

I II III **PRELIMINARY RESULT**

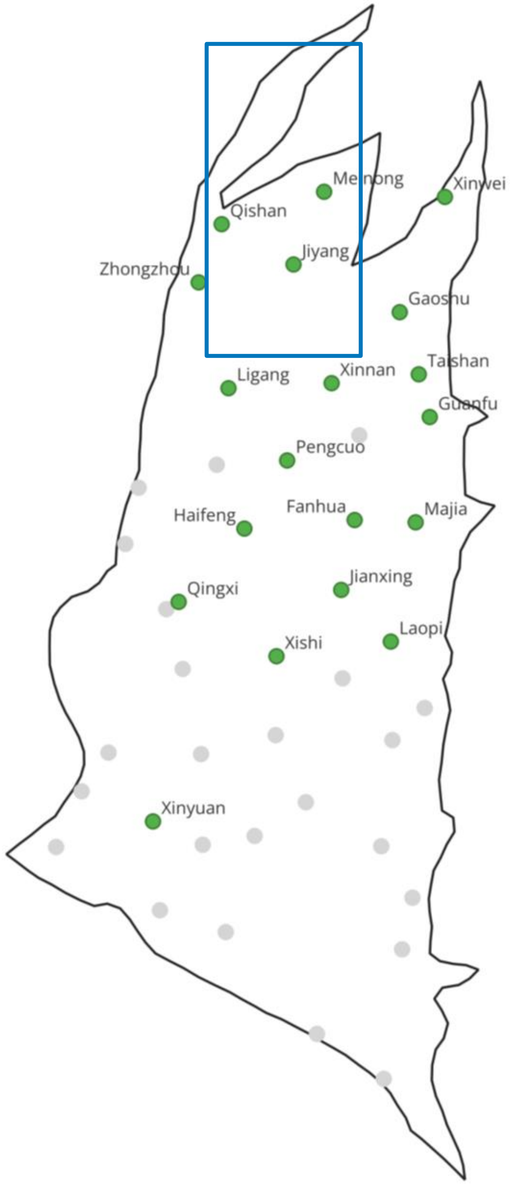
- The model have approximately reflect the trend as observation trend in all station.
- The better result in aquifer 1, with R^2 range from 0.7 – 0.9.
- The result of wells belong to recharge area have the better result in all aquifer layers
- Moving to the south part with the appearance of aquitard, there is the difference simulation accuracy result reduce from aquifer 1 to aquifer 4. The obstruction of aquitard layers make the water movement slower and more difficult to simulation.

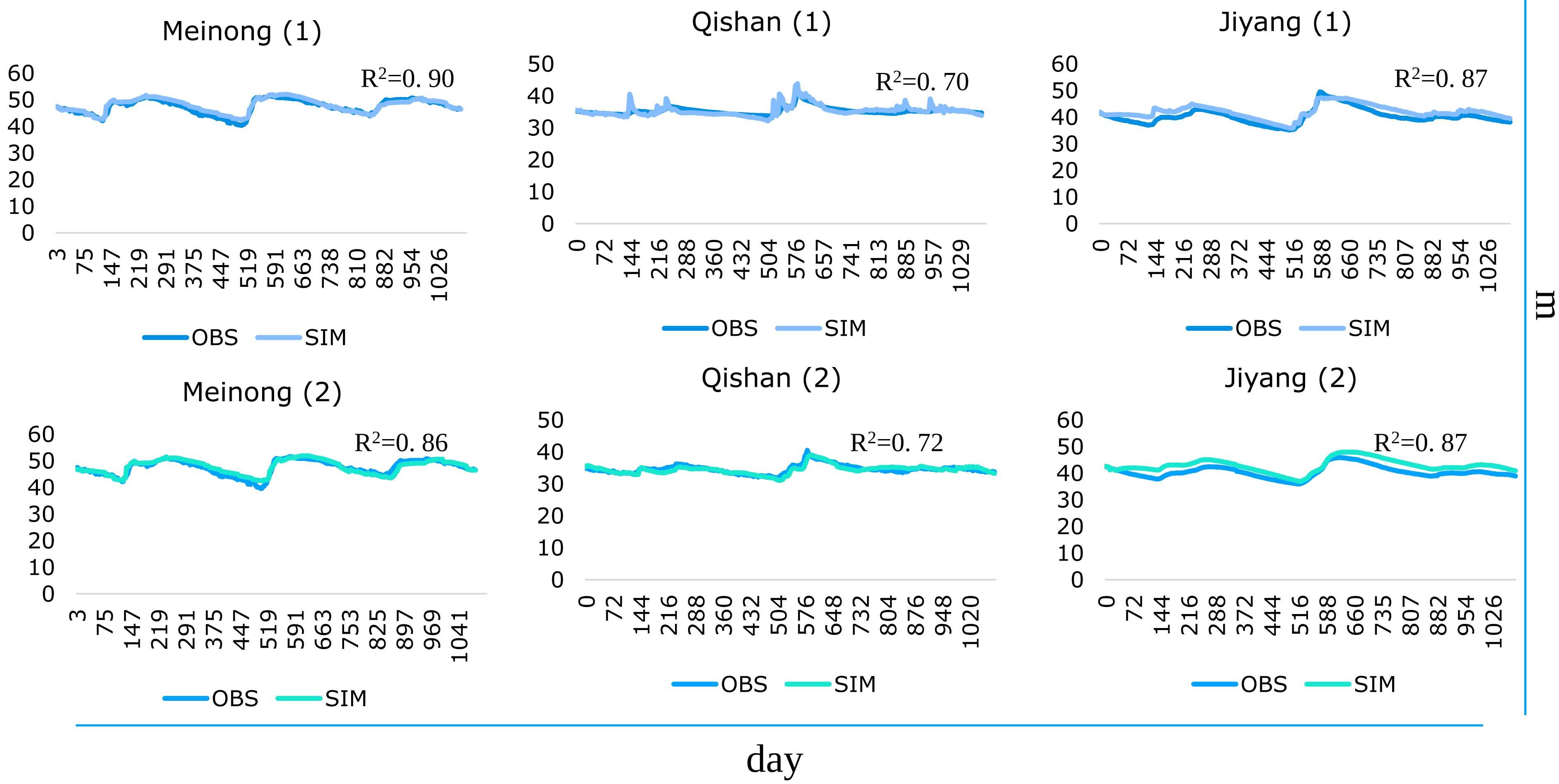
IV FUTURE WORK

- Continue do calibration to improve the accuracy of model and do the calibration for the remain wells.
- Compare final model with previous model in the same study area.

THANK YOU
FOR YOUR ATTENTION

Comparison between observation data and simulation data from 2020 – 2022





The simulation give the better result in recharge area with almost same accuracy of simulation in station in difference depth.

IV FUTURE WORK