Climate-Resilient Groundwater Management:

Construction of a Three-Dimensional Transient Flow Model for the Taoyuan Plateau

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OUTLINE

1. INTRODUCTION

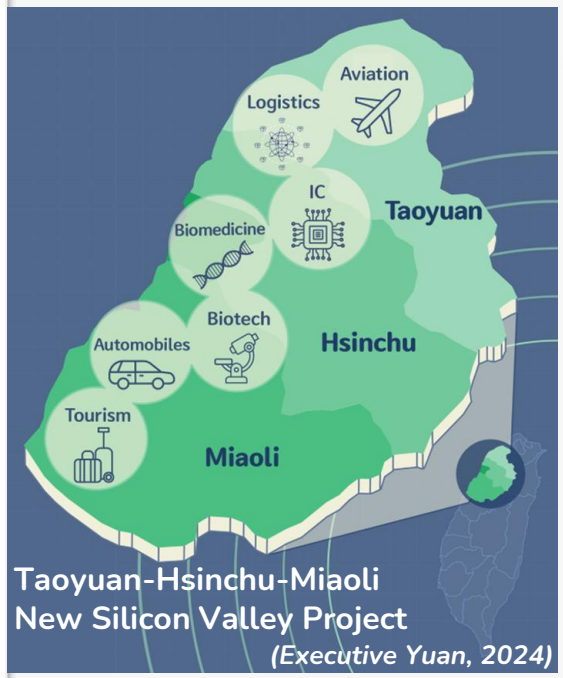
- Problem Identification
- Study Objective

2. METHODOLOGY

- Workflow
- Data collection
- Conceptual Model
- Model setup

3. FUTURE WORK

Taoyuan city: Economic and Industrial development



Taoyuan is **an important link** in Taiwan's new Silicon Valley Project 2024 -2027

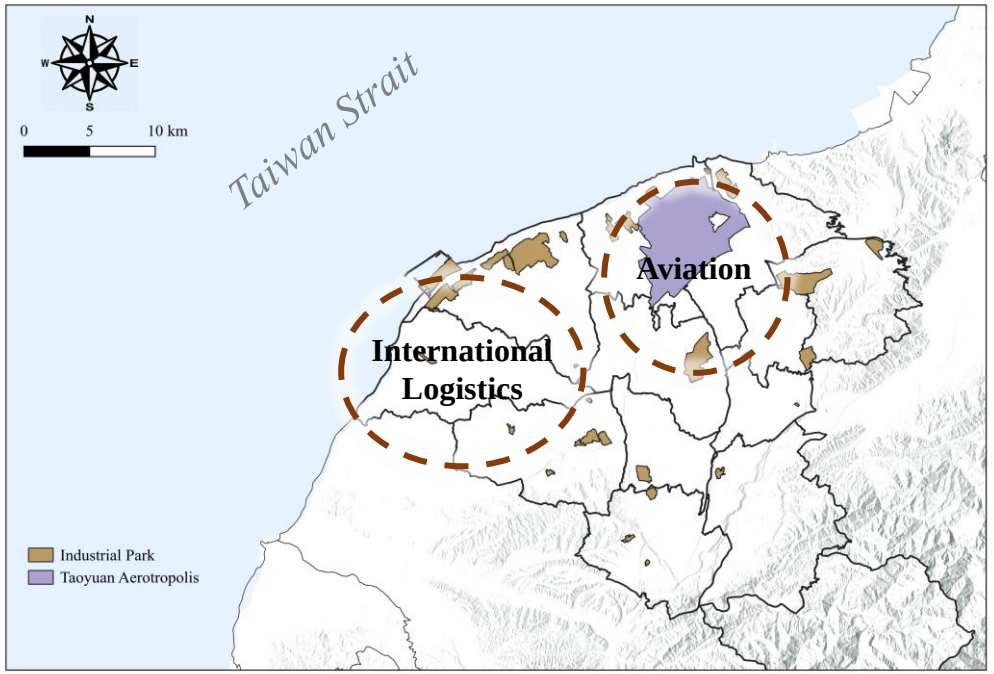
Ranking first in the nation for industrial production value

~90 billion $USD/year

(Taoyuan Investment Service Center, 2026)

59.57% of residents is the labor force

(National Statistics, Republic of China [Taiwan], 2026)



The industrial parks and aerotropolis in Taoyuan

Taoyuan City is one of Taiwan's most significant hubs for economic and industrial development.

37 industrial zones:

Semiconductors
Electronics
Optoelectronics
Aerotropolis
Advanced manufacturing

Taoyuan city: Water Resource Pressure Caused by Increasing Demand

As one of the major industrial hubs in Taiwan, Taoyuan relies heavily on **a stable water supply to support its development.**

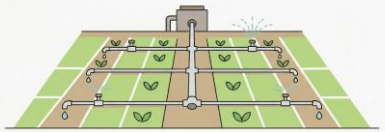
Water Demand

Around **1,045 Mm³/year** (Hsu & Lin, 2024).

Industry

216 Mm³

Agriculture Irrigation



403 Mm³

Domestic Use

442 Mm³

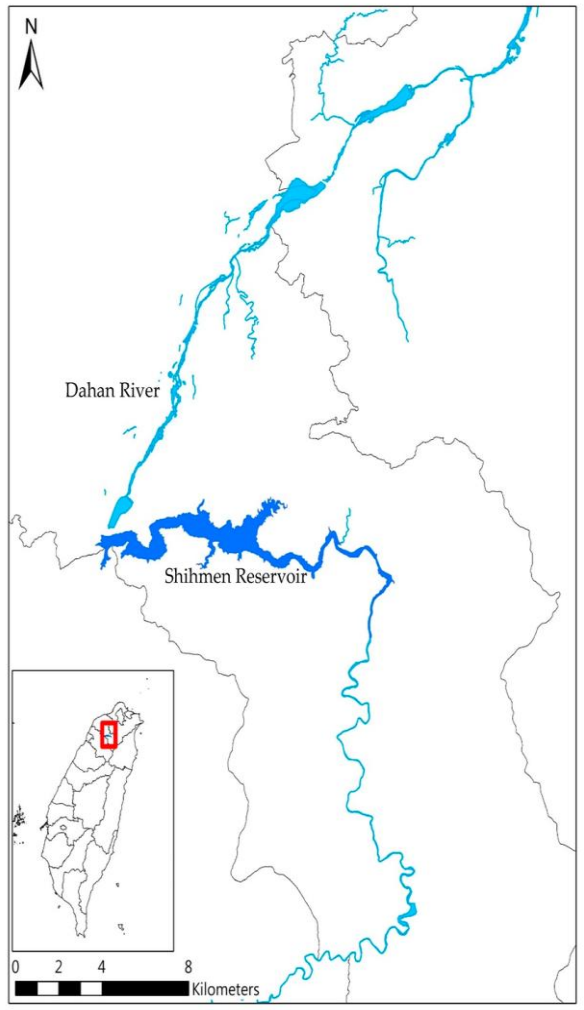
Industrial Growth → **Water shortage in the near future** ! → **Increases pressure on the water supply system**

Water Supply

- Primary Water Source: **Shihmen Reservoir**

  Effective storage capacity: **197 Mm³** (~ 60% of original capacity)
  Annual inflow: **approx. 1,664 Mm³**

- **Reclaimed water:** contributes only a minor share.
- **Rainfall:** plum rain, typhoon
- **Groundwater: 191 Mm³/ year** (18% - 20% of total annual water usage)
  (Hsu & Lin, 2024)



Shihmen Reservoir and Dahan River (Hu *et al. 2019*)

Effect of Climate Change on Taoyuan

Over the last 60 years, Taoyuan has experienced a steady increase in both temperature and precipitation:

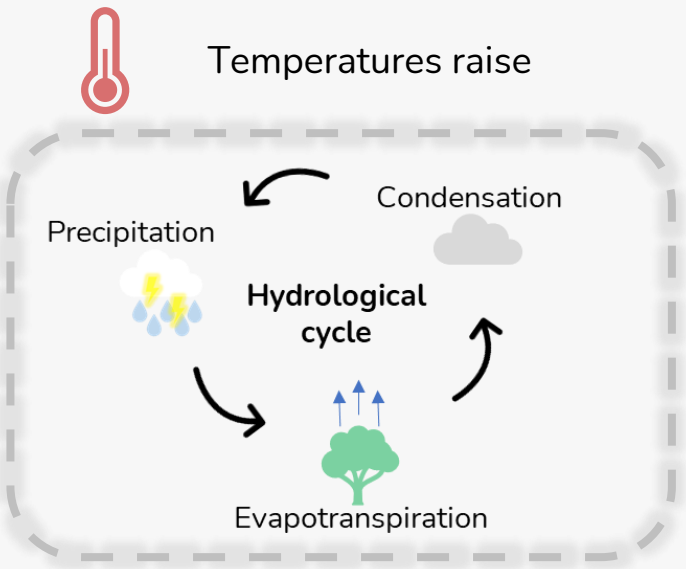
- 1960–2020

  Temperature Rise: **0.09˚C per decade**
  Increased Rainfall: **24 mm per decade**

- 1991–2020

  Temperature Rise: **0.16˚C per decade**
  Increased Rainfall: **42 mm per decade**

(National Science and Technology Center for Disaster Reduction, 2024)



The frequency and intensity of heavy rainfall, and drought events increase.

Reducing Surface Water

Water Supply Vulnerability

Raise the importance of groundwater management

Groundwater management using numerical modeling to capture precipitation infiltration into the unsaturated zone.

Groundwater management by using THMC modeling

THMC is a 3D finite element model of fully coupled simulation processes are developing by **CAMRDA** - Center for Advanced Model Research Development and Application at NCU.

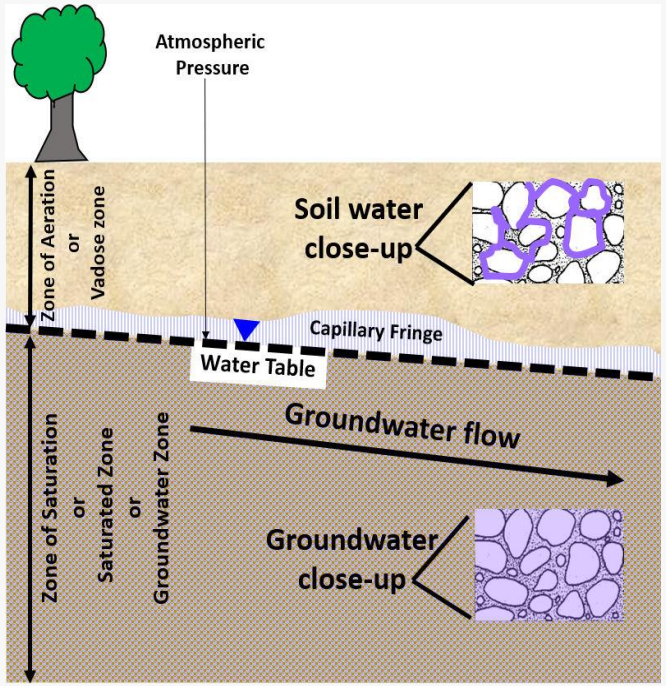
Technology Development Milestones

Professor

Gour-Tsyh (George) Yeh

Pioneer in the research of Thermal transport, Hydraulic flow, Mechanical and Reactive Chemical transport

Advantages of THMC



Schematic of shallow water zones in the subsurface (Woessner, 2020).

Taoyuan contains **shallow lateritic soils** that **inhibit rainfall infiltration**; therefore, THMC processes, particularly within **the unsaturated zone, should be carefully considered.**

	THMC
Computation Method	Finite Element Method (FEM)
Saturated zone	✓
Unsaturated zone	✓
User interface	✓

Literature Review

- The Shimen Reservoir remains the principal water source in the region, **climate variability has weakened the reliability of surface water availability** (Hsu & Lin, 2024)

- National studies for Britain and regional models in Uzbekistan and Taiwan show **more winter recharge** but **reduced or absent summer recharge**, concentrating recharge into fewer months. (Hughes *et al.* 2021; Kadirkhodjaev *et al.* 2025; Ngo *et al.* 2025).

- Intensive groundwater pumping in Iran leads to widespread land subsidence, primarily due to irrigation, threatening the sustainability of water resources (Haghshenas *et al.* 2024)

- InSAR, GPS, and extensometers are widely used to link deformation to groundwater levels and estimate elastic/inelastic storage (Smith et al. 2020; Guzy et al. 2020; Miller et al. 2017)

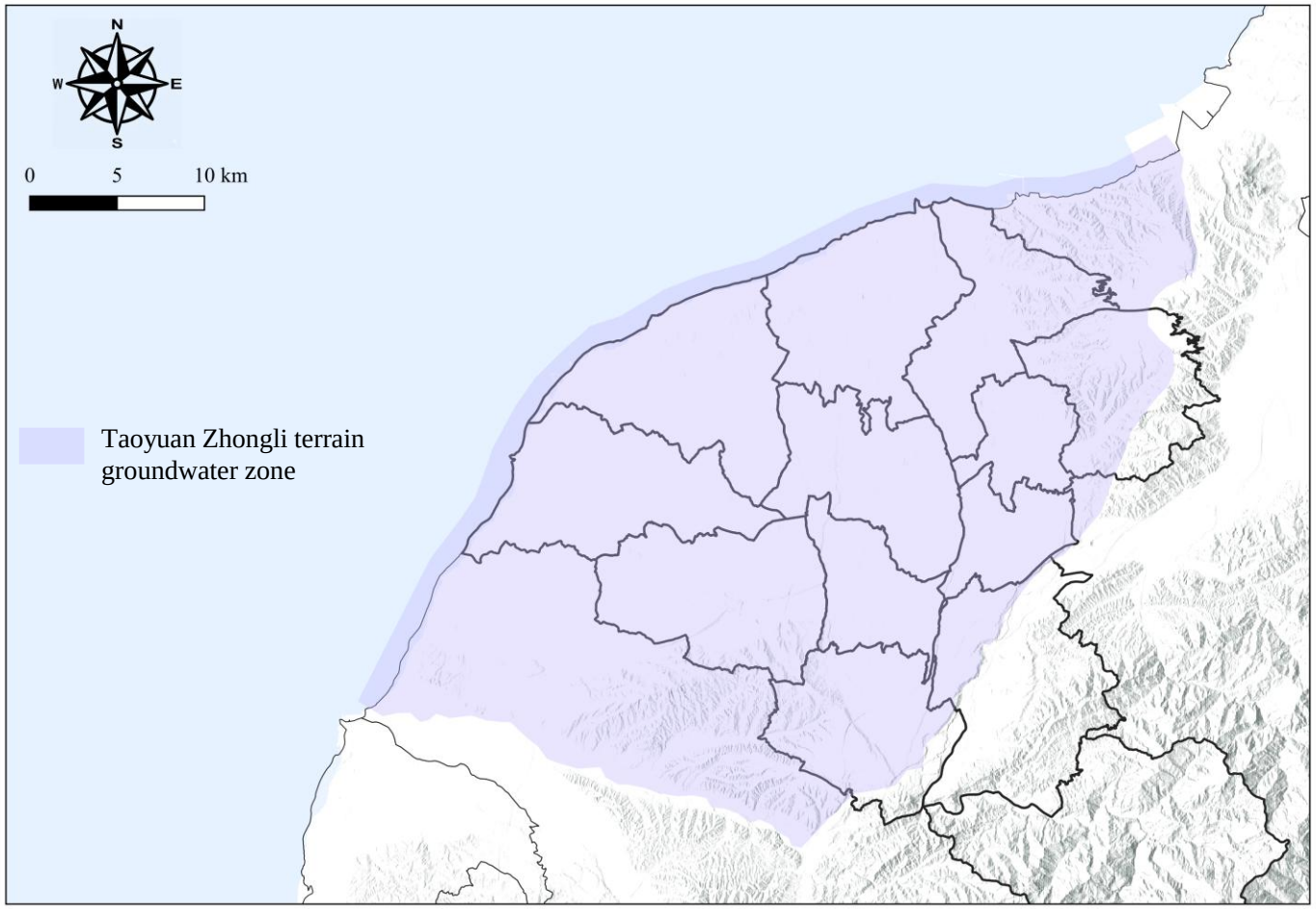
Objective

1. Evaluating the future impacts of climate change on groundwater flow dynamics.

2. Developing adaptive water management strategies through the analysis of depth-specific pumping scenarios.

3. Applying a coupled hydro-mechanical model to investigate aquifer compaction during specific periods of groundwater extraction.

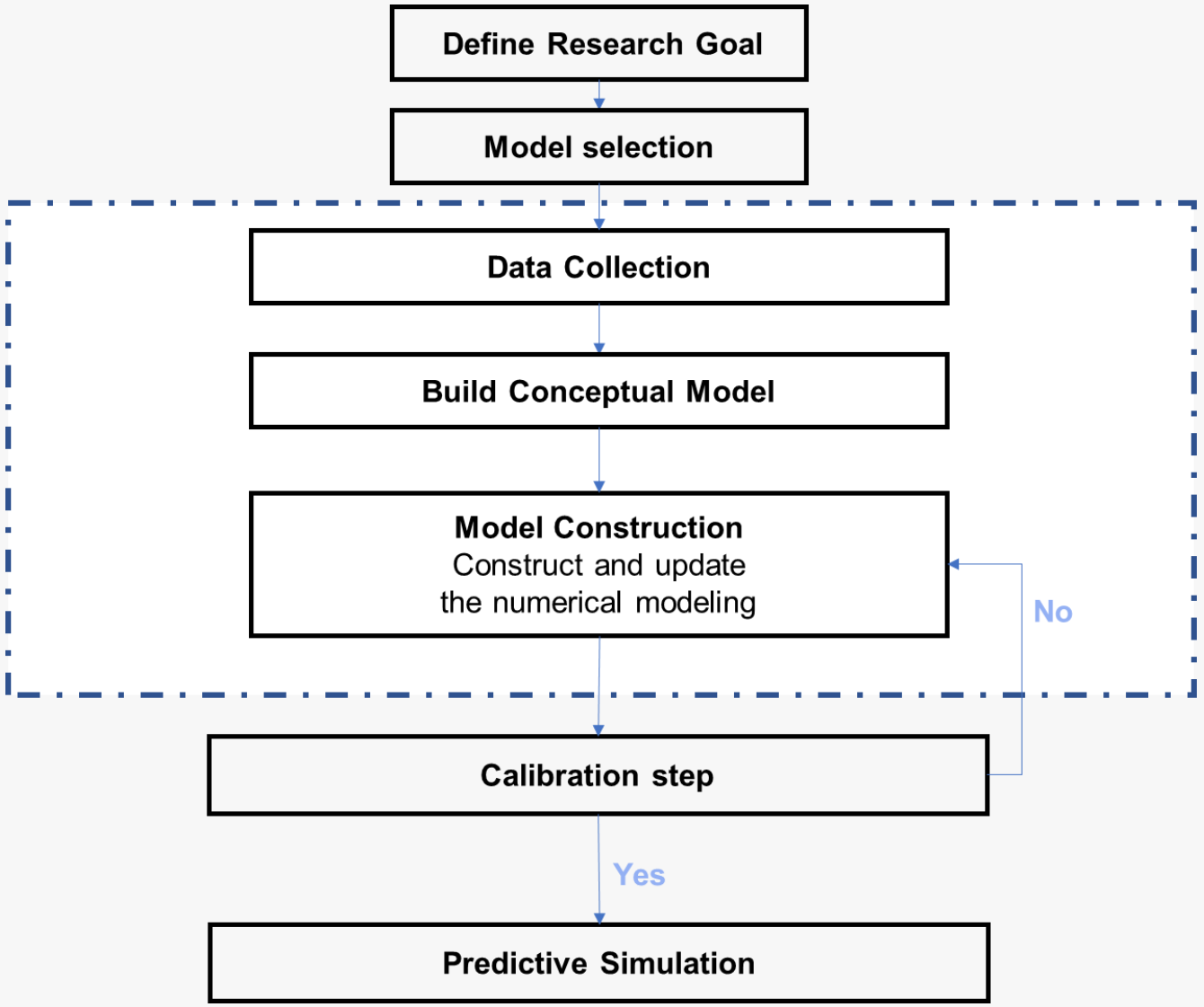
Study area



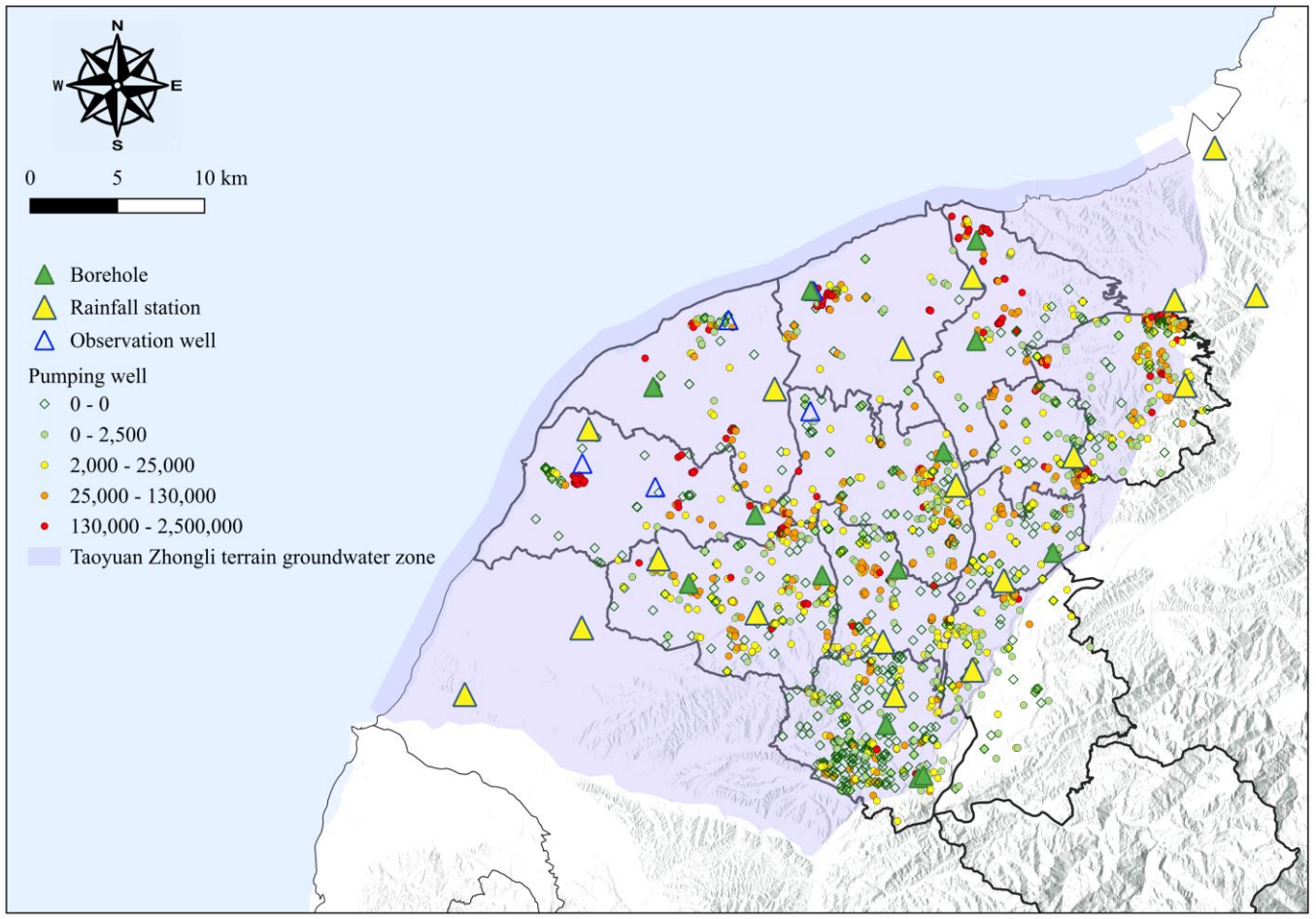
Taoyuan city

- Area: 1,221 km²
- Population: 2,348,859
- Annual average rainfall: 1,500 ~ 2,000 mm

Workflow


Define Research Goal
Model selection
Data Collection
Build Conceptual Model
Model Construction
Construct and update
the numerical modeling
No
Calibration step
Yes
Predictive Simulation

Data collection



The regional distribution of geological borehole, observation well, rainfall station, and pumping well in Taoyuan

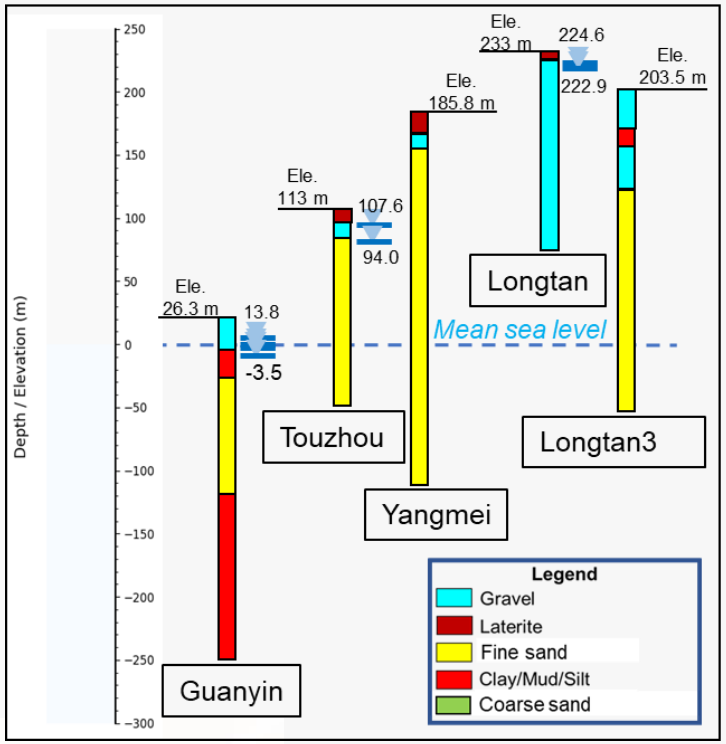
- 15 geological boreholes (Source: Water Resource Agency)
  → used to construct the Taoyuan mesh system.
- 36 observation wells (2020 – 2024) (Source: Water Resource Agency) → used for initial condition setup and calibration.
- 18 rainfall stations and 995 pumping wells (2020 -2024)
  → used as input data for the simulation.

Conceptual model

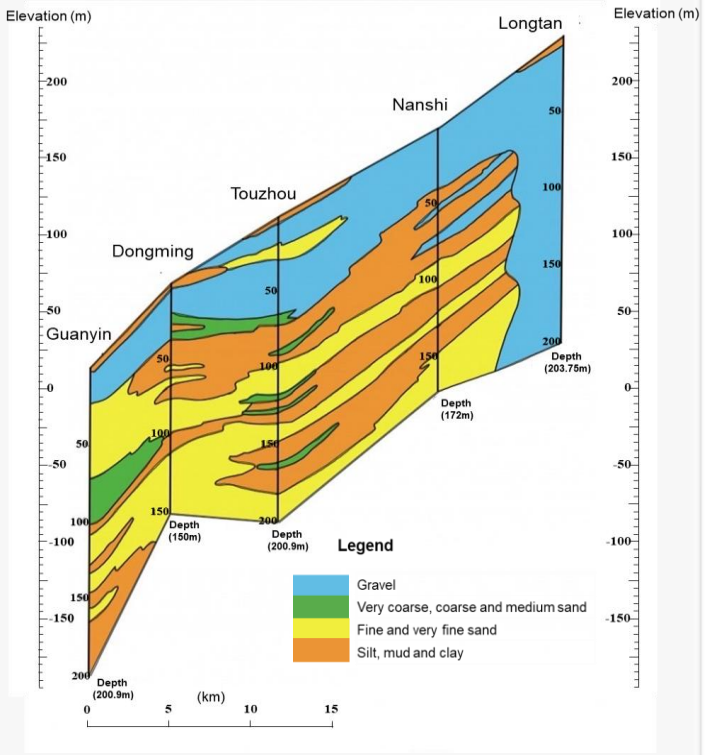
Base on the geological boreholes, geological cross-section, and geological profile of the Taoyuan Plateau. Simplifying the classifying to be **5 materials.**

Laterite predominantly forms the surface soil across most plateau regions.

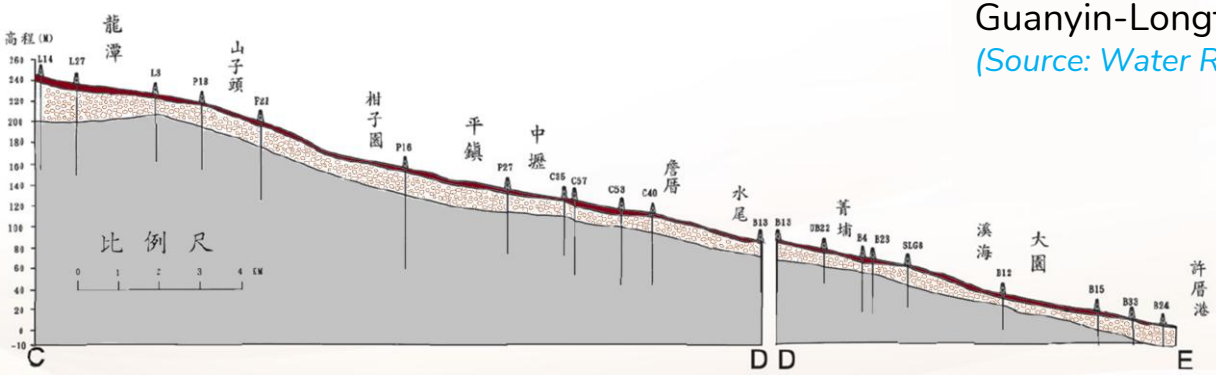
Gravel deposits are mainly distributed at higher elevations in mountainous areas.



Guanyin-Longtan geological boreholes
(Source: Water Resource Agency)



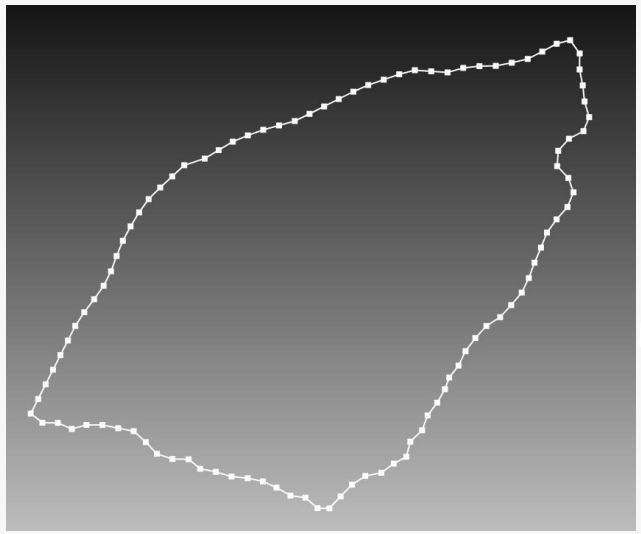
Longtan–Guanyin geological cross section.



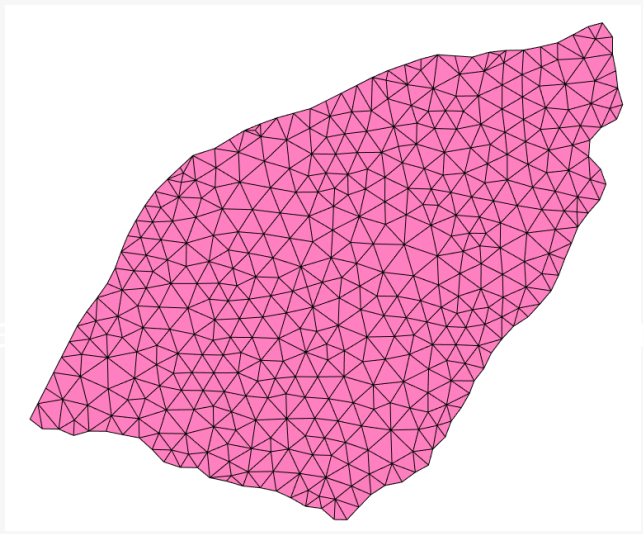
Geological profile of the Taoyuan Plateau (Li, 2003)

Mesh generation

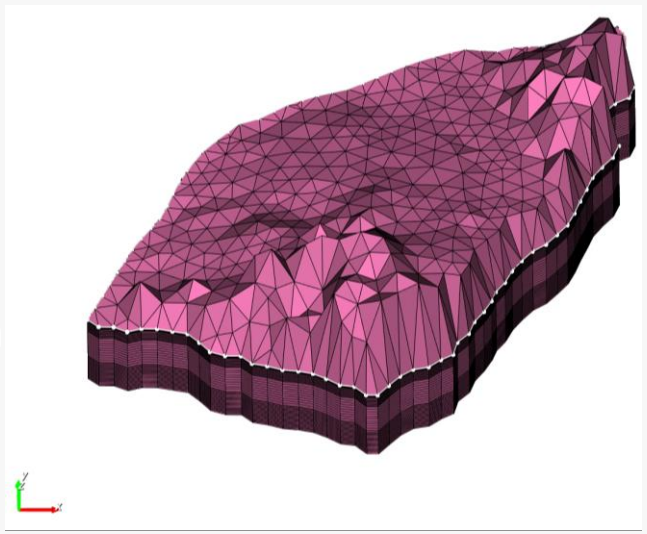
Simulation boundary



Generate 2D mesh



Generate 3D mesh
Extend the depth



The Taoyuan groundwater zoning boundary will be adjusted to match actual terrain conditions.

Domain information:

- Total nodes: 22,491
- Total Elements: 38,950
  (779/layer*20layers)

Governing equations for flow through saturated-unsaturated media of THMC

The general form of the equation for a 3D simulation (Yeh *et al.* 1994a, 1994b):

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

Water storage gradient — Flux flow — Sources/Sinks

ρ: Fluid density

ρ_0: Referenced fluid density at reference pressure p0= 1atm

ρ*: Fluid density of either injection or withdraw (M/L^3)

h: pressure head (L)

t: time (T)

z: potential head

q: source/sink of fluid [(L^3/L^3)/T]

α': modified compresibility of the soil matrix (1/L)

β: modified compressibility of the liquid (1/L)

θ_e: effective moisture content (L^3/L^3)

n_e: effective porosity (L^3/L^3)

S: degree of effective saturation of water

k: permeability tensor (L^2)

Darcy velocity V (L/T):

$$\mathrm{V} = -\mathrm{K} \cdot (\frac{\rho}{\rho_0} \nabla h + \nabla z)$$

Hydraulic Conductivity tensor (K):

$$\mathrm{K} = \frac{\rho \mathrm{g}}{\mu} k$$

Permeability tensor

Generalized storage coefficient F:

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

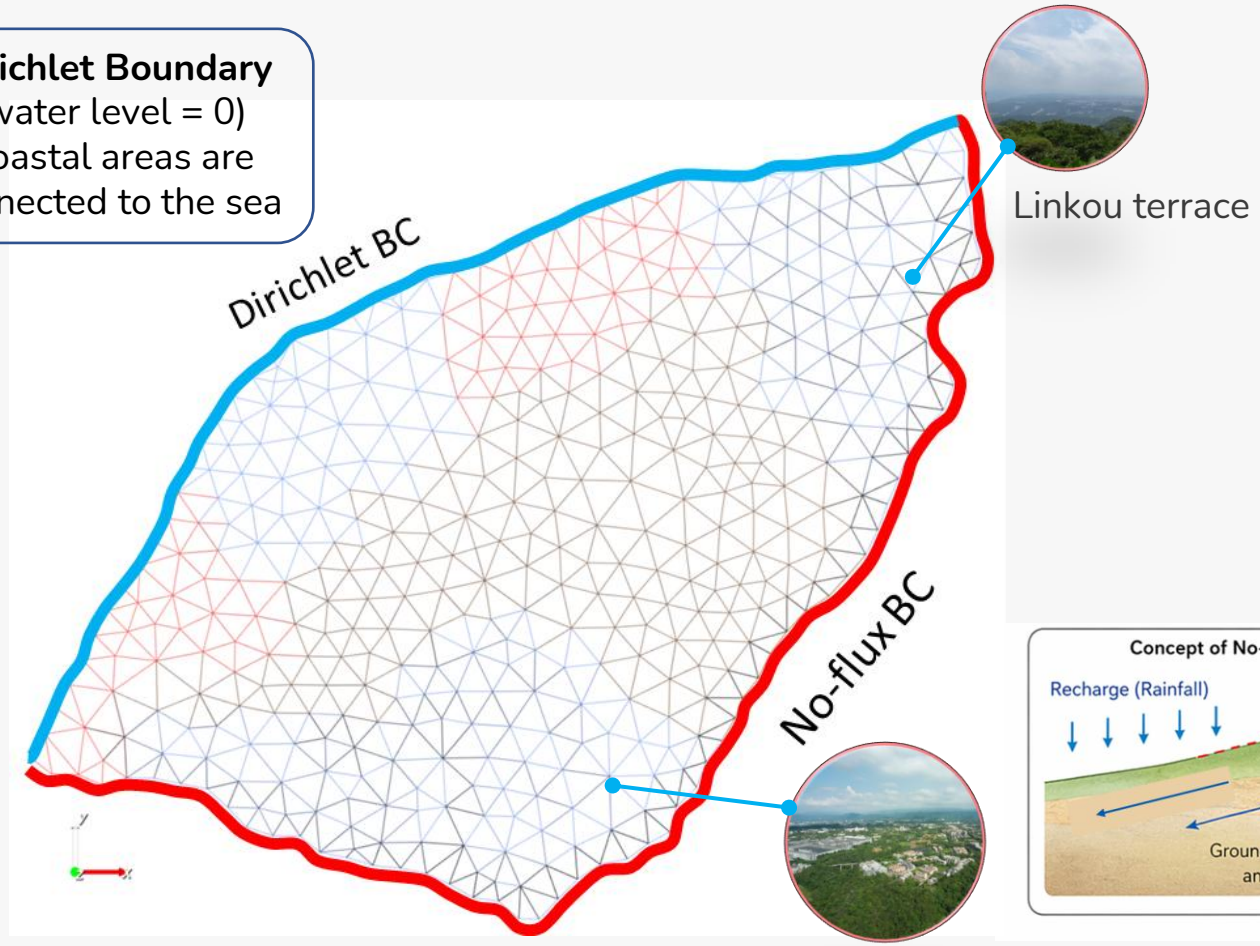
Saturation

Porosity — Effective water content

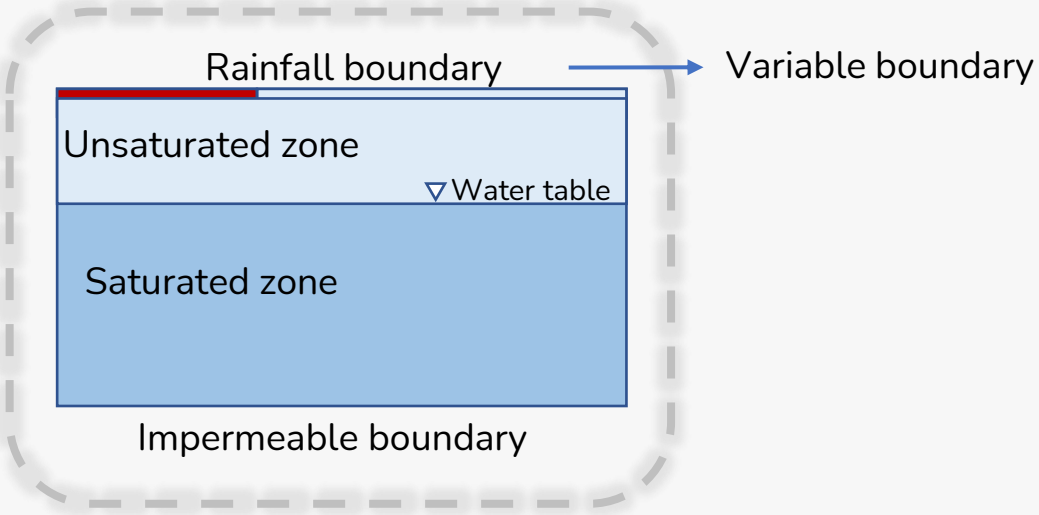
Boundary Condition

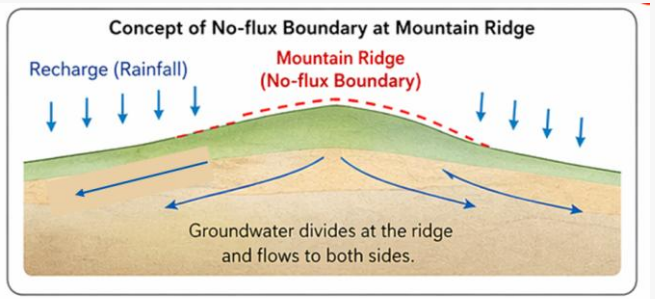
Top view BC

Dirichlet Boundary
(water level = 0)
Coastal areas are connected to the sea



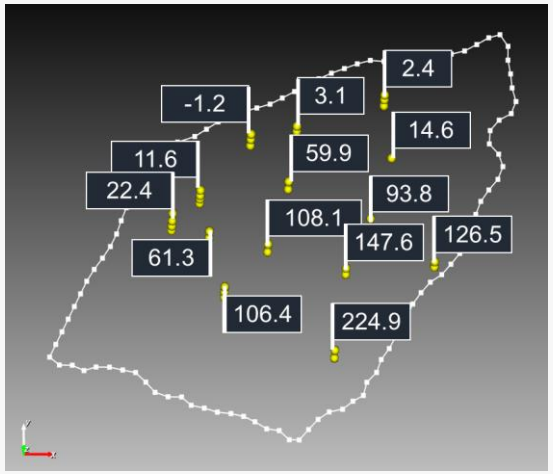
Side view BC



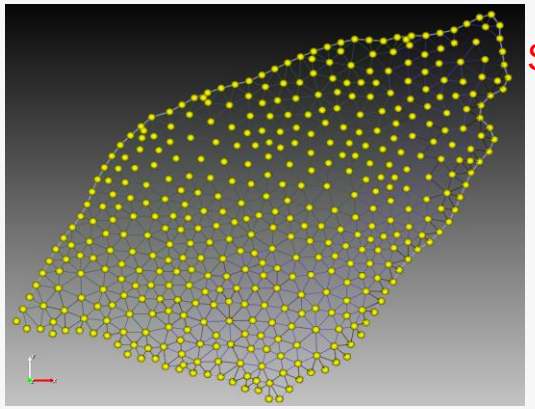


Boundary conditions were established along the coastline and the mountain to represent the regional hydraulic limits.

Initial Condition

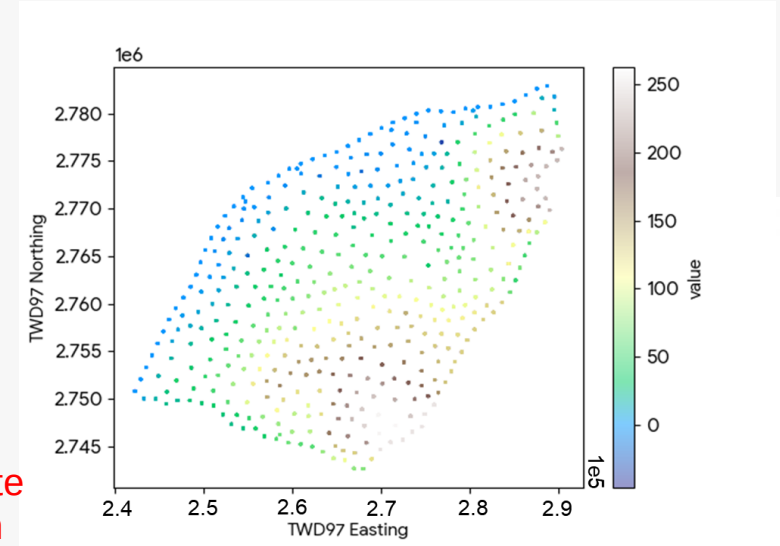


Groundwater level – A known hydraulic head.

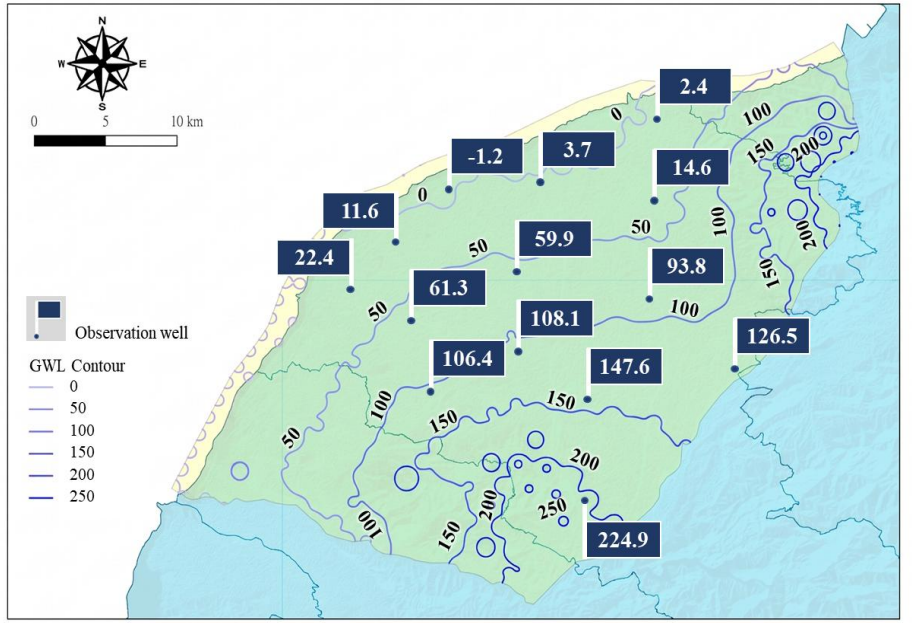


Total 22,491 node

Steady-state simulation



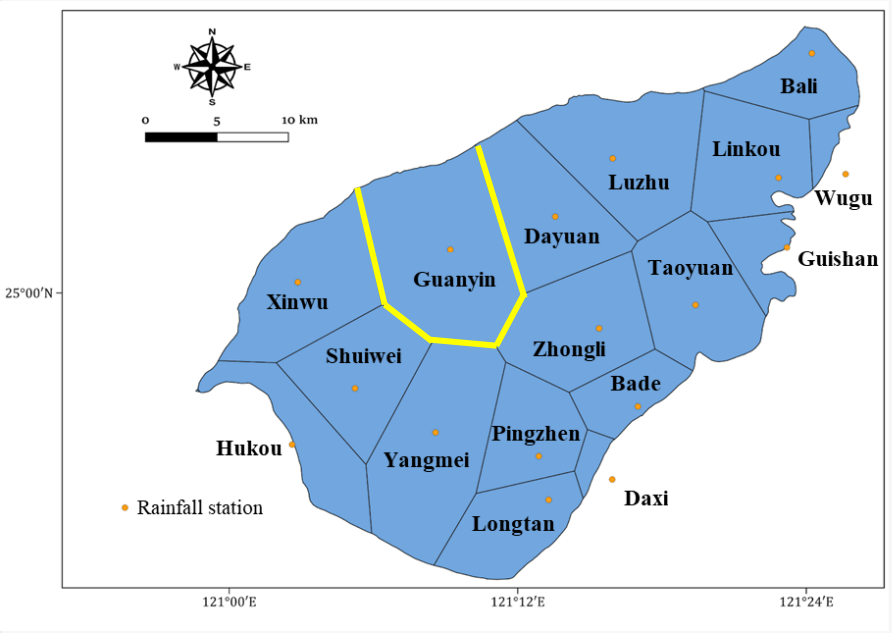
Dirichlet boundary (constant head): The groundwater level is fixed and known along the boundary.



Initial condition for all domain – steady state result

A steady-state groundwater flow field used as the initial condition for transient simulations.

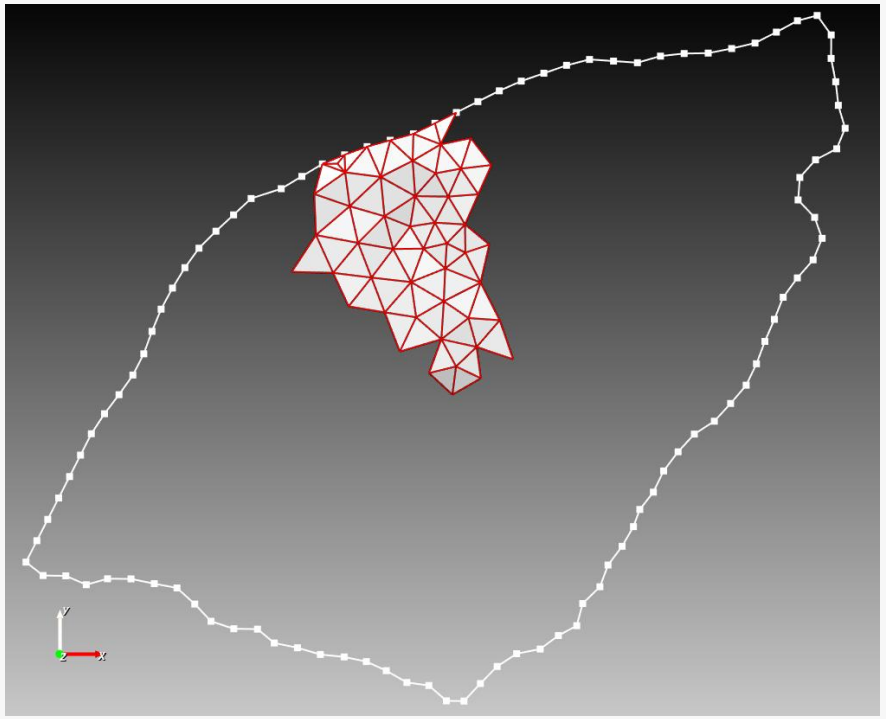
Rainfall setting - Variable Boundary Condition



Average Taoyuan regional rainfall distribution (17 rainfall stations) base on Thiessen polygon method.

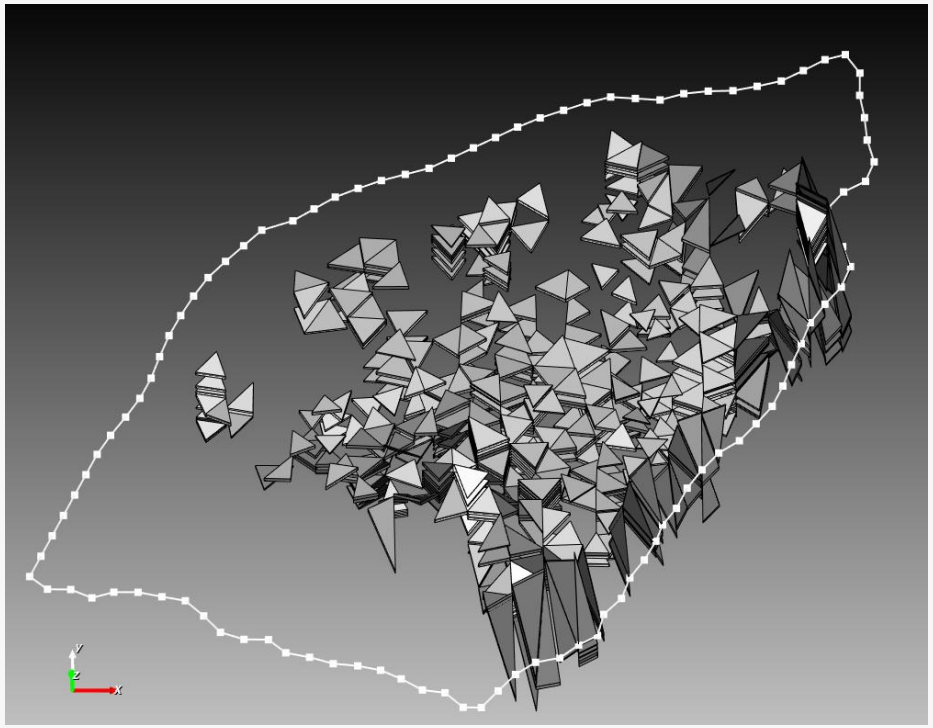
In numerical modeling, rainfall is treated as a **variable boundary condition as top surface.**

Data from 17 rainfall stations in Taoyuan from 2020 – 2024 (daily)



Rainfall setting in Guanyin area

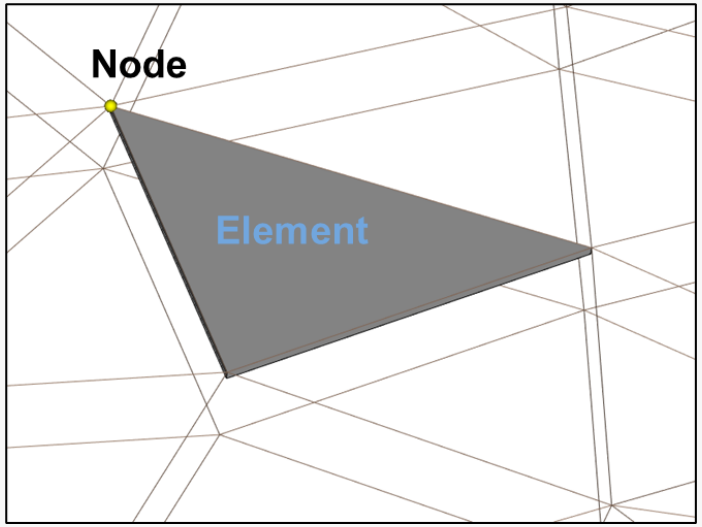
Pumping setting – Element Source/Sink



The distribution of pumping area as element source/sink setting

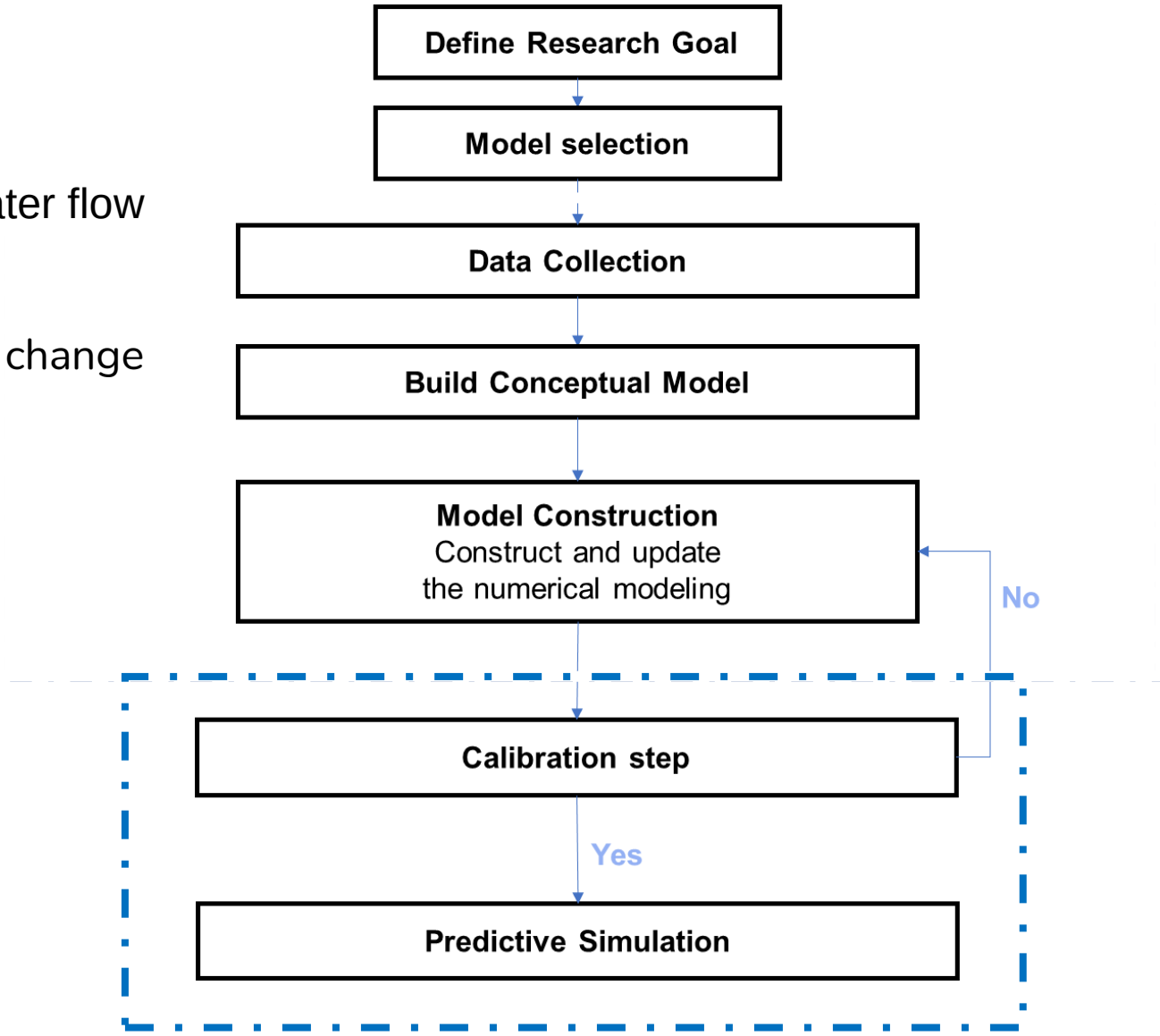
Element source/sink

- **Smooth, stable gradients**
- **Catch the accuracy**
  (Volume-based)

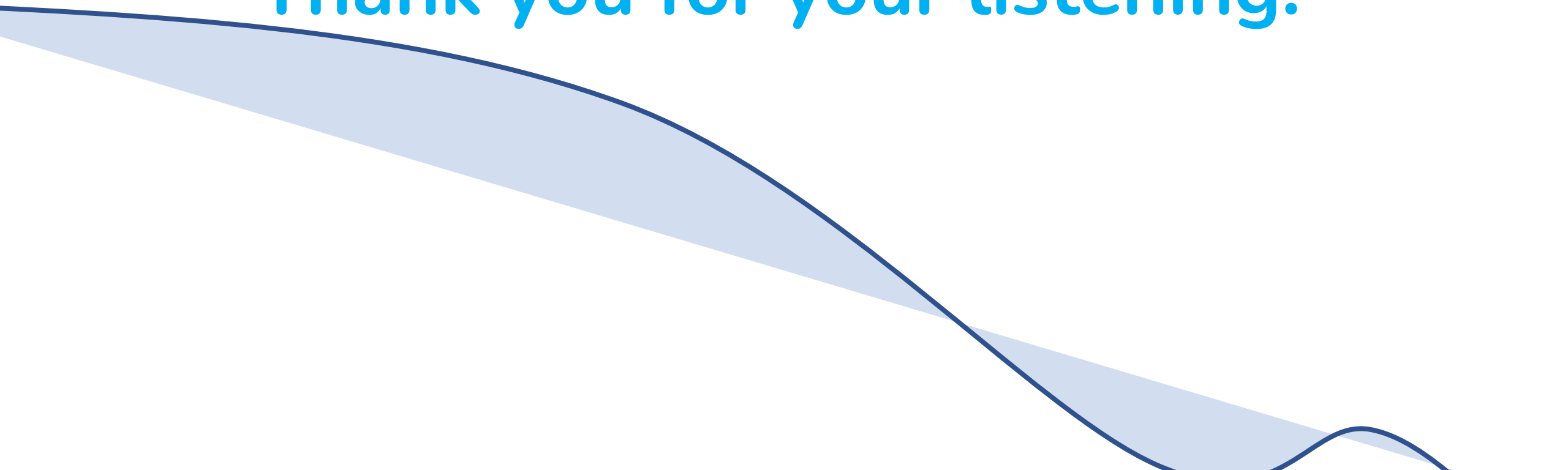


FUTURE WORK

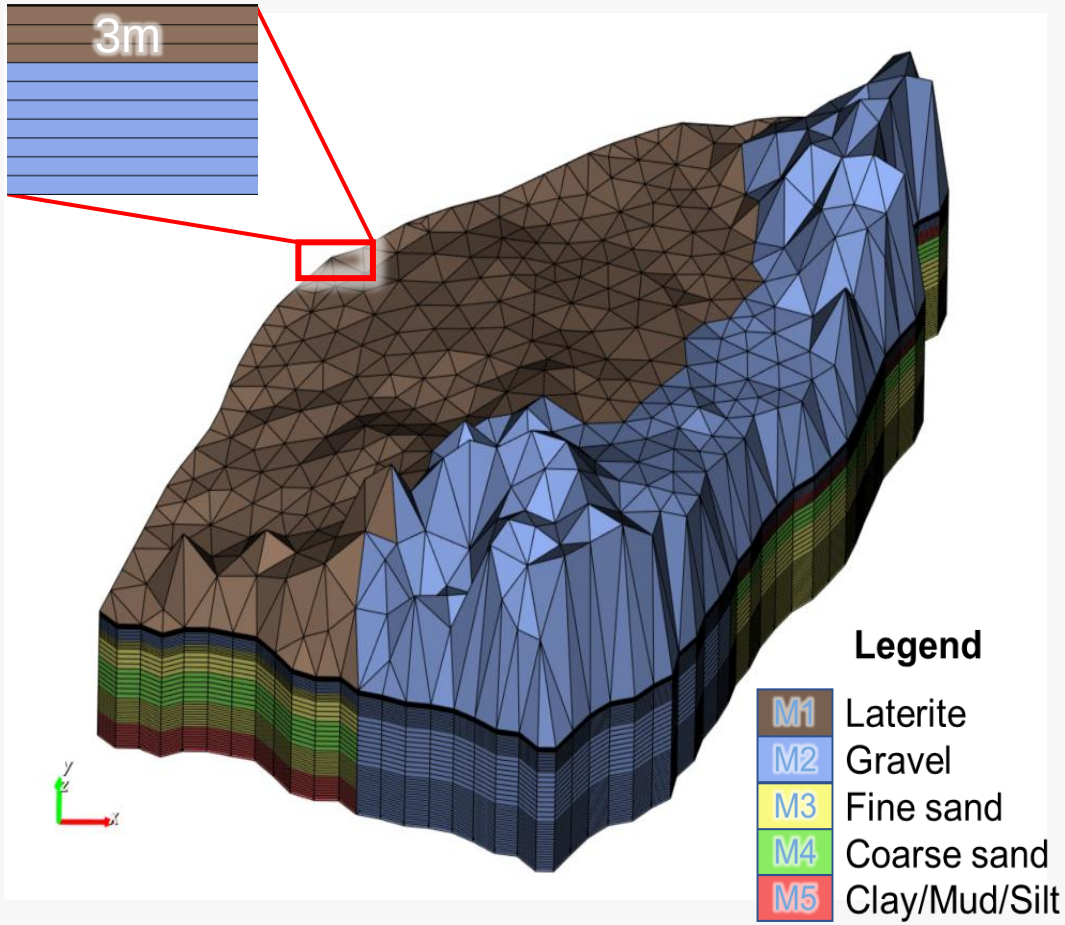
- Complete the calibration step
- The model is applied to predict groundwater flow under long-term conditions.
- Evaluating the future impacts of climate change on groundwater flow dynamics



Thank you for your listening!



Subsurface material and hydraulic conductivity (K value)



- The geological characteristics were simplified into **5 distinct materials**.

Table1. Hydraulic conductivity (K) range

Material	K Range (m/s)	Source
Laterite	10^{-7} to 10^{-5}	Osinubi *et al.* 2005
Gravel	$3*10^{-4}$ - $3*10^{-2}$	
Coarse sand	$9*10^{-7}$ - $6*10^{-3}$	Zheng *et al.* 2002
Fine sand	$2*10^{-7}$ - $2*10^{-4}$	
Clay/Mud/Silt	$1*10^{-11} – 5*10^{-9}$	