The impact of climate conditions and pumping strategies on the groundwater system in the Mekong Delta, Vietnam

Kim-Hung Nguyen[1] and Chuen-Fa Ni[1]

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

Abstract: The Vietnamese Mekong Delta (VMD) is one of the largest economic centers in Vietnam, providing nearly 18 million people with food and water. Groundwater is the crucial water source for domestic, agricultural, and industrial uses in the VMD. For decades, groundwater levels have been depleting rapidly due to over-extraction and climate change, negatively impacting human lives and infrastructures. Therefore, it is necessary to understand the hydrological mechanisms and forecast the future changes in groundwater levels in the VMD, supporting groundwater resource management. This study adopted USGS-MODFLOW 2005 to develop a groundwater model and simulate the groundwater flow in the VMD. The model domain was generated based on input data, including stratigraphic columns from drilling boreholes, observed groundwater levels, river stages, and precipitation. The preliminary results showed that the transient-state model could relatively simulate the groundwater levels in the study area during 2000 - 2020 (RMSE = 0.89 m, NSE = 0.95). The calibrated model can be used to forecast groundwater level and salinity in each aquifer. The results demonstrated that, despite the deep aquifer suffering a greater rate of groundwater level decrease than the shallow aquifer, the intensity of groundwater salinity is less serious in deep aquifers, suggesting the necessity to have an efficient groundwater management strategy.

1. INTRODUCTION

The Mekong Delta, located in southern Vietnam, is one of the largest deltas in the world, providing food and residence for over 18 million people (**Fig. 1**). Since the 1990s, people have started to extract groundwater for domestic and industrial use. Due to over-extraction and climate change effects, groundwater levels in the VMD have been depleting rapidly (Le Duy et al., 2021). Along with declining groundwater levels, groundwater resources in the VMD are being salted, as seen by the rising total dissolved solids (**Fig. 2**). For sustainable development in the VMD, a reasonable groundwater management strategy is essential.

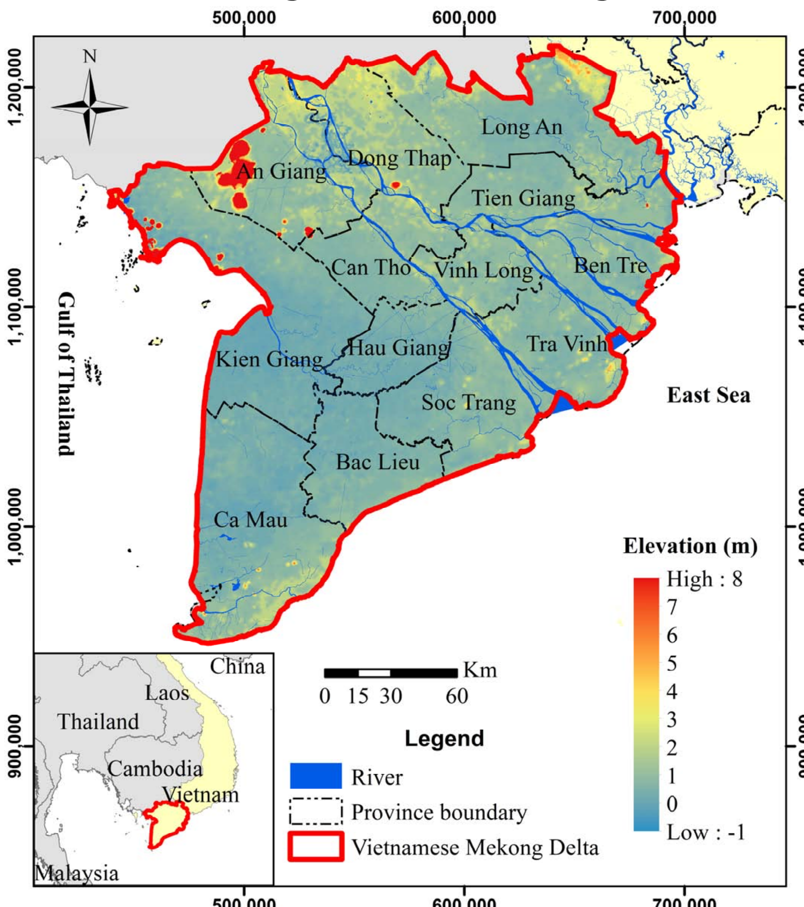

Fig. 1: Study area and elevation of the VMD.

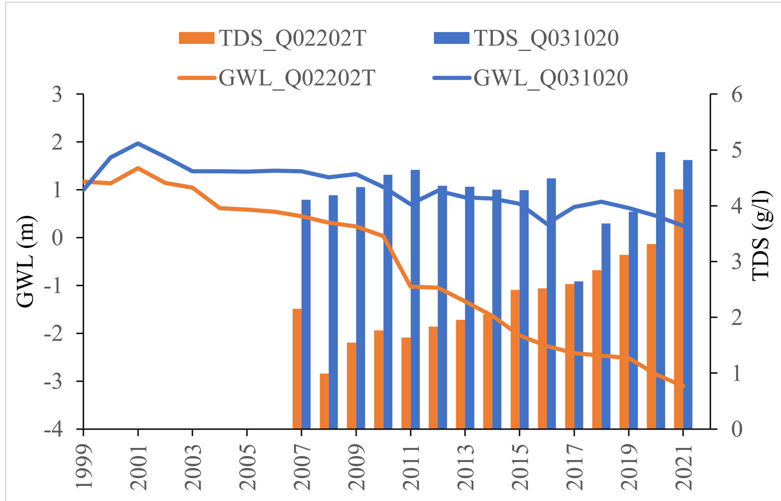

Fig. 2: Observed GWL and TDS

This study aims to predict Groundwater Quantity and Quality in the VMD until 2100 under various climate and human activity scenarios, which helps to identify areas highly prone to environmental hazards. Furthermore, this study can be a reference for decision-makers to introduce appropriate future groundwater management strategies.

2. METHODOLOGY

GROUNDWATER FLOW SIMULATION — **MODFLOW**: three-dimensional (3D) transient groundwater flow, heterogeneous and anisotropic

GROUNDWATER SOLUTE TRANSPORT — **MT3D**: Groundwater Solute Transport Simulator for MODFLOW

VARIABLE-DENSITY GROUNDWATER FLOW AND TRANSPORT — **SEAWAT**: Variable-density groundwater flow and transport. Coupled version of MODFLOW and MT3D

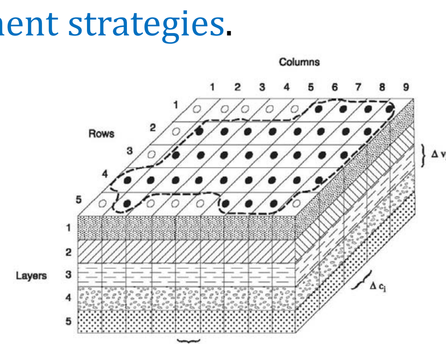

Fig. 3: A discretized hypothetical aquifer system. (Modified from McDonald and Harbaugh, 1988.).

MODEL EVALUATION

Mean Absolute Error: $MAE = \frac{1}{n}\sum |h_{obs} - h_{sim}|_i$

Root Mean Squared Error: $RMSE = \sqrt{\frac{1}{n}\sum (h_{obs} - h_{sim})_i^2}$

Nash-Sutcliffe efficiency: $NSE = 1 - \frac{\sum |h_{obs} - h_{sim}|_i^2}{\sum |h_{obs} - \overline{h_{obs}}|_i^2}$

Where: h_{obs}: observed heads
h_{sim}: simulated heads
n: number of observations
$\overline{h_{obs}}$: mean of observed head

(Anderson et al., 2015)

3. GROUNDWATER MODEL SETUP

3.1. Groundwater flow model

In the study area, aquifer systems are divided into eight aquifers based on formation age: Holocene (qh), Upper Pleistocene (qp_3), Middle Pleistocene (qp_{2-3}), Lower Pleistocene (qp_1), Middle Pliocene (n_2^2), Lower Pliocene (n_2^1), Upper Miocene (n_1^3), and Middle Miocene (n_1^{2-3}) (not considered due to a lack of data) (Van Pham et al., 2019)

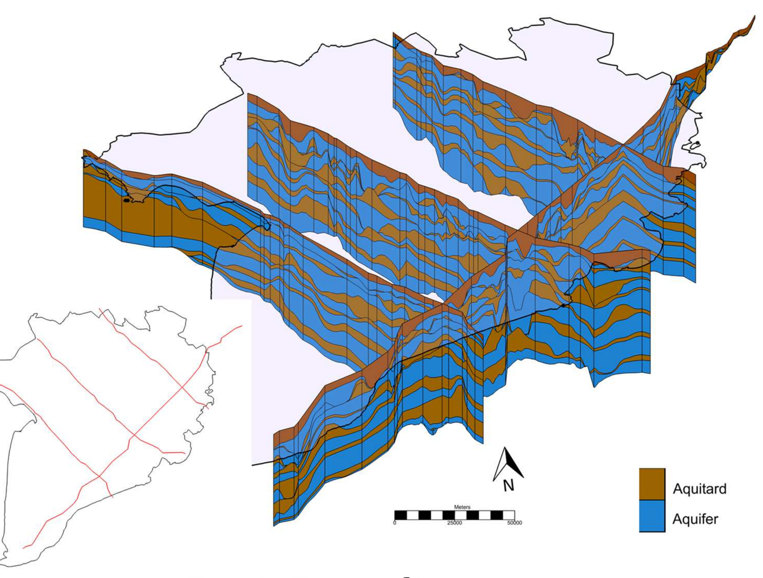

Fig 4: Fence diagram of groundwater system in the VMD.

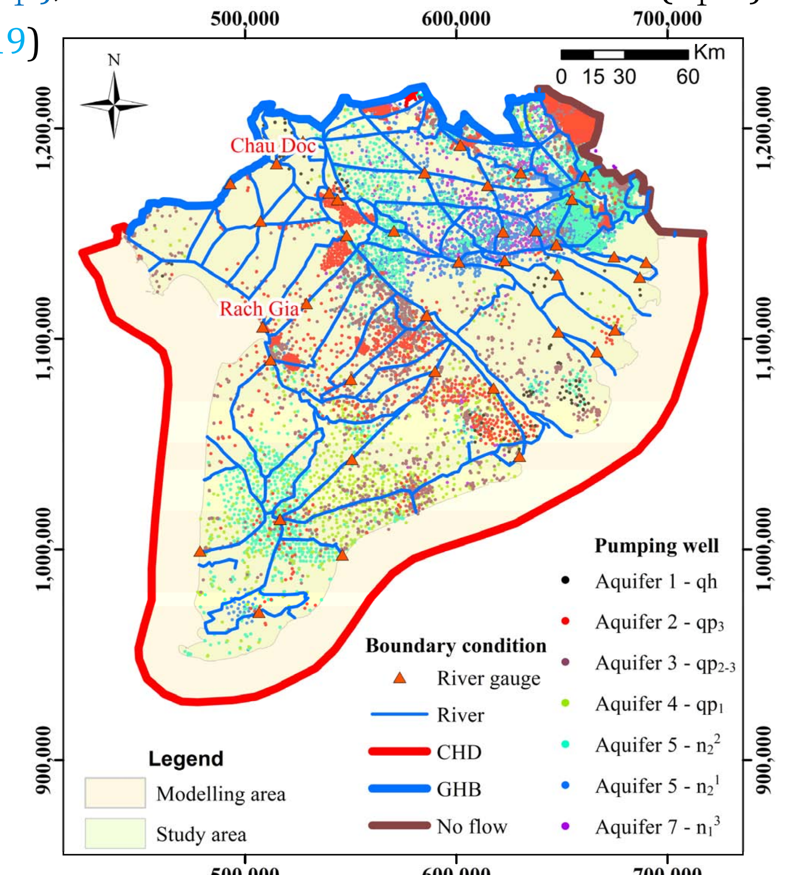

Fig. 5: Modeling area and boundary conditions for groundwater flow model.

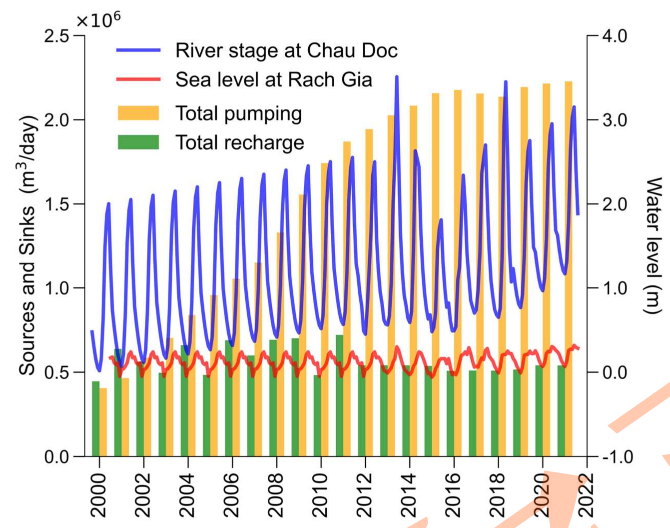

Fig. 6: Observed groundwater levels.

3.2. Groundwater salinity model

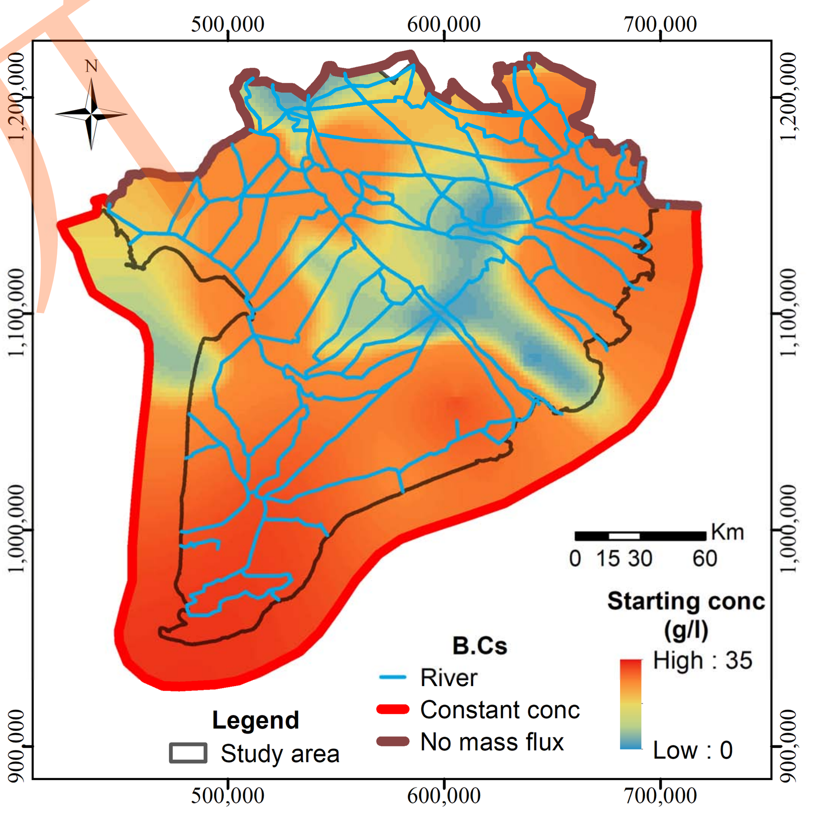

Fig. 7: Boundary conditions for groundwater salinity model.

3.3. Future scenarios

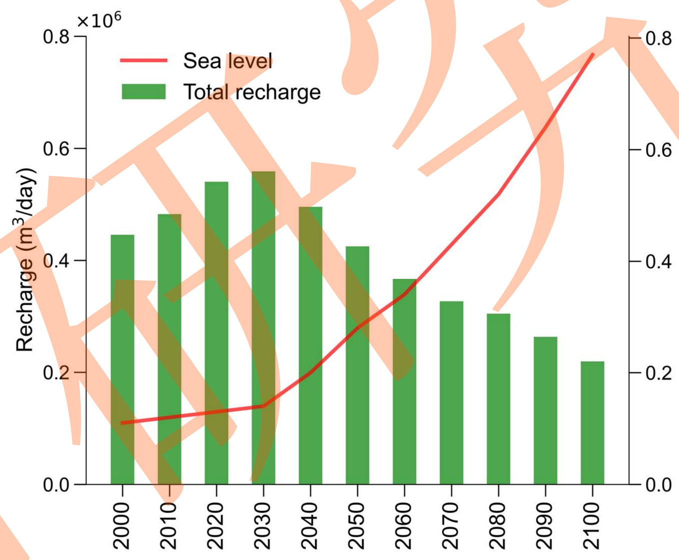

Fig. 8: Future boundary conditions.

4. RESULTS AND DISCUSSION

4.1. Groundwater flow

Groundwater flow model calibration

Solve the inverse problem by history matching: **simulated head versus observed head**. Parameters were adjusted, such as hydraulic conductivity, storativity, recharge rate, and boundary conditions (Anderson et al., 2015).

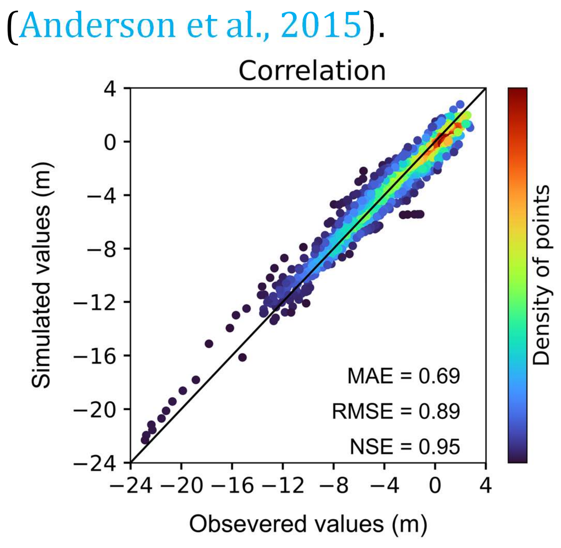

Fig. 9: Observed vs. Simulated GWL.

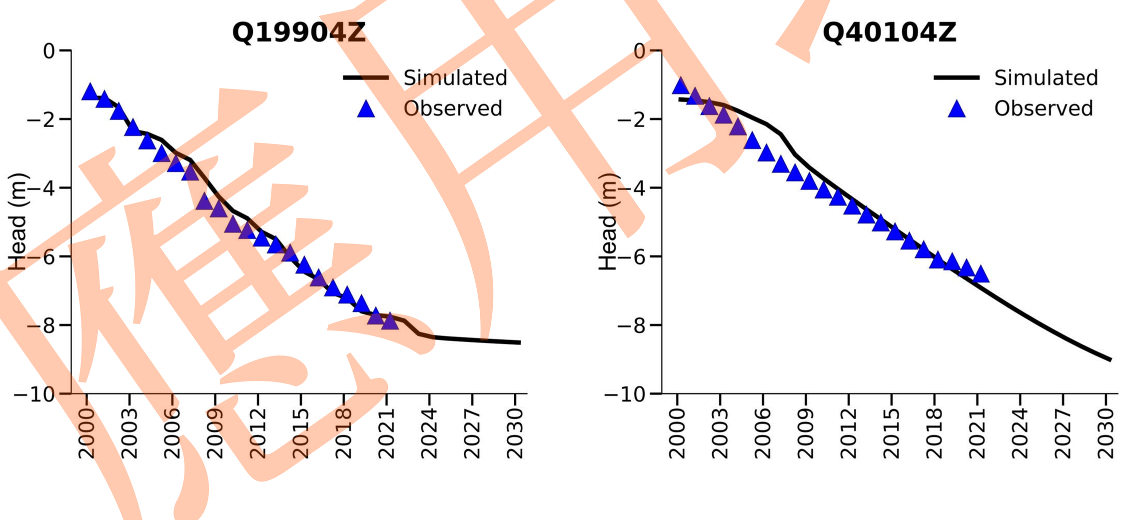

Fig. 10: Observed vs. Simulated GWL

Forecasting groundwater level

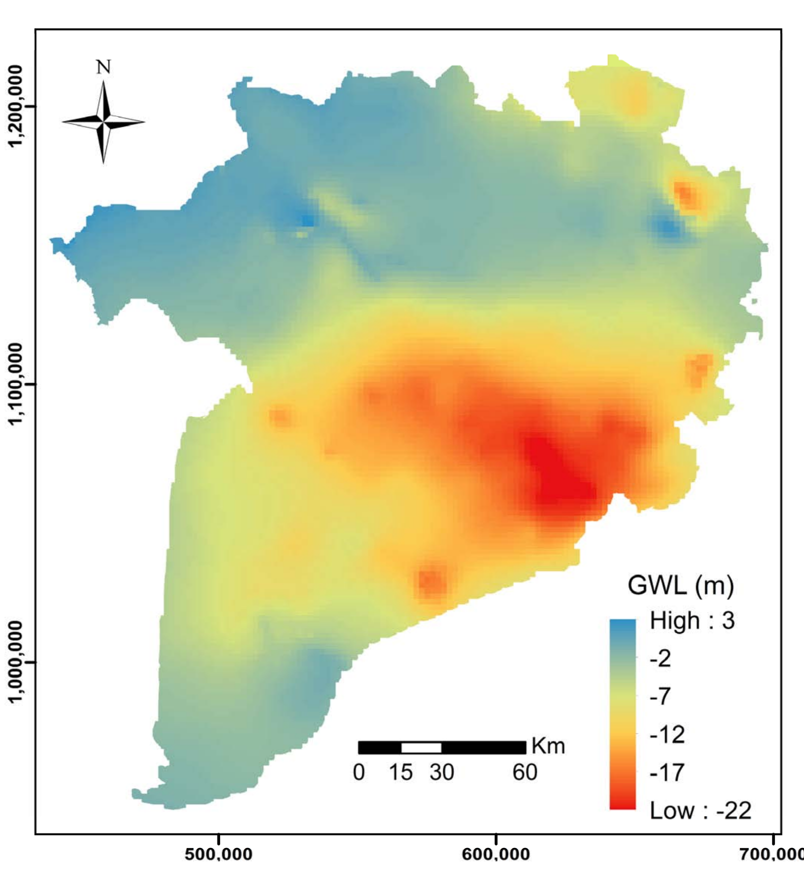

Fig. 11a: Simulated GWL for the Upper Pleistocene aquifer in 2100.

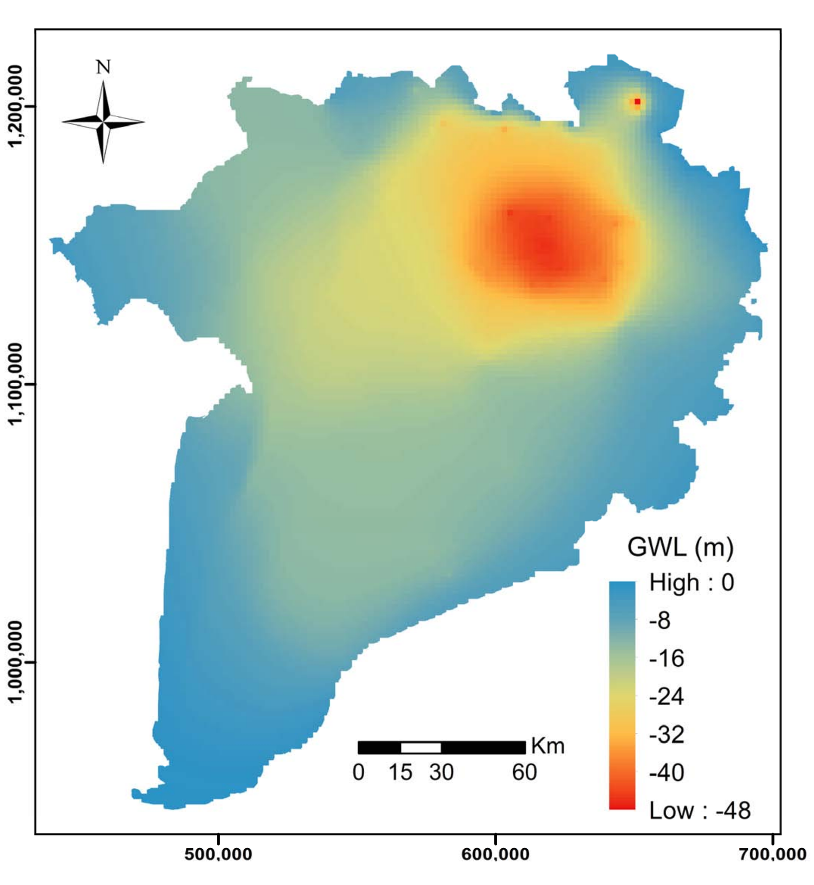

Fig. 11b: Forecasted GWL for the Upper Miocene aquifer in 2100

4.2. Groundwater salinity

Groundwater salinity model calibration

Similar to the groundwater flow model, the groundwater salinity model also needs to be calibrated before it can be used to predict groundwater salinity in the future. The acceptable range of TDS error is below 3.5 g/l, NSE > 0.75 (Zheng et al., 2012). Once the model is able to hindcast groundwater salinity, it will be used to predict groundwater salinity in the future.

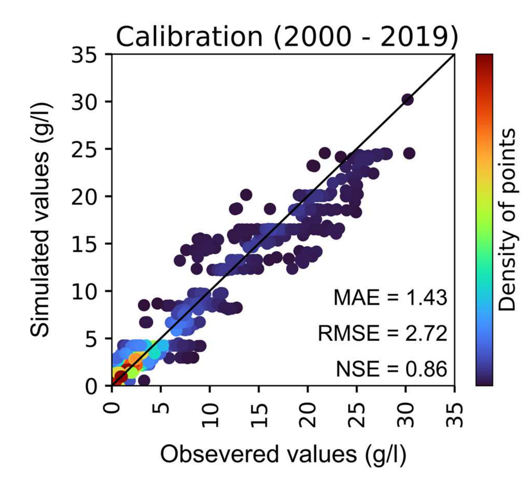

Fig. 12: Observed vs. Simulated TDS.

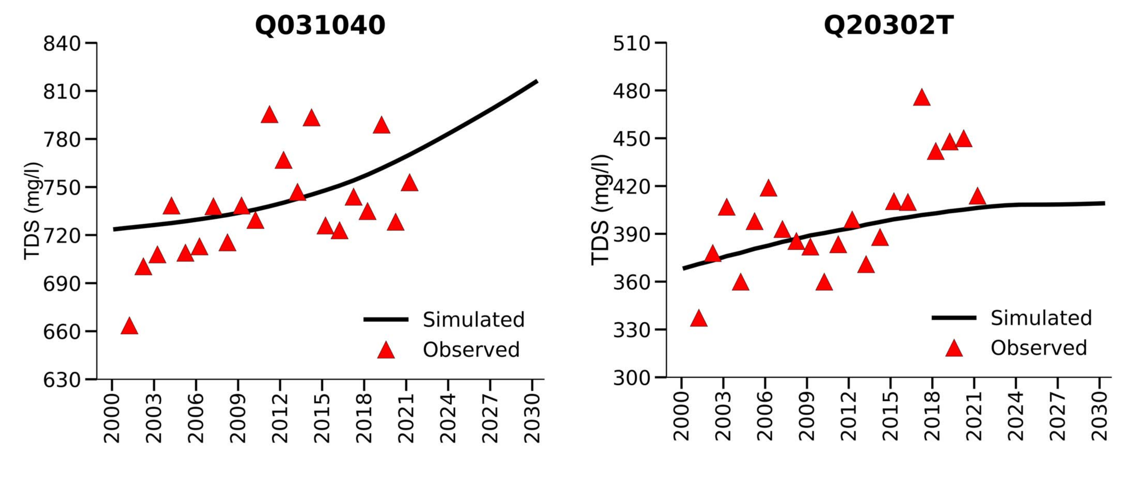

Fig. 13: Observed vs. Simulated TDS.

Predicting salinity

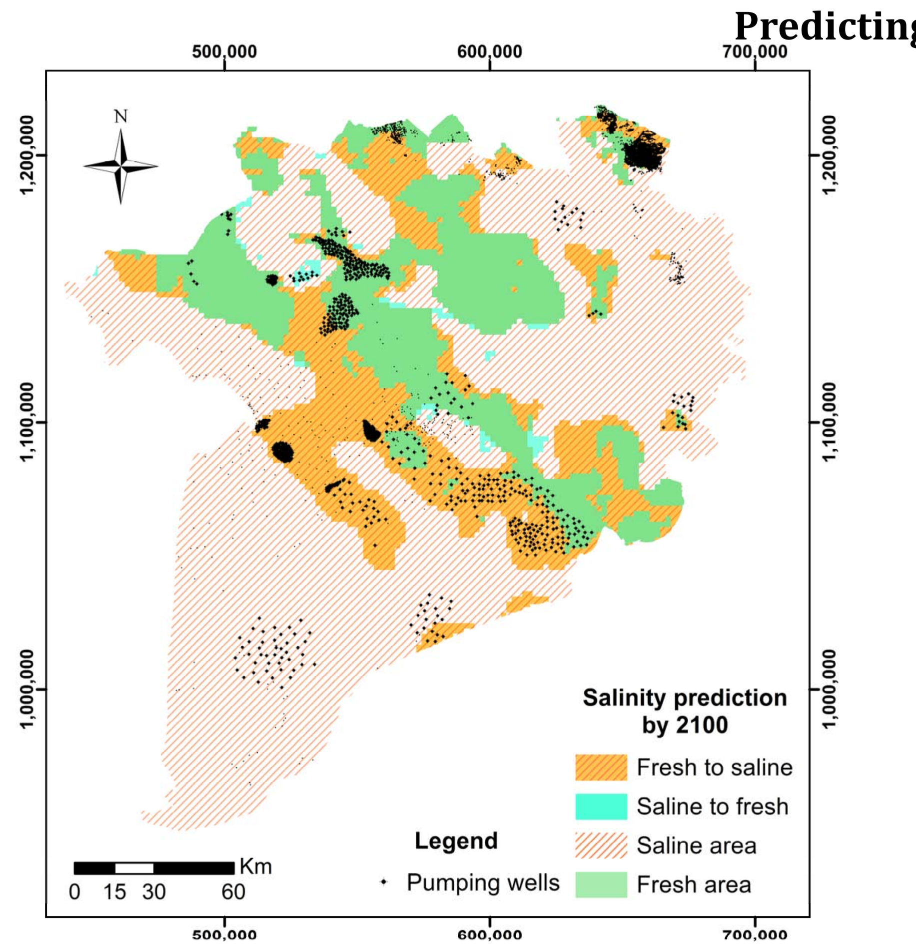

Fig. 14: Predicted salinity for the Upper Pleistocene aquifer

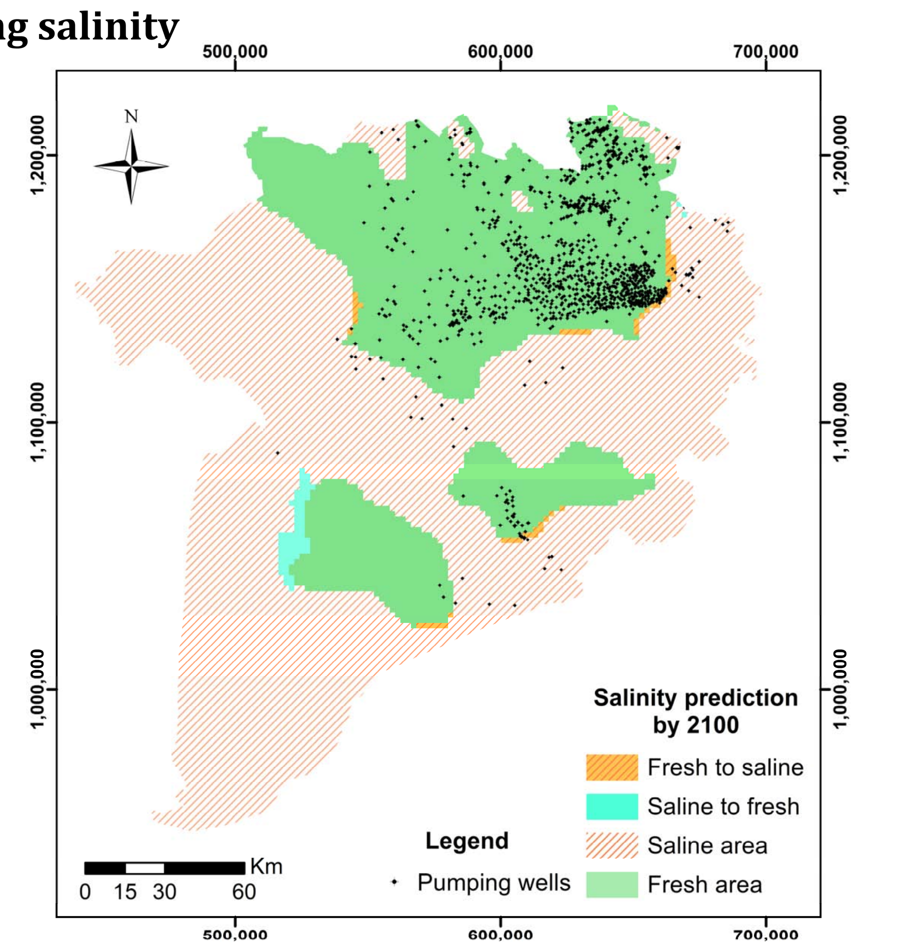

Fig. 15: Predicted salinity for the Upper Miocene aquifer

* Saline water is defined as water that has TDS > 1500 mg/l.

5. CONCLUSIONS

This study successfully developed a numerical model to simulate the complex groundwater system in the VMD. The calibrated model can be used to forecast groundwater level and salinity in the future by applying reasonable scenarios. The model results show that (1) groundwater levels will continue to decline, especially in deep aquifers where groundwater extraction is concentrated. (2) Less salinity has been seen in deep aquifers compared to shallow aquifers, demonstrating the necessity and efficacy of having a suitable groundwater management strategy.

⇒ Apply this study: find a suitable groundwater resource management strategy.

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Kim-Hung Nguyen
Email: kimhungdctv@gmail.com
Tel: +886 965429408

Chuen-Fa Ni
Email: nichuenfa@geo.ncu.edu.tw
Tel: +886-3-4227151 ext. 65874