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

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Outline

I INTRODUCTION

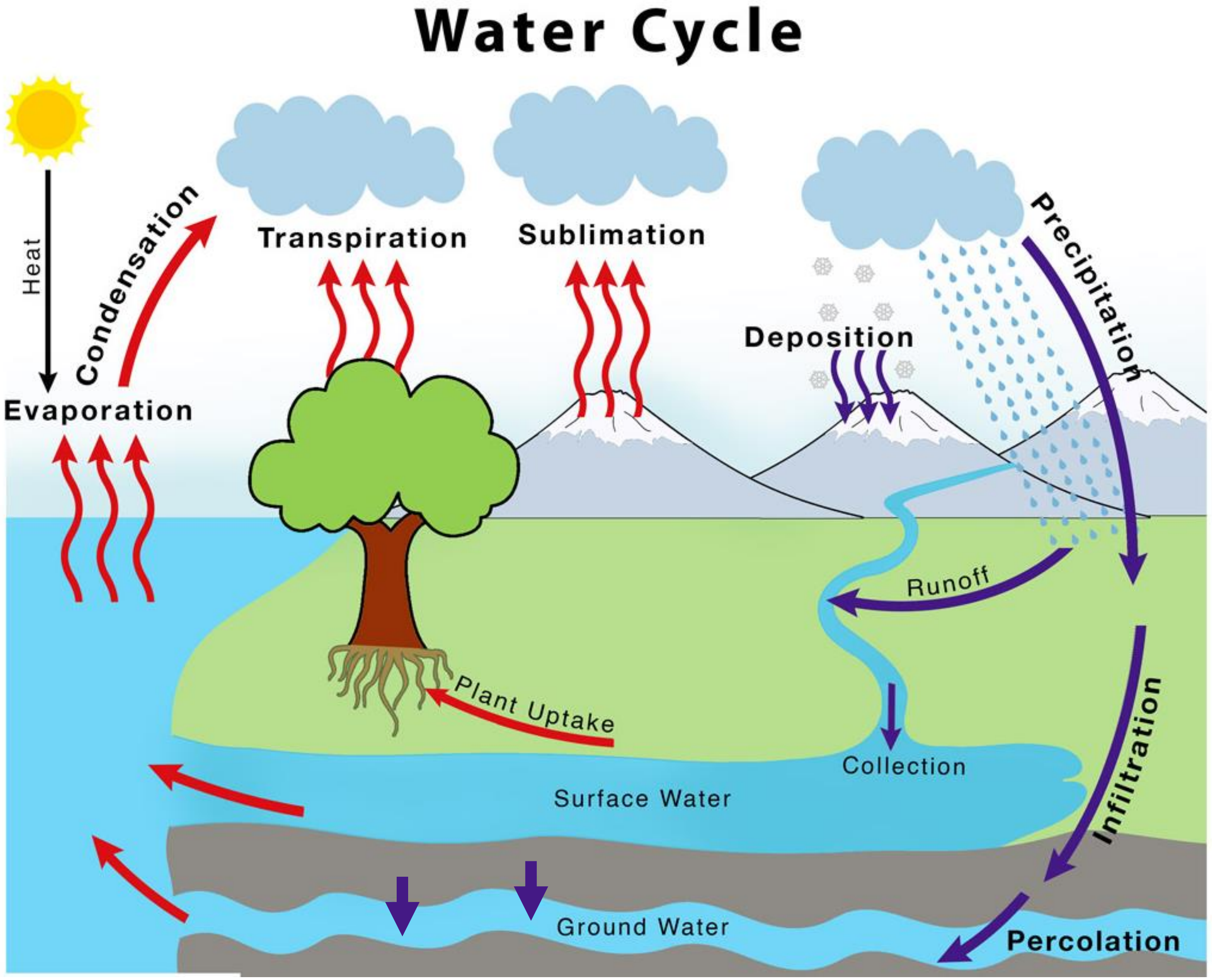
II METHODOLOGY

III PRELIMINARY RESULT

IV FUTURE WORK

- Groundwater is an important water resource for human life with different purpose of using:

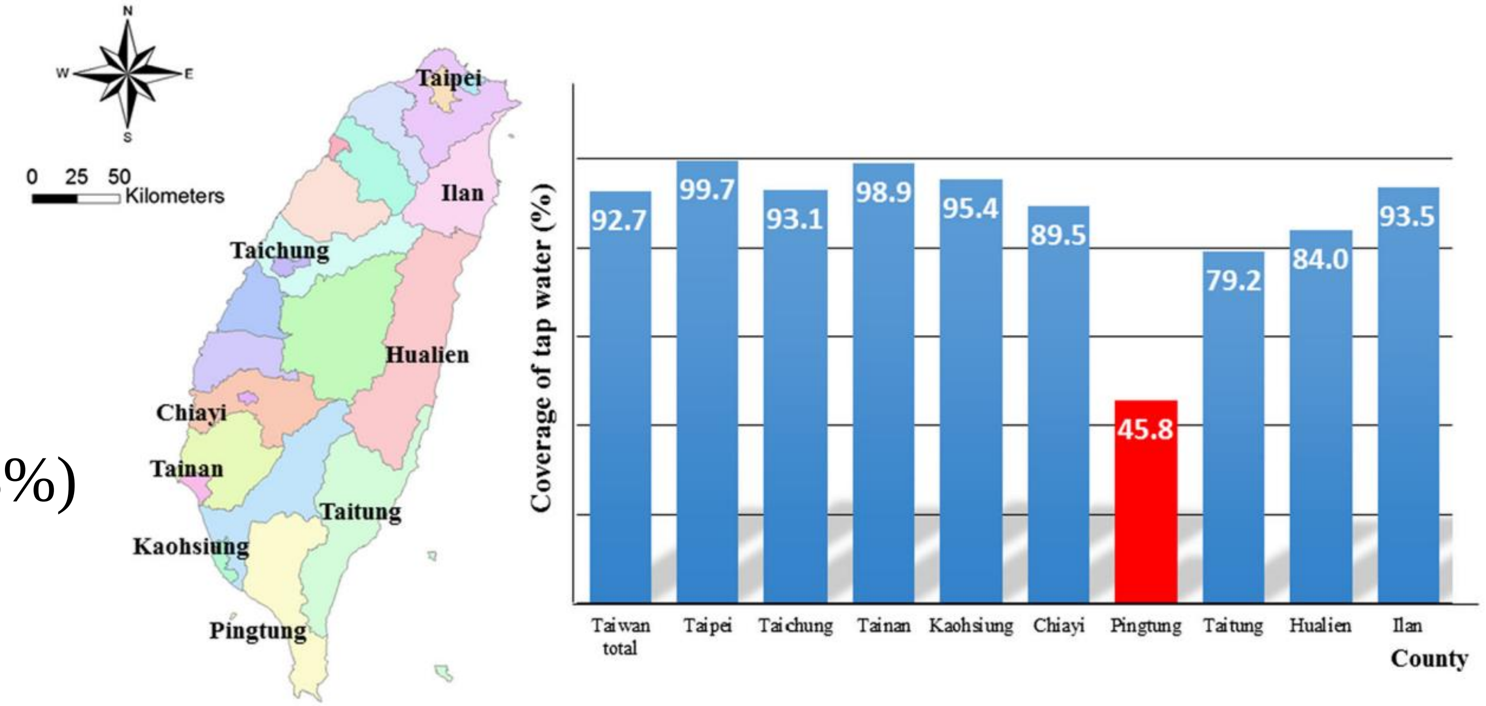
The groundwater withdrawal amount in Asia account for the majority is 72% of global usage. (Lee et al., 2018)



Water cycle (sciencefacts)

In Taiwan, tap water coverage average rate is 92.7 %

- Limited surface water
- Lowest ratio of tap water use (45.8%)
- Over-exploitation groundwater



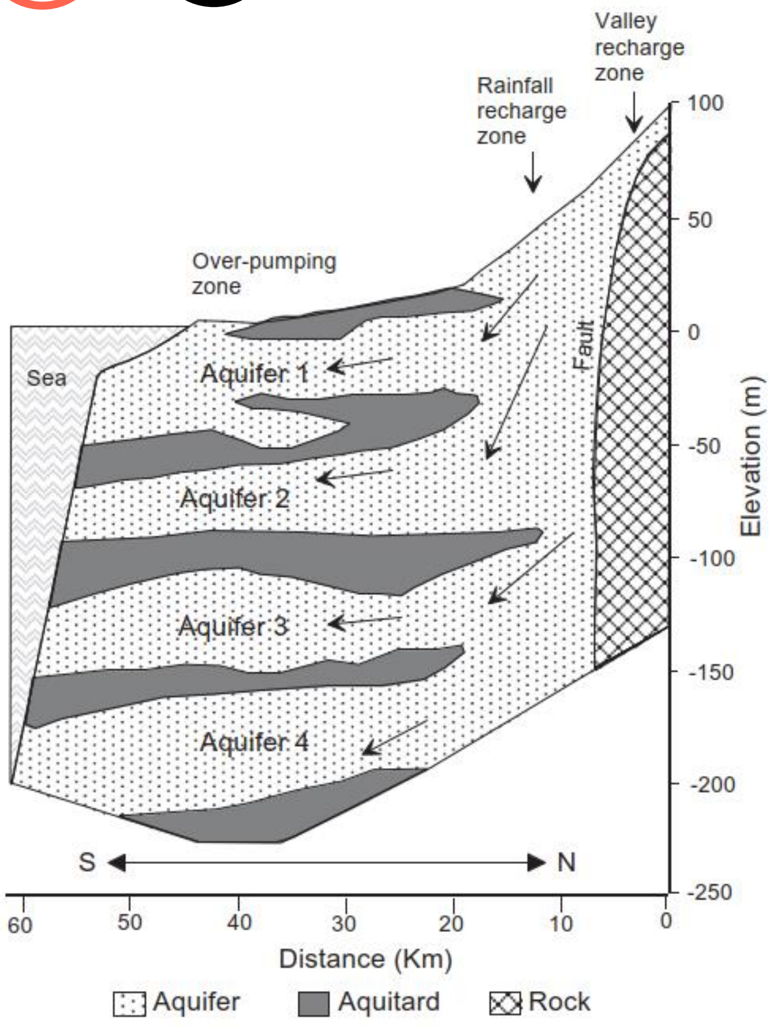
The coverage of the tap water in main city in Taiwan (Liang et al., 2016)

Seawater intrusion, and land subsidence in over the past 5 decades (Ting et al., 1998)

Understanding the behavior of groundwater – groundwater flow with the aim of using this resource in a reasonable and sustainable way.

Study area - Pingtung plain

- 1210 km^2
- Natural boundary
- High annual rainfall rate
- Unconsolidated Quaternary



Hydrogeological

- Aquifer: high permeable coarse sediment.
- Aquitard: low permeable fine sediments

Objective

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

THMC evolution (Thermal – Hydrology – Mechanic – Chemical)

1981

FEMWATER

- ✓ Water flow
- ✓ Water quality transmission

1991

HYDROGEOCHEM

- ✓ Water flow
- ✓ Water quality transmission & chemical reaction
- ✓ Heat transfer

2013

THMC

- ✓ Water flow
- ✓ Water quality transmission & chemical reaction
- ✓ Heat transfer
- ✓ Mechanism

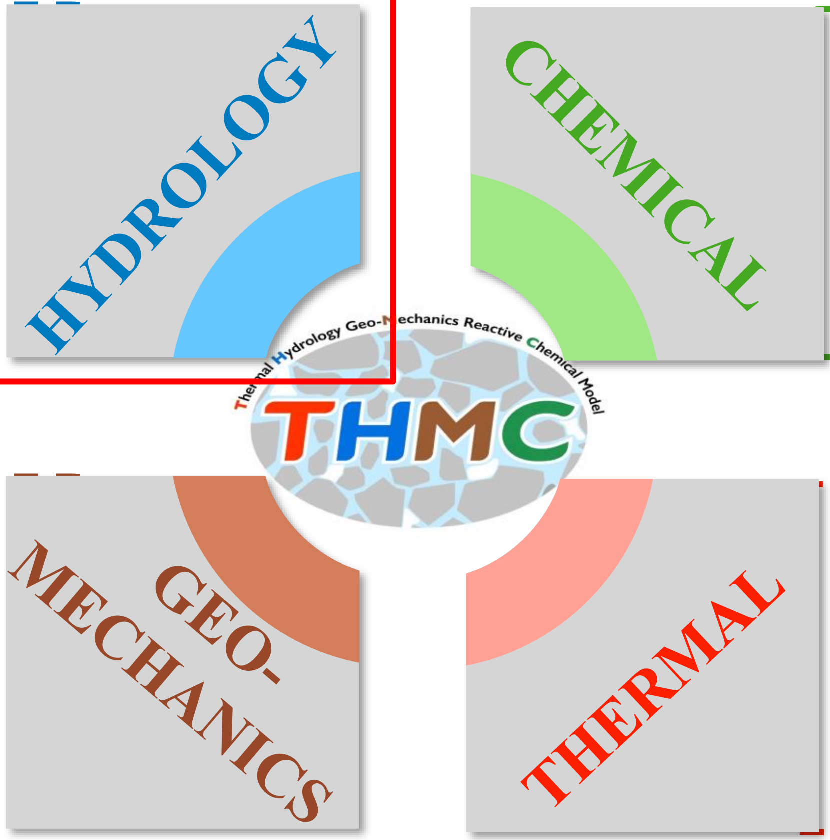
- ➢ Combine with the soil characteristic of unsaturated layer
- ➢ Precipitation is used to calculate infiltration and percolation
- ➢ Applying under saturated and unsaturated mode

THMC software application

- ✓ Wide application
- ✓ Graphical Users Interface (GUI) display
- ✓ Accurately predict subsurface process

- Groundwater management
- Groundwater recharger

- Water quality assessment
- Seawater intrusion
- Land utilization management

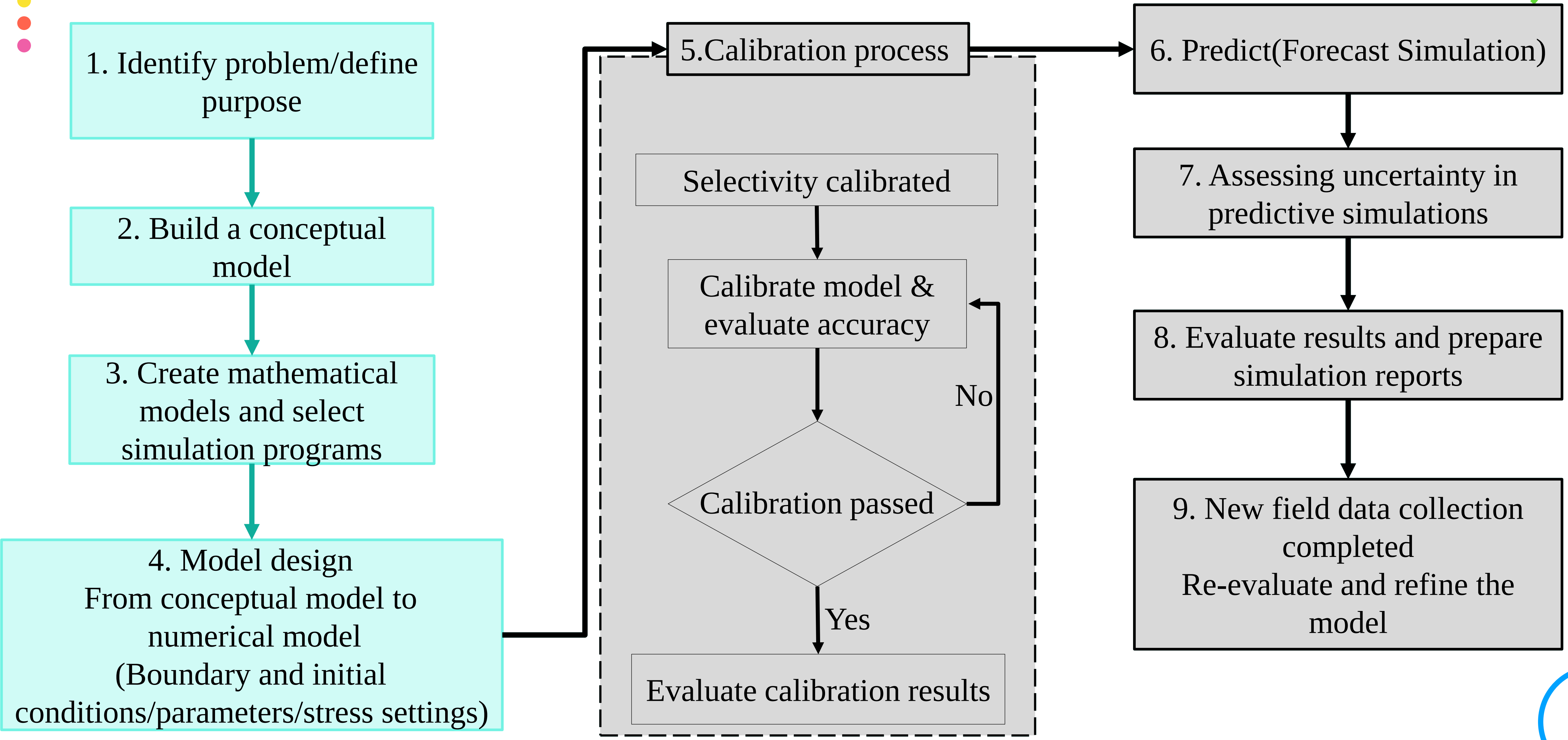


- Slope area management
- Subsidence assessment
- Conservation of soil and water assessment

- Hot spring groundwater
- Geothermal energy

II METHODOLOGY

Working flow



Governing equation

Boundary Condition

Data input

Governing equation for flow through saturated-unsaturated media using in 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

Boundary Condition

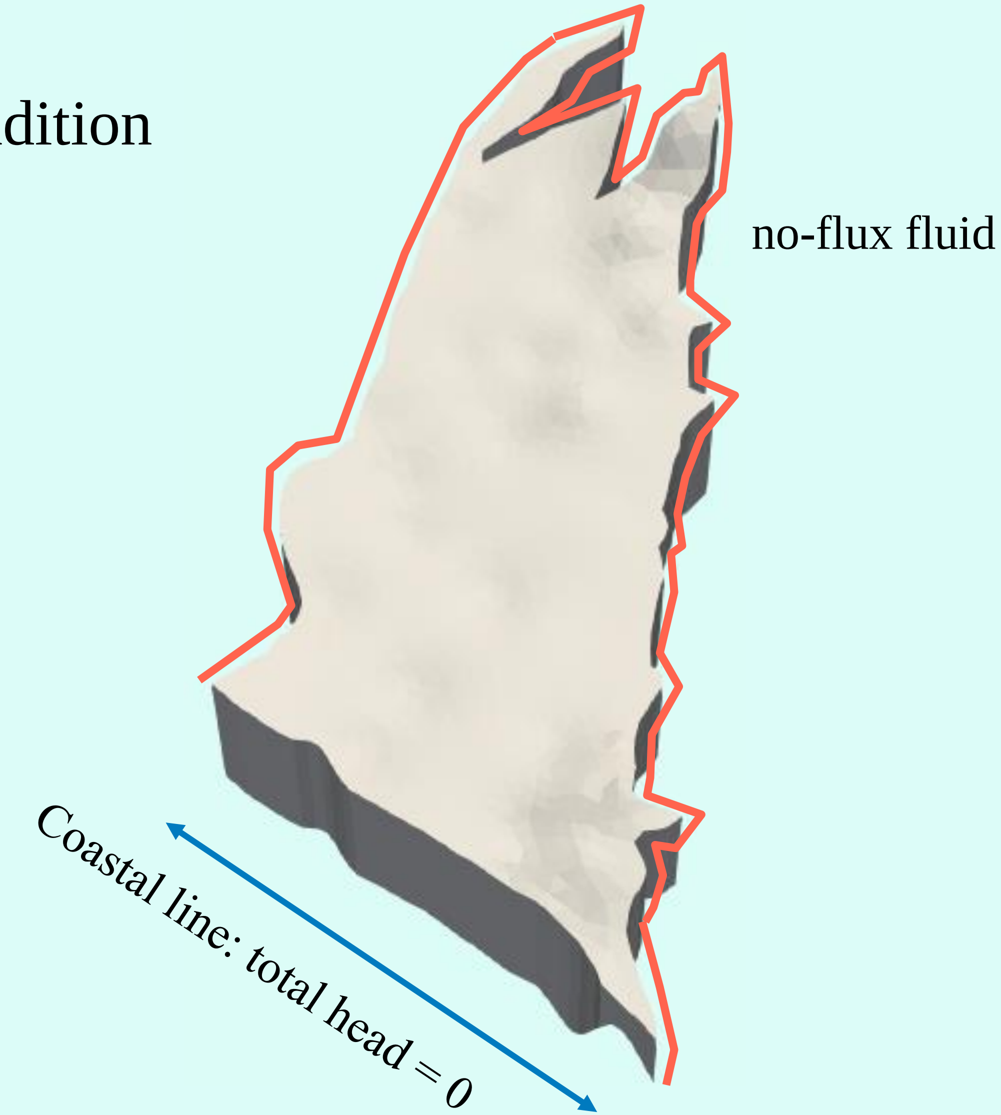
Data input

Steady-state simulation for Initial condition

- ✓ Dirichlet boundary condition
- ✓ Rainfall: variable BC

Initial result

Transient simulation

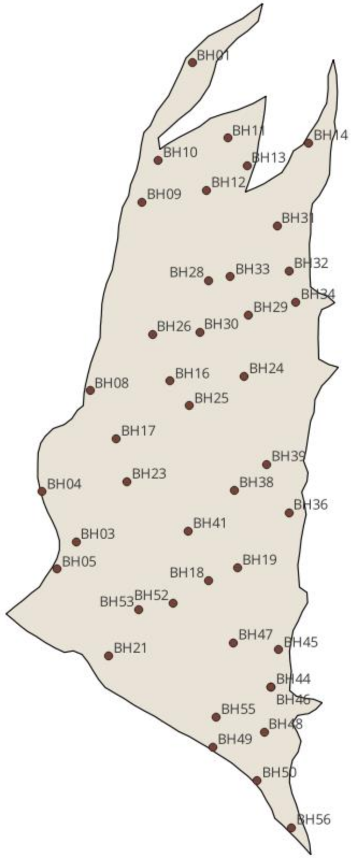


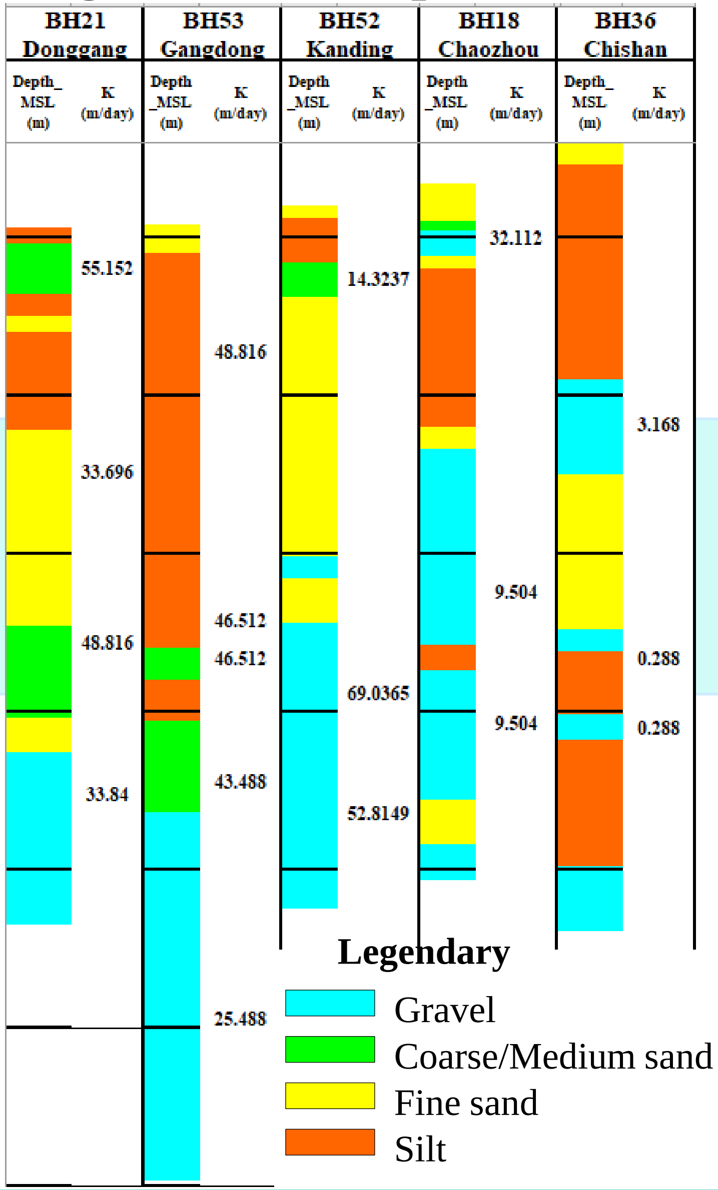
Governing equation

Boundary Condition

Data input

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





1 material (1st layer)
4 aquifers
3 aquitards

Governing equation

Boundary Condition

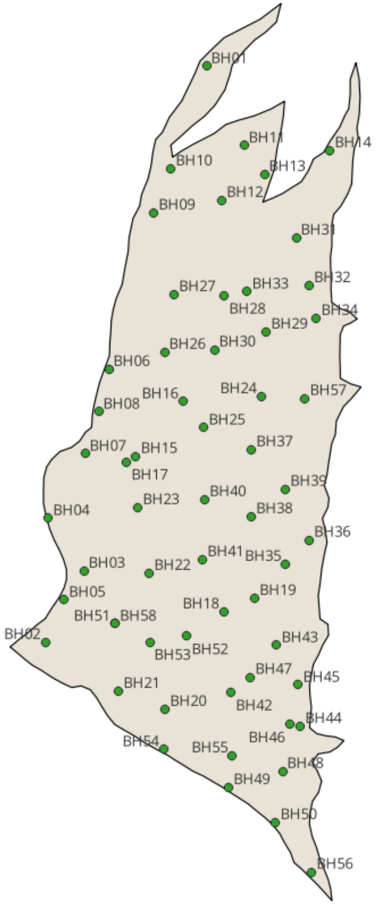
Data input

- K value reference:

  Aquifer: 148 wells → Pumping test result from CGS report

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

Layer	Material	K value range (m/day)	Average K (m/day)
1	Material 8	0.8640 – 8.64864	5.7294
2	Aquifer1	0.0057 – 461.52	89.681
3	Aquitard1	0.8640 – 8.64864	4.1285
4	Aquifer2	0.4320 – 171.792	34.291
5	Aquitard2	0.8640 – 8.64864	2.9126
6	Aquifer3	2.2920 – 171.936	40.076
7	Aquitard3	0.8640 – 8.64864	6.0537
8	Aquifer4	5.472 – 14.5152	9.5688



Governing equation

Boundary Condition

Data input

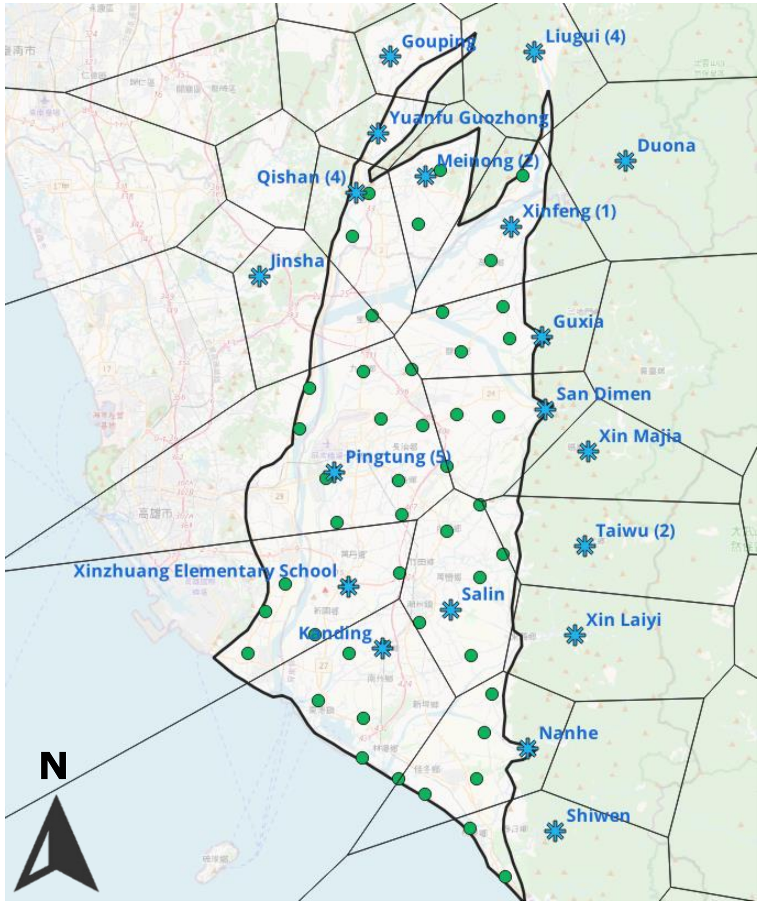
Groundwater level: daily data 2020 – 2022 of 122 stations (WRA)

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
1730P107	Qishan (4)	1770	[illegible]	1380
1730P109	San Dimen	2102	[illegible]	1462
[illegible]	[illegible]	[illegible]	[illegible]	779
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	4
[illegible]	[illegible]	[illegible]	[illegible]	1803
1730P150	Gouping	1797	[illegible]	1437
1730P151	Yuanfu Guozhong	1631	[illegible]	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

Governing equation

Boundary Condition

Data input

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

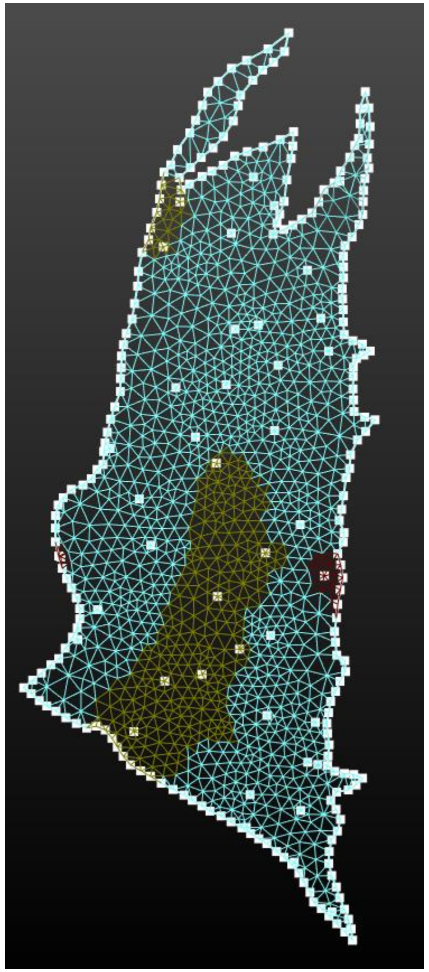
Unit: $10^6 m^3$

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	84.63	76.44	84.30	81.49	83.92	68.08	240.67	84.46	81.95	84.70	81.83	70.44	1122.92
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

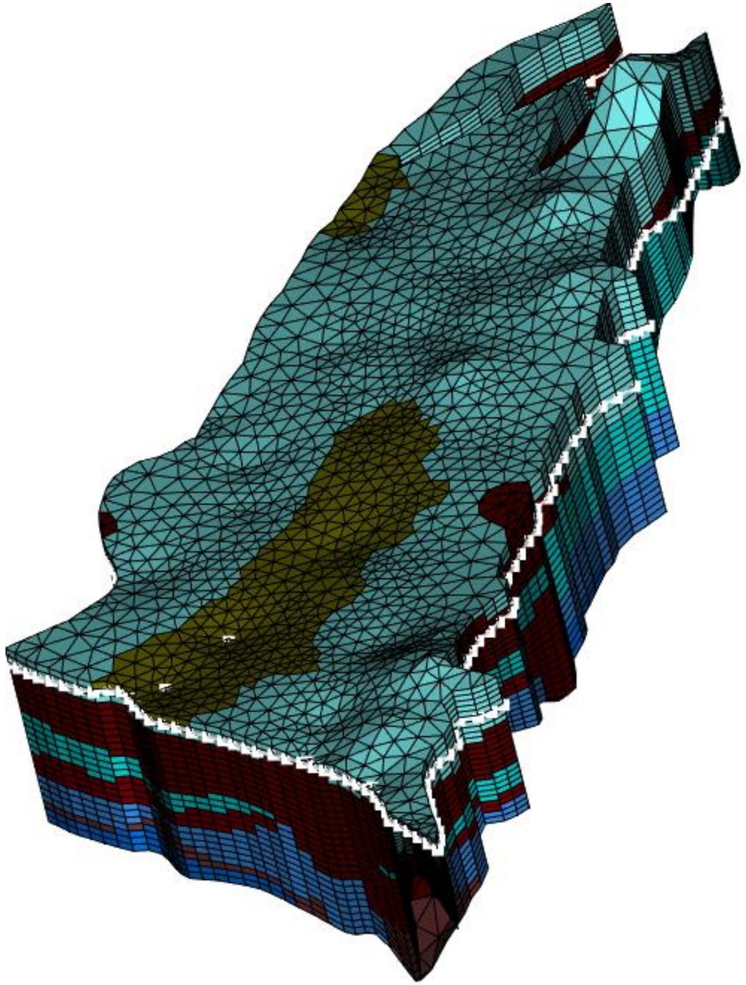
Infiltration and percolation: using the land use/land cover to identify built area (building and road) which is assigned as impermeable surface.

III PRELIMINARY RESULT

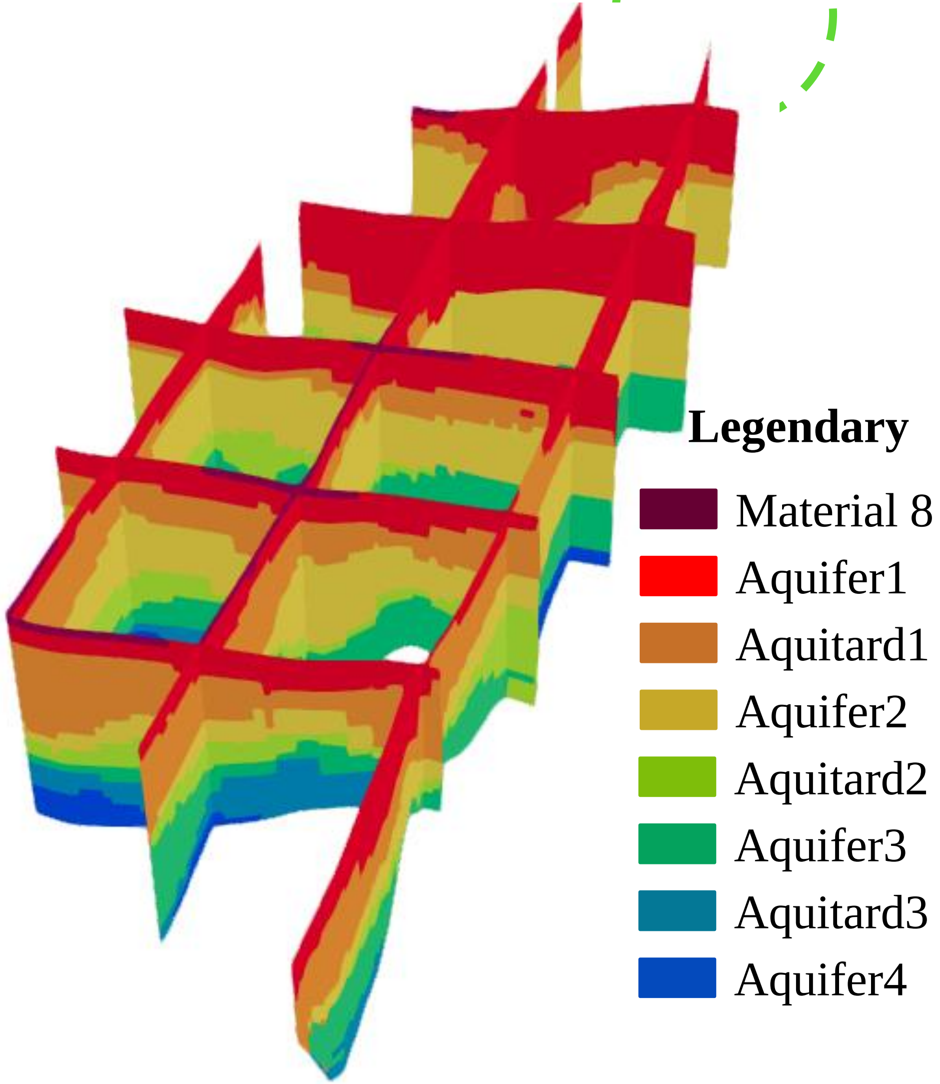
Conceptual hydrological domain



Triangular column grid system with 33,826 nodes and 10,329 elements

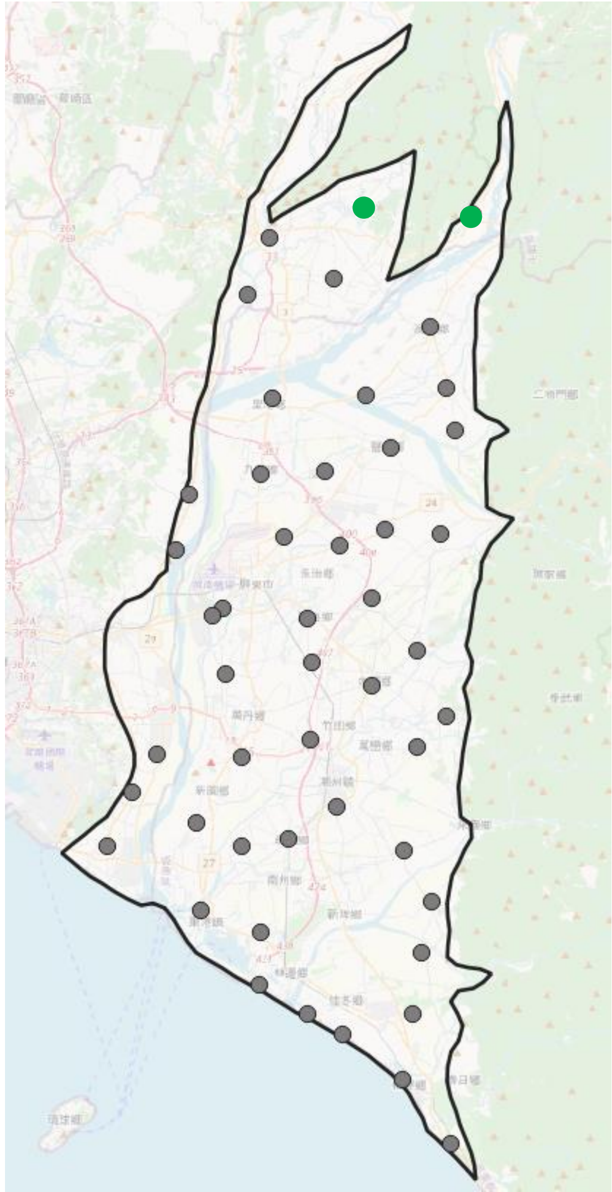


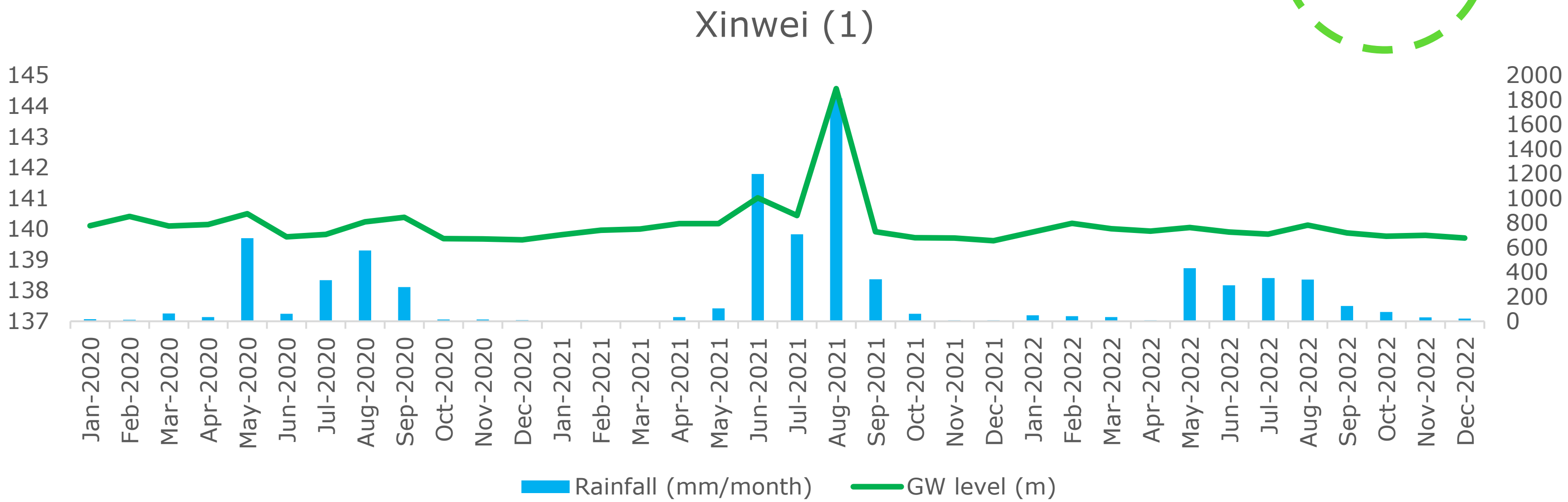
3D Geological model generation

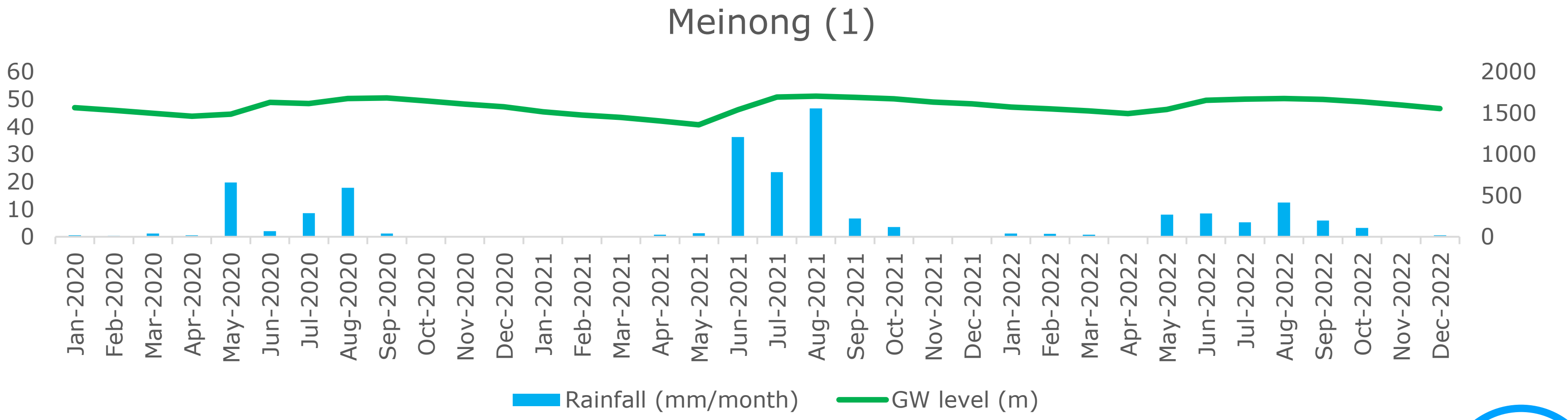


Cross-section of geological model

Groundwater level and rainfall distribution relationship

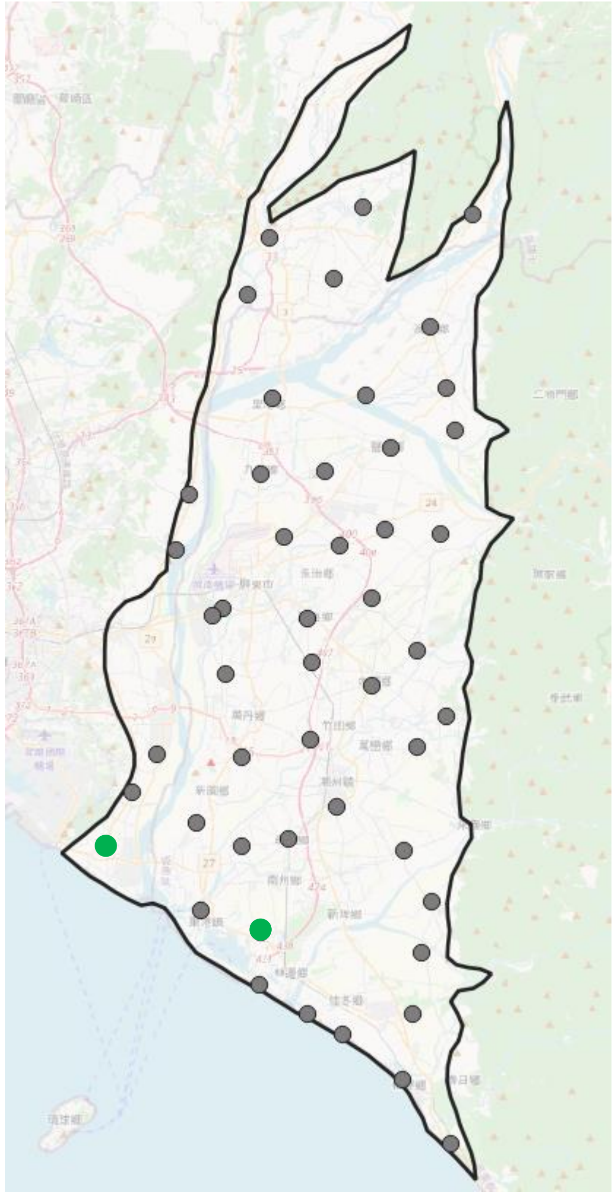


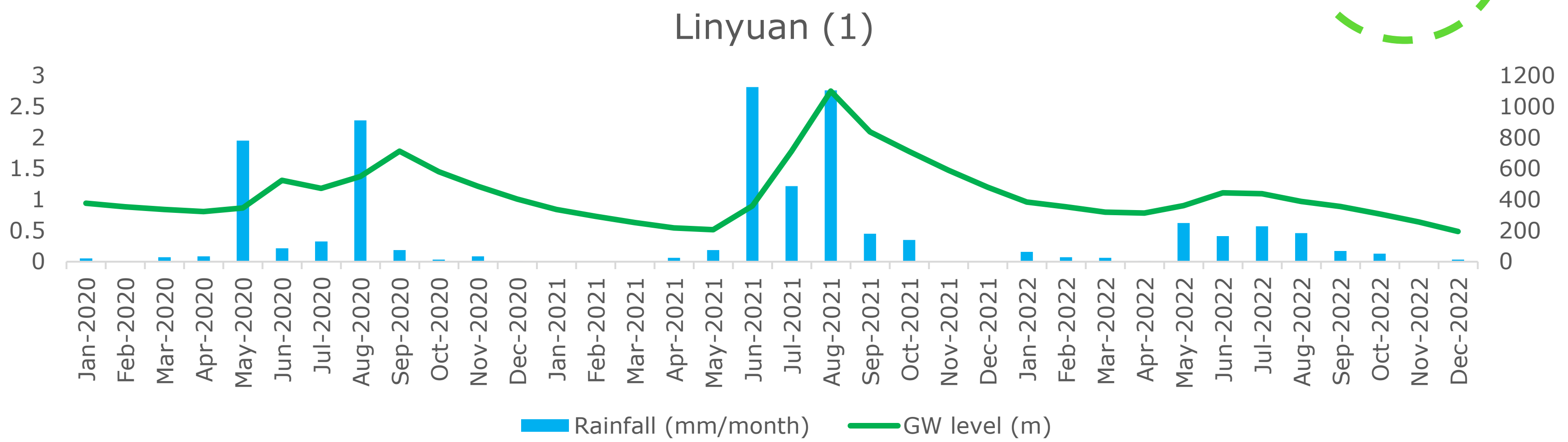


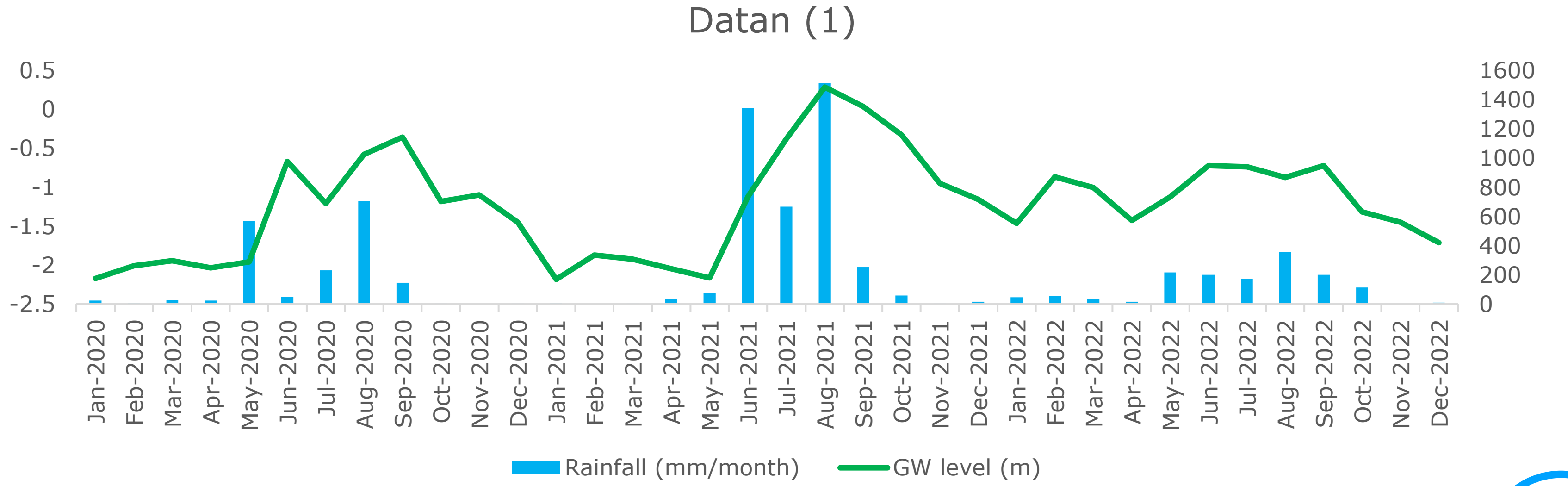


- Groundwater immediately increase after raining time

Groundwater level and rainfall distribution relationship

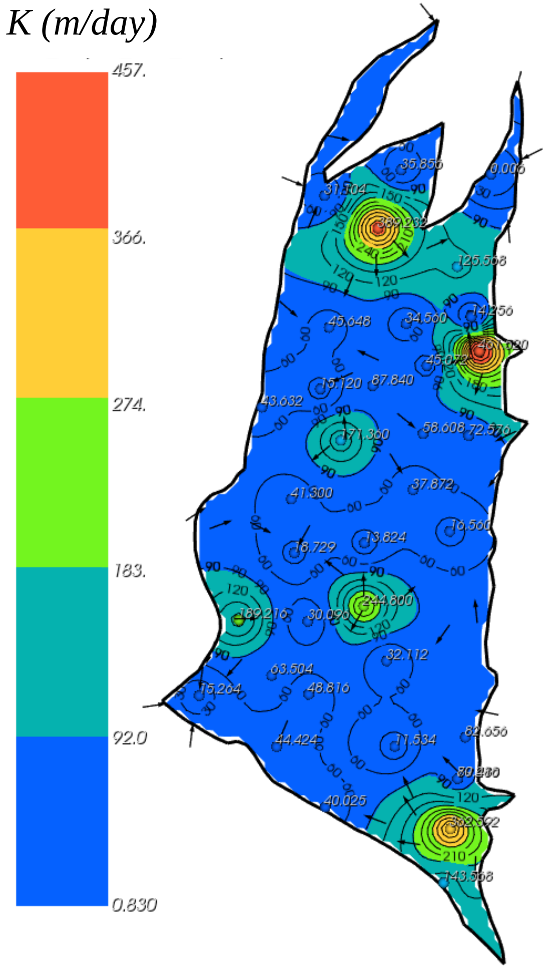




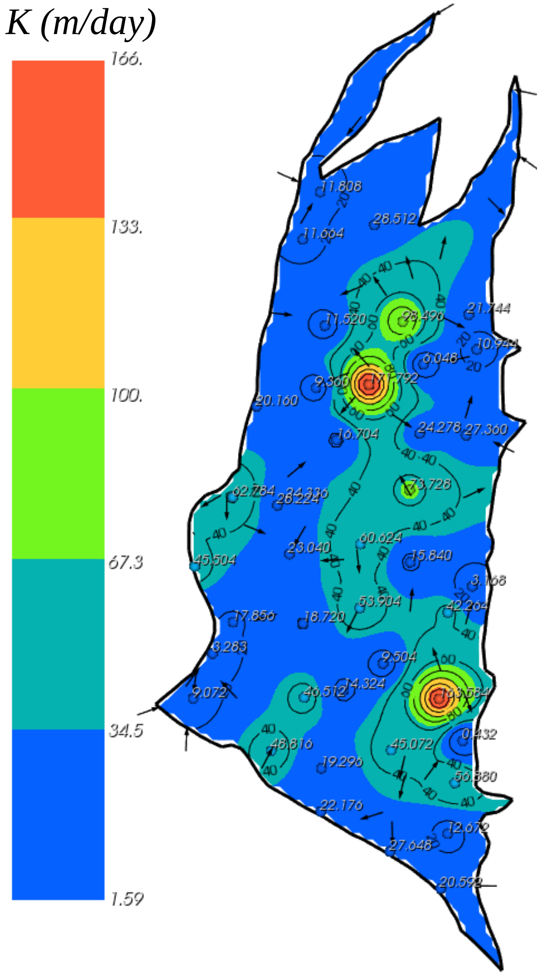


- Groundwater increase after a month from raining time

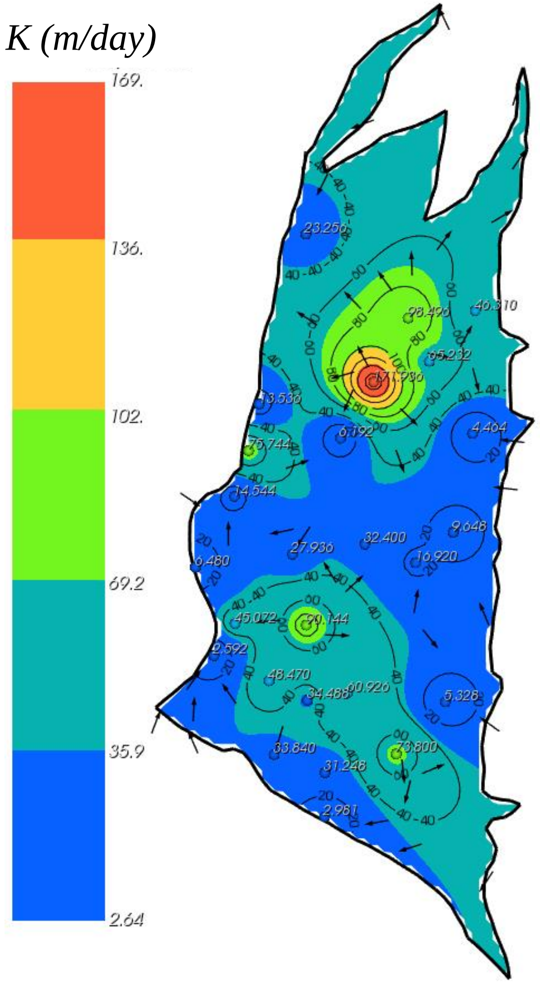
K value spatial distribution



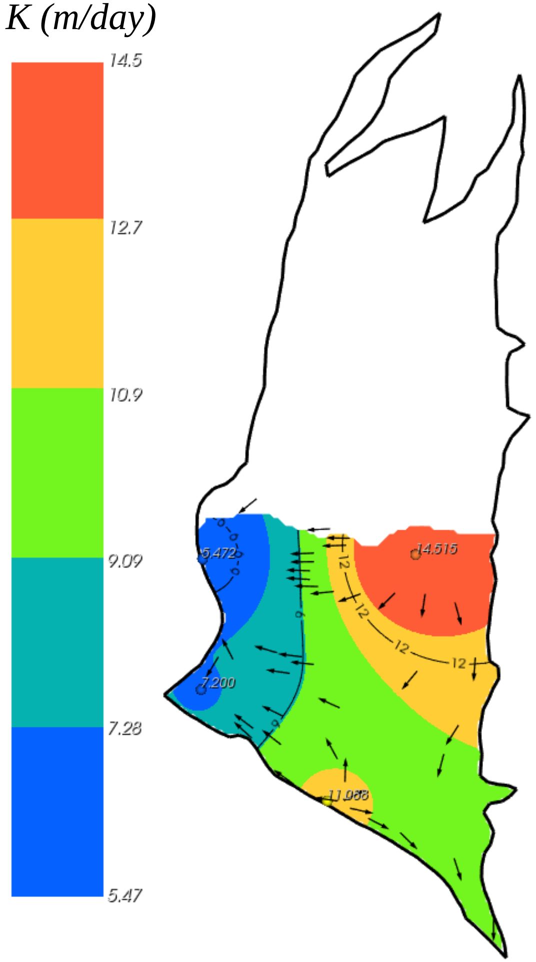
Aquifer 1



Aquifer 2



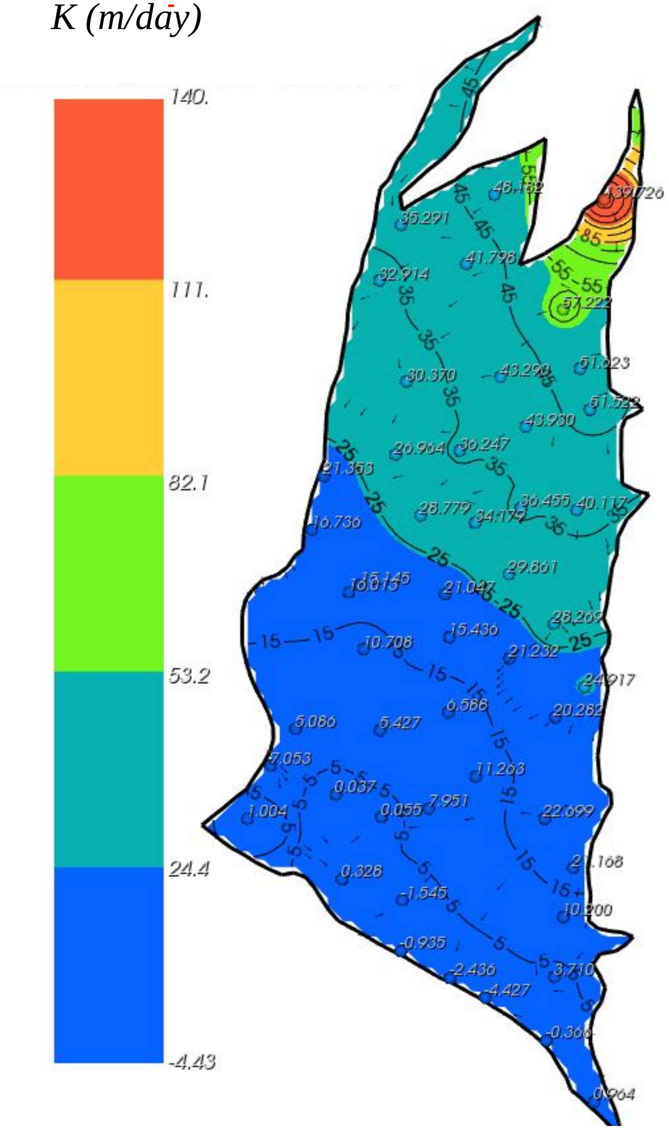
Aquifer 3



Aquifer 4

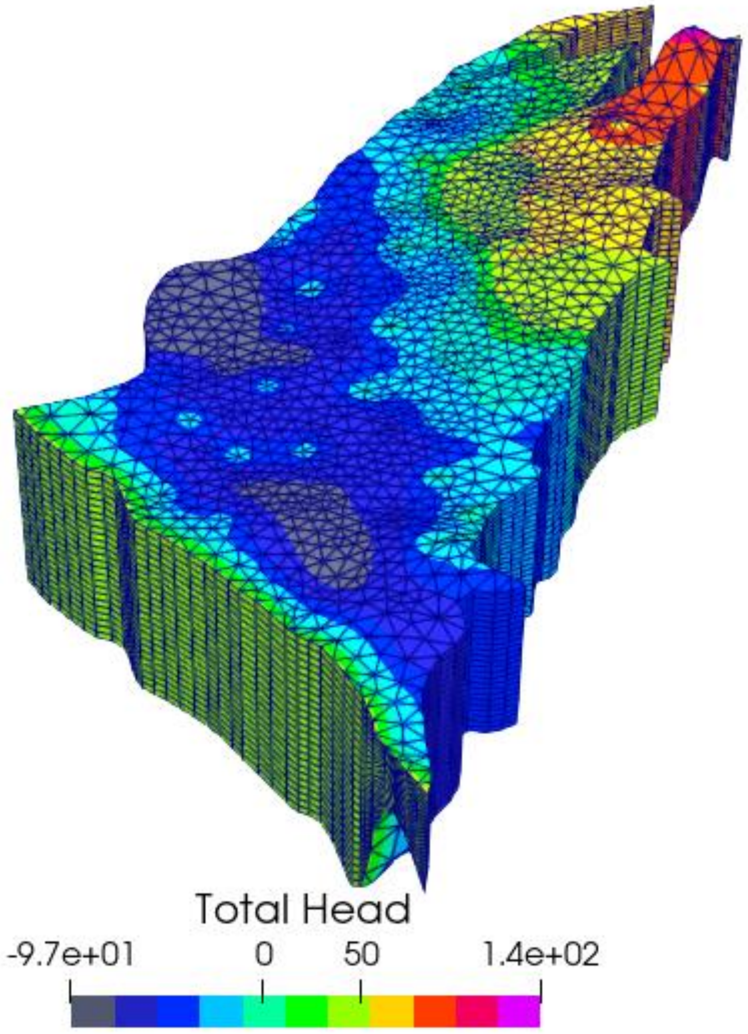
Steady-state simulation

Rainfall average rate input: $0{,}625 \times 10^{-3}$ m/day



Groundwater level distribution

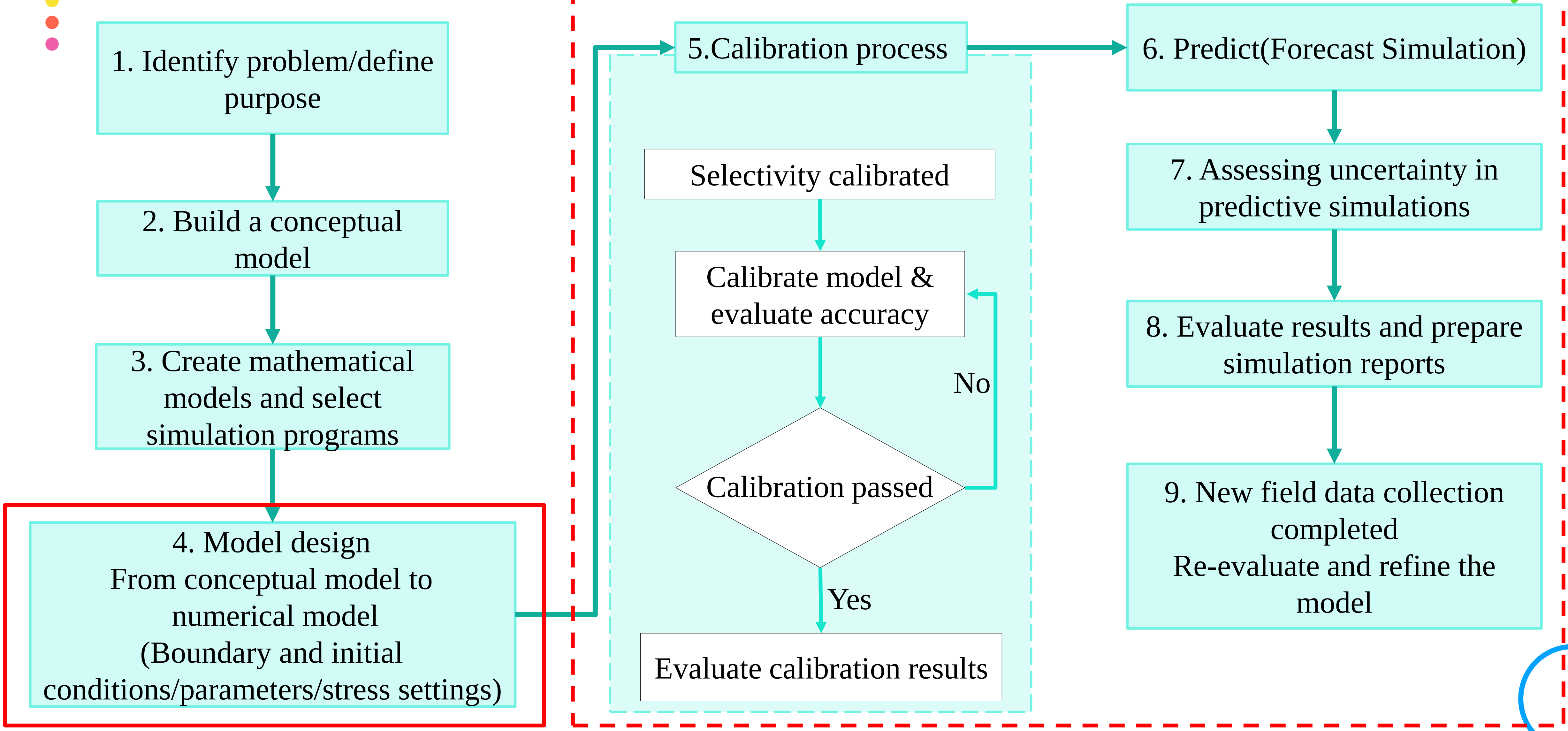
Initial result
(2020 – Jan -01)



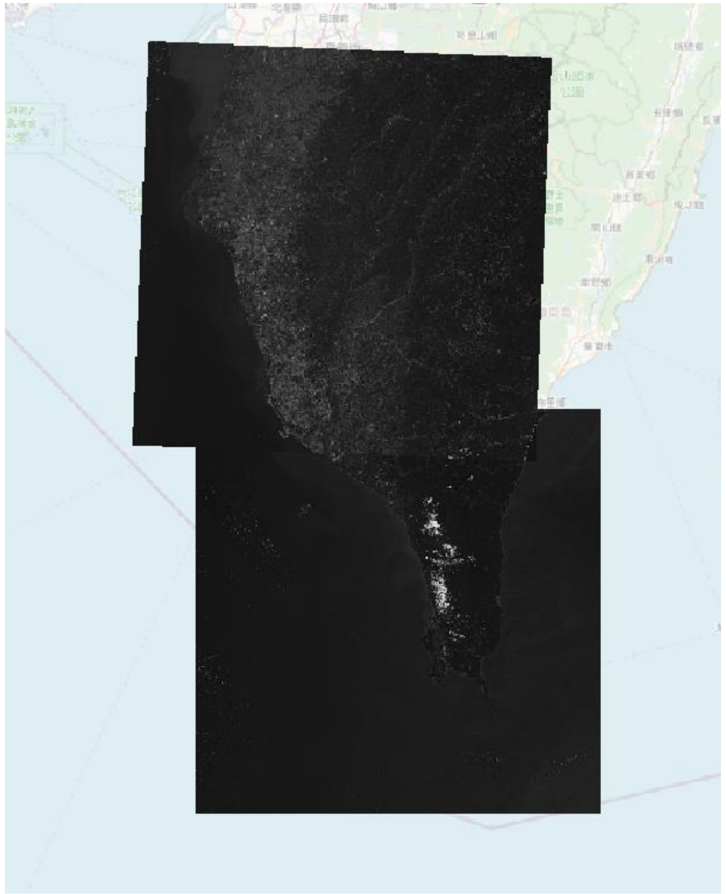
Initial head distribution results

IV FUTURE WORK

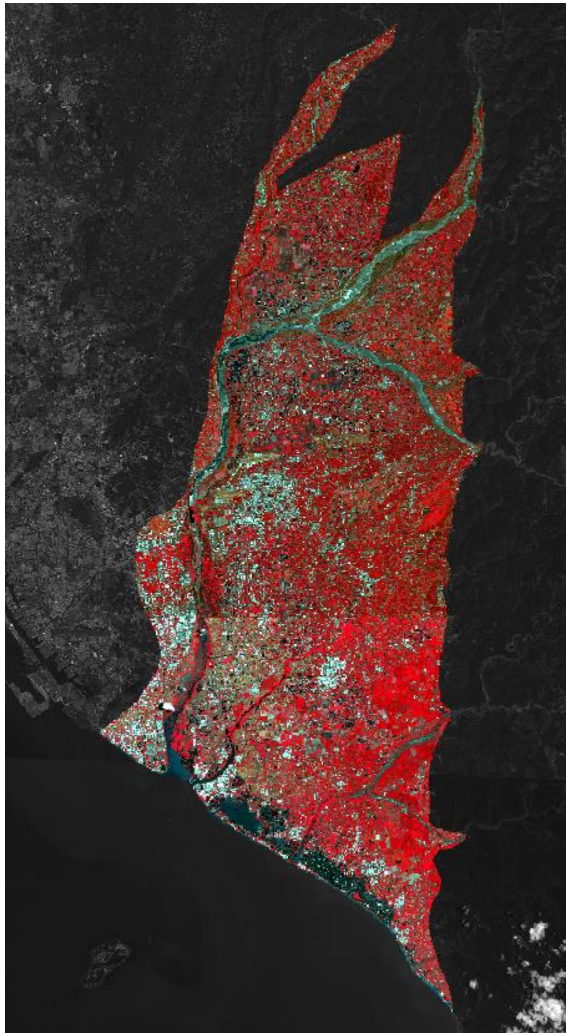
IV FUTURE WORK



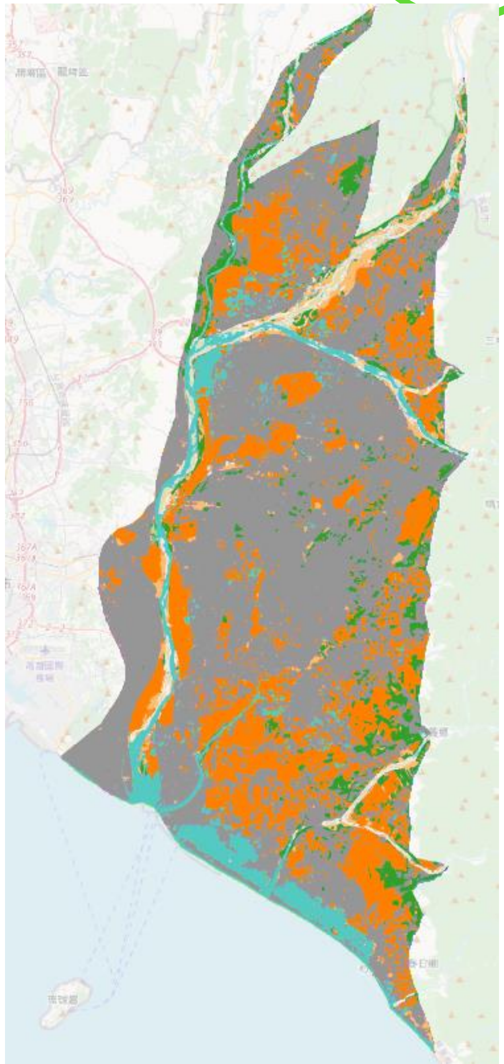
Using satellite image for classifying permeable and impermeable zone



Sentinel image



Mosaic with geometric correction



Target classification (source: USGS)

THANK YOU
FOR YOUR ATTENTION

Q & A

FUTURE WORK

Data collection (CGS)

Groundwater level

Borehole data
(44 wells)

SET UP STUDY DOMAIN - THMC

Simplify rock material → Set hydrogeologic unit

Hydraulic conductivity

Porosity

Combine

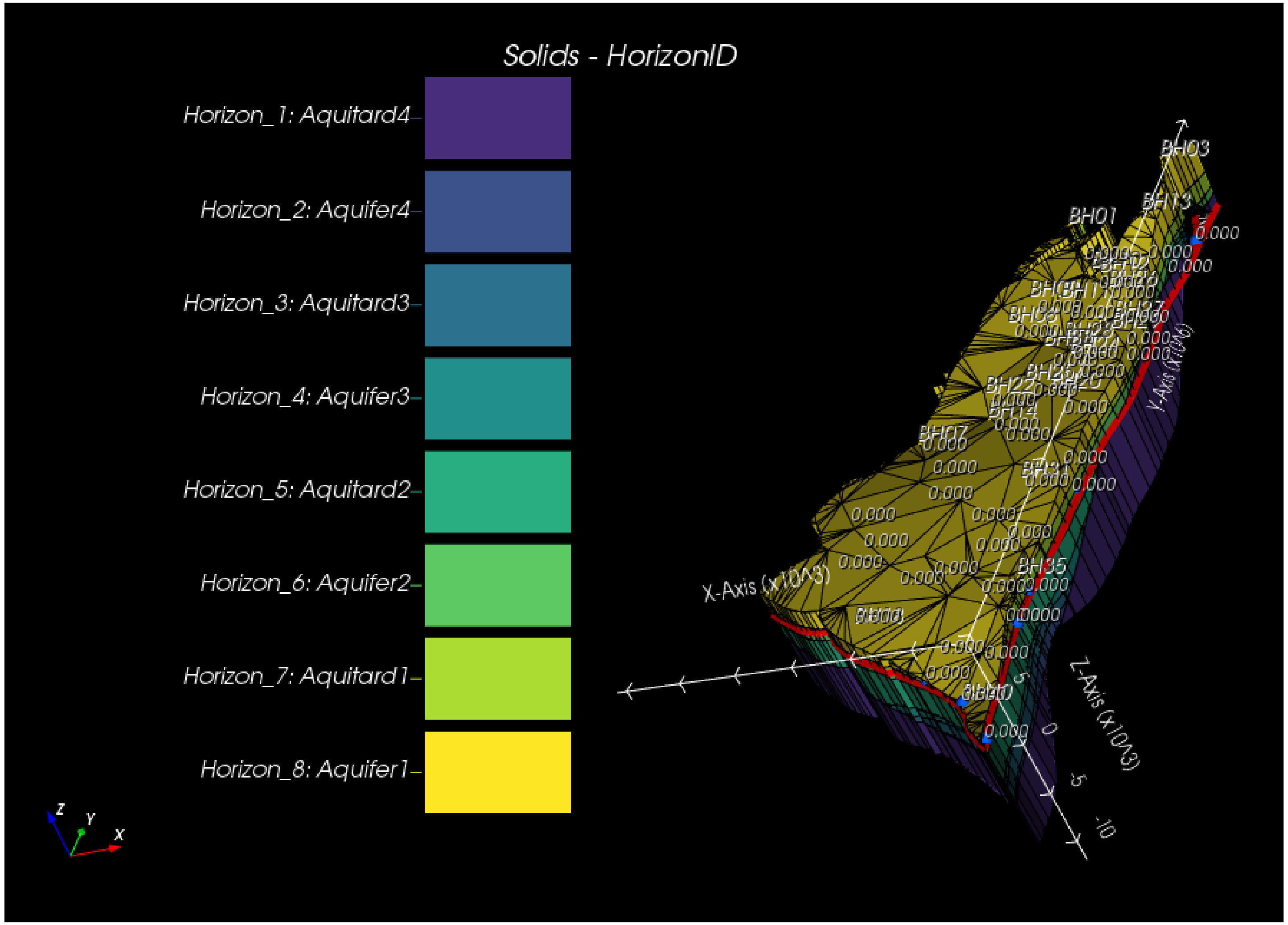
Simplify according thickness and set material ID

8 layers
- 4 aquifer layers
- 4 aquitard layers

Set and simplify according layer range limit

FUTURE WORK

Primarily simplified data test result for building study area domain



- The limited range of layers have not in expect
- Density in the middle too larger

Governing equation for flow through saturated-unsaturated media follow below equation:

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla.\left[\boldsymbol{K}.\left(\nabla h + \frac{p}{p_0}\nabla z\right)\right] + \frac{\rho^*}{\rho_0} q$$

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

θ: effective moisture content (L^3/L^3)
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k_r: relative permeability or relative hydraulic conductivity (dimensionless)

F: generalized storage coefficient (1/L)

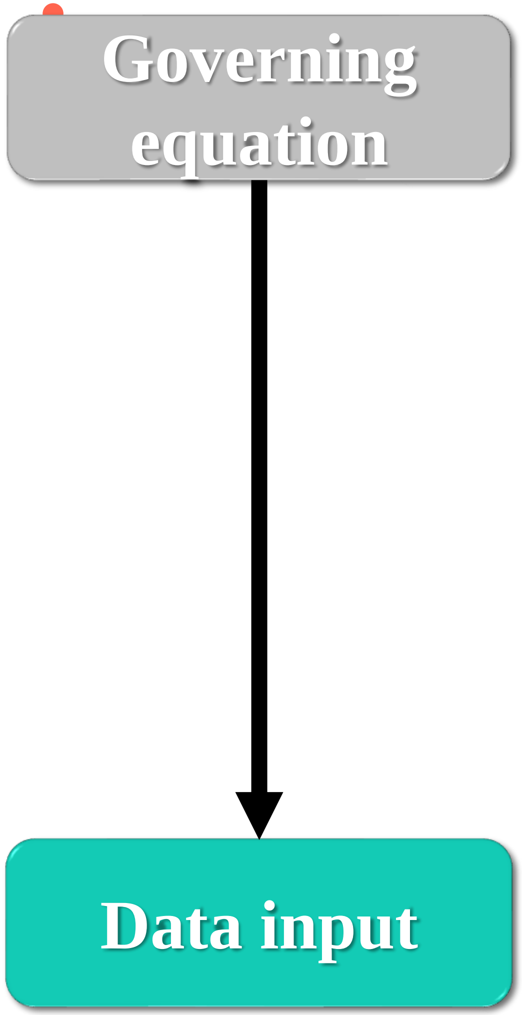
$$F = \alpha' \frac{\theta}{n_e} + \beta'\theta + n_e \frac{dS}{dh}$$

K : hydraulic conductivity tensor (L/T) with

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

Darcy's velocity (L/T)

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



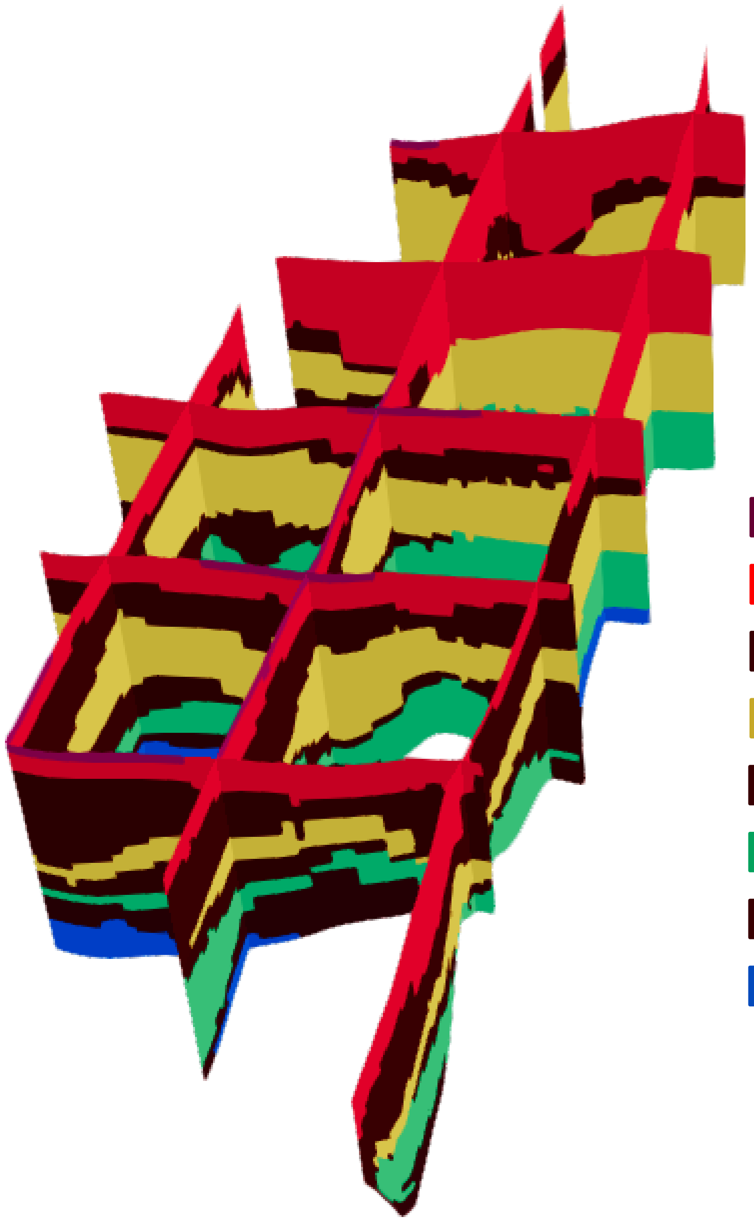
- Conceptual hydrological: build up from 42 borehole cores (CGS website)
- K value reference:

  Aquifer: 148 wells → Pumping test result from CGS report

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

Material	K lowest (m/day)	K highest (m/day)
Fine sand	0.017280000	17.280000
Silt	0.000086400	1.728000
Clay	0.000000864	0.000432

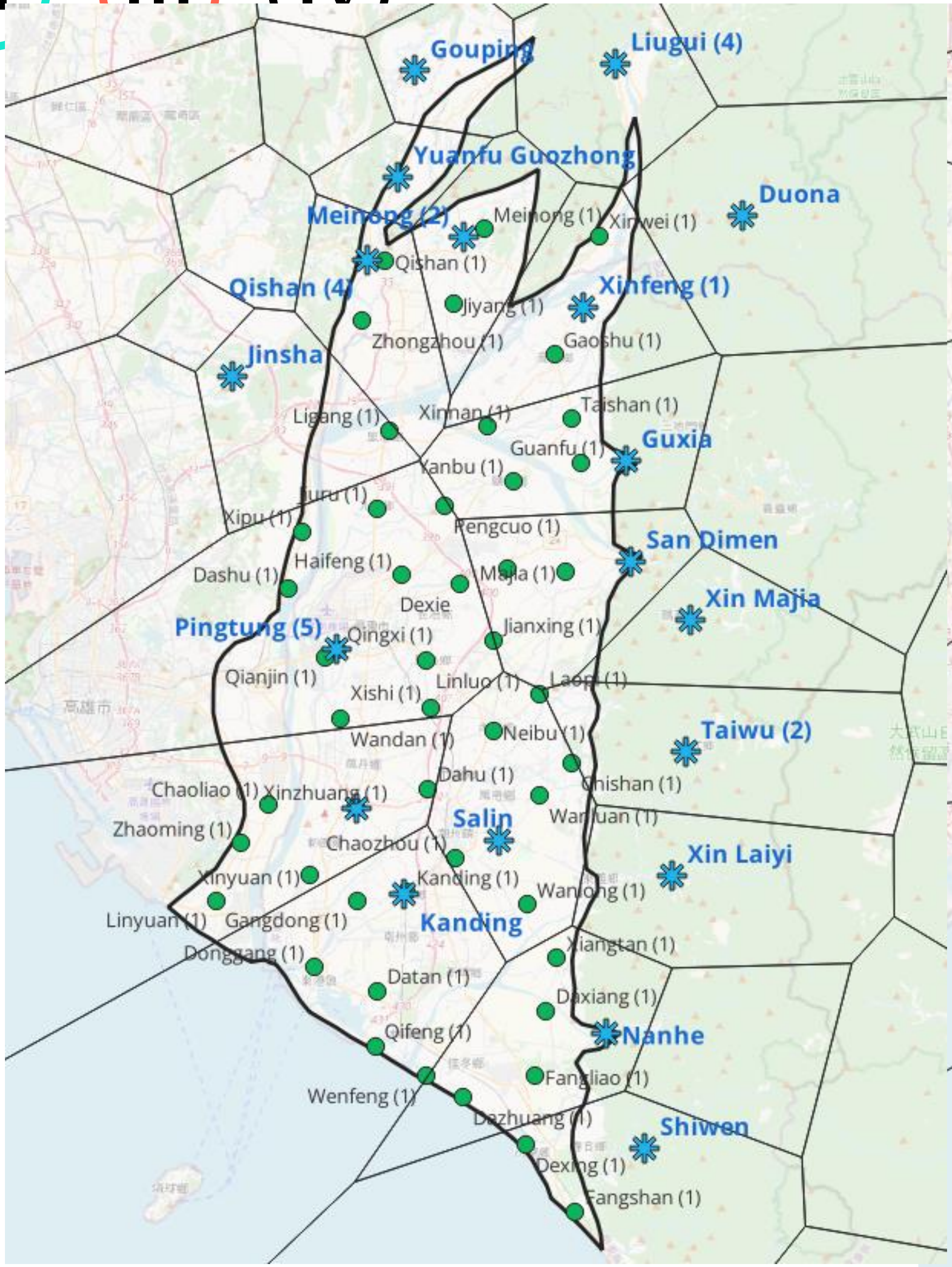
- Groundwater level: daily data from 2020 – 2022 of 122 stations (WRA)
- Rainfall rate: daily data from 2020 – 2022 of 8 stations (WRA)

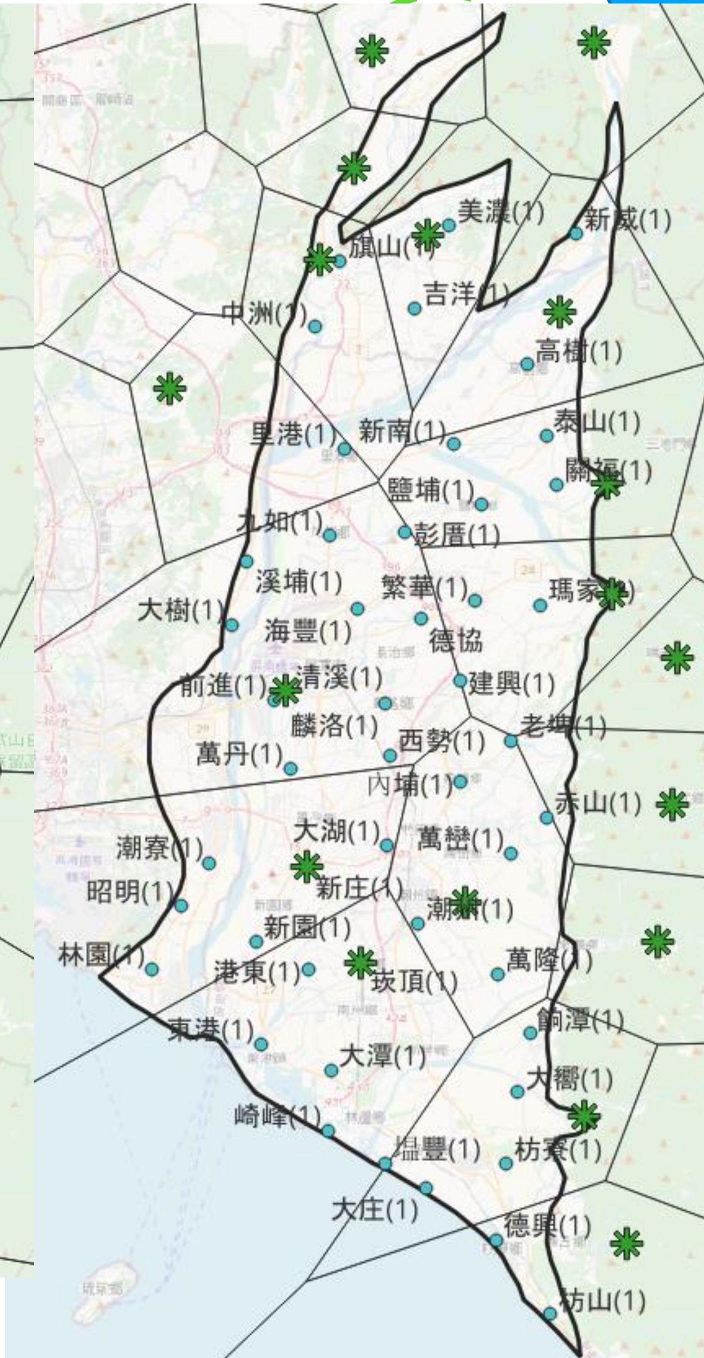


Legendary

- Material 8
- Aquifer1
- Aquitard1
- Aquifer2
- Aquitard2
- Aquifer3
- Aquitard3
- Aquifer4

THMC software

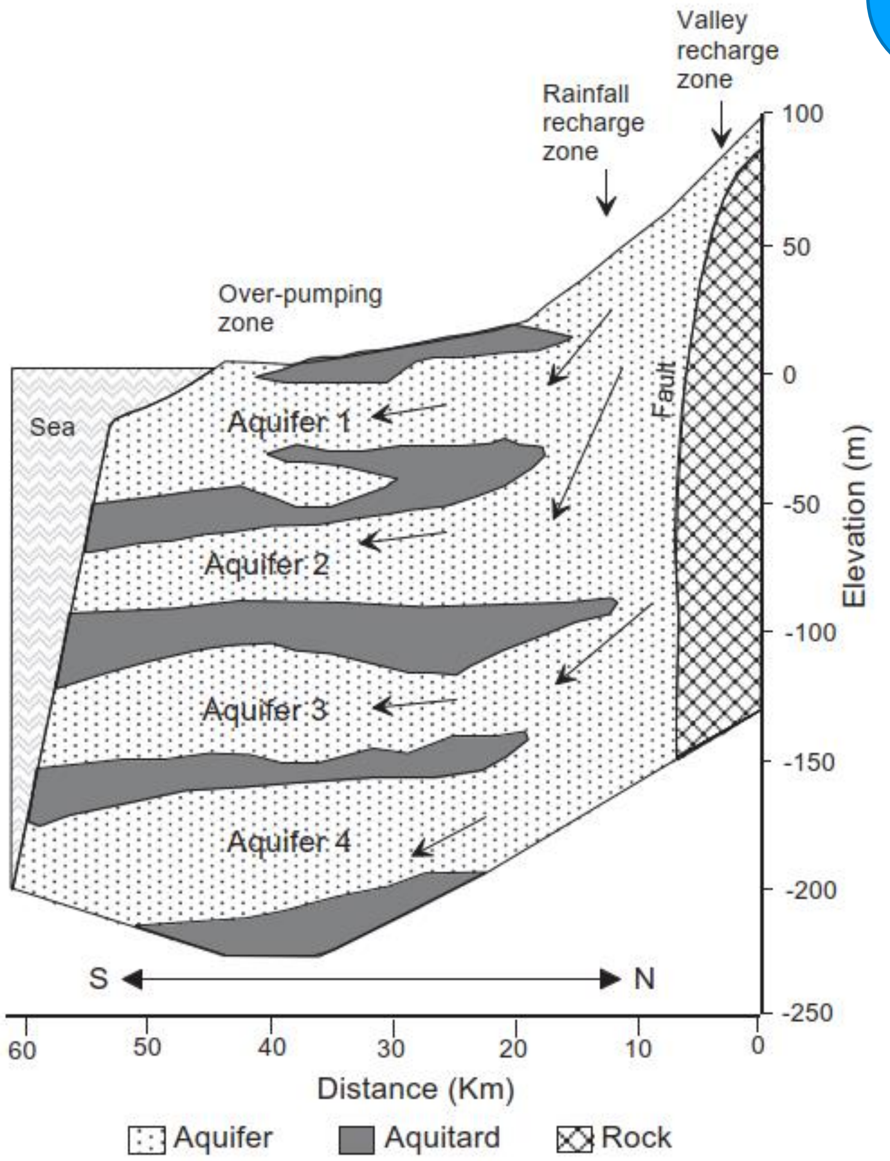




Hydrogeological

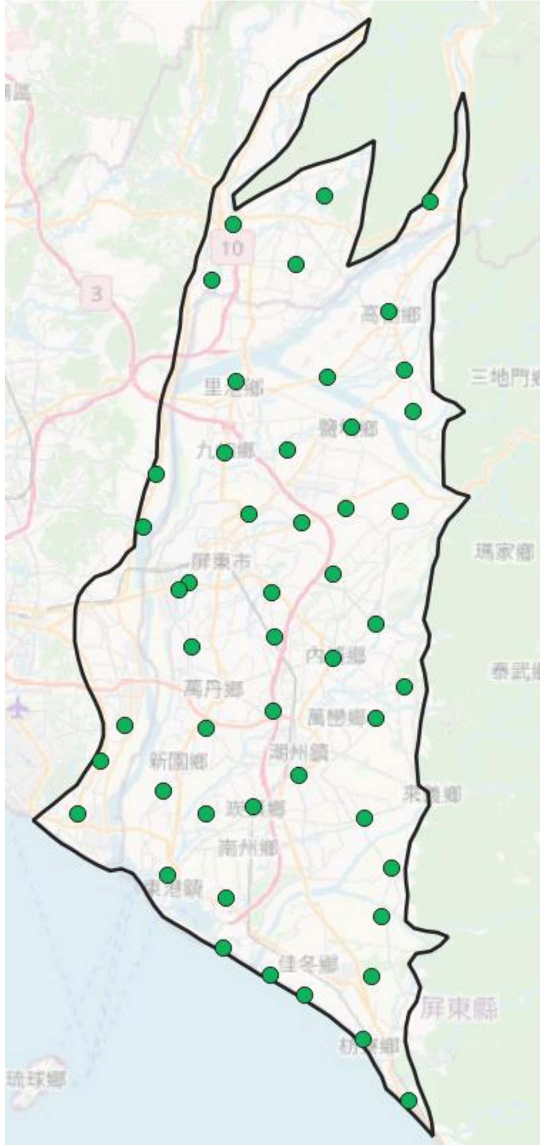
The plain sediments can divide into 8 layers:

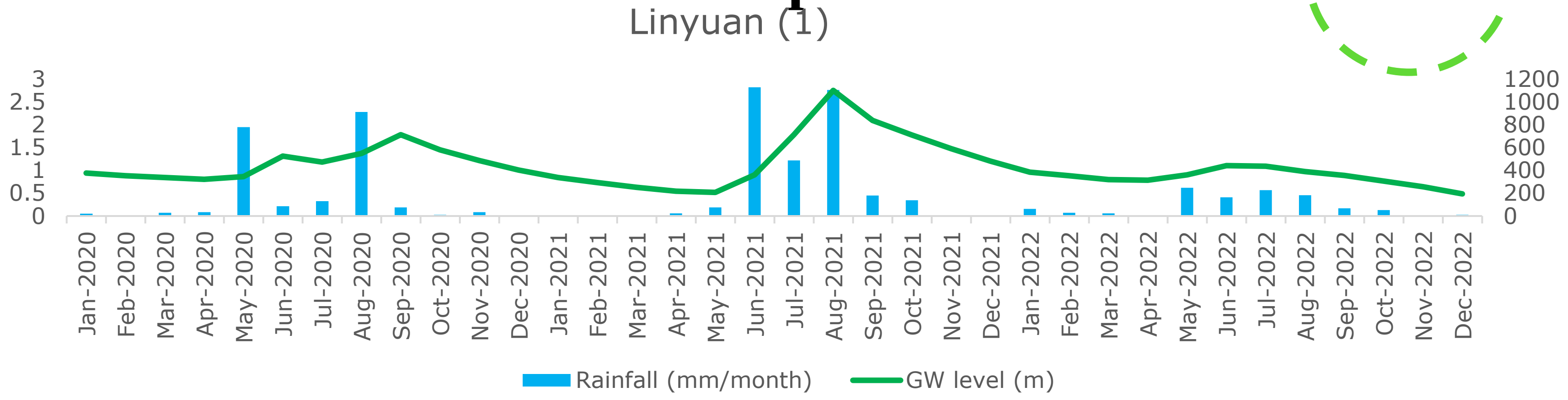
- ➢ Aquifer: high permeable coarse sediments, ranging from medium sand to gravel.
- ➢ Aquitard: low permeable fine sediments, ranging from clay to fine sand

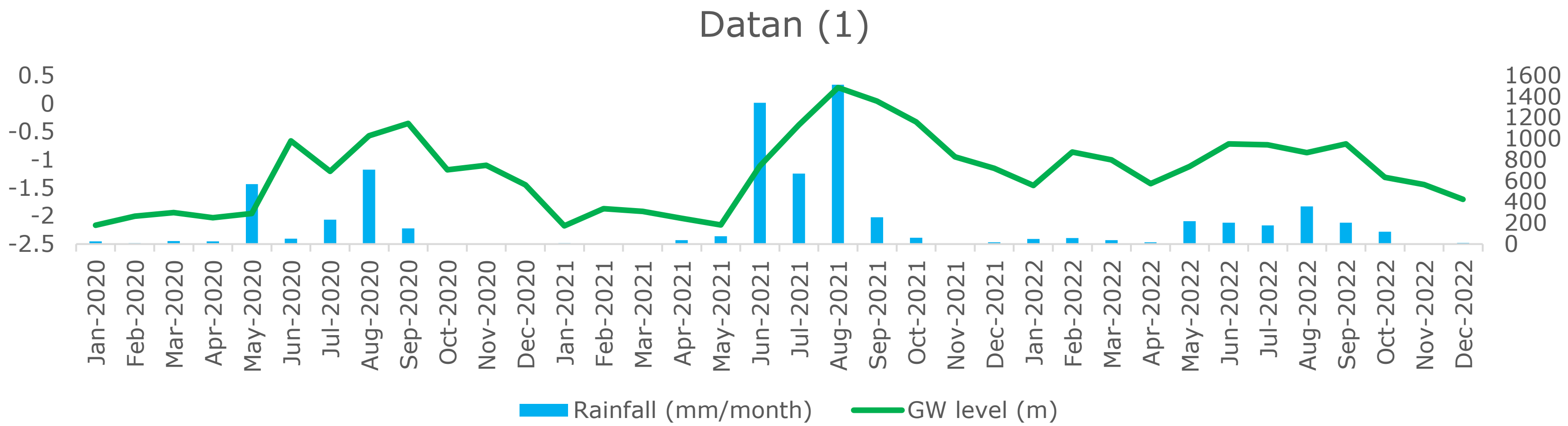


A conceptual hydrogeological profile of the Pingtung Plain (Jang et al., 2016)

Groundwater level and rainfall distribution relationship



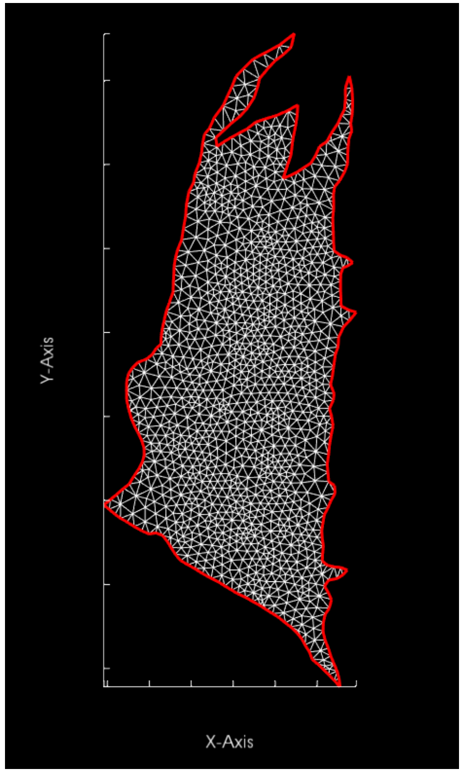


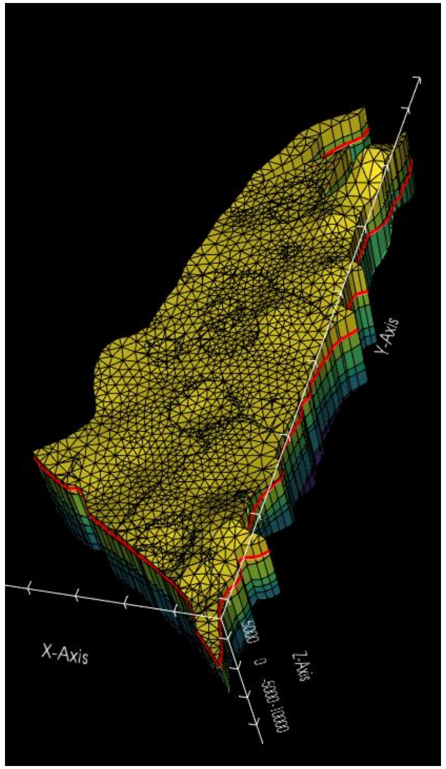


Groundwater increase after a month from raining time

Conceptual hydrological domain

- Create triangular grid and generate 3D domain





Uniform cells