Investigation of sustainable resource management of Jiaoxi hot spring by using the hydro-thermal numerical simulation in a heterogeneous hydrogeological model

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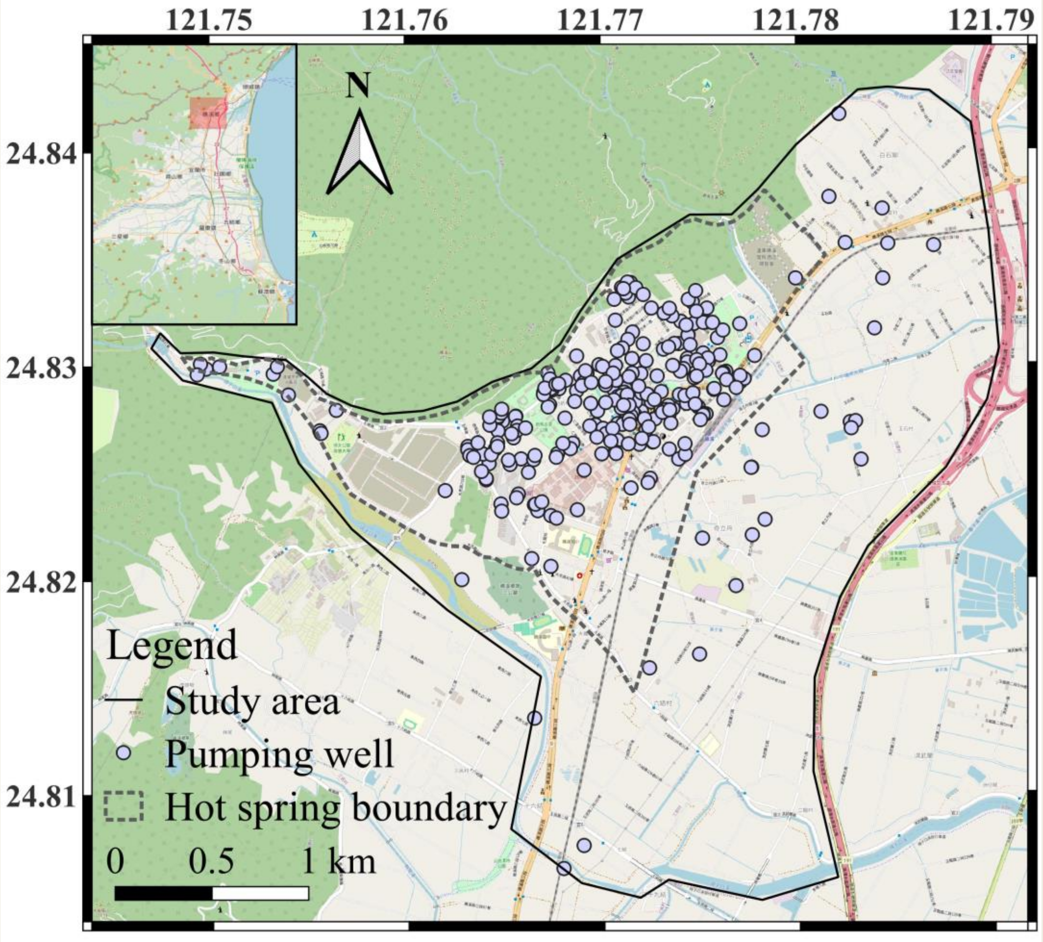
Outline

- Introduction
- Methodology
- Results and discussion
- Conclusions

Introduction

- Jiaoxi has a unique flatland sodium bicarbonate hot spring in Taiwan, which always attracts tourists from all over the country during holidays.
- As the number of tourists increases, the usage of hot springs also increases accordingly.
- This study aims to evaluate the suitable usage of hot spring by integrating the hydro-thermal numerical simulation in a heterogeneous hydrogeological model .



Introduction

Groundwater Modeling System

Drilling borehole data

- Yilan county government
- Engineering geological investigation databank
- Hydrogeological database

Hydrological observation data

- < River data > Yilan county government
- < Groundwater level > Jiaoxi monitoring wells
- < Temperature > Jiaoxi monitoring wells

Geological model

- Sediment (heterogeneity)
- Basement (homogeneity)

Set boundary conditions

Choose the representative geological model

MODFLOW

Input hydrological observation data (pumping data)

Groundwater flow model validation

MT3DMS

Obtain the distribution of temperature

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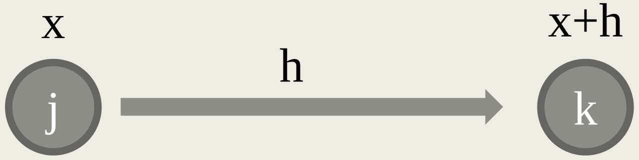
Methodology – Markov chain



x : a spatial location

h : separation vector

k, j : categories of material

t_{jk} : transition probability

- Use 1D continuous-lag Markov chain model

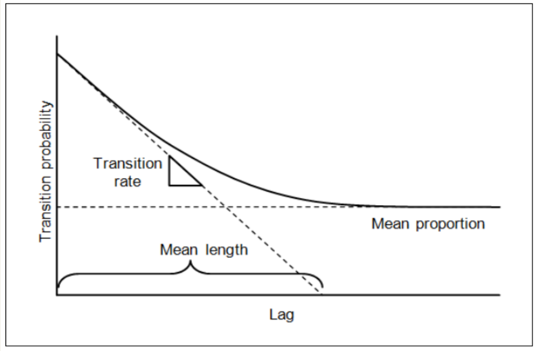
$$t_{jk}(h) = Pr\{k\ occurs\ at\ x + h \mid j\ occurs\ at\ x\}$$

We found material j at x, so what is the probability of finding material k at x+h?

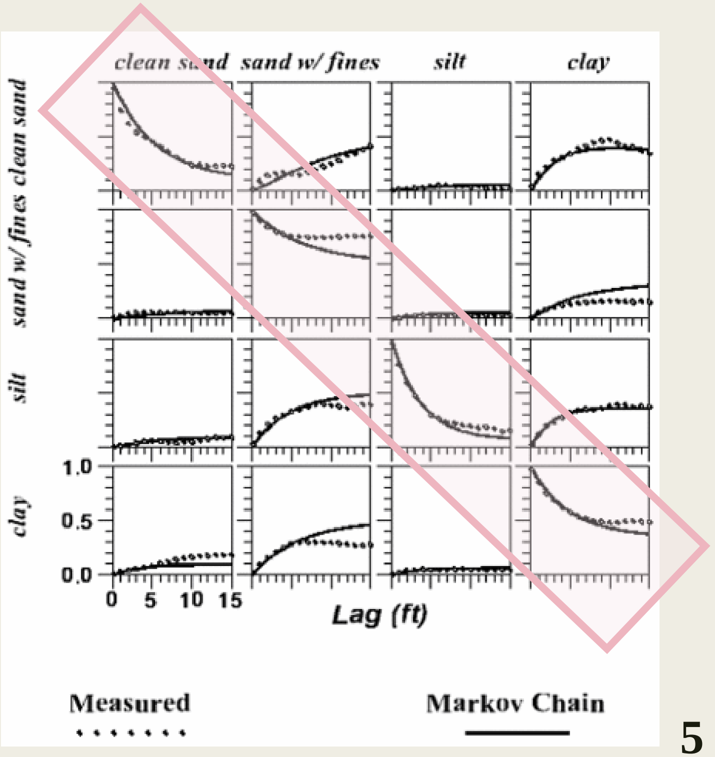
- **Transition rate matrix** in z direction R_z

$$R_z = \begin{bmatrix} r_{jj,z} & \cdots & r_{jk,z} \\ \vdots & \ddots & \vdots \\ r_{kj,z} & \cdots & r_{kk,z} \end{bmatrix}$$

$$r_{jk,z} = \frac{\partial t_{jk}(0)}{\partial h_z}$$



$r_{jk,z}$: the rate change from category j to category k per unit length in the direction z



Diagonal transition $(r_{11}, r_{22}, \ldots, r_{NN}) = \dfrac{1}{mean\ length(\bar{L}_k)}$

Material's continuity

Methodology – MODFLOW

- MODFLOW(Modular Three-Dimensional Finite-Difference Ground-Water Flow Model) is a 3D, cell-centered, finite difference, saturated flow model developed by the United States Geological Survey (McDonald & Harbaugh, 1988).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

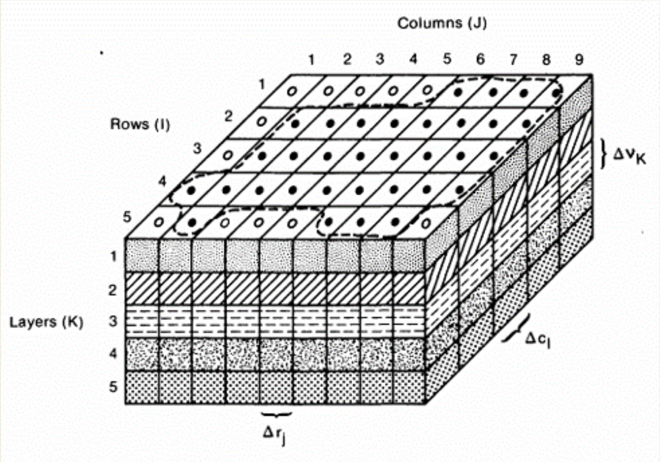
K_{xx}, K_{yy}, K_{zz} : Hydraulic conductivity along the x, y, and z coordinate axes [LT^{-1}]

h : Hydraulic head [L]

W : Sources and/or sinks [T^{-1}]

S_s : Specific storage [L^{-1}]

t : Time [T]



Methodology – MT3DMS

- MT3DMS (Modular Transport, 3-Dimensional, Multi-Species model) is a modular three-dimensional transport model for the simulation of **dispersion**, **advection** in groundwater systems (Zheng, 1990).

Solute transport

$$\left(1+\frac{\rho_b K_d^k}{\theta}\right)\frac{\partial(\theta C^k)}{\partial t} = \boldsymbol{\nabla}\cdot\left[\boldsymbol{\theta}\left(\boldsymbol{D_m^k}+\boldsymbol{\alpha}\frac{\boldsymbol{q}}{\boldsymbol{\theta}}\right)\boldsymbol{\nabla C^k}\right] - \boldsymbol{\nabla}\cdot\left(\boldsymbol{qC^k}\right) + q_s C_s^k$$

Heat transport

$$\left(1+\frac{\rho_b K_d^T}{\theta}\right)\frac{\partial(\theta T)}{\partial t} = \boldsymbol{\nabla}\cdot\left[\boldsymbol{\theta}\left(\boldsymbol{D_m^T}+\boldsymbol{\alpha}\frac{\boldsymbol{q}}{\boldsymbol{\theta}}\right)\boldsymbol{\nabla T}\right] - \boldsymbol{\nabla}\cdot\left(\boldsymbol{qT}\right) + q_s T_s$$

θ : Porosity

ρ : Fluid density [ML^{-3}]

ρ_s : Solid density [ML^{-3}]

ρ_b : Bulk density [ML^{-3}]

α : Dispersivity tensor [L]

T : Temperature [Θ]

T_s : Source temperature [Θ]

q : Specific discharge [LT^{-1}]

q_s : Fluid source or sink [T^{-1}]

C^k : Concentration of species [ML^{-3}]

D_m^k : Molecular diffusion coefficient [L^2T^{-1}]

D_m^T : Thermal diffusivity for the temperature species [L^2T^{-1}]

K_d^k : Distribution coefficient of species [L^3M^{-1}]

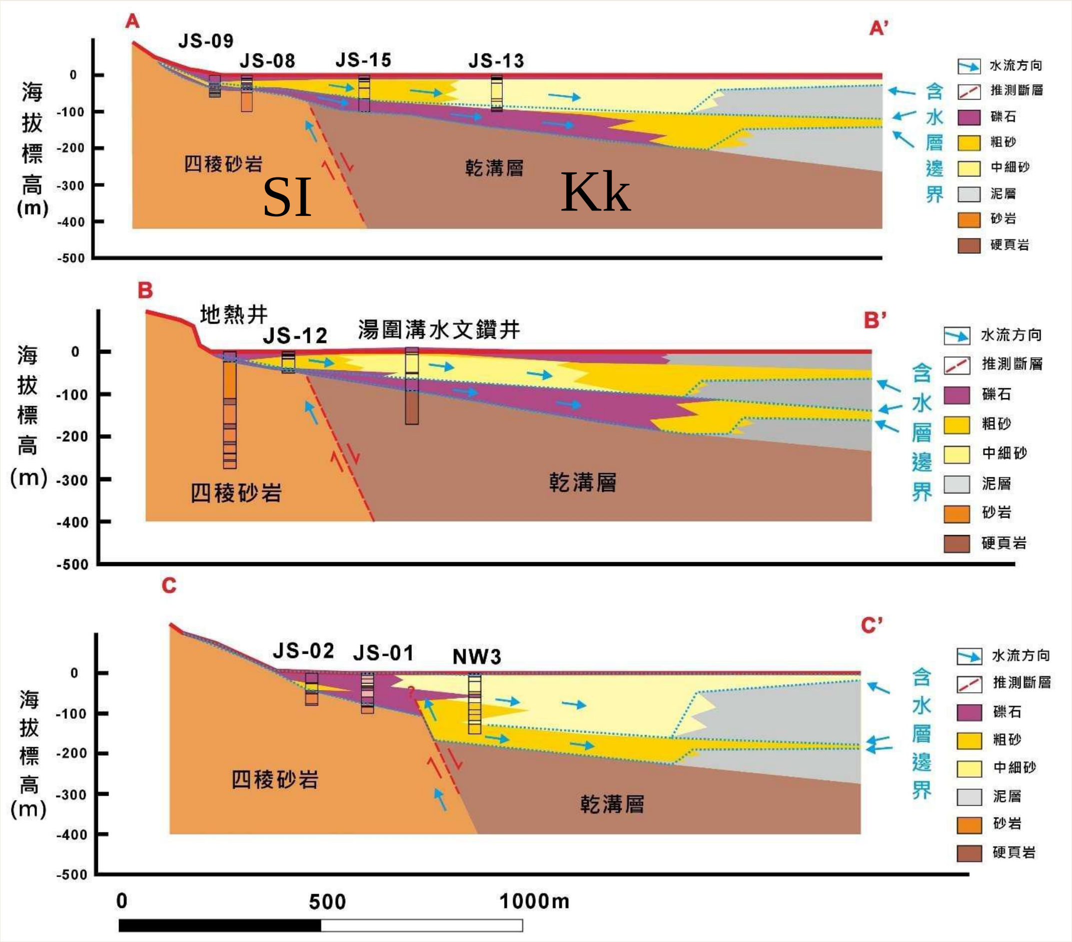
K_d^T : Distribution coefficient for the temperature species [L^3M^{-1}]

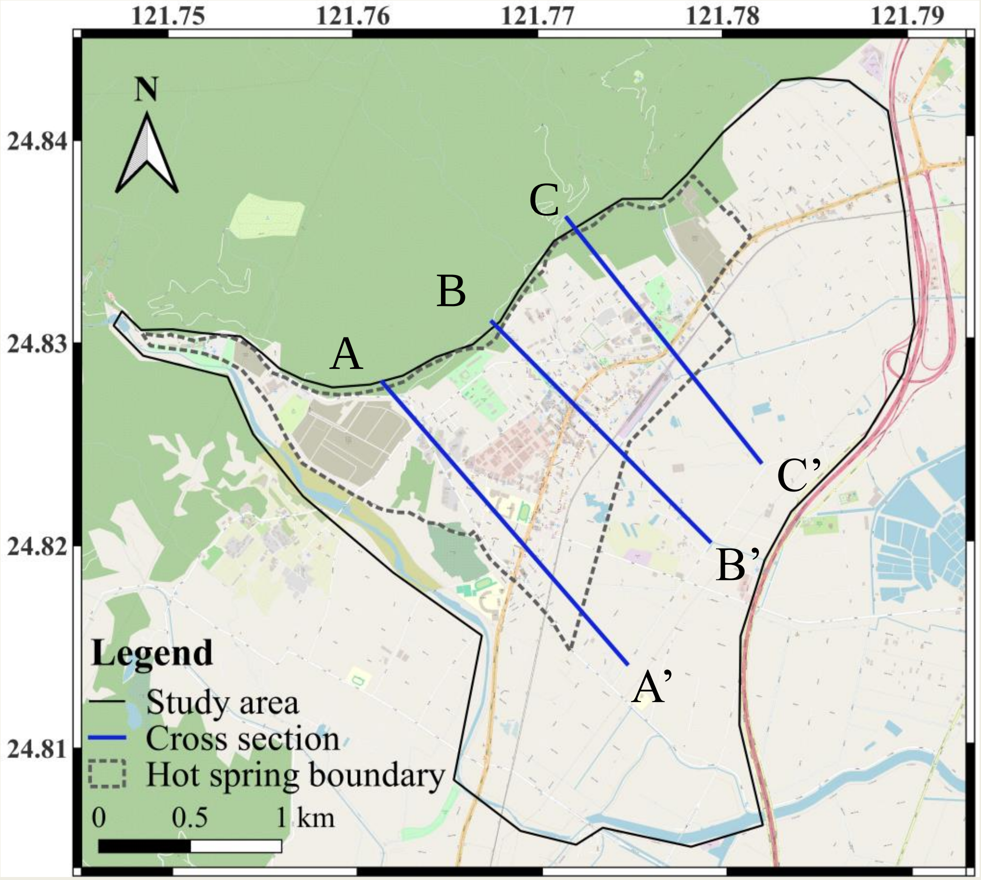
Part A

Build the representative geological model

Results and discussion

- Build a basement homogeneous model based on cross sections, geological maps, and drilling data.





(宜蘭縣政府, 2022)

Results and discussion

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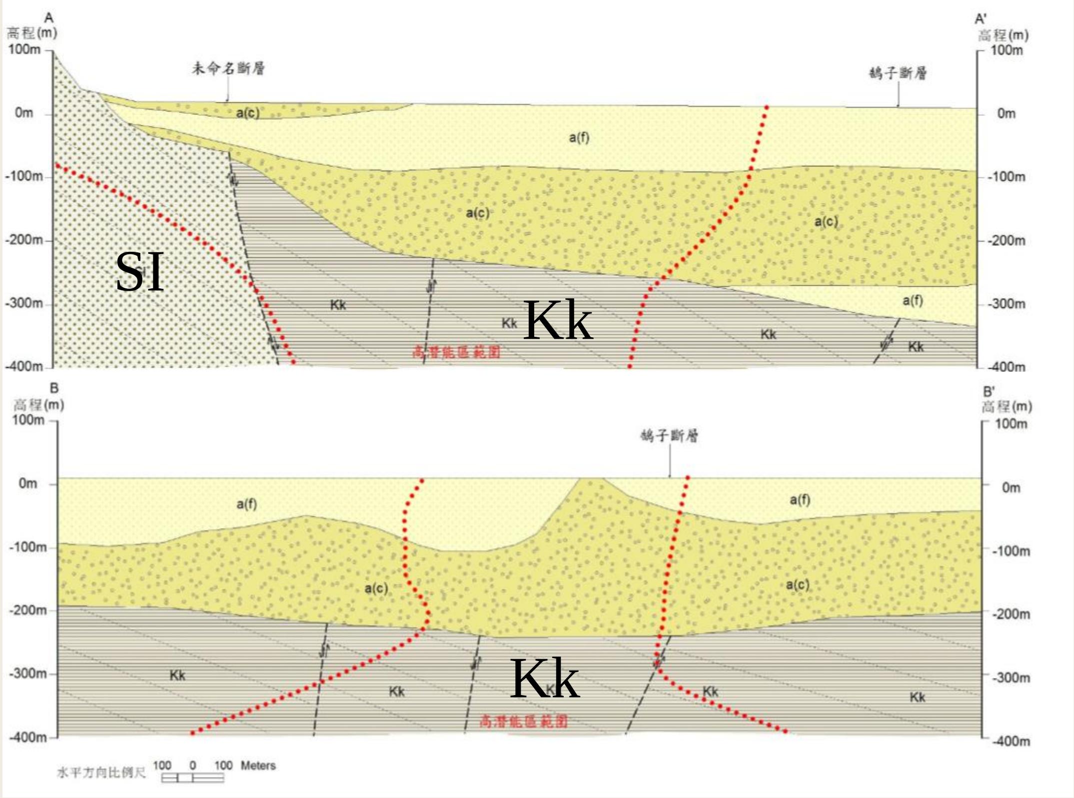

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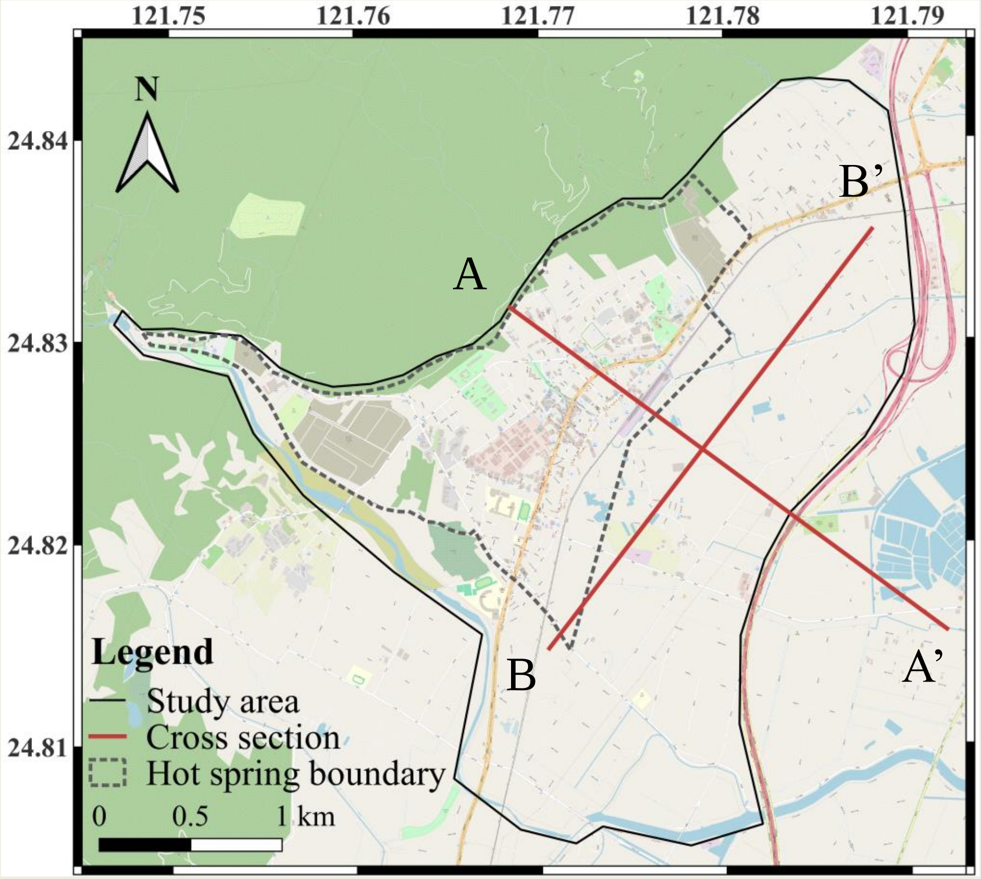

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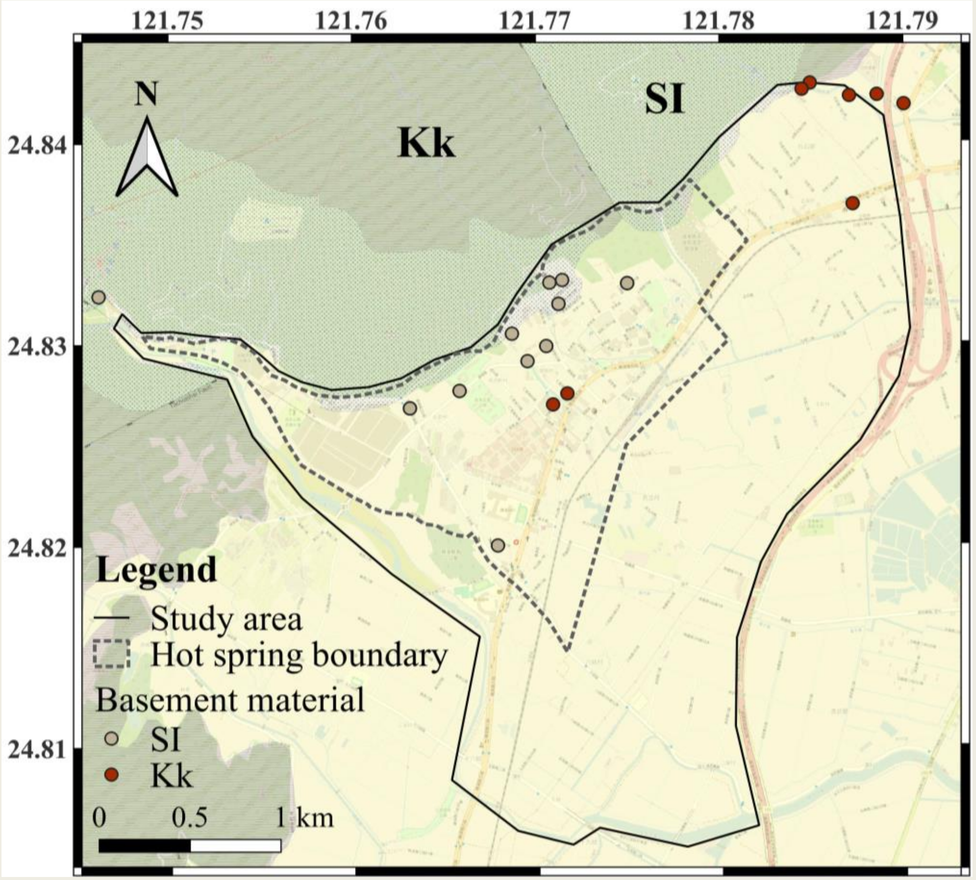

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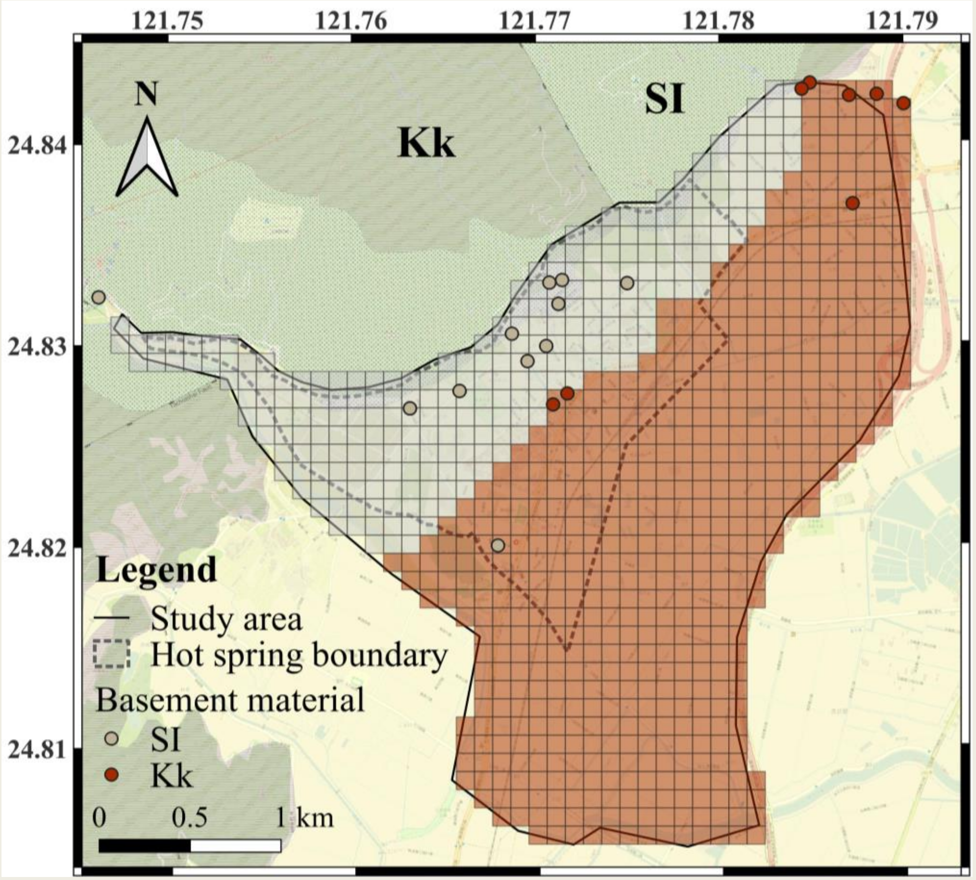
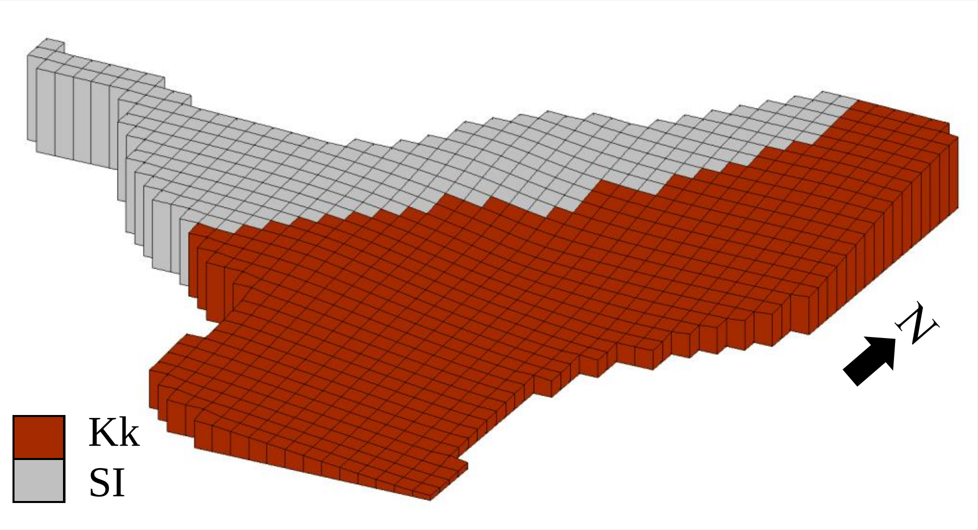
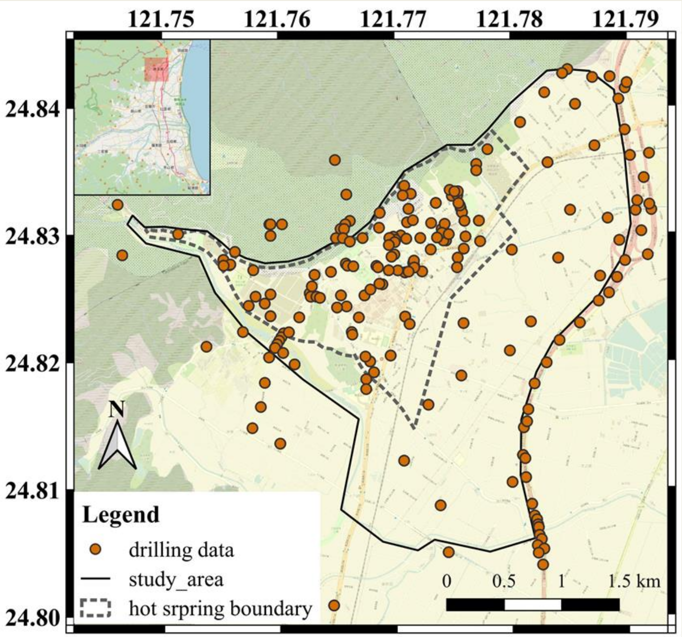




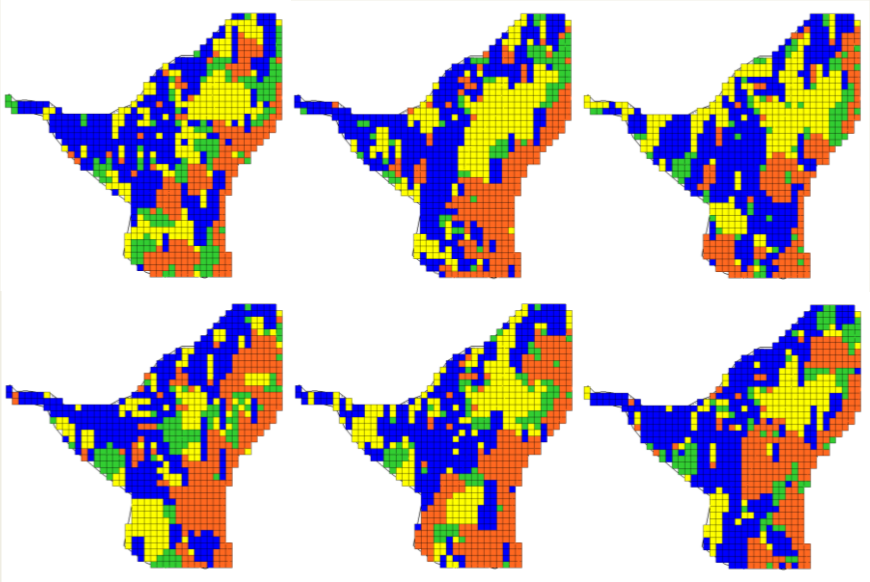
Results and discussion

- Use indicator kriging and rose diagram to find out the primary continuity of materials along the N10˚E.
- Set mean length into T-PROGS package to generate dozens of realizations of sedimentary heterogeneity hydrogeological models using the Markov chain method.
- Integrate the individual realizations with the homogeneous basement into a 3D geological model.



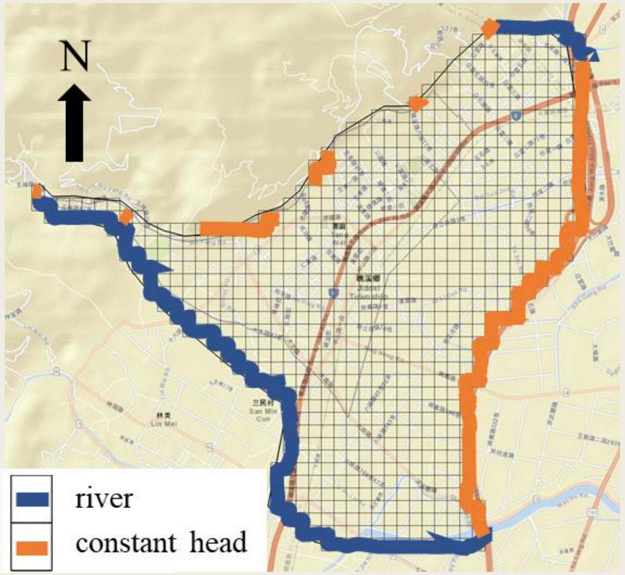
	N10˚E	S80˚E
Gravel	500	200
Coarse sand	250	250
*Fine sand	600	410
Clay and silt	320	250

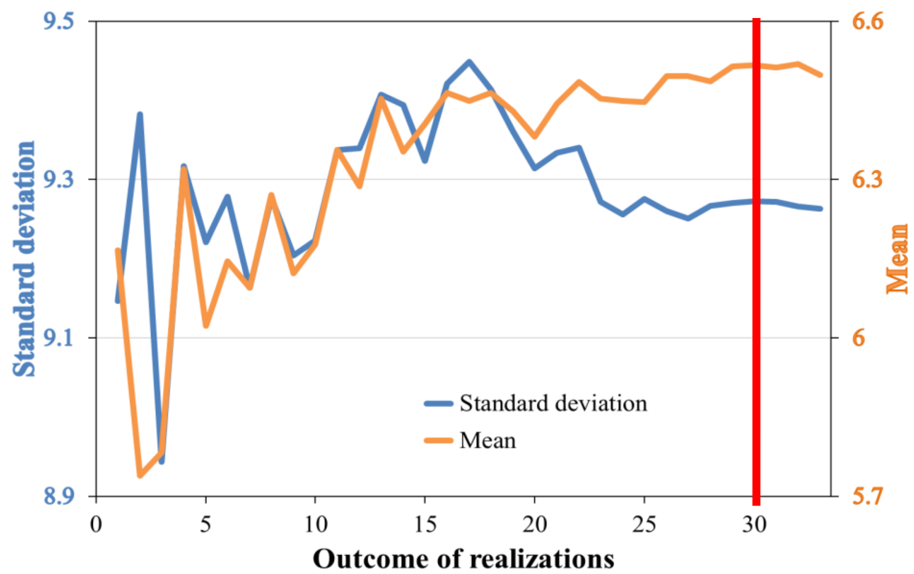
* Background material (Unit : m)

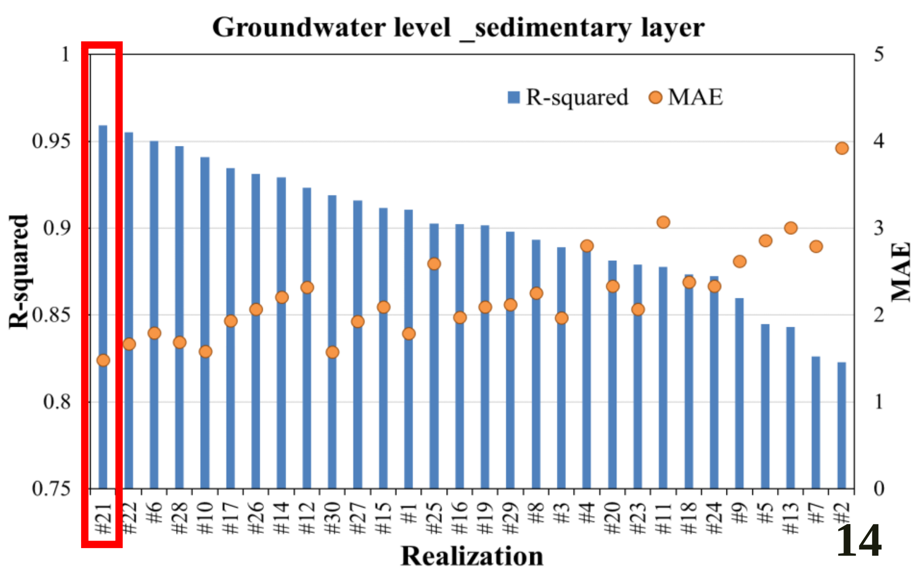


Results and discussion

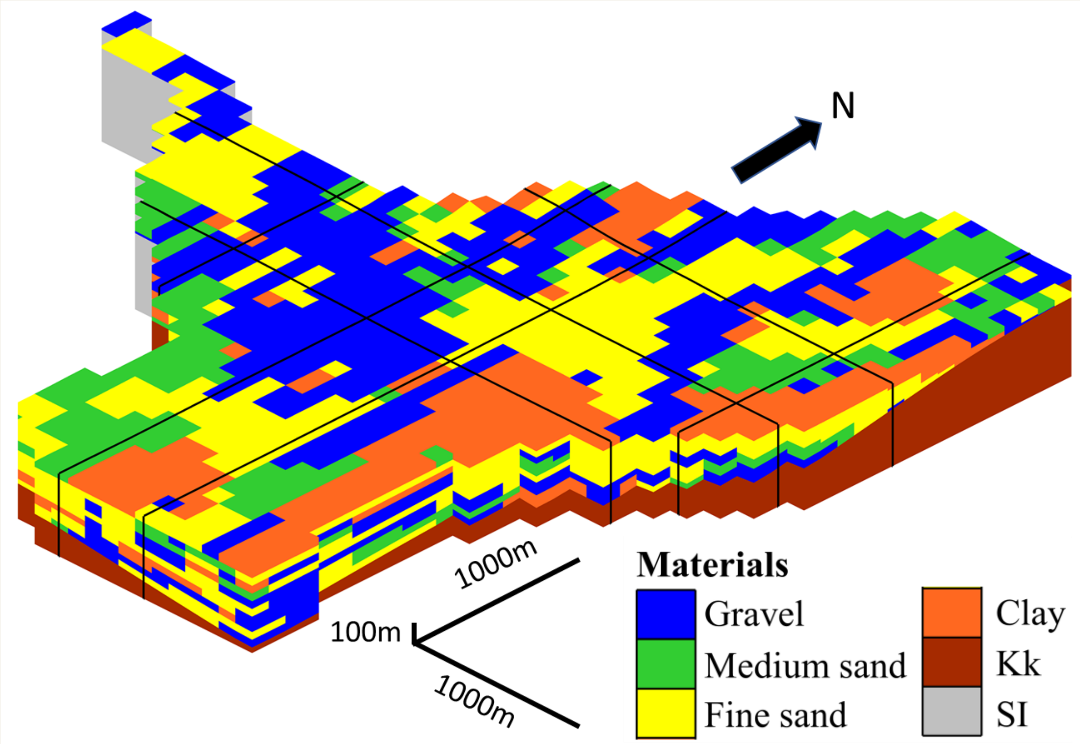
- Under the proper hydrological conditions, we observe that the overall standard deviation and mean value of the groundwater level stabilize when the number of realizations reaches 30.
- Calculate the average water level for each grid in the 30 models, considering it as the ideal water level, and determine which realization among those created is most similar to it.
- Choose the realization with highest R^2 and lowest MAE (Mean absolute error) to serve as the representative model.

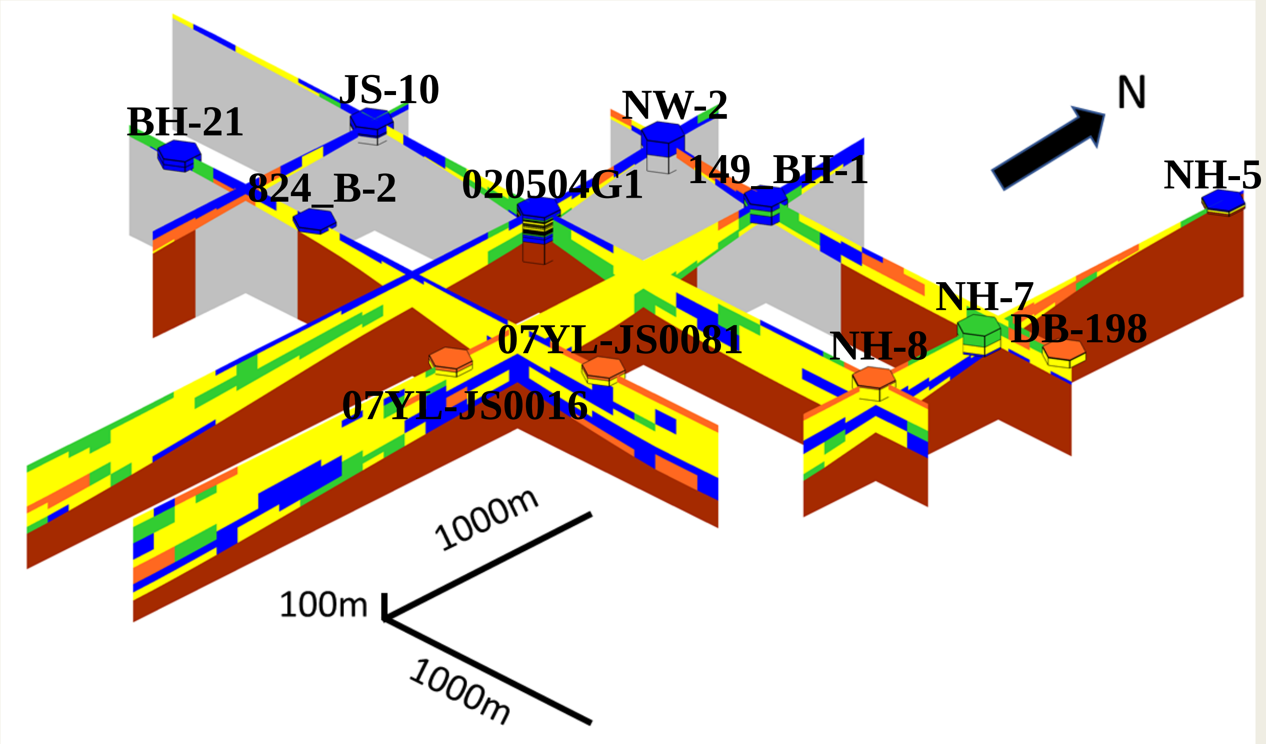






Results and discussion - representative model



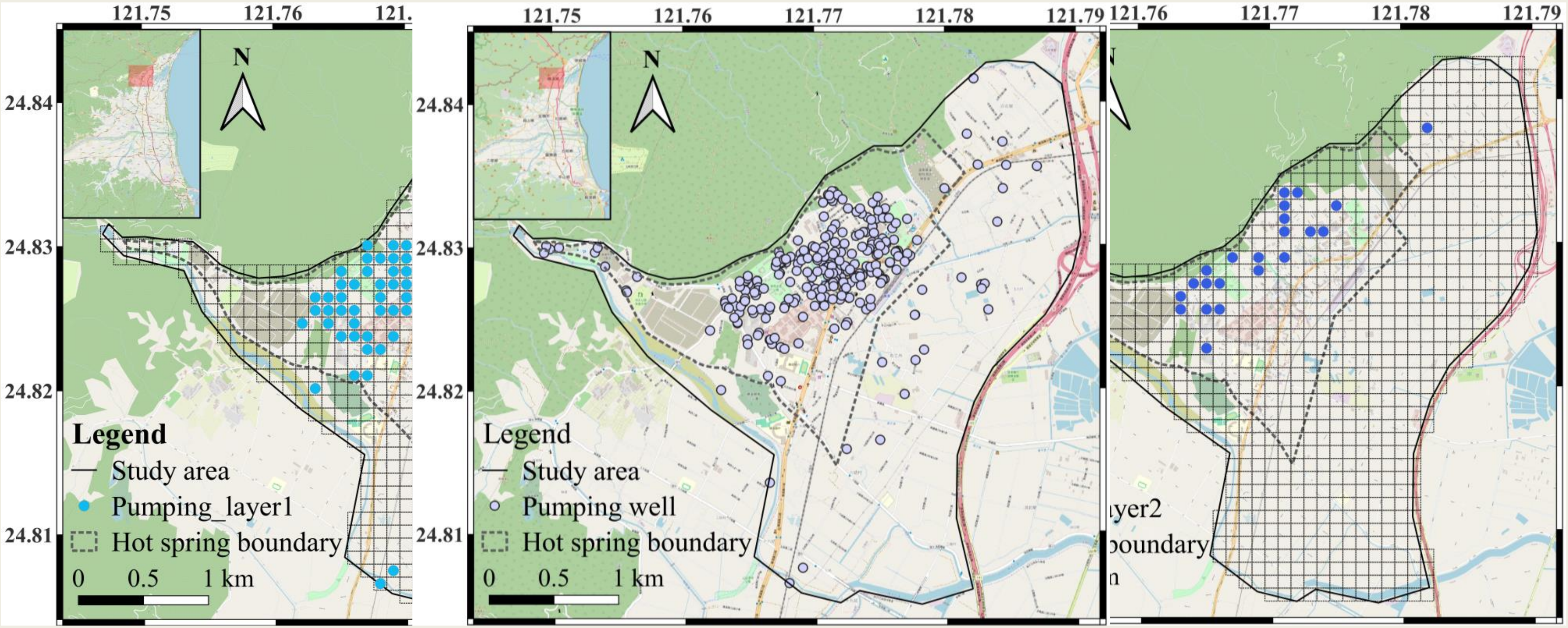


Part B

Numerical model

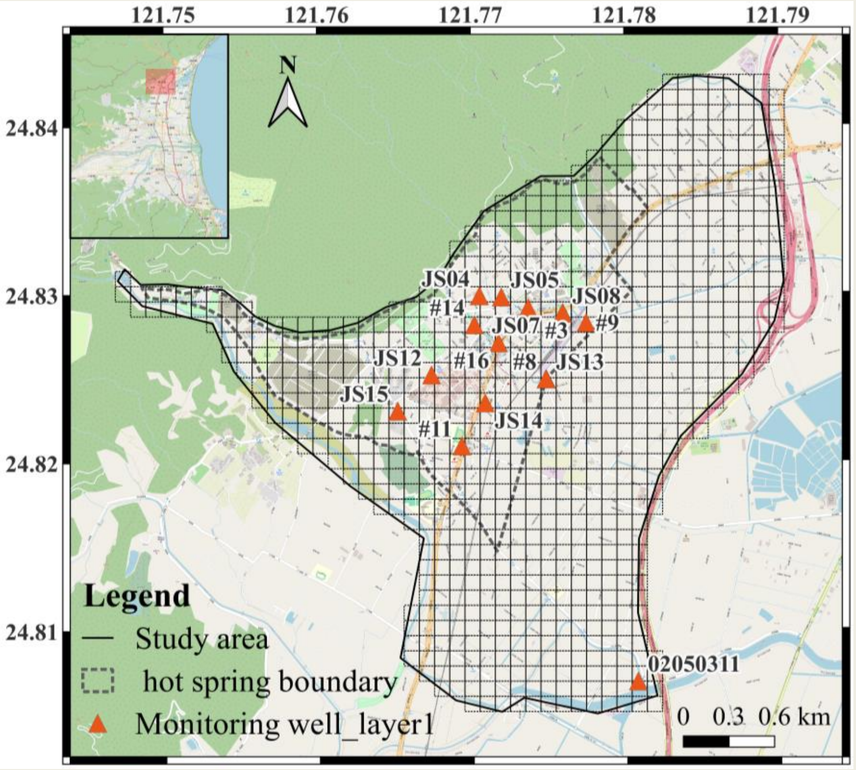
Results and discussion – MODFLOW

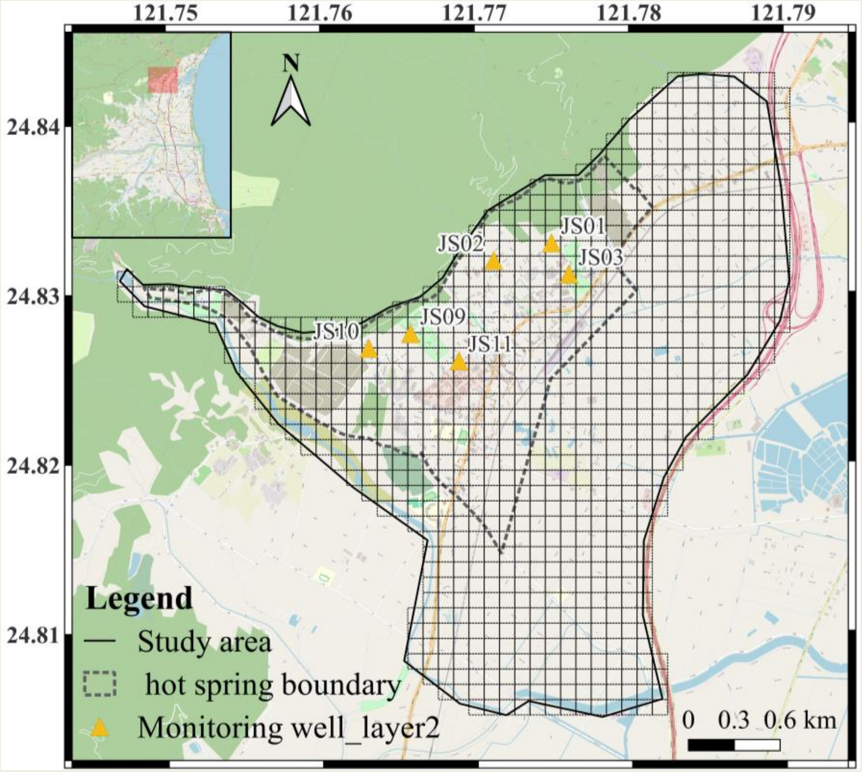
- Comparing the elevation of pumping well screens with the elevation of the bedrock for stratification.
- Due to the presence of multiple pumping wells within a grid cell, the pumping rates within the same grid cell are aggregated to calculate the total pumping rate.



Results and discussion – MODFLOW

- Comparing the elevation of monitoring well screens with the elevation of the bedrock for stratification.
- Layer 1(sedimentary layer) has 15 monitoring wells；layer 2 (basement layer) has 6.





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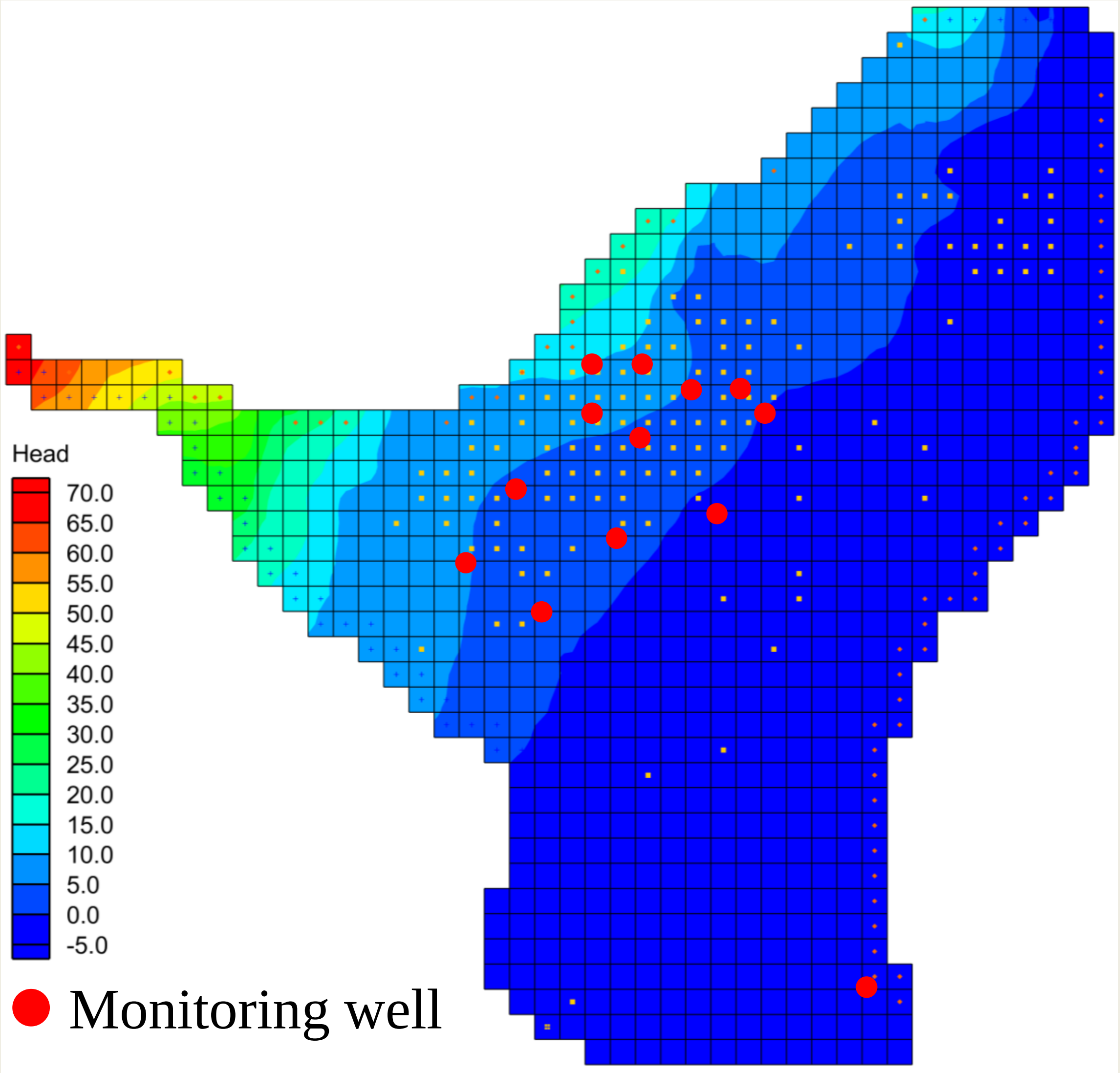

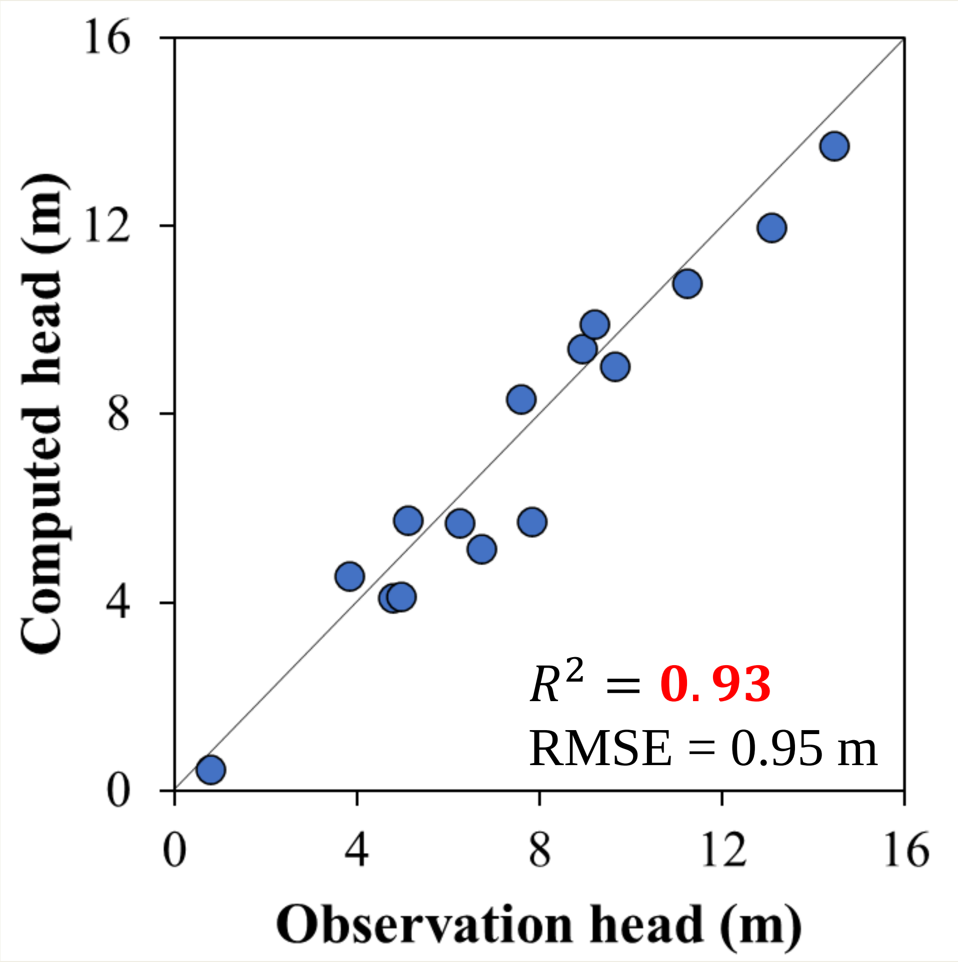

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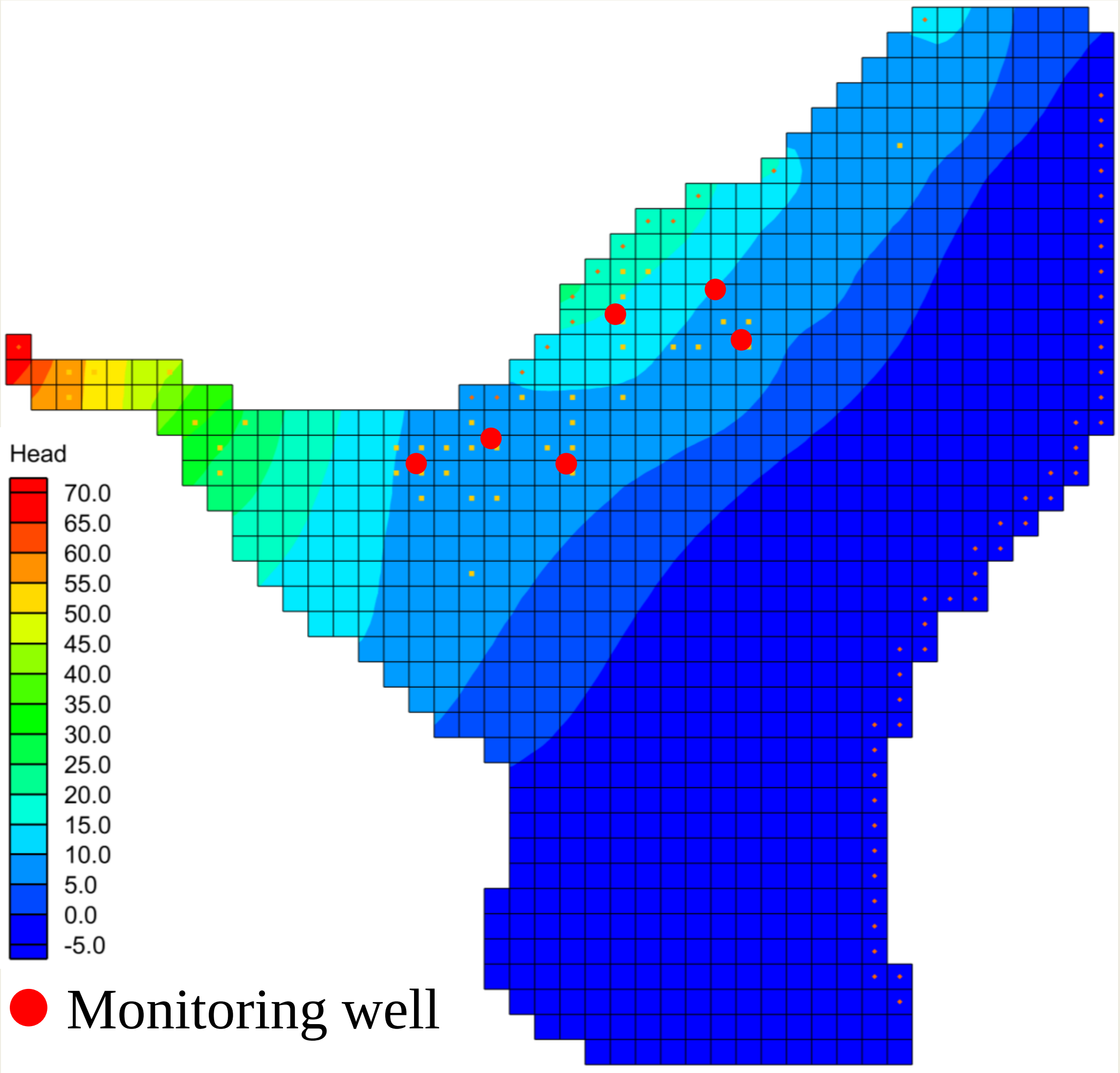
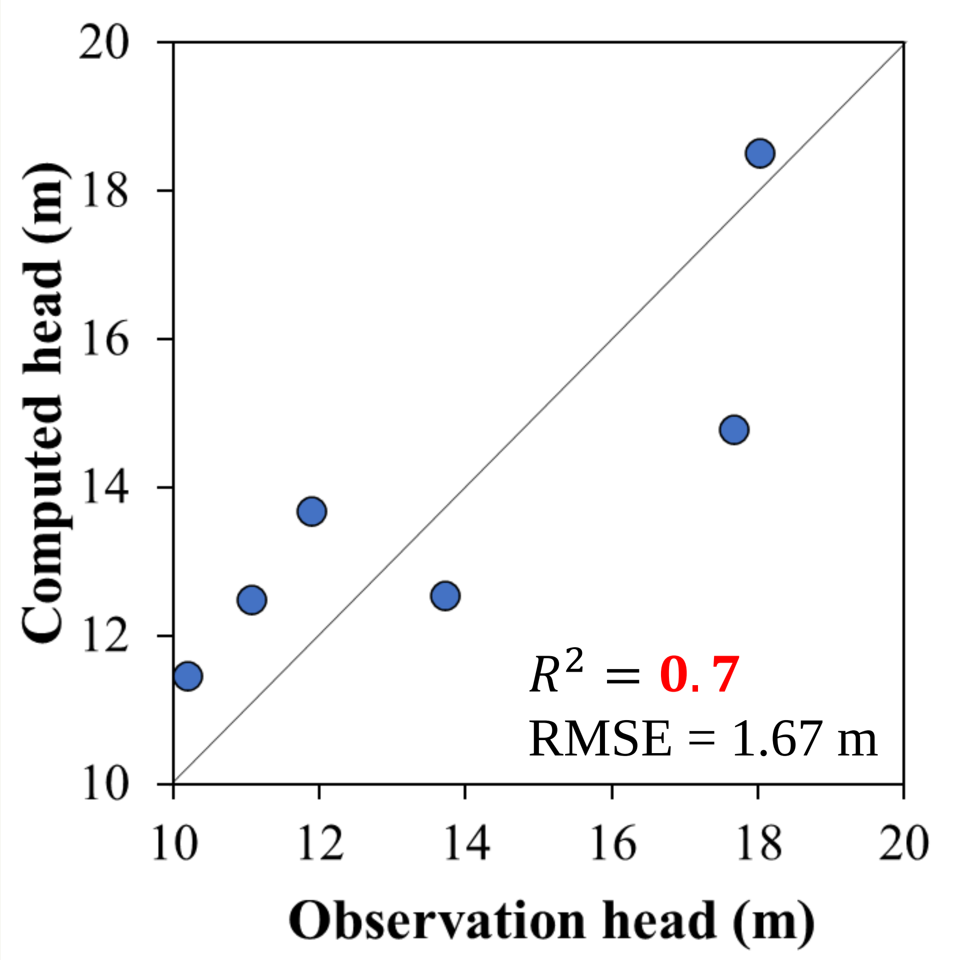




Results and discussion – MT3DMS

- Collect the observed temperature data from the monitoring well and pumping well .

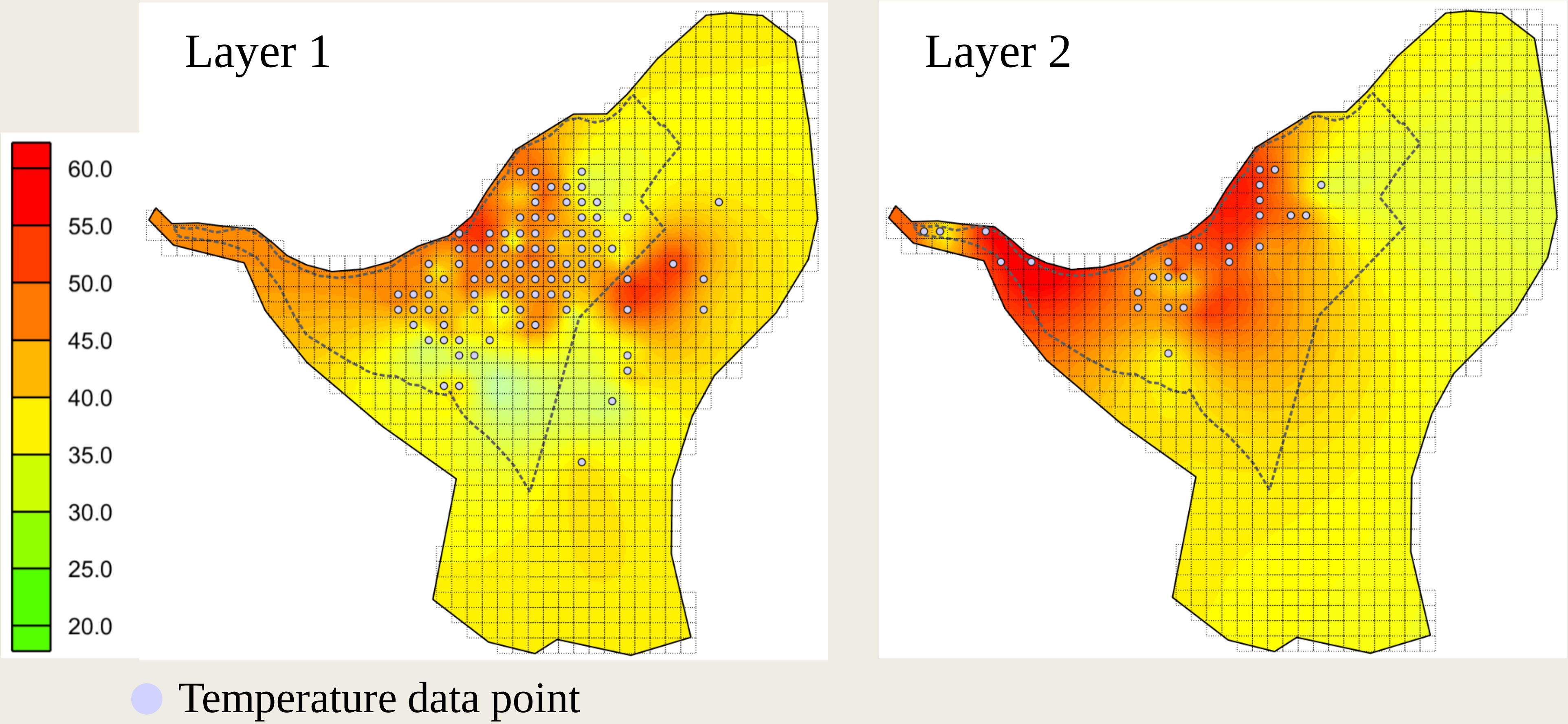
NO.	Name	TWD97_X	TWD97_Y	elevation shallow_sensor	elevation deep_sensor	top of bedrock	layer shallow_sensor	layer deep_sensor
JS01	公園路	328328	2747499	15.786	-74.214	-58.45545	1	2
				15.393	-34.607	-6.9566	1	2
				4.72	-131.48	-99.87865	1	2
				9.105	-24.895	-22.10389	1	2
				4.004	-35.996	-51.42593	1	1
				3.683	-83.317	-105.8949	1	1
				0.164				
				4.709				
				6.748				
				5.881				
				5.196				
				-4.28				
				1.271				
				4.514				
				-0.7				
				-4.31				
				-4.02				
				-4.02		-167.0136	1	
				2.86		-99.19733	1	
				1.87		-99.19733	1	
				2.84		-58.11945	1	
				2.88		-58.11945	1	
16號	太子	328008.6437	2746843.235	-0.82		-105.7014	1	

	TWD97_X	TWD97_Y	T_shallow	T_deep	T_layer1
JS01	328328	2747499	34.187		34.187
JS02	327950	2747385	37.56991667		37.56991667
JS03	328442	2747295	32.08883333		32.08883333
JS04	327883	2747153	23.07708333		23.07708333
JS05	328027	2747145	26.76616667	56.86991667	41.81804167
JS07	328203	2747074	35.84433333	46.70175	41.27304167
JS08	328432	2747039	39.84675	43.58916667	41.71795833
JS09	327406	2746906	37.78808333		37.78808333
JS10	327133	2746810	48.41783333		48.41783333
JS11	327723	2746728	37.41091667		37.41091667
JS12	327568	2746631	38.74933333		38.74933333
JS13	328324	2746605	26.59425	50.64491667	38.61958333
JS14	327922	2746447	31.96658333	50.89475	41.43066667
JS15	327346	2746393	30.17083333	32.571	31.37091667
3號(停車場淺)	328430	2747041	41.6675		41.6675
8號(奇立丹淺)	328321	2746606	27.03666667		27.03666667
9號(大排深)	328585	2746977	38.14416667		38.14416667
10號(大排淺)	328585.1	2746977.1	36.60833333		36.60833333
11號(新小深)	327768	2746163	24.67916667		24.67916667
12號(新小淺)	327768.1	2746163.1	24.64083333		24.64083333
14號(湯圍淺)	327850	2746962	44.15833333		44.15833333
15號(湯圍深)	327850.2731	2746961.971	44.10166667		44.10166667
16號(太子)	328009	2746843	46.12916667		46.12916667

	TWD97_X	TWD97_Y	T_layer2
JS01	328328	2747499	39.16675
JS02	327950	2747385	52.7205
JS03	328442	2747295	39.61391667
JS04	327883	2747153	56.08683333
JS09	327406	2746906	58.33825
JS10	327133	2746810	48.08833333
JS11	327723	2746728	56.09433333
JS12	327568	2746631	56.252

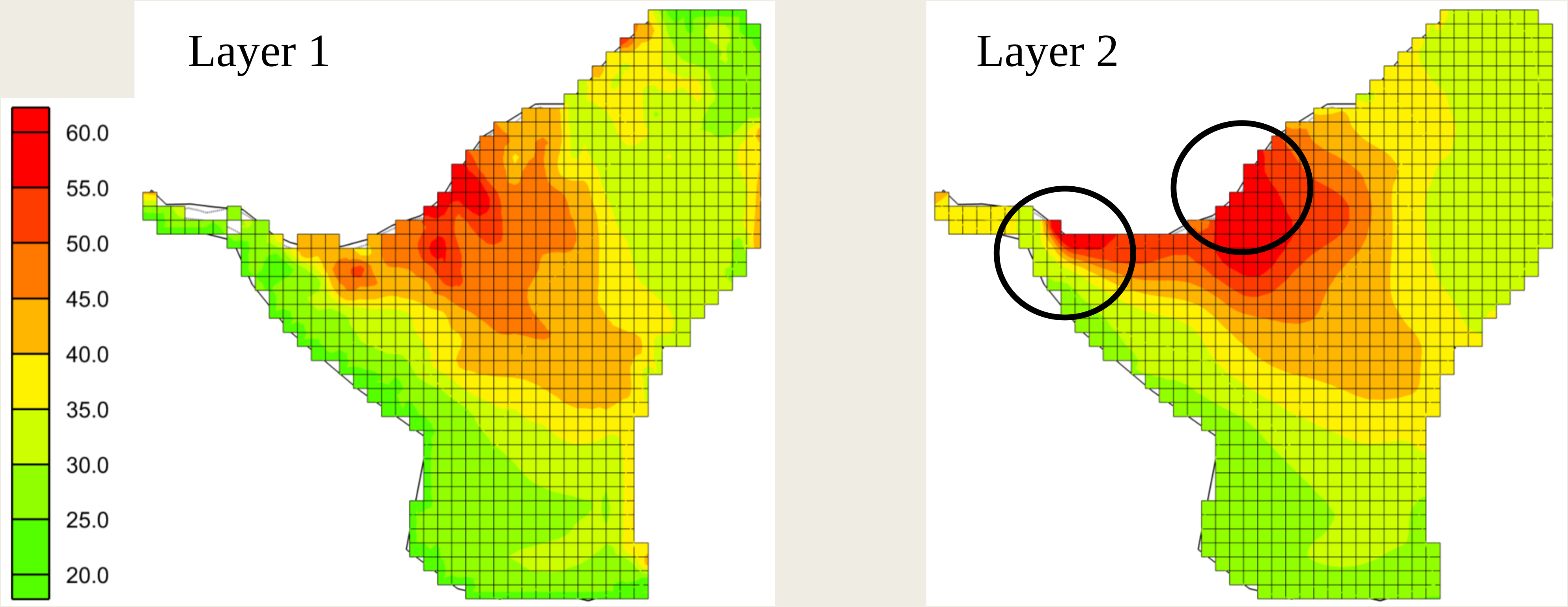
Results and discussion – MT3DMS

- Collect the observed temperature data from the pumping well and monitoring well.
- Use kriging method to get the distribution of the temperature of Jiaoxi area.



Results and discussion – MT3DMS

- Integrate the groundwater flow field with the MT3DMS package for hydro-thermal simulation.
- According to 陳文福、呂學諭(2010) and distribution of the observed temperature, we set two heat source at the layer 2.

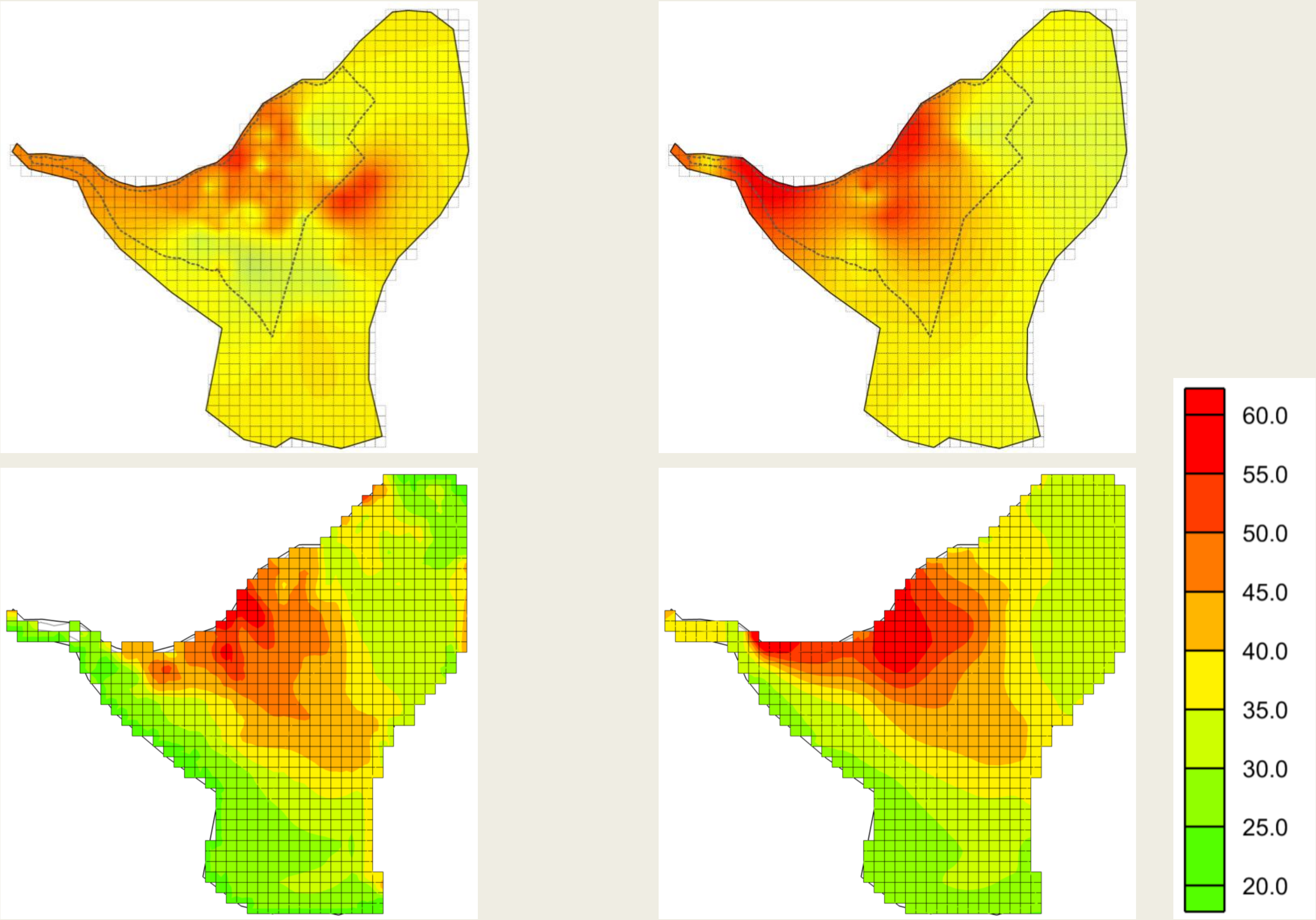


Results and discussion – MT3DMS

Layer 1 **Layer 2**

Observation

Simulation



Conclusions

- Use indicator kriging and rose-diagram shows that the primary continuity of materials along the N10°E.
- Select the model with highest R^2 and lowest MAE from the 30 models as the representative.
- Compared to observed groundwater level, R^2 for the sedimentary layers were 0.93, indicating the representativeness of the groundwater flow model established in this study.
- Thermal transport simulation showed that the temperature distribution of groundwater in basement is similar to that of observation.
- After considering the water usage and water temperature, the suitable water pumping quantity in the study area was further evaluated to provide a reference for future hot spring resource planning in the Jiaoxi area.

Thanks for your listening