Water Table Response to Rainfall and Groundwater Simulation Using Physics Based Numerical Model WASH123D

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Outline

- Introduction
- Methodology
- Results
- Conclusions

- Over-pumping and overuse of groundwater are common in southern Taiwan

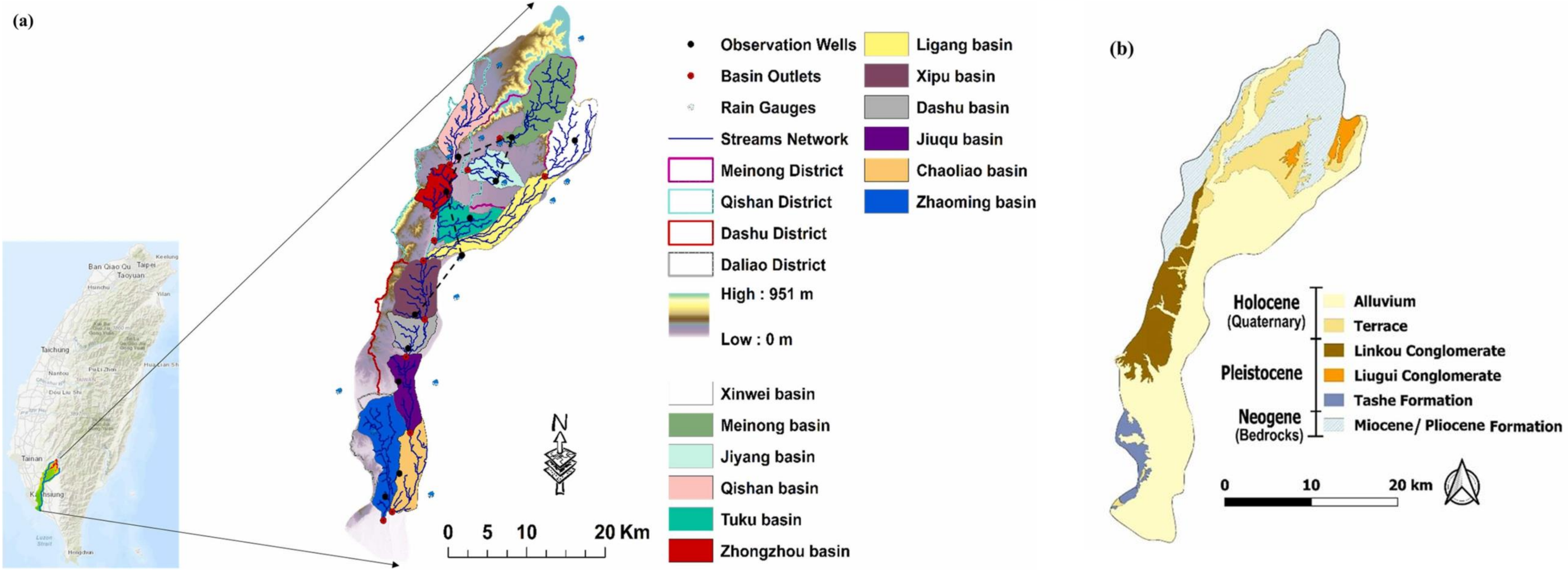
→ severe regional ground subsidence and seawater intrusion, as well as corresponding social and economic problems. (Hsu et al., 2015, Tran and Wang, 2020)

- Effective management of groundwater resources requires considering the interaction of surface water and groundwater at different spatial and temporal scales.

- Using physics-based groundwater models to simulate coupled surface water and groundwater flows in watershed systems can inform decision-making regarding the exploration, operation, and management of groundwater resources. (Khan et al., 2017, Shih et al., 2019)

Objective

- To evaluate the groundwater level response to rainfall and prove the usability of WASH123D in this situation.



- Sub-regional area in Kaohsiung (Meinong, Qishan, Dashu, Daliao)
- 13 observation wells included
- Area: 594km^2, sea level ~ 951m
- Annual rainfall: 2500mm (69% in rainy season)

- Outcrop: sedimentary rock (Holocene & Pleistocene ~ Pliocene & Miocene)

WASH123D

- An integrated multimedia, multiprocess, physics-based watershed model suitable for various spatio-temporal scales.
- One of the most appropriate protocol to simulate surface-water/groundwater interactions based on full St. Venant equations (1D/2D) and 3D Richards' equation.

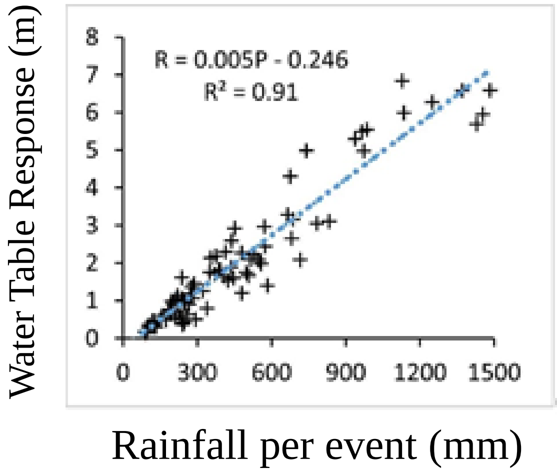
Data collection:

- Long-term (2001-2019) monitoring data: WRA website.
- Necessary input data for WASH123D: Government agencies.
    - Eg. Ministry of Interior and Central Geological Survey (CGS), Ministry of Economic Affairs, Taiwan.

- Regression equation provides parameter (specific yield, and response ratio (best fit slope))

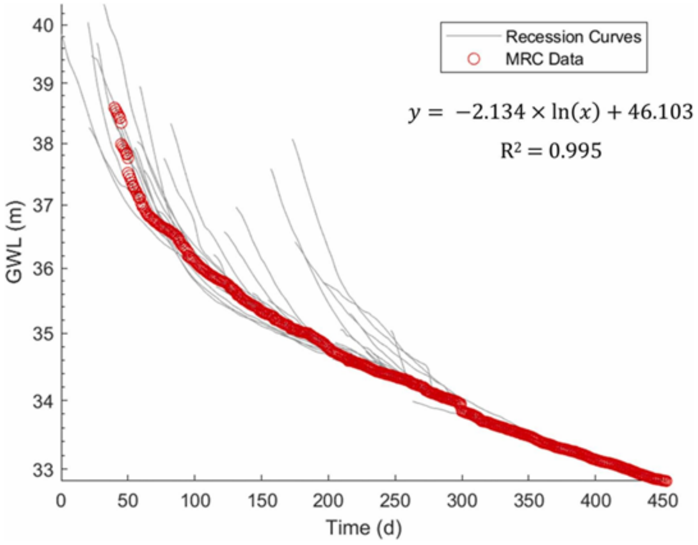
- Specific yield: Inverse of the slope of regression line between rise in groundwater level associated with rainfall.

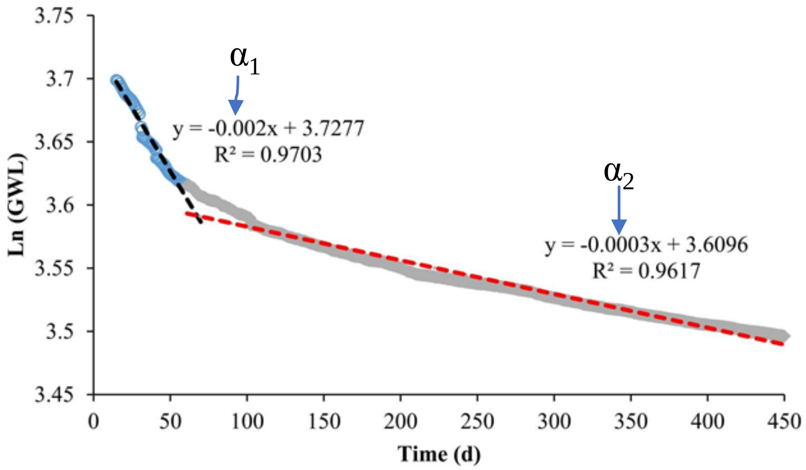
- Correlation coefficient: Evaluate regression strength analysis.



Mass recession curve (MRC)

- Constructed by combining several individual recession curve segments.
- To understand groundwater flow mechanism.
- Used to estimate hydrogeological parameters (k, recession constant α_1, α_2).





Hydraulic conductivity estimation

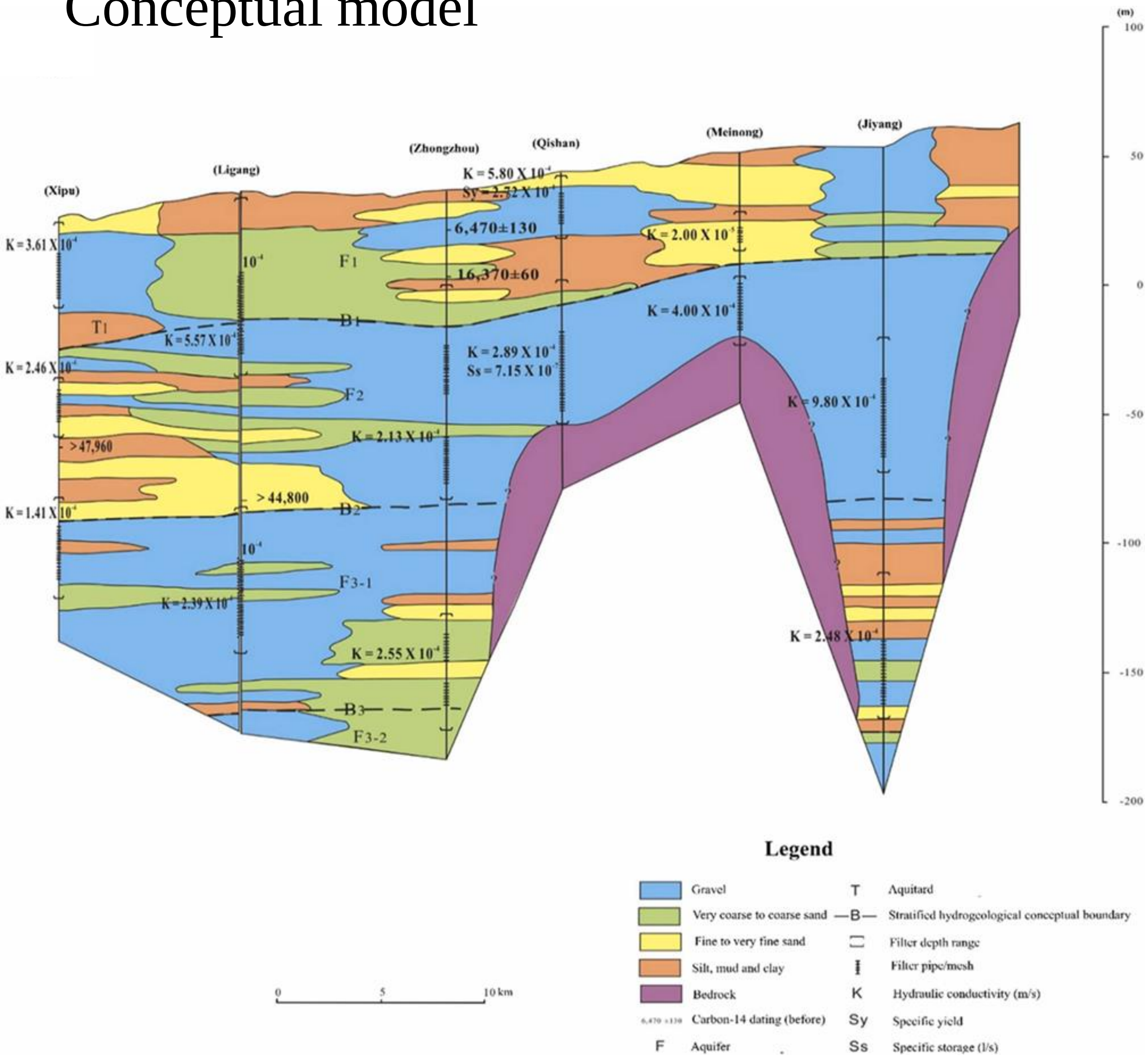
- Rorabaugh equation (1964) : $\frac{\mathrm{T}}{\mathrm{S_y}} = \frac{0.933 * \mathrm{B}^2 * \ln\left(\frac{\mathrm{h_1}}{\mathrm{h_2}}\right)}{\mathrm{t_2} - \mathrm{t_1}}$

$$\rightarrow \quad \frac{\mathrm{T}}{\mathrm{S_y}} = \frac{\mathrm{B}^2 * \alpha}{1.071} \qquad \left(\because \alpha = \frac{\ln\left(\frac{\mathrm{h_1}}{\mathrm{h_2}}\right)}{\mathrm{t_2} - \mathrm{t_1}}\right)$$

- $\mathrm{T} = \mathrm{kD}$
- $\mathrm{k} = \frac{\mathrm{B}^2 * \alpha * S_y}{1.071 * D}$

T: transmissivity
S_y: specific yield
h: height
t: time
B: aquifer half-width (A/2L)
α: recession constant
D: effective aquifer depth

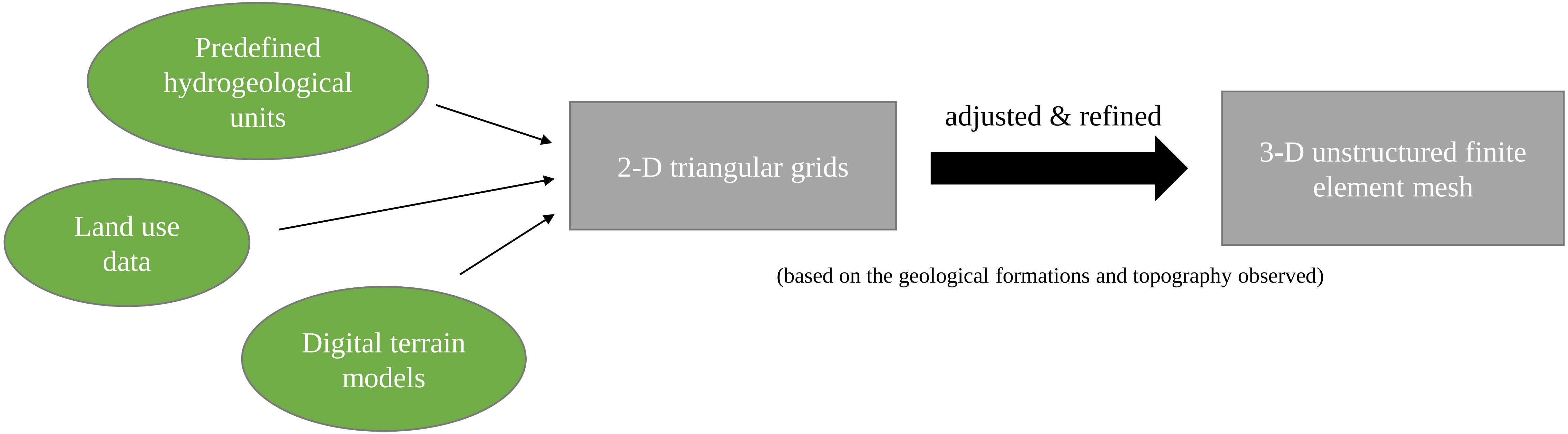
Conceptual model



- From top to bottom: Aquifer 1 (F1), Aquitard 1 (T1), Aquifer 2 (F2), Aquitard 2 (T2), Aquifer 3-1 (F3-1), Aquitard 3 (T3), and Aquifer 3-2 (F3-2)

- Total 14 vertical layers have been used to conceptualize the quasi-3D groundwater flow i.e. the horizontal flow occurs only within the aquifer layers and vertical flow occurs only between the aquifer layers.

- 3D mesh development: GMS-Aquaveo (specialized software for groundwater modeling).



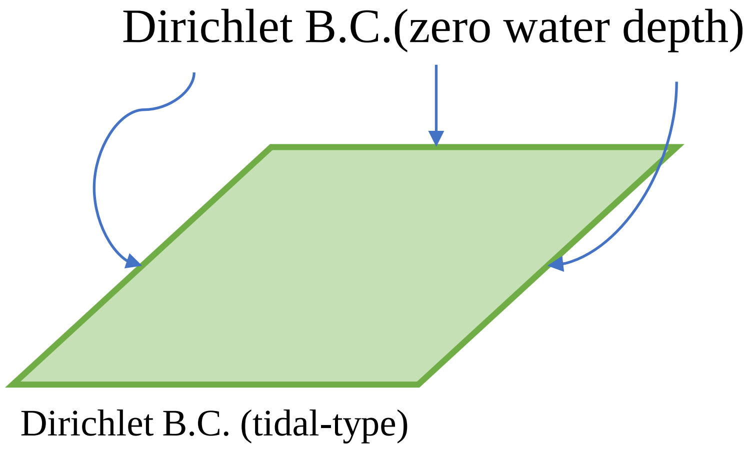
*Refinements:

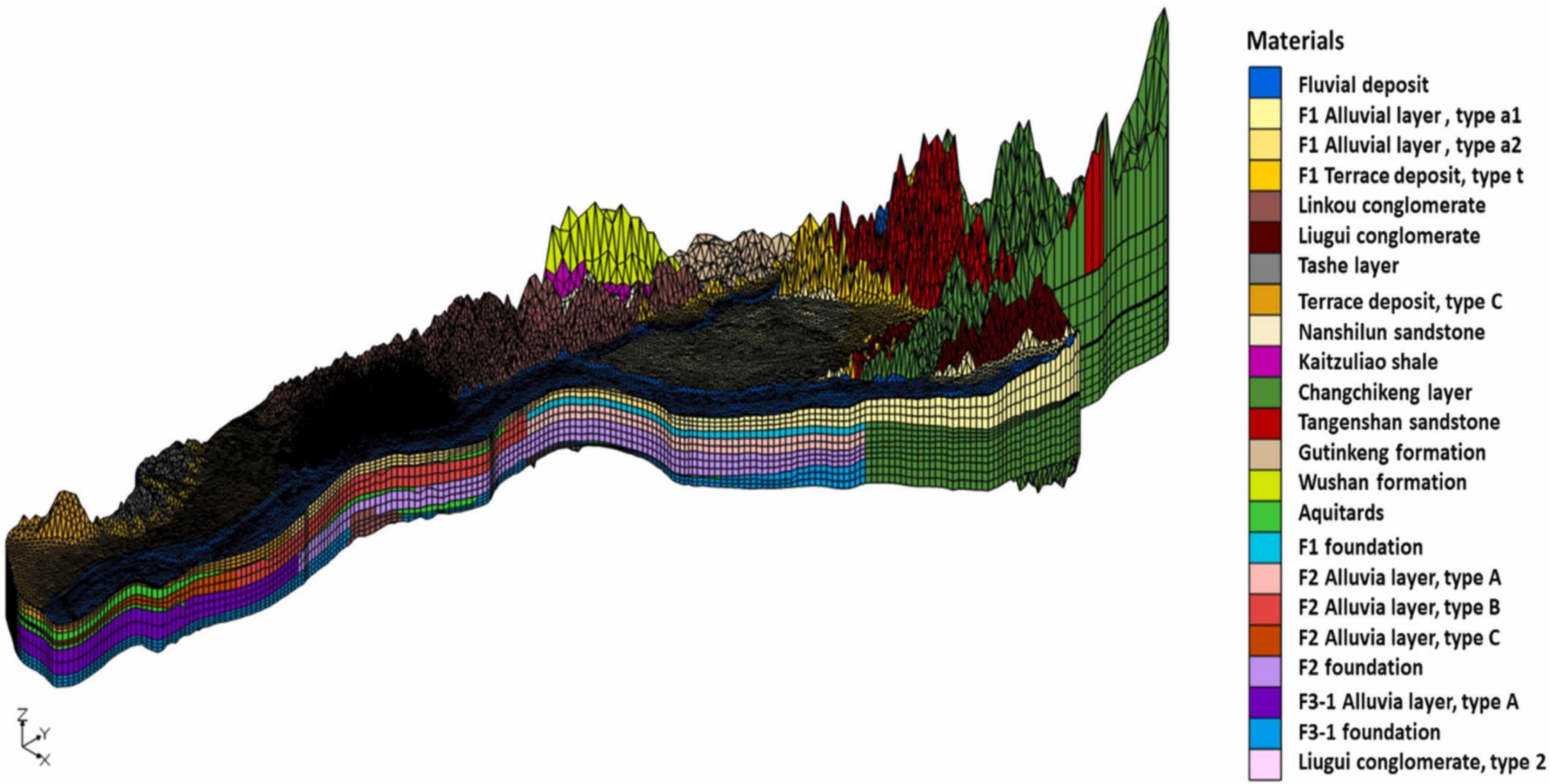
- Correcting the interface layers between aquifers and impermeable layers.
- Adjusting the mesh geometry to accurately represent the syncline morphology and interbedding of different outcropped formations.

Boundary conditions

2D boundary condition
- Zero water depth as a Dirichlet boundary condition (to prevent water passing over the border boundary nodes)
- Zero water stage as a tidal-type Dirichlet boundary condition (along the coastline)
- Input force: rainfall

3D boundary condition
- Initial enforced head attributes: time-dependent total head as a Dirichlet boundary condition
- Variable flux boundary: Rainfall rate (for surface/subsurface interaction)





3-D mesh used for WASH123D simulations
*Z magnification: 15.0

Table 5
Hydrogeological units and associate hydraulic conductivity (k) used in this study.

ID	Hydrogeological unit	Symbol	(F1)	(F2)	(F3)	(F3-2)	Lateral k (m/s)
13	Fluvial deposit	F	✔	–	–	–	5.60×10^{-4}
2	Alluvial formation	a1	✔	–	–	–	9.20×10^{-5}
3	Alluvial formation	a2	✔	–	–	–	2.74×10^{-4}
14	Terrace deposit	t	✔	–	–	–	7.74×10^{-5}
12	Linkou conglomerate	Lk	✔	✔	✔	✔	5.16×10^{-5}
26	Liugui conglomerate	Le	✔	–	–	–	1.02×10^{-5}
20	Tashe layer	Ts	✔	–	–	–	5.57×10^{-6}
4	Terrace deposit	C	✔	✔	✔	✔	1.00×10^{-6}
24	Nanshilun sandstone	Nl	✔	✔	✔	✔	5.07×10^{-7}
23	Kaitzuliao shale	Kz	✔	✔	✔	✔	3.07×10^{-7}
16	Changchikeng layer	Cc	✔	✔	✔	✔	1.75×10^{-6}
25	Tangenshan sandstone	Tn	✔	✔	✔	✔	6.87×10^{-6}
21	Gutinkeng formation	Gt	✔	✔	✔	✔	8.39×10^{-7}
22	Wushan formation	Wu	✔	✔	✔	✔	1.07×10^{-7}
18	F1 foundation	D1	✔	–	–	–	3.50×10^{-6}
6	F2 Alluvial layer	F2/A	–	✔	–	–	2.25×10^{-4}
7	F2 Alluvial layer	F2/B	–	✔	–	–	3.95×10^{-5}
8	F2 Alluvial layer	F2/C	–	✔	–	–	5.00×10^{-6}
9	F2 foundation	D2	–	✔	✔	–	9.00×10^{-7}
10	F3–1 Alluvial layer	F3–1/A	–	–	✔	–	1.11×10^{-6}
11	F3–1 foundation	D3–1	–	–	✔	✔	5.00×10^{-5}
27	Liugui conglomerate	Le-2	–	✔	✔	✔	1.00×10^{-8}
15	Aquitards	T1-T3	✔	✔	✔	✔	1.00×10^{-8}

Statistical criteria

- $MAE = \frac{1}{N}\sum_{i=1}^{N}|GWL_{si} - GWL_{oi}|$
- $RMSE = \sqrt{\frac{\sum_{i=1}^{N}(GWL_{oi} - GWL_{si})}{N}}$
- $PBIAS = \left[\frac{\sum_{i=1}^{N}(GWL_{oi} - GWL_{si})}{\sum_{i=1}^{N}(GWL_{oi})}\right] * 100$
- $NSE = 1 - \frac{\sum_{i=1}^{N}(GWL_{si} - GWL_{oi})^2}{\sum_{i=1}^{N}(GWL_{oi} - \overline{GWL_o})^2}$
- $KGE = 1 - \sqrt{(CC-1)^2 + \left(\frac{GWL_{ss}}{GWL_{os}} - 1\right)^2 + \left(\frac{\overline{GWL_s}}{\overline{GWL_o}} - 1\right)^2}$
- $R^2 = \left[\frac{\sum_{i=1}^{N}[(GWL_{si} - \overline{GWL_s})(GWL_{oi} - \overline{GWL_o})]^2}{\sum_{i=1}^{N}(GWL_{si} - \overline{GWL_s})^2 \sum_{i=1}^{N}(GWL_{oi} - \overline{GWL_o})^2}\right]$

*Abbreviations

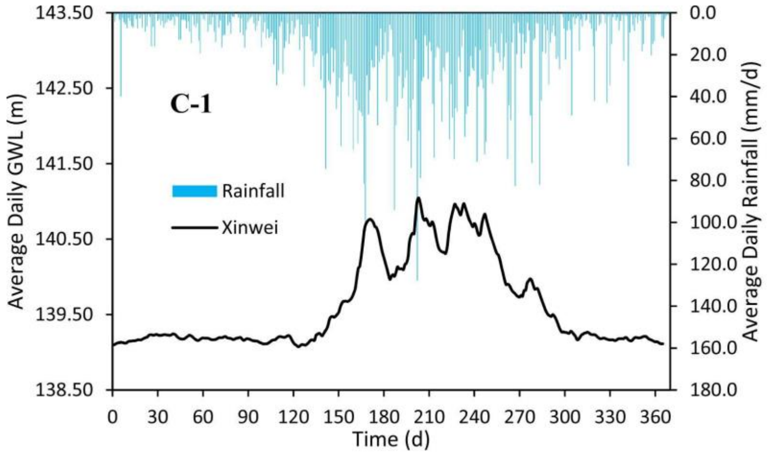
MAE: mean absolute error
RMSE: root mean square error
PBIAS: percent bias
NSE: Nash-Sutcliffe efficiency
KGE: Kling-Gupta efficiency
GWL: ground water level
o: observed
s: simulated

MAE = 0, RMSE = 0, PBIAS = 0, NSE = 1, KGE = 1, R^2 = 1
→ The highest agreement between simulated and observation values is reached.

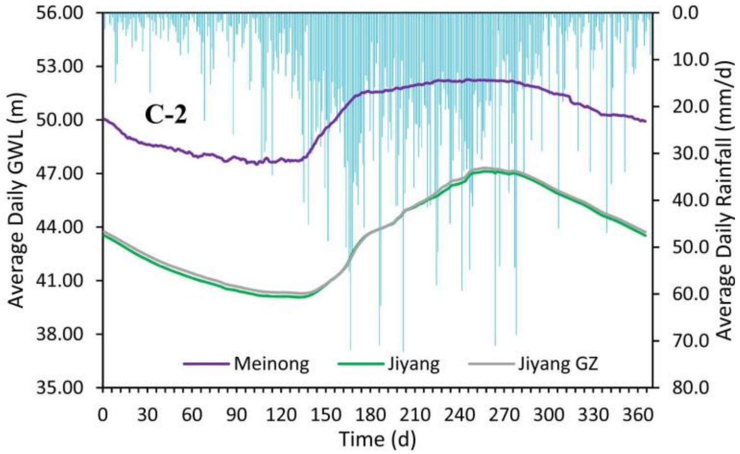
	Formular	Range
Mean absolute error	$\frac{1}{N}\sum_{i=1}^{N}\lvert GWL_{si}-GWL_{oi}\rvert$	0~∞
Root mean square error	$\sqrt{\frac{\sum_{i=1}^{N}(GWL_{oi}-GWL_{si})}{N}}$	0~∞
Percent bias	$\left[\frac{\sum_{i=1}^{N}(GWL_{oi}-GWL_{si})}{\sum_{i=1}^{N}(GWL_{oi})}\right]$	-100%~100%
Nash-Sutcliffe efficiency	$1-\frac{\sum_{i=1}^{N}(GWL_{si}-GWL_{oi})^2}{\sum_{i=1}^{N}(GWL_{oi}-\overline{GWL_o})^2}$	−∞~1
Kling-Gupta efficiency	$1-\sqrt{(CC-1)^2+\left(\frac{GWL_{ss}}{GWL_{os}}-1\right)^2+\left(\frac{\overline{GWL_s}}{\overline{GWL_o}}-1\right)^2}$	−∞~1
R^2	$\left[\frac{\sum_{i=1}^{N}[(GWL_{si}-\overline{GWL_s})(GWL_{oi}-\overline{GWL_o})]^2}{\sum_{i=1}^{N}(GWL_{si}-\overline{GWL_s})^2\sum_{i=1}^{N}(GWL_{oi}-\overline{GWL_o})^2}\right]$	$0\leq R^2\leq 1$

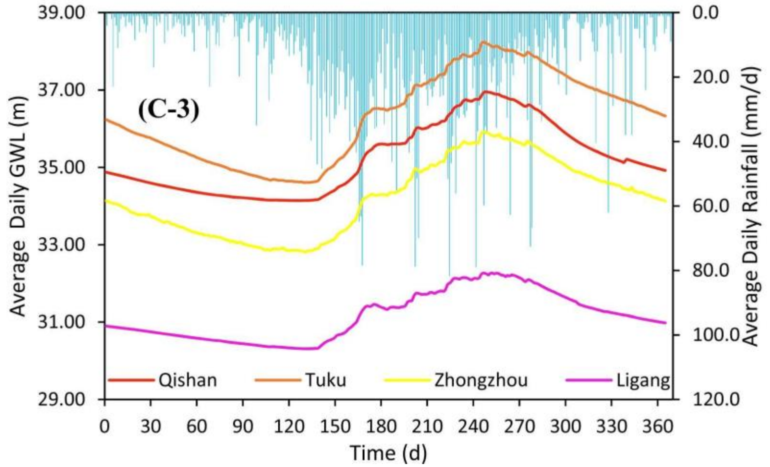
Rainfall in four clusters

flashy response

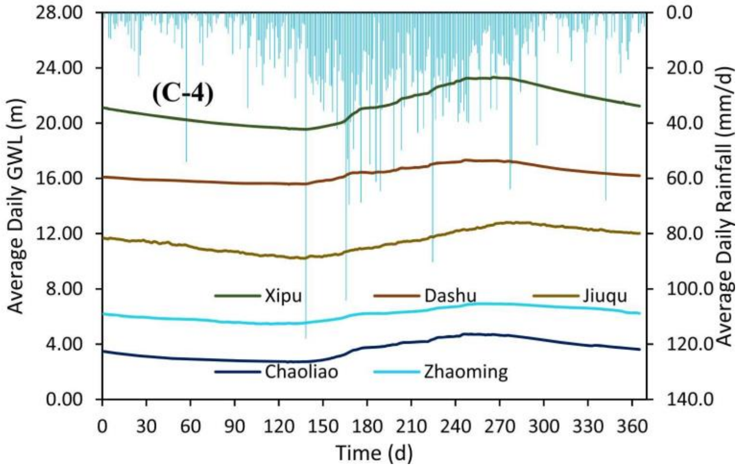


smooth response

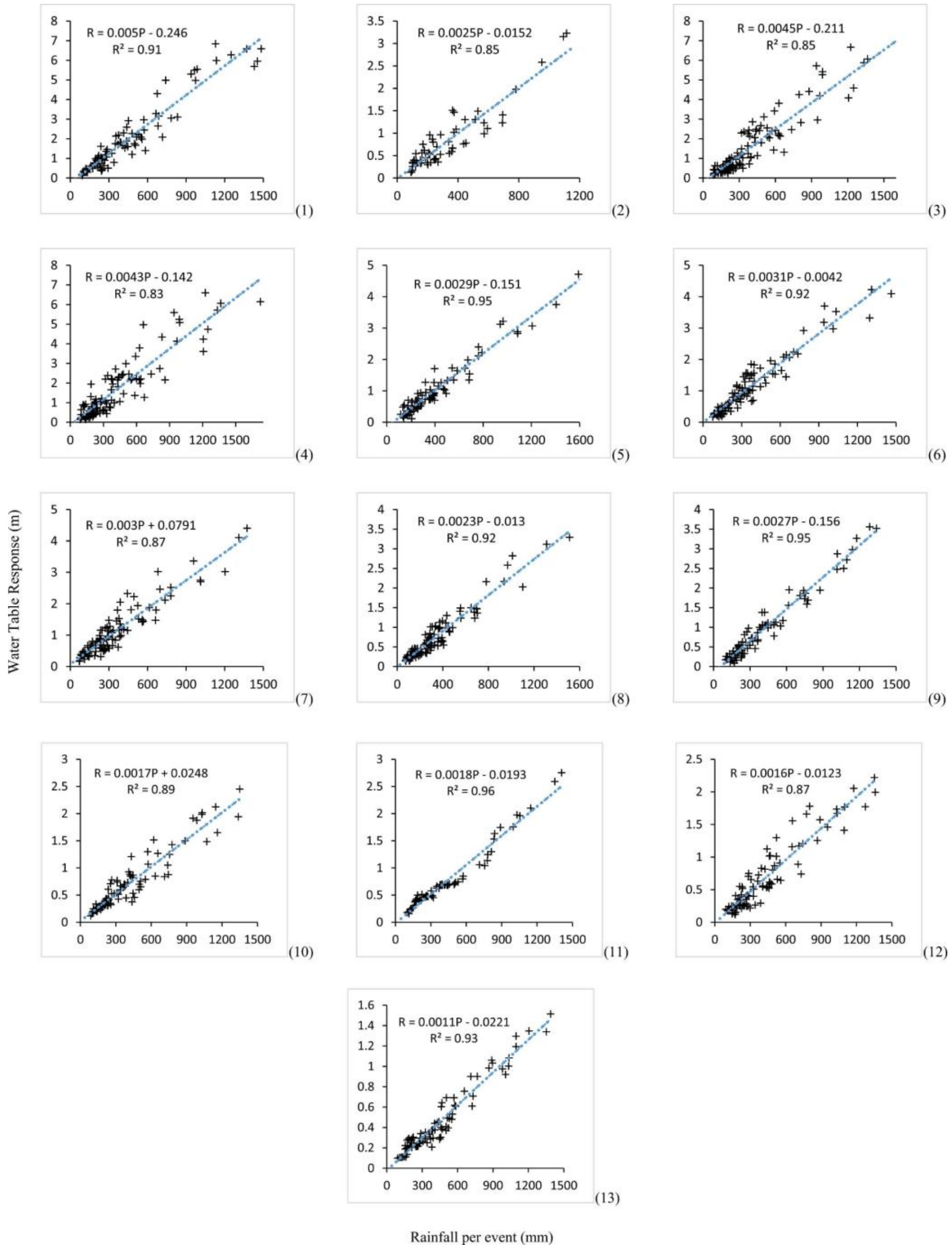




smooth response



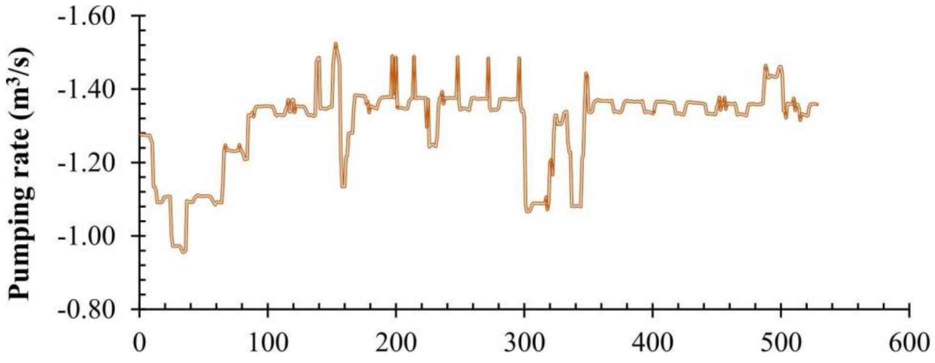
no apparent response

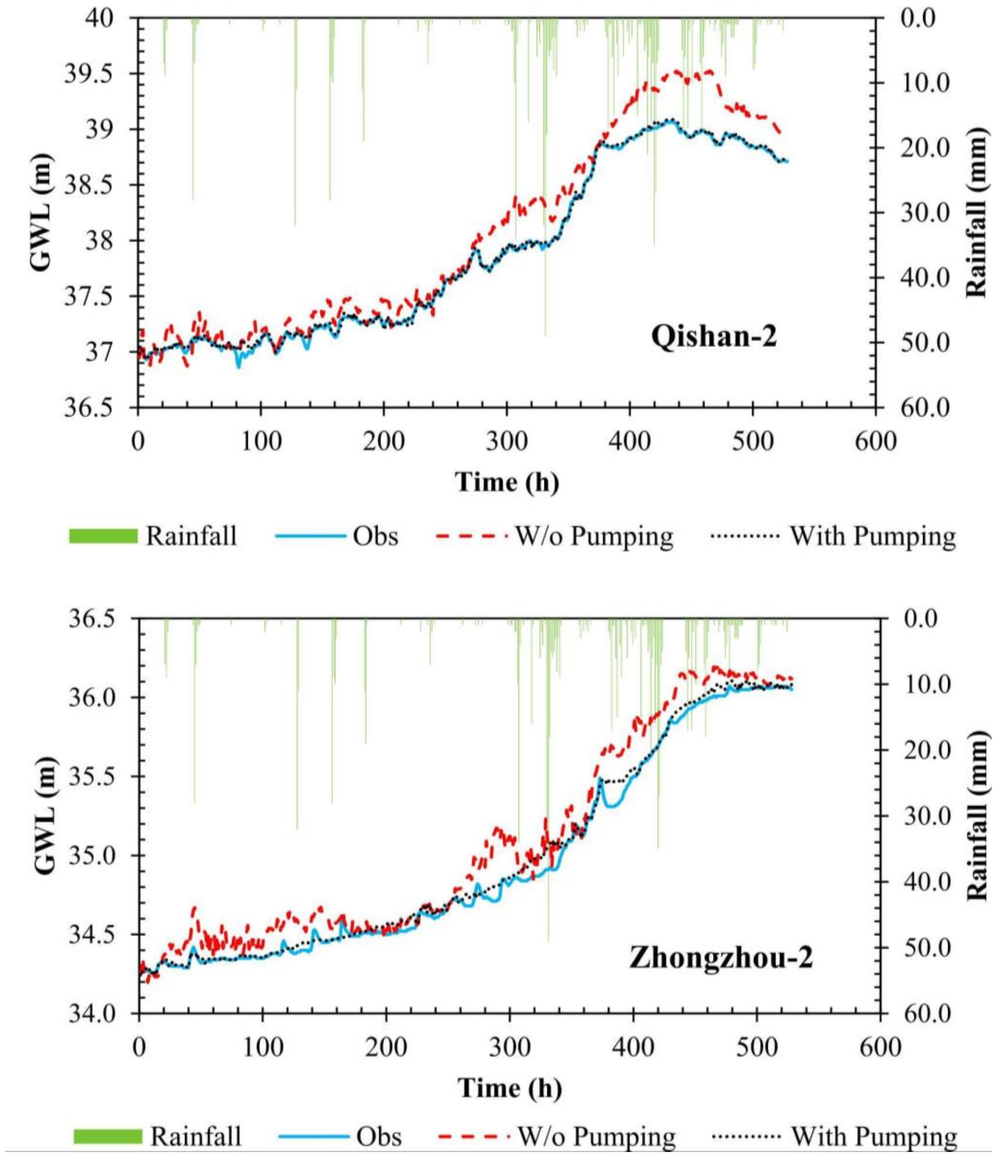


Observation well	R^2
Xinwei	0.91
Meinong	0.85
Jiyang	0.85
Jiyang GZ	0.83
Qishan	0.95
Tuku	0.92
Zhongzhou	0.87
Ligang	0.92
Xipu	0.95
Dashu	0.89
Jiuqu	0.96
Chaoliao	0.87
Zhaoming	0.93

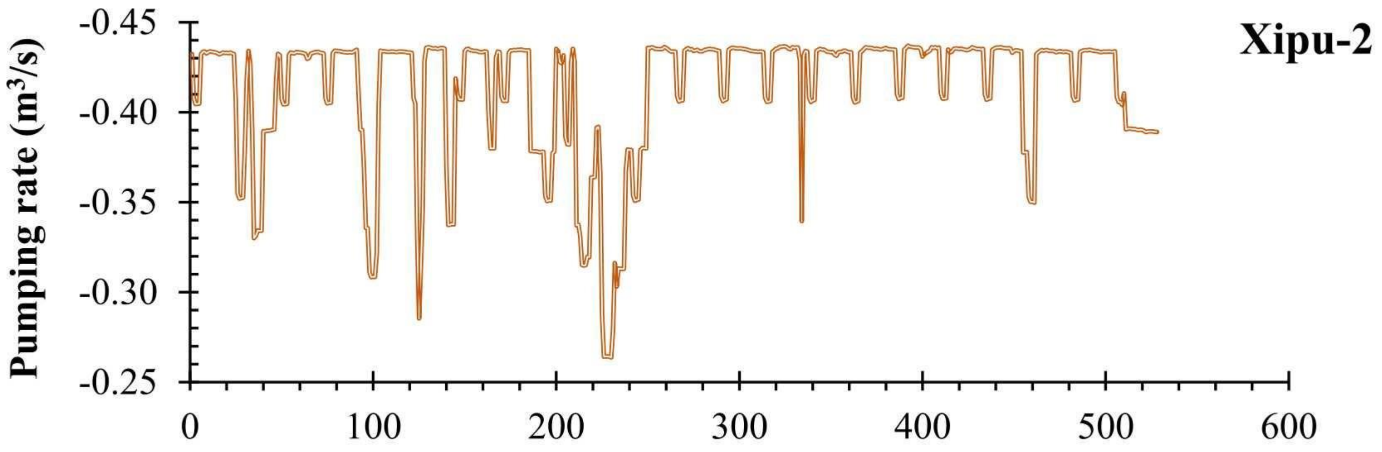
There exists a strong linear relationship between rainfall and groundwater level fluctuations at all sites.

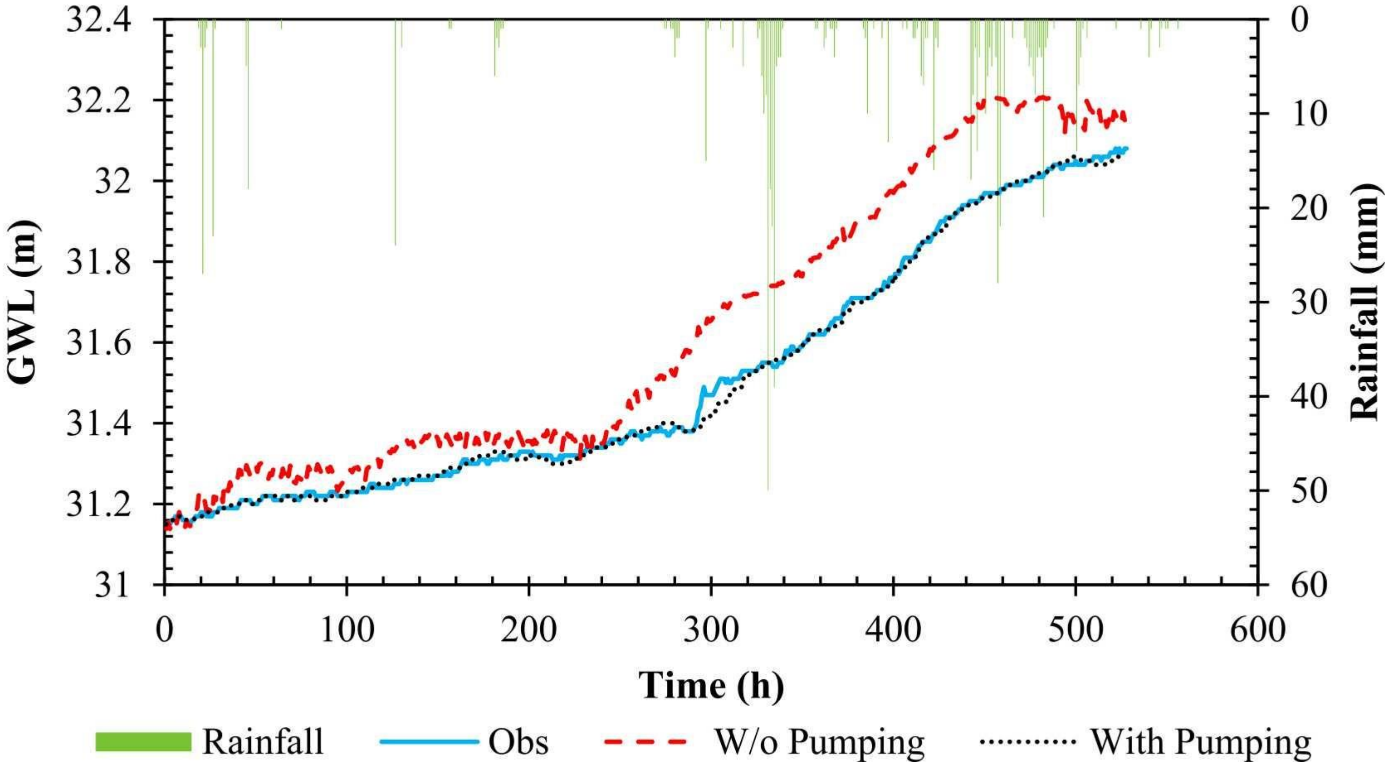
Simulation results





- Average pumping rate = 1.303m^3/s,
- Average ground water level dropped 0.10~0.50m





- Average pumping rate = $0.412 m^3/s$
- Average ground water level dropped 0.10~0.25m

Table 6
Statistical model performance evaluation at three selected sites with and without pumping data.

Obs. Wells	MAE (m)	RMSE (m)	PBIAS (%)	NSE	KGE	R^2
	Without Pumping Data					
Qishan-2	0.20	0.25	-0.50%	0.89	0.84	0.98
Zhongzhou-2	0.13	0.16	-0.40%	0.93	0.95	0.97
Xipu-2	0.12	0.14	-0.40%	0.79	0.82	0.97
	With Pumping Data					
Qishan-2	0.018	0.027	-0.01%	0.99	0.99	0.99
Zhongzhou-2	0.036	0.052	-0.10%	0.99	0.98	0.99
Xipu-2	0.010	0.014	-0.01%	0.99	0.99	0.99

- The simulation results with and without pumping data are relatively comparable with observations
- There is a reasonable hydrological response of groundwater levels to rainfall and pumping data.

- A good linear correlation relationship was found between groundwater level responses to associated rainfall.
- Through WASH123D, the simulated results seemed similar to observation data.
- WASH123D is an appropriate protocol to investigate the surface-subsurface interaction in the selected study region and should be a credible approach for future research work and management of groundwater resources.

Thank you for your attention.