Review Paper

Water table response to rainfall and groundwater simulation using physics-based numerical model: WASH123D

Hussain, F., Wu, R. S., & Shih, D. S. (2022). *Journal of Hydrology: Regional Studies, 39, 100988.*

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Groundwater challenges in southern Taiwan:

- 21% annual decrease in GWL in some southern regions
- Over-extraction exceeds natural recharge by 230 million m^3/year
- Land subsidence affect 1,100 km^2 of coastal areas
- Less available surface water supply during dry season

Not all water level changes cause rainfall, and not all rainfall becomes recharge.

How can **quantify groundwater recharge** from **rainfall** using limited **observational data**?

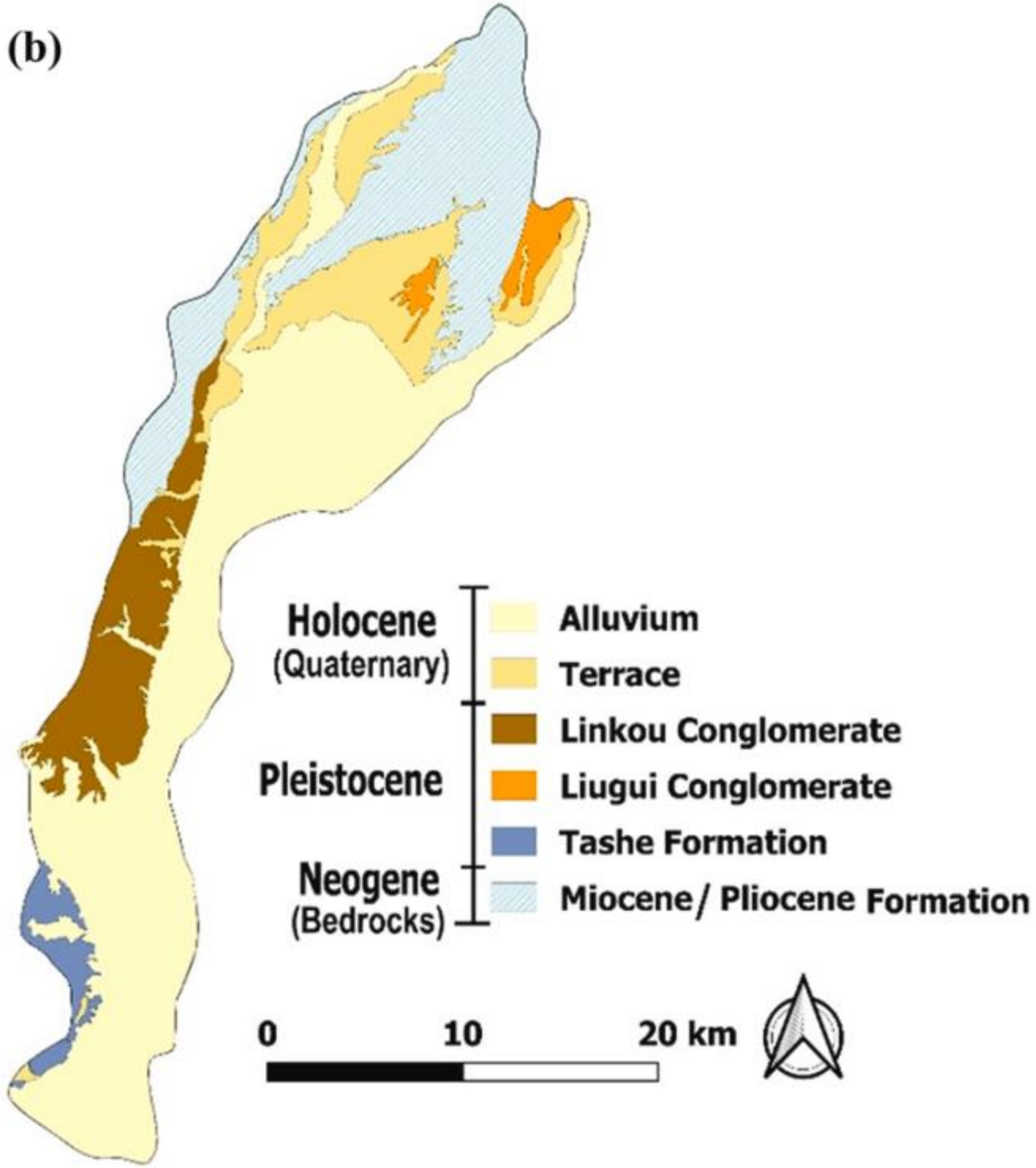


Fig.1: geological information in study area

Objective

Using WASH123D to assess groundwater levels response to rainfall under real-world pumping conditions – determine recharge potential for shallow aquifer and then, provide a reference to sustainable water management.

Study area

Sub-regional area of Kaohsiung city, southern Taiwan

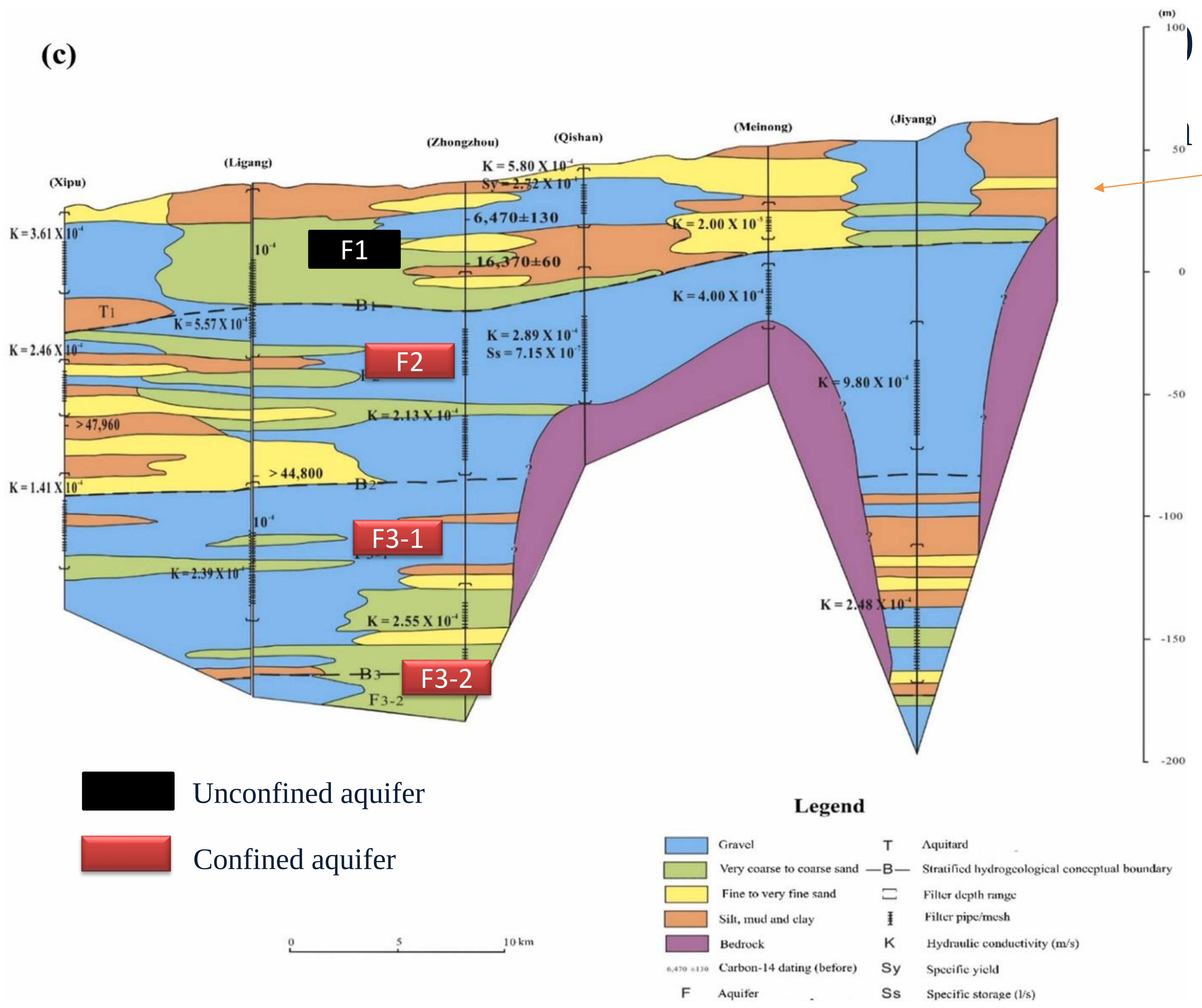


Fig.3: Geological cross section along orange line

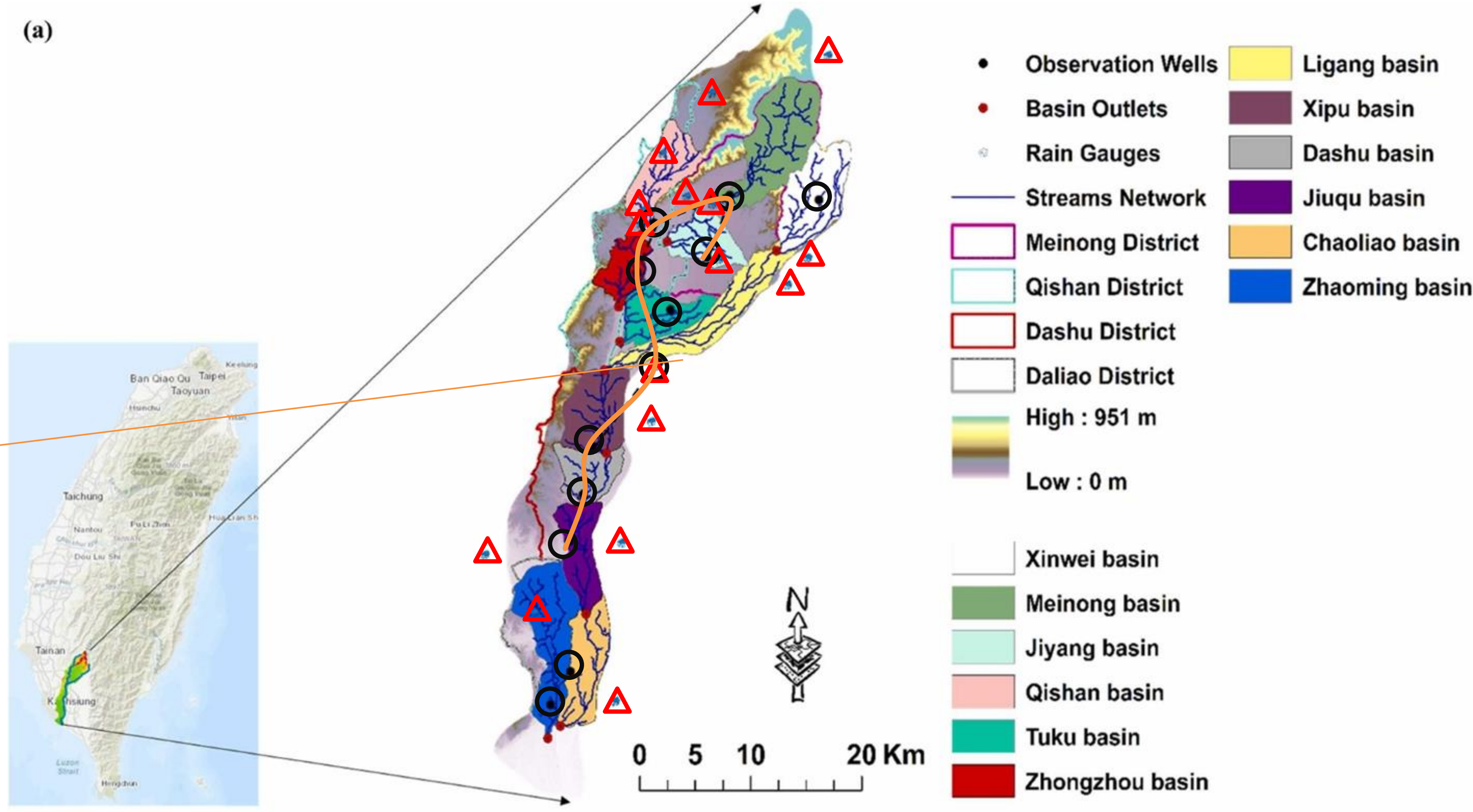


Fig.2: Study area map with location of observation well, rain gauges and demarcated sub-basin

- Formation: sedimentary rocks
- Ages: from Holocene and Pleistocene (Quaternary) to the Pliocene and Miocene (Neogene)
- Materials range from gravel to fine sand and clay
- All of the aquifers: connect

Workflow

CALCULATE PRIOR SPECIFIC YIELD S_y

↓

CALCULATE HYDRAULIC CONDUCTIVITY **k**

↓

WASH123D simulation

Utilize recession analysis

1. ΔGWL Response = Peak of GWL – GWL start to drop
2. Construct linear regression by using best-fitting line between **associated cluster rainfall** and **ΔGWL Response**.
3. Determine threshold, find effective rainfall
4. Prior **Sy** = **inverse of the slope** (compared with Morris et al.)

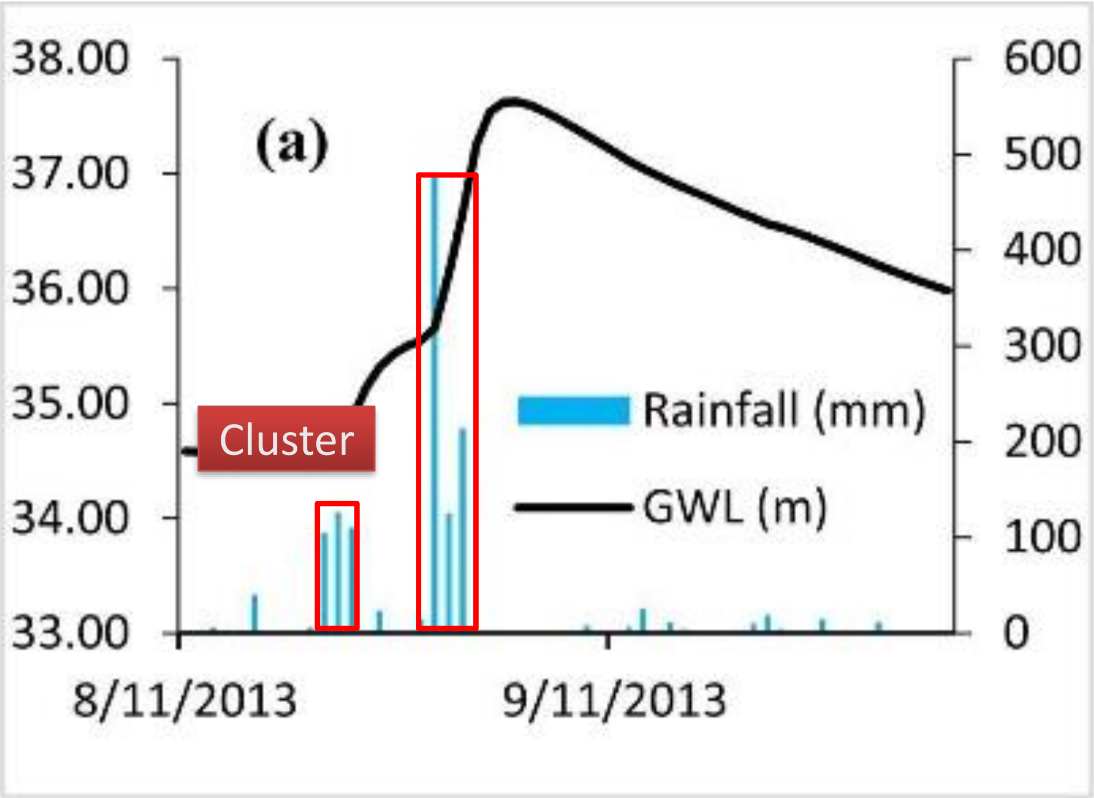
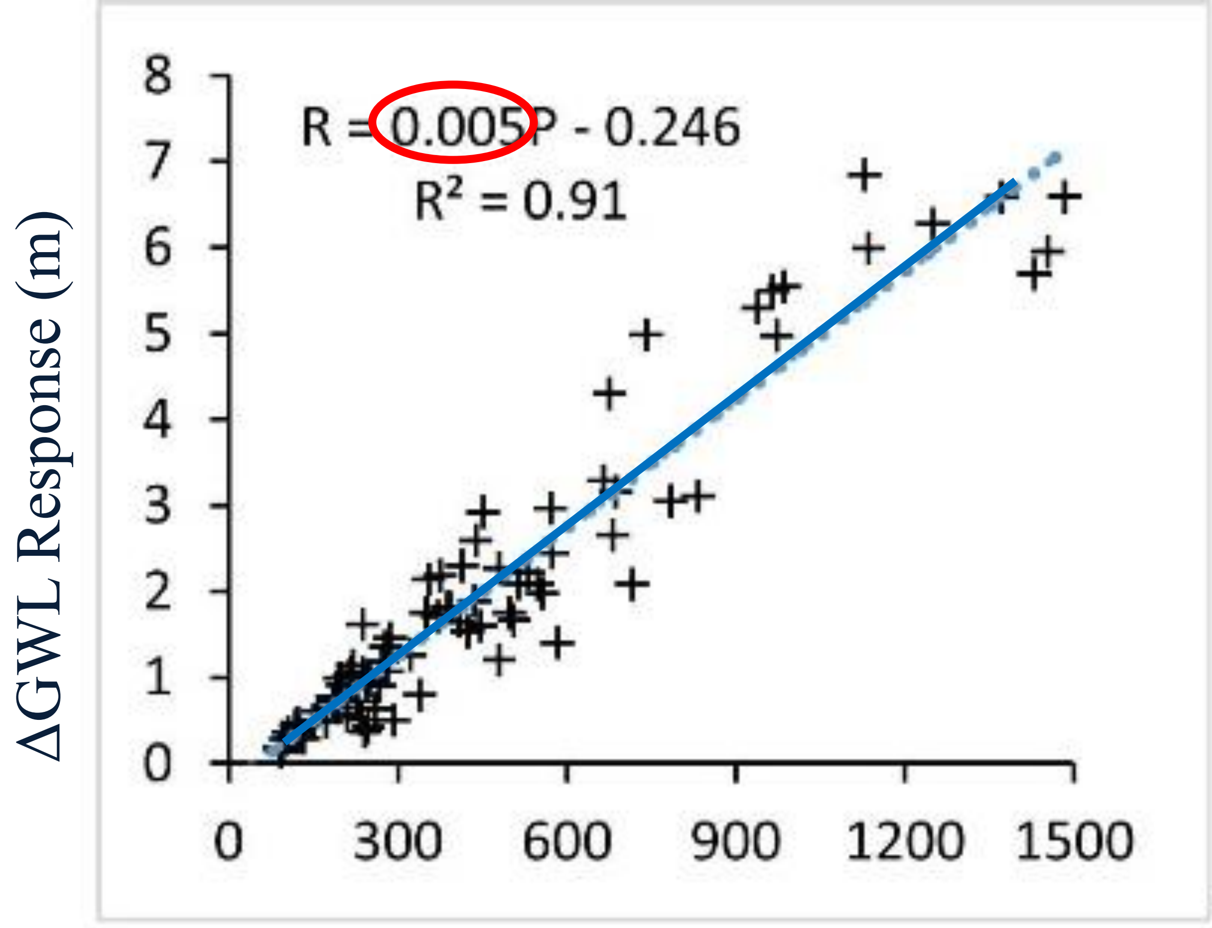


Fig.4: An example groundwater hydrograph of Qishan site



Rainfall per event (mm)

(1)

Workflow

CALCULATE PRIOR SPECIFIC YIELD S_y

↓

CALCULATE HYDRAULIC CONDUCTIVITY **k**

↓

WASH123D simulation

For unconfined aquifer

$$\frac{T}{S_y} = 0.933 \times B^2 \times \frac{\ln(\frac{h_1}{h_2})}{t_2 - t_1}$$

$T = k \times D$

$\frac{\ln(\frac{h_1}{h_2})}{t_2 - t_1} = \alpha$

⇩

$$k = 0.933 \times \frac{B^2 \times \alpha \times S_y}{D} \quad \text{Eq. 2}$$

Where:

k: hydraulic conductivity (m/s)

D: effective aquifer depth (m)

T: transmissivity

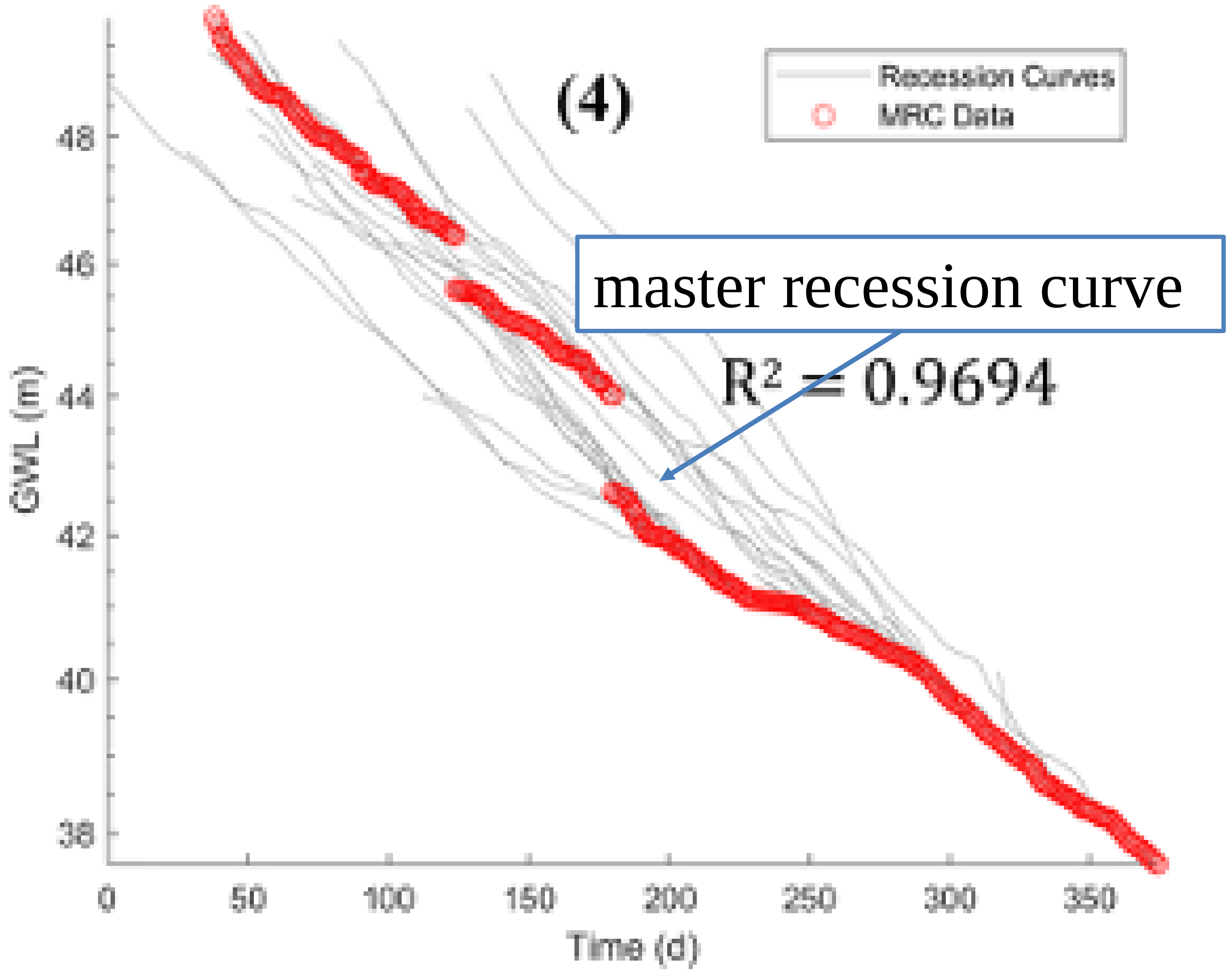
S_y: specific yield

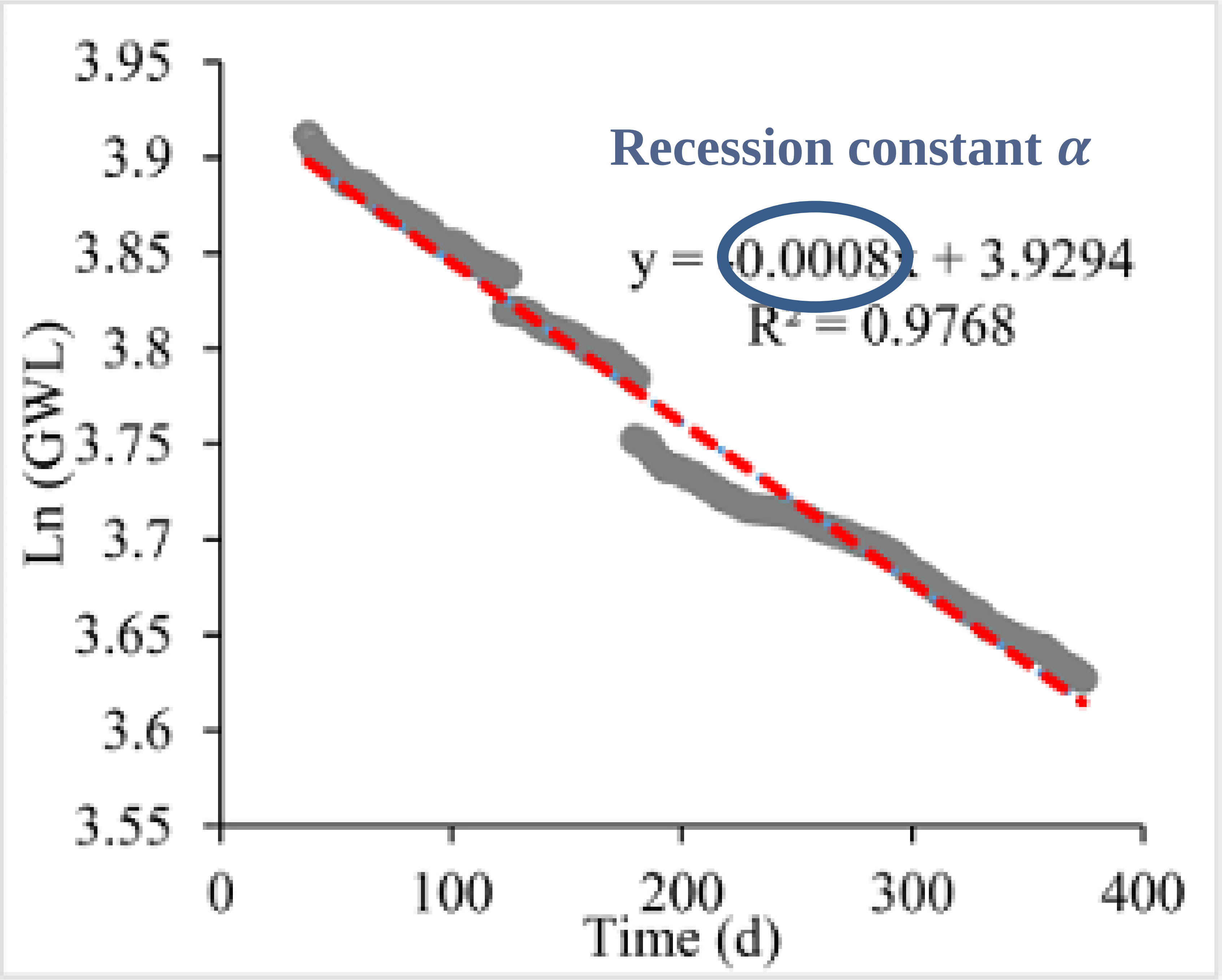
B: aquifer half width (km)

α: recession constant

Construct a Master Recession Curve (MRC) using the matching strip method to calculate **recession constant *α***

$$k = 0.933 \times \frac{B^2 \times \alpha \times S_y}{D}$$ Eq. 2





Workflow

CALCULATE PRIOR SPECIFIC YIELD $\boldsymbol{S_y}$

↓

CALCULATE HYDRAULIC CONDUCTIVITY **k**

↓

WASH123D simulation

Governing equation for 3D:

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla . \left[K \left(\nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho^*}{\rho_0} q \qquad \text{Eq. 3}$$

Water storage gradient = Flux + sources/sinks

Where:

ρ: density of water (~1g/ml)

ρ^*: density of source water

$\boldsymbol{h}$: pressure head [L]

$\boldsymbol{K}$: hydraulic conductivity [L/t]

$\boldsymbol{z}$: elevation head [L]

q: the source/sink

$\boldsymbol{F}$: water capacity [1/L]

Workflow

CALCULATE PRIOR SPECIFIC YIELD $\boldsymbol{S_y}$

↓

CALCULATE HYDRAULIC CONDUCTIVITY **k**

↓

WASH123D simulation

Governing equation for 3D:

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$$\rho = \rho_0 = \rho^*$$

Diagonal K: $K_{xy} = K_{xz} = K_{yz} = K_{yz} = K_{zx} = K_{zy} = 0$

Horizontal axe: $K_{xx} = K_{yy}$

Vertical axe: $K_{zz} = 0.1 K_{xx}$

$$F \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K_{xx} \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y}\left[K_{xx} \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z}\left[0.1 K_{xx} \frac{\partial h}{\partial z} \right] + q$$

Groundwater numerical modeling - *Conceptual model*

- Unconfined shallow aquifer (F1) to 40m depth
- Three confined aquifers (F2, F3-1, F3-2) to 200m depth
- 14 vertical layers to capture geological complexity

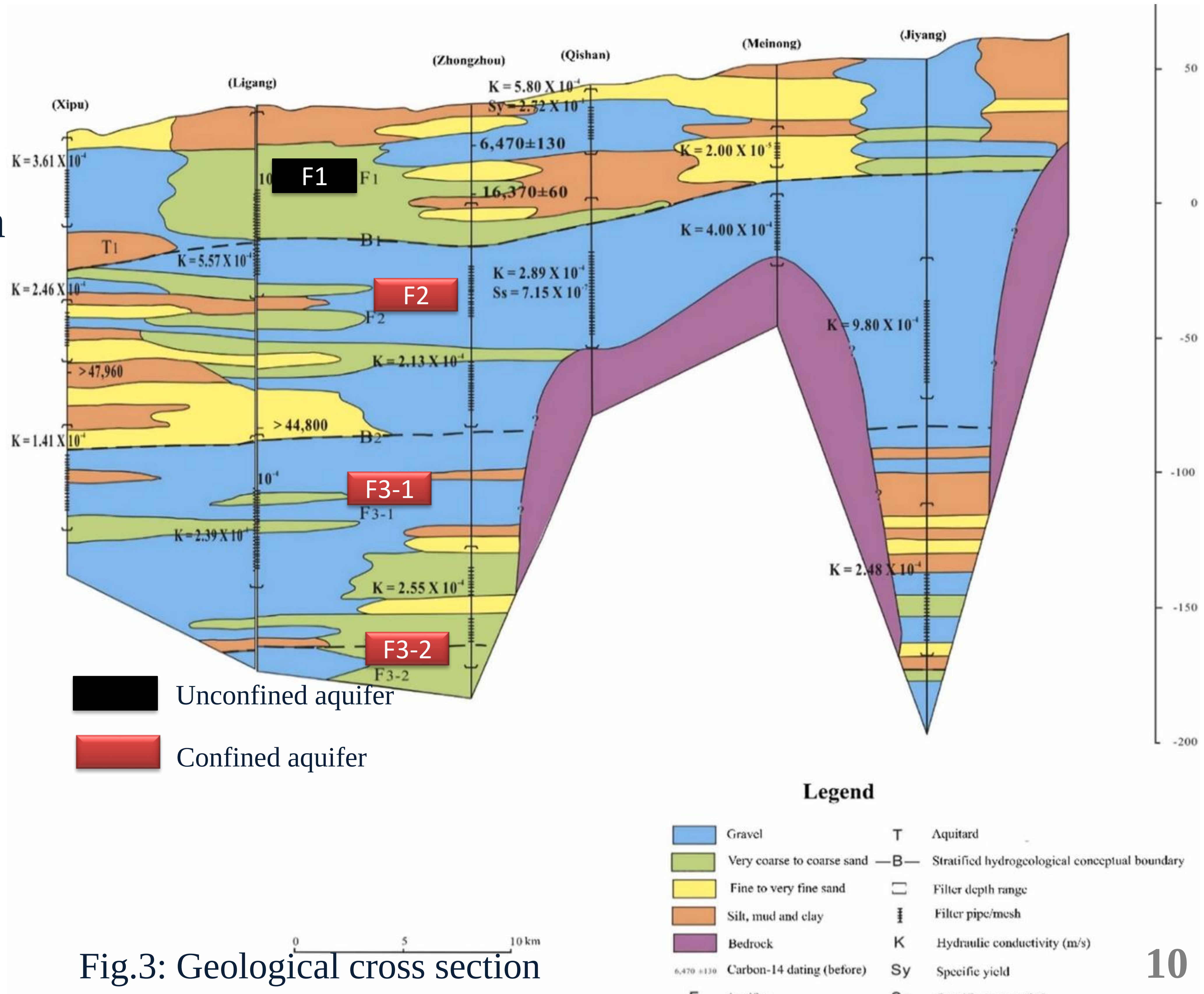
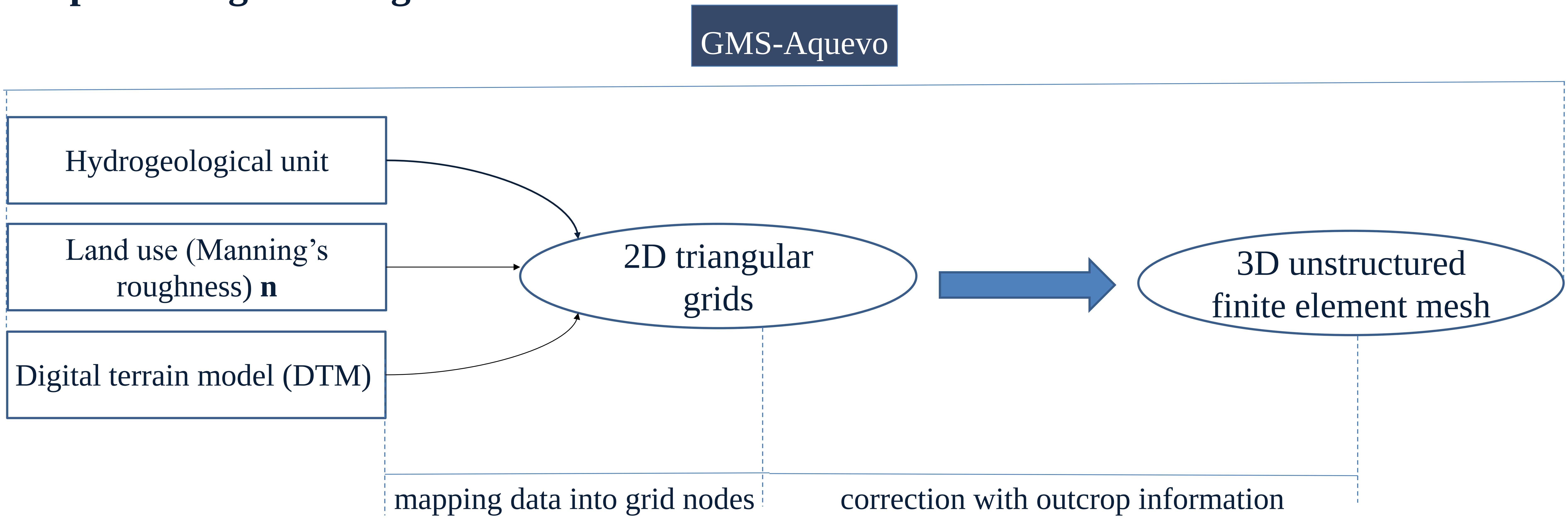


Fig.3: Geological cross section

Pre-processing – Mesh generation



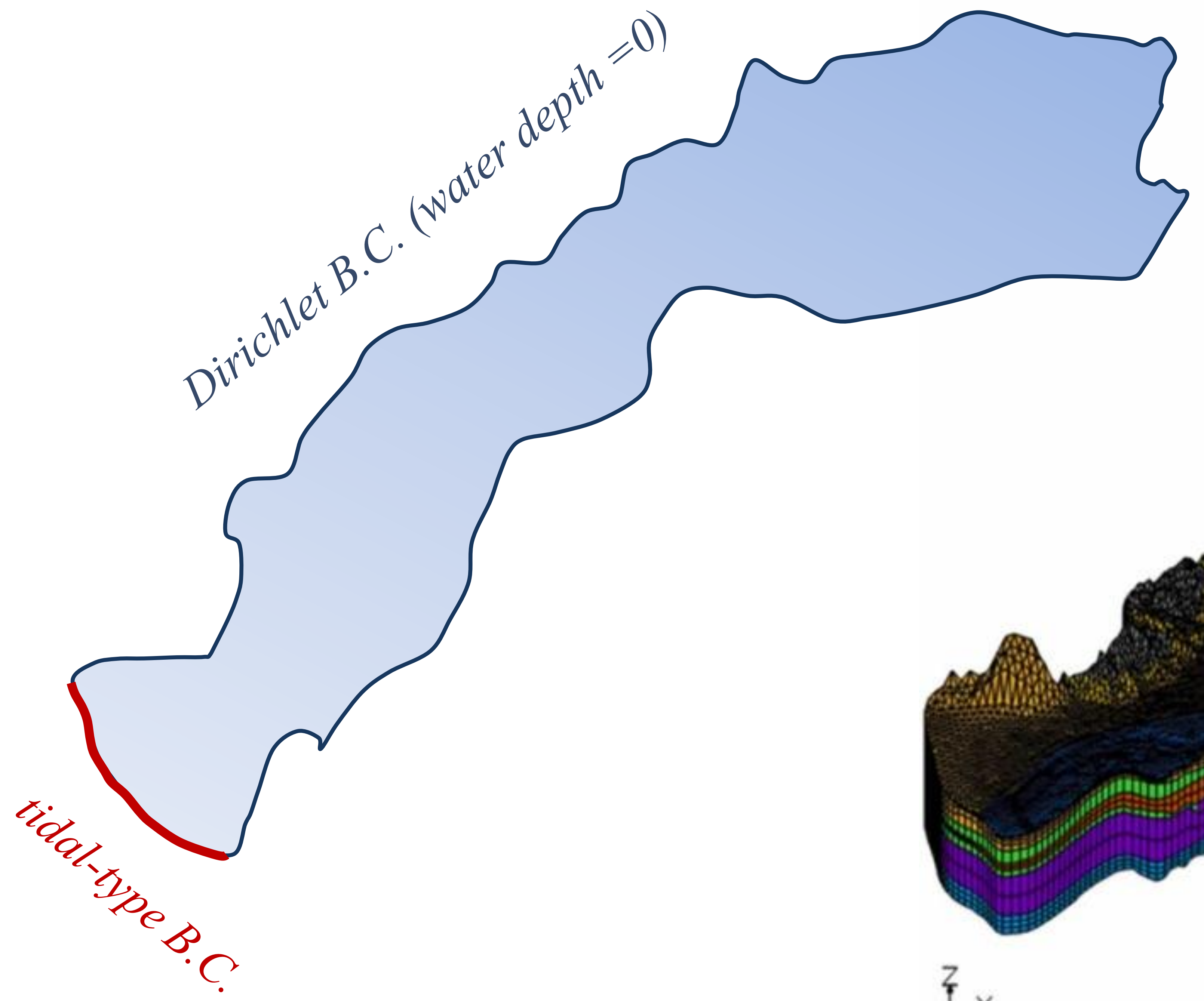
For 2-D overland mesh:

- 47,088 nodes and 46,580 elements

For 3D:

- 353,160 nodes and 652,129 unstructured elements
- Grid sizes range from 30 – 200m

Initial conditions – Boundary condition for WASH123D



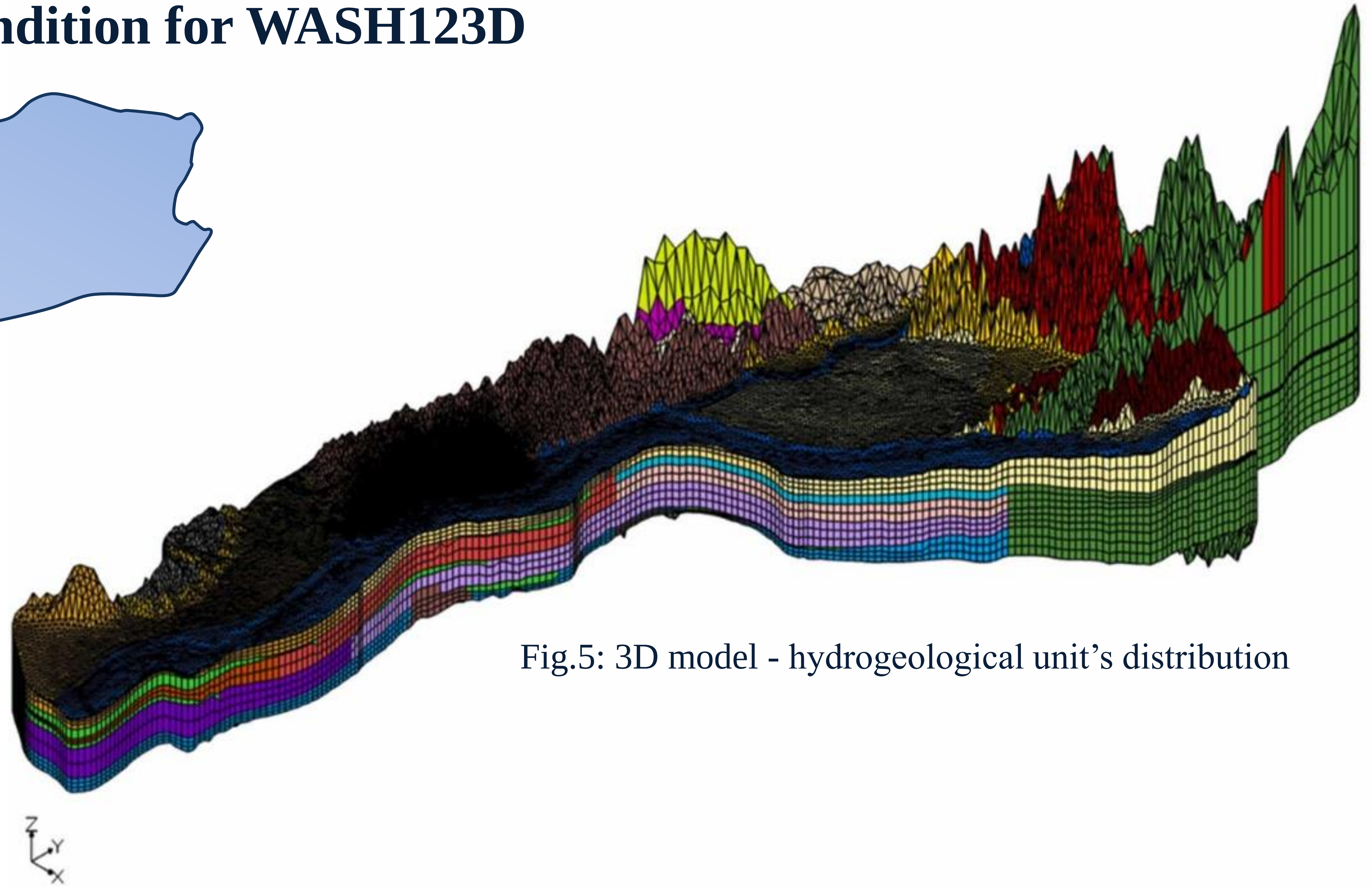
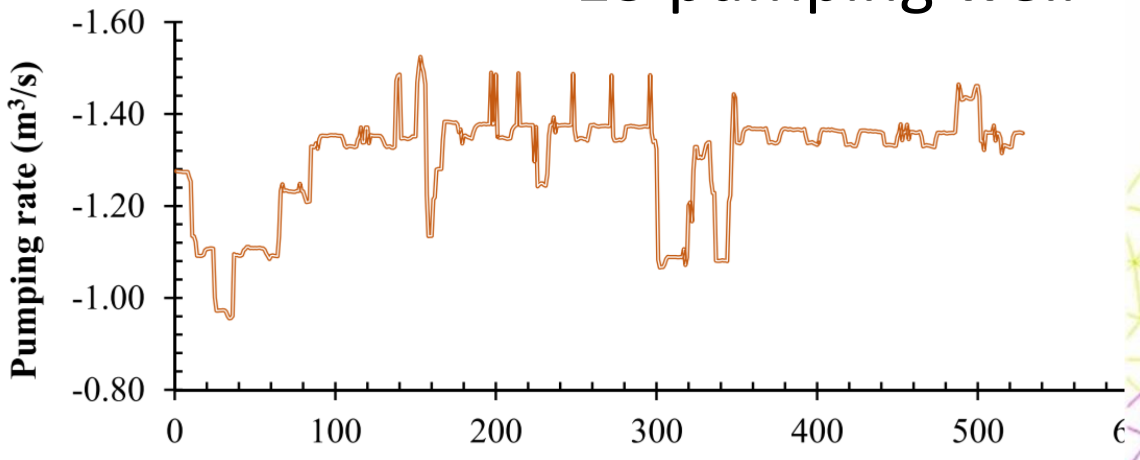


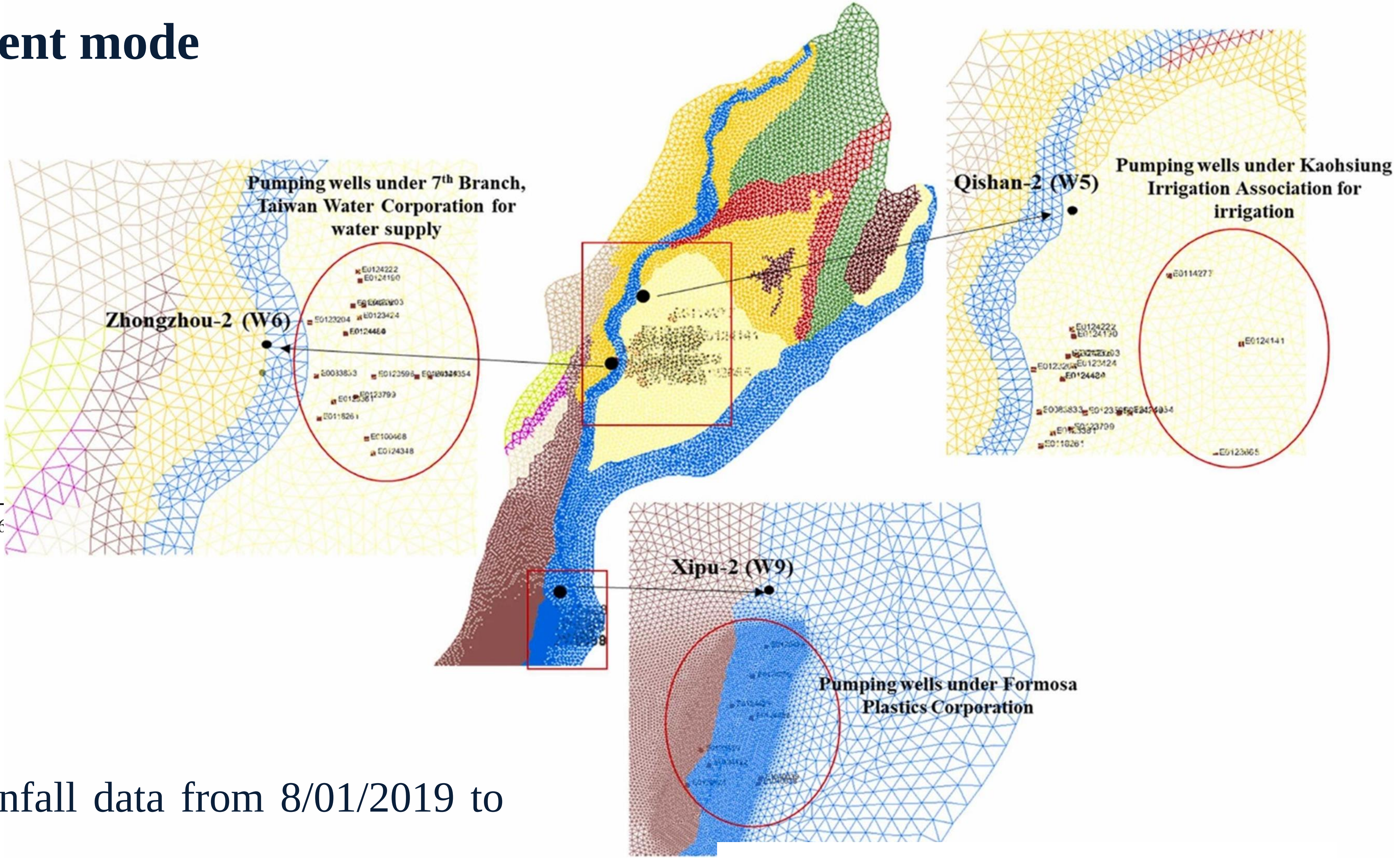
Fig.5: 3D model - hydrogeological unit's distribution

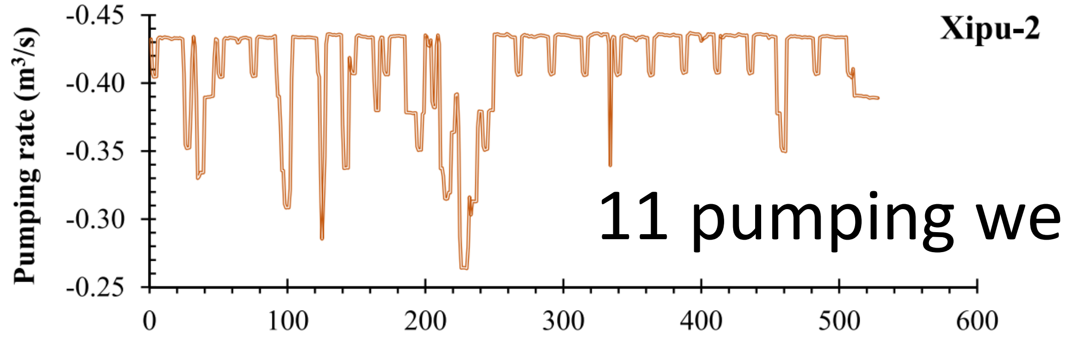
The interface between the 2D and 3D models is handled using variable flux B.C.

WASH123D simulate transient mode

13 pumping well







- First, simulations with only rainfall data from 8/01/2019 to 8/22/2019
- Then, the same time simulation by incorporating pumping data together with rainfall

Statistical evaluation of transient groundwater modeling

How one can assess the goodness of fit of model and how to improve the model fit?

6 statistical are used as error measures for determining adequate sets of model parameters.

Statistical	Ranges	Highest value*
Mean absolute error (MAE)	$0 \sim \infty$	0
Root mean square error (RMSE)	$0 \sim \infty$	0
Percent bias (PBIAS)	-100% ~ 100%	0
Nash–Sutcliffe efficiency (NSE)	$-\infty \sim 0$	1
Kling-Gupta efficiency (KGE)	$-\infty \sim 0$	1
coefficient of determination (R^2)	$0 \leq R^2 \leq 1$	1

Table 1:statistical types are used in this study

* Model predictions perfectly match actual measurements at their highest values

GWL response to rainfall

- ✓ Good linear correlation relationship was found between groundwater level responses to associated rainfall

(R^2 = 0.83-0.96)

Rainfall may be primary factor affecting groundwater recharge in the study area

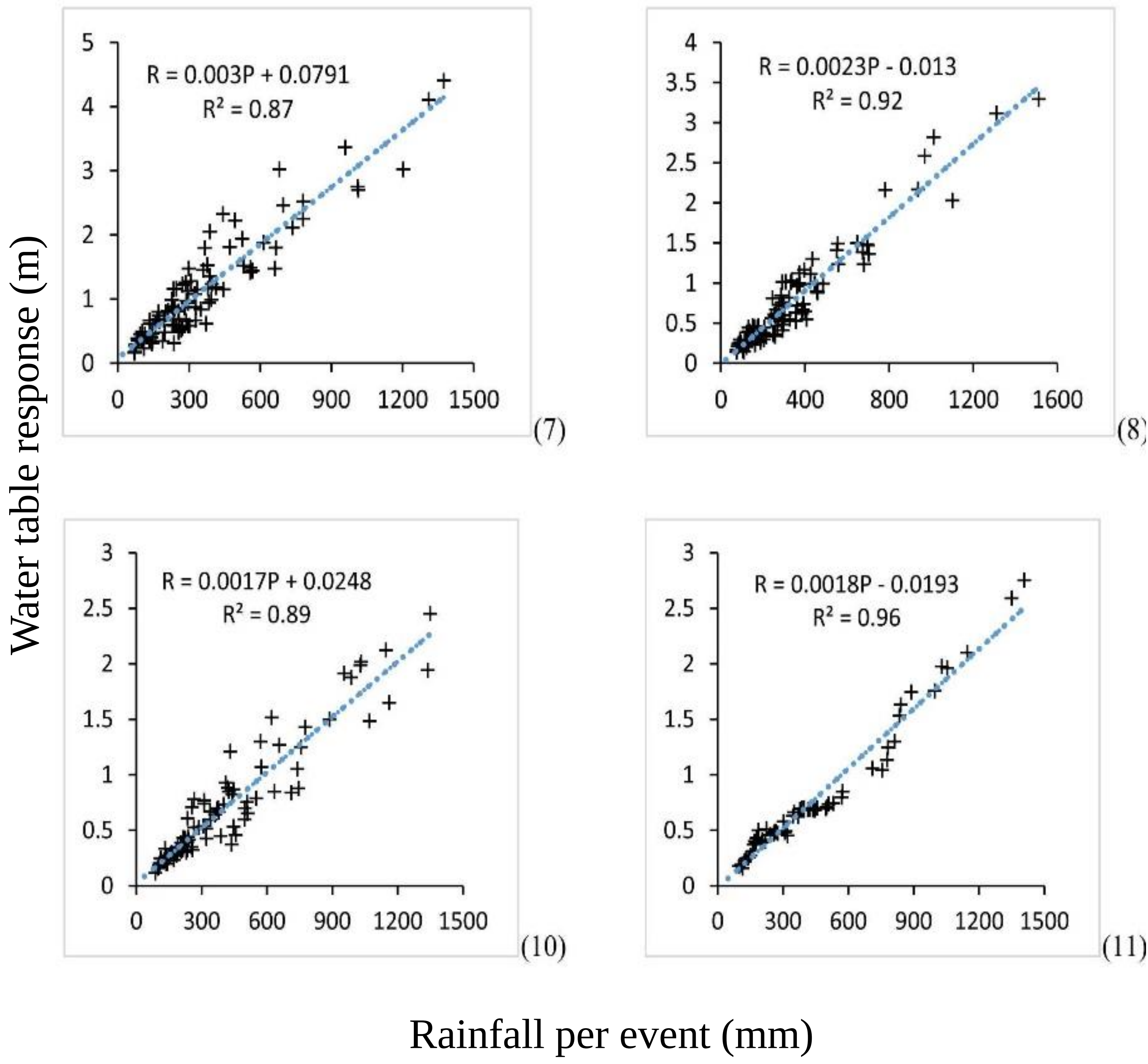
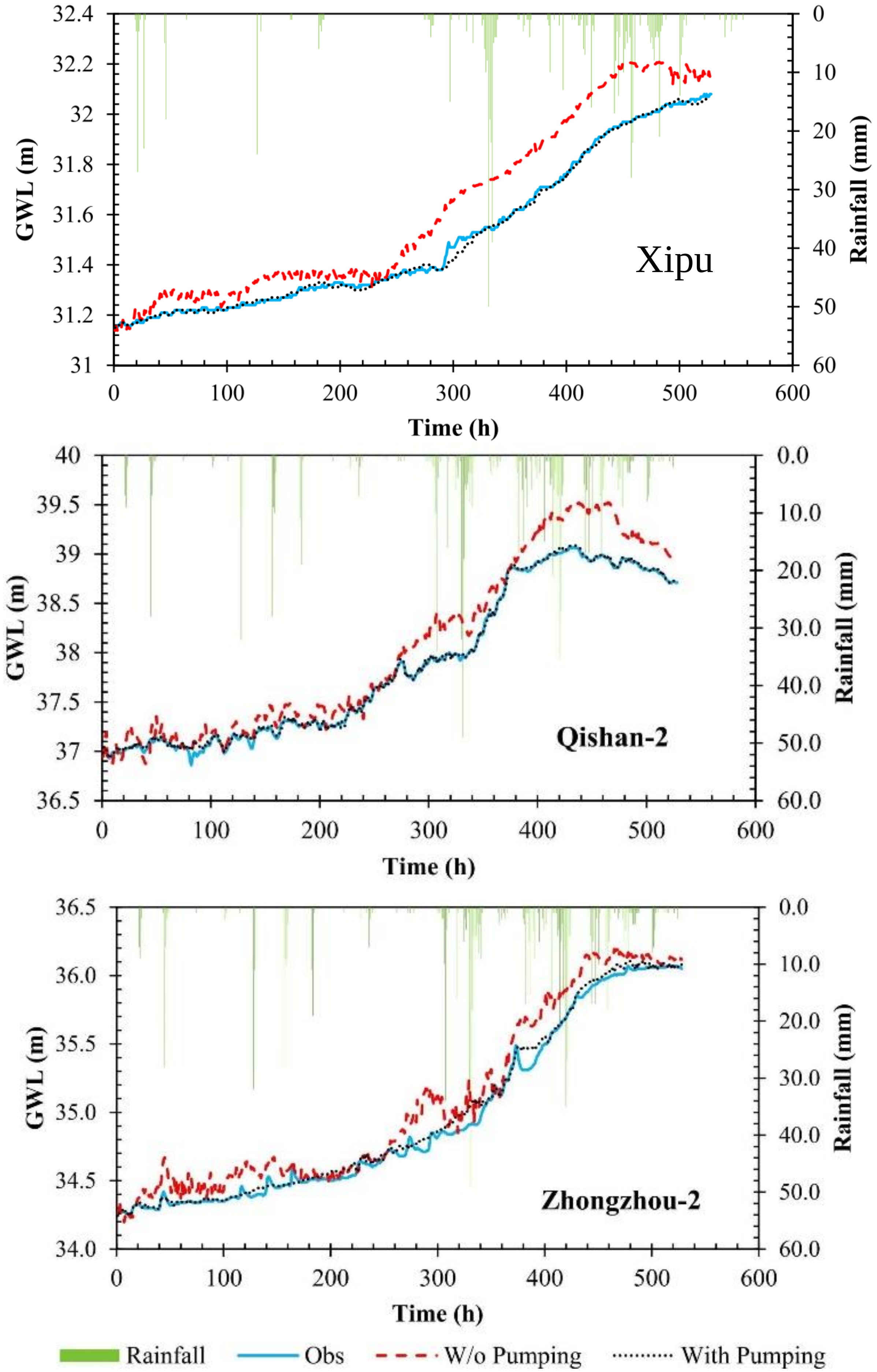


Fig.6: Relationship between GWL response and rainfall event. The best fit line in plot used to estimate Sy and k

WASH123D simulation for real-time scenarios



The average total pumping rate: 1.303 m^3/s of 13 pumping wells
The average groundwater level drop approximately 0.10–0.50 m.

Observation well	MAE	RMSE	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
Highest agree value	**0**	**0**	**0**	**1**	**1**	**1**

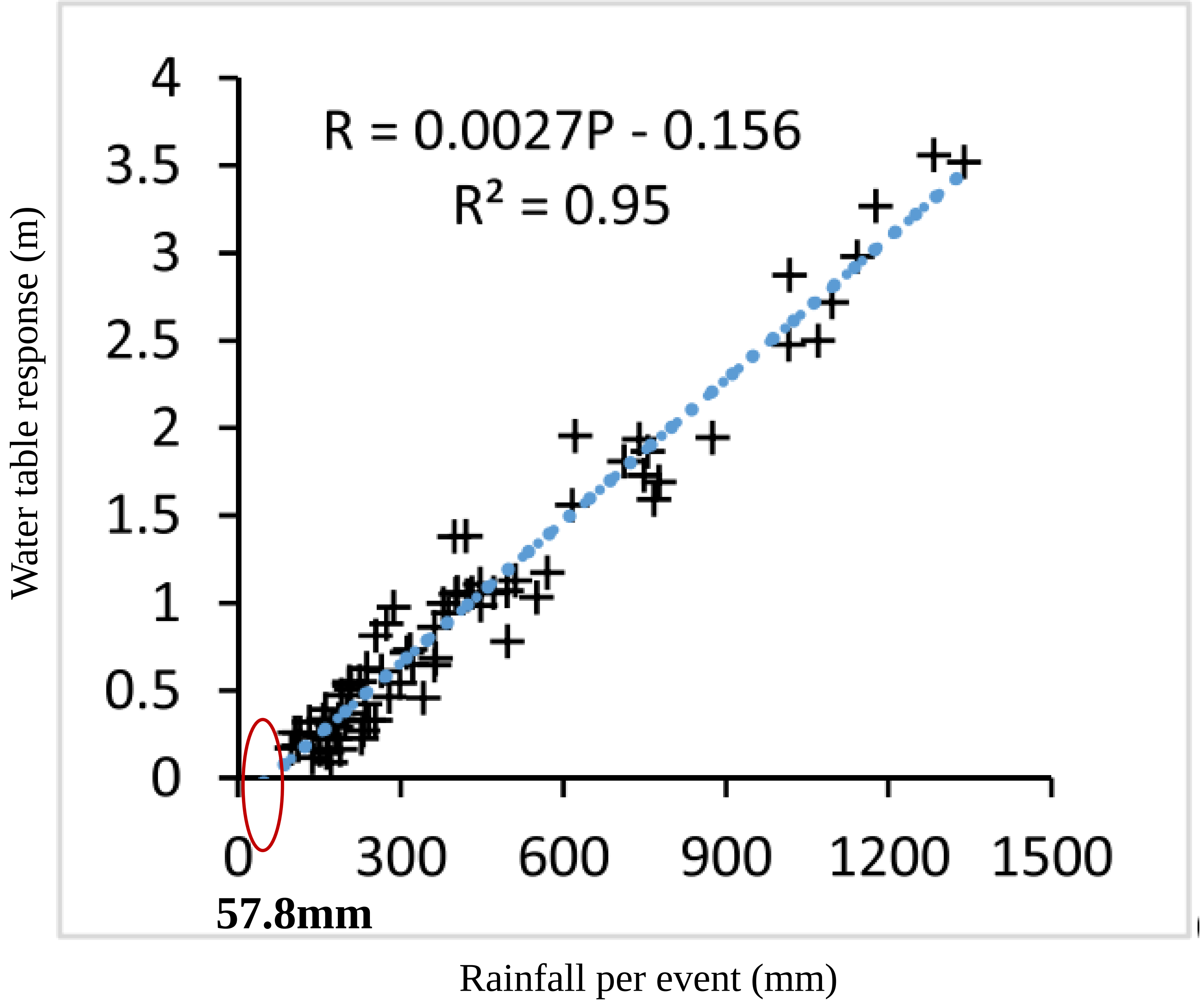
High agreement between Sim. vs. Obs.
Good performance of model

- ✓ Simple approach (**The regression procedure and MRC method**) to **estimate Sy (approximate 0.20 ~ 0.51)** and **k** in **unconfined aquifer** from rainfall and water level data.
- ✓ Rainfall is primary factor affect groundwater recharge in the study area
- ✓ Successfully **quantified pumping effects** on groundwater levels

→ provide framework for evaluating pumping impacts on groundwater systems

What did I learn from this study?

✓ Response threshold indicates **rainfall needed** before **recharge begins**



Initial water loss such as evapotranspiration, change in soil moisture storage may be caused by 2 reason:

- Upper layer consists of finer sediment particles of clay, mud and silt, which provides permeability variations
- Steep topography create quick runoff and more loss of rainfall.

THANK YOU FOR YOUR ATTENTION