From Data to Models: Understanding the Importance of Heterogeneous Hydrogeological Models in Geohydrology Studies

Duc-Huy Tran[1*], and Shih-Jung Wang[1,2]

[1] Graduate Institute of Applied Geology, National Central University, Taiwan

[2] Department of Earth Sciences, National Central University, Taiwan

* Email: tdhuygeo13@gmail.com

Abstract In the complex aquifer systems of the Choushui River Alluvial Fan, Taiwan, effective groundwater management and land subsidence mitigation are crucial in the fields of geohydraulic, engineering geology, and environmental science. This study aims to clarify the impact of heterogeneous hydrogeological models (HHMs) on geohydrology, spanning from data to modeling. Our objectives address three primary challenges: (1) quantifying the influence of uncertainty of HHM on local-scale simulations of groundwater flow and land subsidence; (2) assessing the impact of borehole density on the construction and effectiveness of three-dimensional heterogeneous hydrogeological models in the basin scale; and (3) developing an uncoupled-model for groundwater and compaction that quantifies land subsidence at a basin scale. This study utilizes extensive borehole data, employing the one-dimensional (1D) continuous-lag Markov chain, the spMC package, and geostatistical methods to generate realistic hydrogeological model realizations. The Groundwater Modeling System (GMS) software, integrated with the TPROGS, MODFLOW, and SUB packages, enables simulations of transient groundwater flows and models land subsidence. These models are evaluated through Monte Carlo simulations to ascertain the variability and uncertainty of the results.

In the local scale, our findings highlight the significant impact of hydrogeological model uncertainty on the reliability of simulations for groundwater flow and land subsidence. We also explore the effects of boundary conditions on simulation outcomes, noting that assumed boundary conditions enhance the stability of groundwater flow across different models and reduce uncertainty. **At the basin scale**, findings highlight that higher borehole densities produce more detailed and complex hydrogeological models, enhancing the representation of geological discontinuities. Conversely, lower densities result in more continuous and uniform patterns, potentially oversimplifying subsurface complexities, yet sufficient for expansive assessments. This study emphasizes the critical role of borehole density in reducing model uncertainty and enhancing the reliability of hydrogeological model. Furthermore, an uncoupled-model for groundwater and compaction was well developed with the calibration and verification. Results from the model have demonstrated high credibility. The simulations reveal that shallow groundwater pumping significantly impacts deeper hydrogeological layer, notably along the Taiwan High-Speed Rail, contributing markedly to land subsidence. It shows that pumping activities within shallow layers account for 6% to 35% of deep compression, with variations dependent on specific hydrogeological characteristics and pumping behaviors.

In conclusion, this research provides deep insights into the dynamics affecting groundwater flow and land subsidence, emphasizing the essential roles of uncertainty of hydrogeological model, borehole density, and groundwater pumping practices in the geohydrology study. The implications of these findings are significant for groundwater management, environmental assessments, and land subsidence evaluations in regions facing severe hydrogeological and anthropogenic changes. Future research should integrate additional natural factors, such as variations in the hydrological cycle, to further refine the understanding and mitigation strategies **for land subsidence and groundwater resource management.**

1. INTRODUCTION *Literature review:

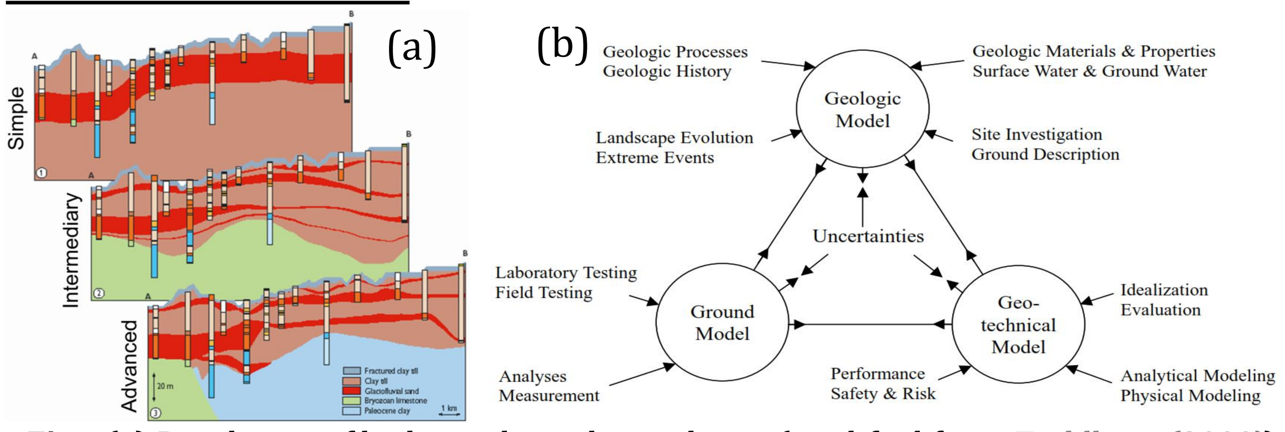


Fig. : (a) Resolution of hydrogeological complexity (modified from *Troldborg (2000)*); (b) uncertainty types, and its relationship (modified from *Keaton (2013)*).

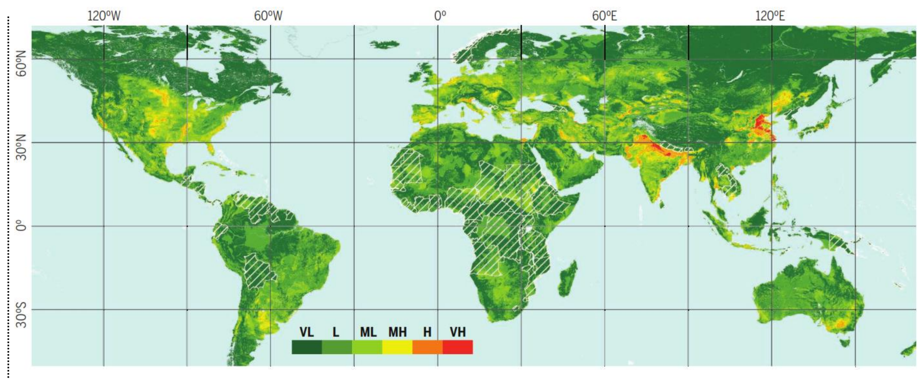


Fig. : Potential global subsidence in the world. The color scale represents the probability intervals categorized from very low (VL) to very high (VH) (*Herrera-García et al., 2021*).

*Outline of the research:

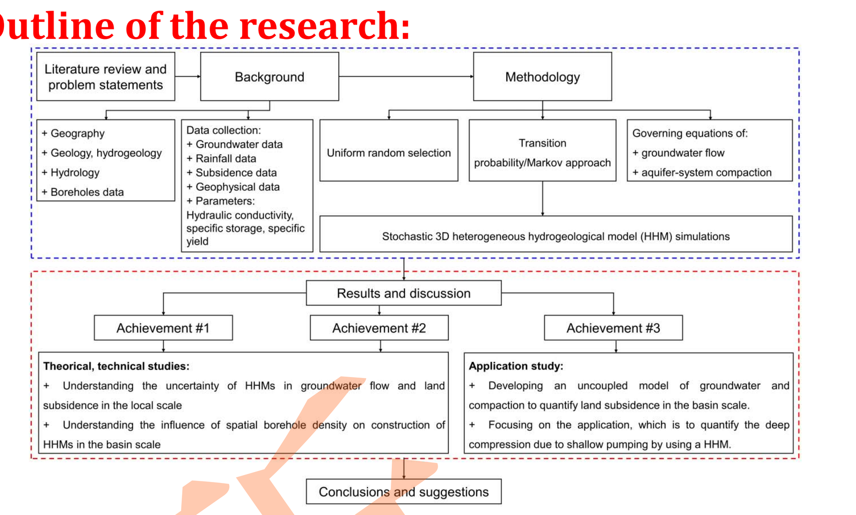


Fig. : Flowchart of the dissertation.

2. BACKGROUND *Geology, hydrogeology, and borehole data

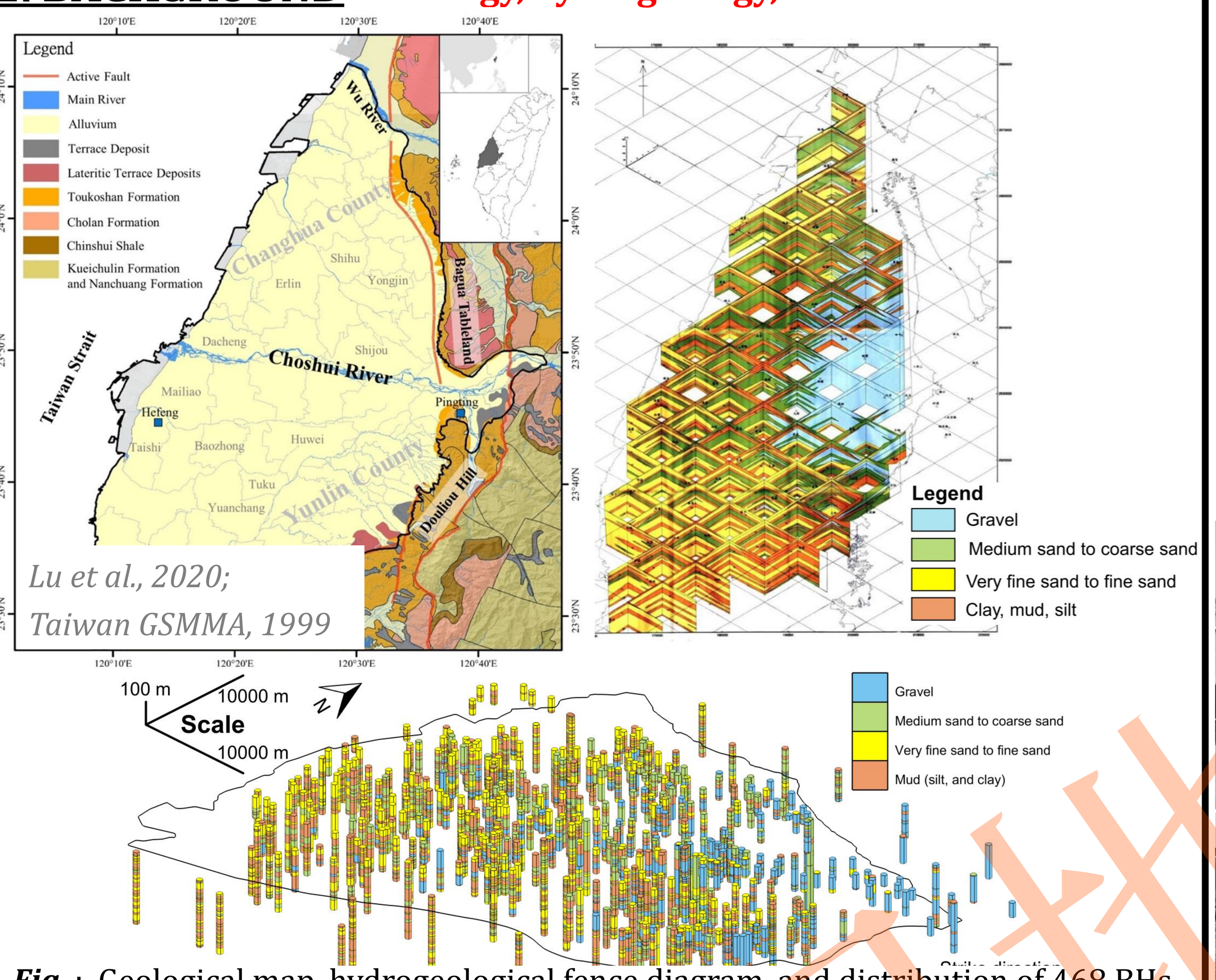


Fig. : Geological map, hydrogeological fence diagram, and distribution of 468 BHs with four kinds of hydrogeological material .

*Current subsidence in Taiwan

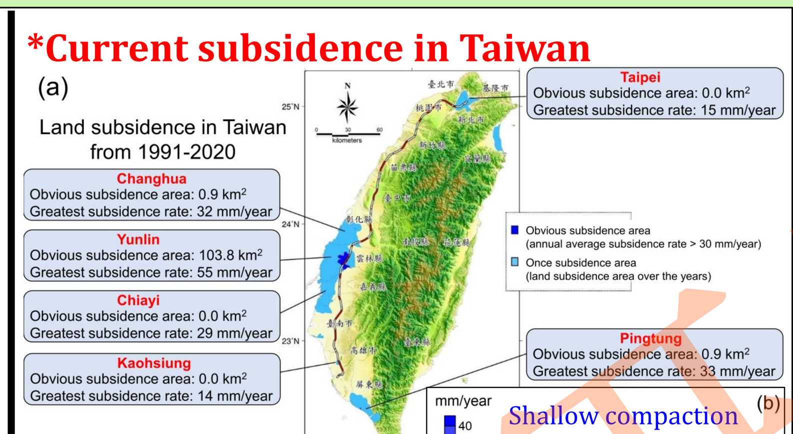


Fig. : (a) Land subsidence in Taiwan from 1991 to 2020

South CRAF

Pingtung Plain

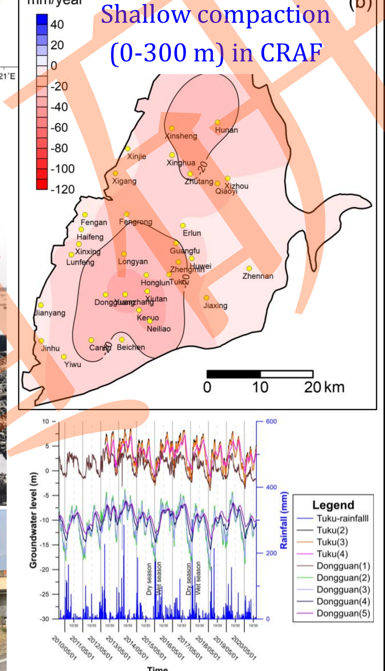
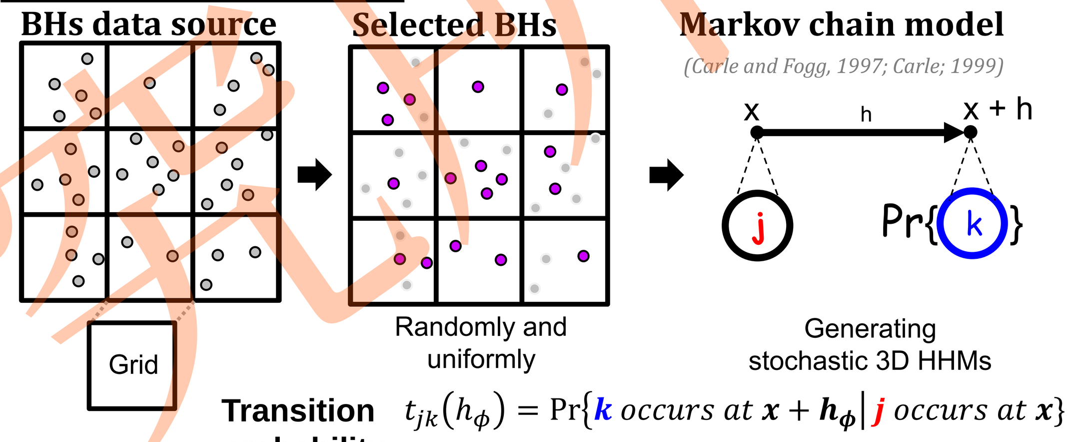


Fig. : Hydrological data for South CRAF.

3. METHODOLOGY



Transition probability: $t_{jk}(h_\phi) = \Pr\{\boldsymbol{k}\ occurs\ at\ \boldsymbol{x}+\boldsymbol{h_\phi} \mid \boldsymbol{j}\ occurs\ at\ \boldsymbol{x}\}$

where x is the spatial location, Δh is the lag distance [L], and j, k denotes mutually exclusive materials.

❖ **MODFLOW: Governing equation of groundwater flow**

MODFLOW describes the 3D movement of groundwater flow through porous media with the following governing equation (*Rushton and Redshaw, 1979*):

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where: h is the hydraulic head [L], S_s is the specific storage of the porous material [L^{-1}], W is the volumetric flux [L^{-1}], $K_{x,y,z}$ is the hydraulic conductivities in x, y, z directions [L T^{-1}], t is time [T].

❖ **SUB: Governing equation of aquifer-system compaction**

In the early half of the 20th century, model, field, and laboratory research revealed how hydraulic head decline compacts limited unconsolidated aquifer systems (*Terzaghi, 1925; Meinzer, 1928; Jacob, 1940*).

$$\Delta b = S_{sk} b \Delta h$$

Δb is the change in thickness, b of sediment layer [L], Δh is the change in hydraulic head [L], S_{sk} is the skeletal specific storage [L^{-1}].

4. RESULTS AND DISCUSSION

Achievement #1: Uncertainty of Stochastic HHMs in Groundwater Flow and Land Subsidence Simulations on the Local Scale

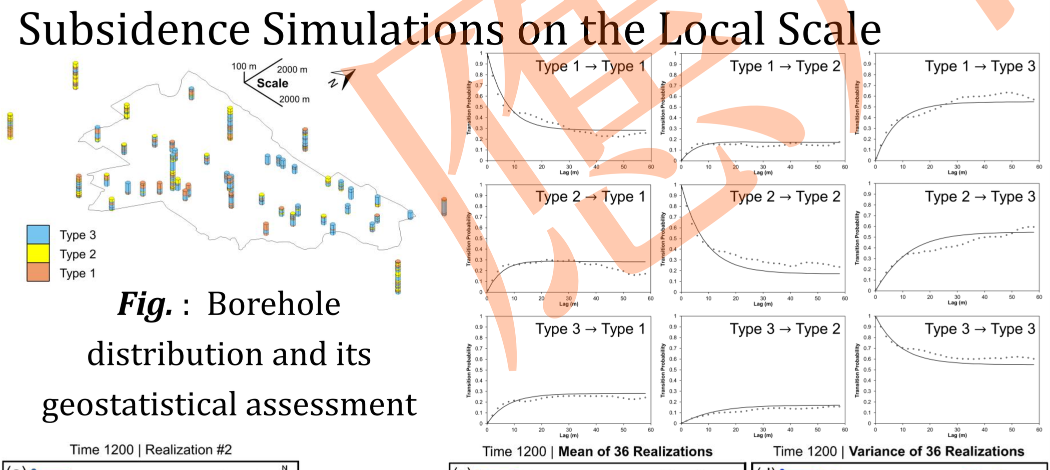


Fig. : Borehole distribution and its geostatistical assessment

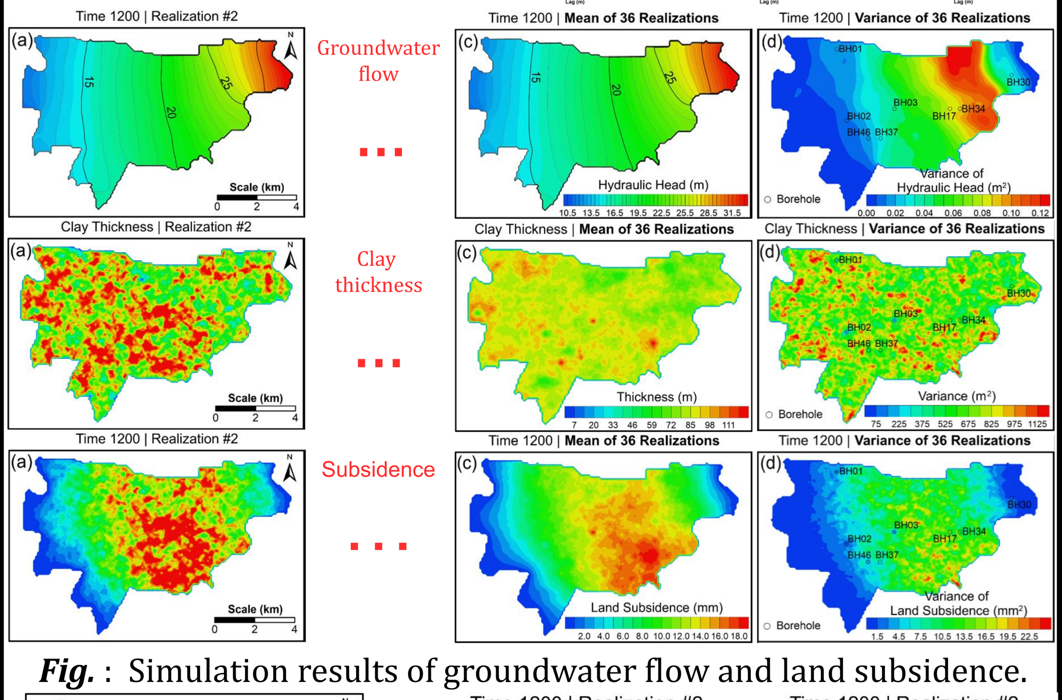


Fig. : Simulation results of groundwater flow and land subsidence.

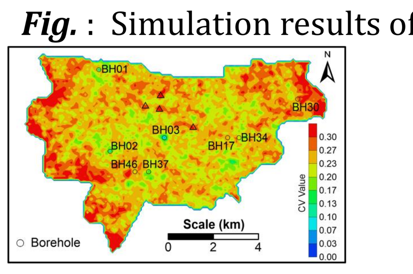


Fig. : Land subsidence CV distribution.

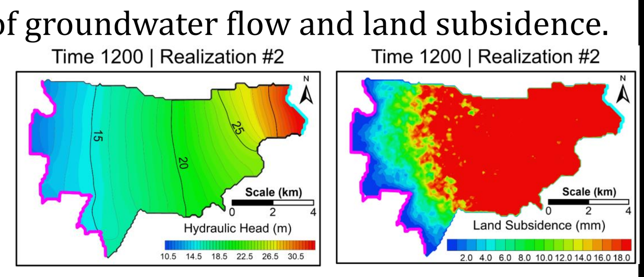


Fig. : Boundary condition perturbation by considering specified flow boundary.

Achievement #2: The Influence of Spatial Borehole Density on the Estimation of Geostatistical Properties and the Construction of HHMs

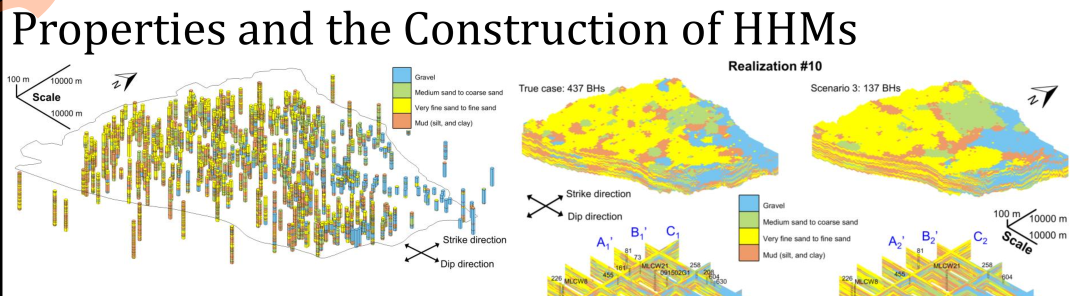


Fig. : Borehole distribution and generation of stochastic 3D HHMs.

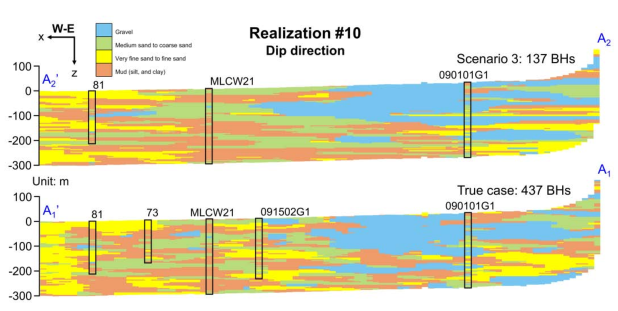


Fig. : Comparison of 2D hydrogeological cross-section of AA' in realization #10 between scenario 3 and the true case in the dip direction.

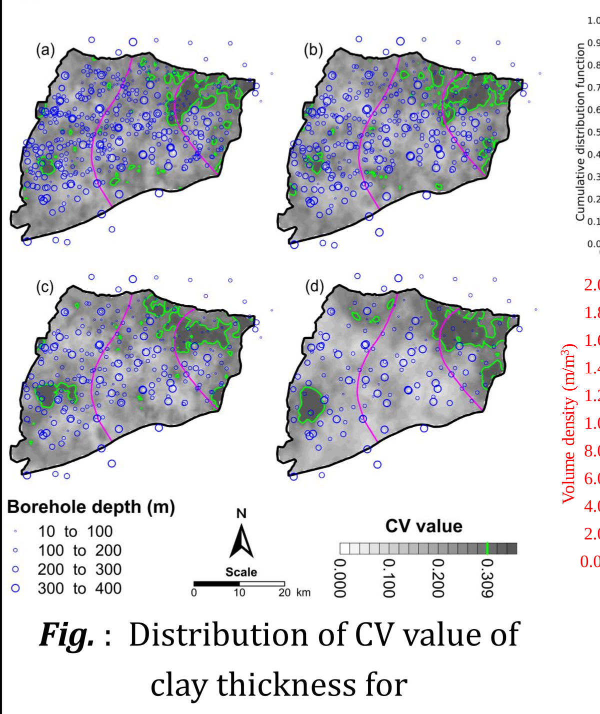


Fig. : Distribution of CV value of clay thickness for (a) the true case, (b) scenario 1, (c) scenario 2, and (d) scenario 3.

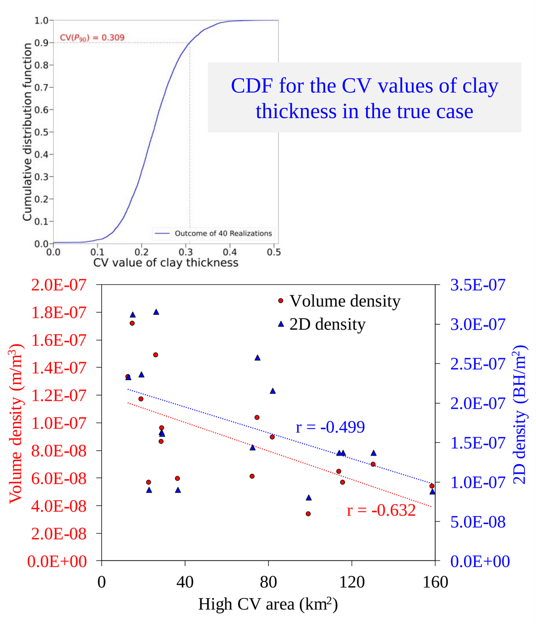


Fig. : Area of high uncertainty versus 2D borehole density and volume density.

Achievement #3: Using a HHM to Quantify the Deep Compression due to Shallow Groundwater Pumping

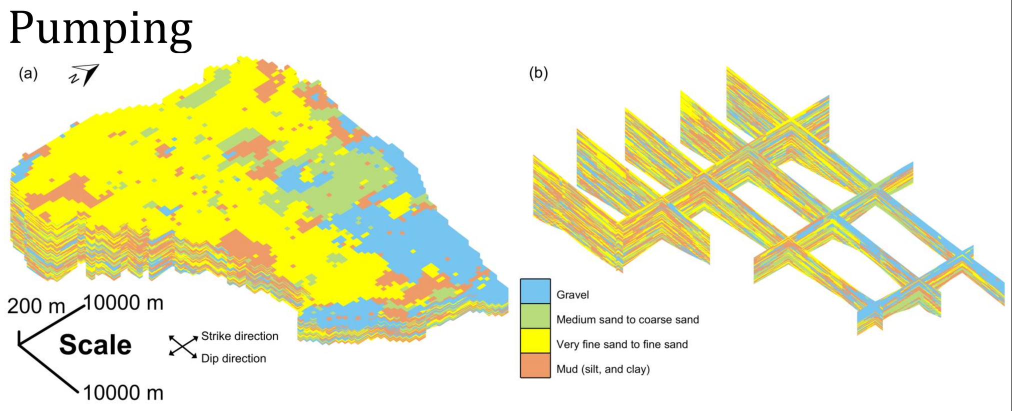


Fig. : The representative hydrogeological model used for groundwater flow and land subsidence simulations.

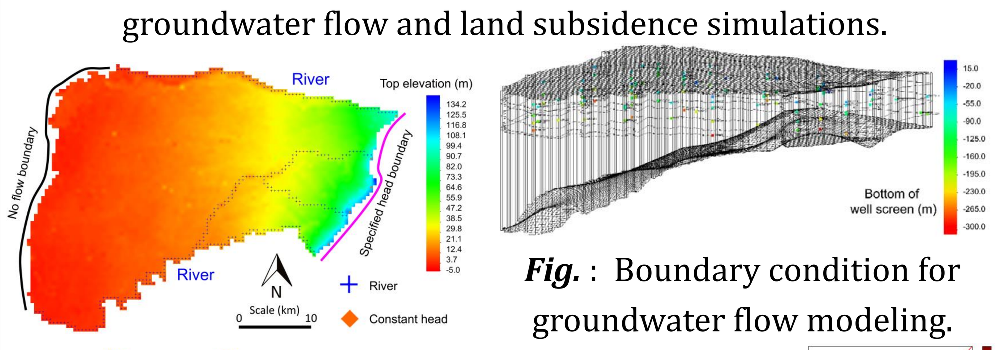


Fig. : Boundary condition for groundwater flow modeling.

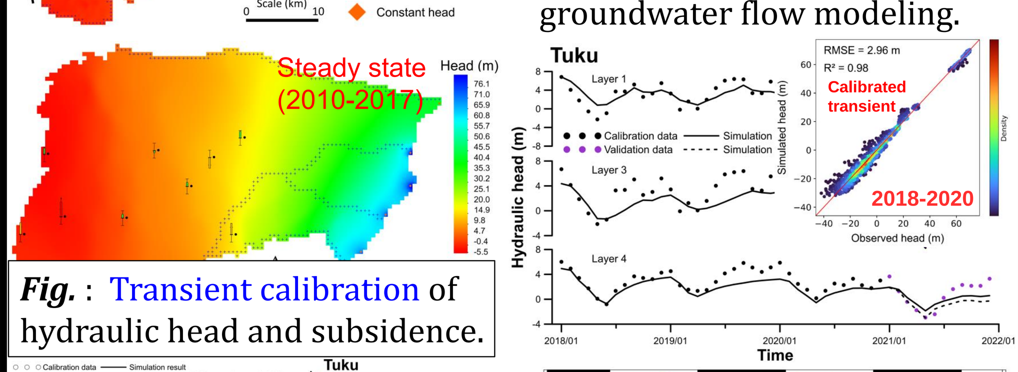
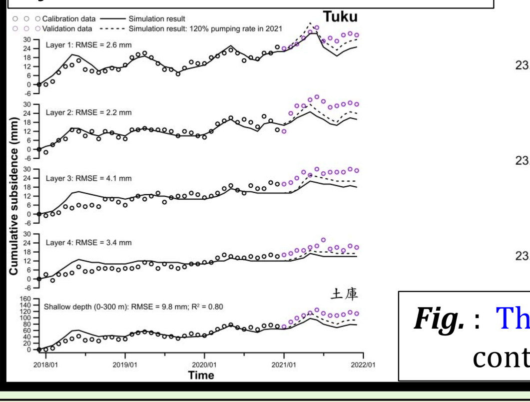


Fig. : Transient calibration of hydraulic head and subsidence.



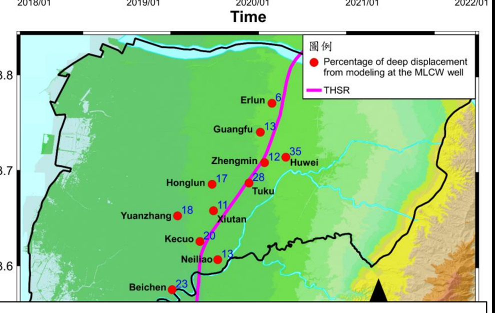


Fig. : The proportion of deep compression contribute to the total subsidence.

5. CONCLUSIONS

- In this study, **several points of knowledge** have been explored:
  - ➢ How importance of understanding the hydrogeological materials distribution.
  - ➢ How importance of not only the distribution of fine-grained material but also the prescribed boundary condition in the groundwater flow and land subsidence simulations.
  - ➢ How importance of the spatial borehole density such as depth of the borehole as volume density and the density of the borehole as 2D density.
- Those contributions above will be a big step forward in understanding the effects of **HHM uncertainty**. More specifically, the differences of the 3D heterogeneous aquifer system with **uncoupled model** (e.g., from fluid to geomechanics) and **poroelasticity model** (e.g., coupled geomechanics-fluid) will be explored in the near future.

* **REFERENCES**:

1. Herrera-García, G., Ezquerro, P., Tomás, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., . . . Shujun, Y. (2021). Mapping the global threat of land subsidence. *Science, 371*(6524), 34-36.
2. Tran, D.-H., Wang, S.-J., & Nguyen, Q. C. (2022). Uncertainty of heterogeneous hydrogeological models in groundwater flow and land subsidence simulations–A case study in Huwei Town, Taiwan. *Engineering Geology,* 106543. doi:https://doi.org/10.1016/j.enggeo.2022.106543
3. Troldborg, L. (2000). Effects of geological complexity on groundwater age prediction. *81*(48), F435.