Numerical Study of Groundwater Transfer and Injection Pilot Project in the Mississippi River Valley Alluvial Aquifer using a Groundwater Model with Airborne Resistivity Data

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Extended Abstract

Declines in groundwater levels resulting from agricultural irrigation have been observed and reported for the past decades in the Mississippi River Valley Alluvial Aquifer (MRVAA), showing that the current management of groundwater resources is not sustainable. To mitigate this problem, a Groundwater Transfer and Injection Pilot (GTIP) project was initiated by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) at Shellmound, Mississippi (MS) by combining riverbank filtration with groundwater transfer and injection. One extraction well was positioned near the Tallahatchie River while two injection wells were installed 3.0 km west of the extraction site (Figure 1). The extraction and injection sites were connected through a pipeline. To monitor the responses of the regional groundwater to the GTIP operation, seventeen observation wells were drilled in the vicinity of the extraction and injection sites, in which fourteen were in the MRVAA, and three were in the underlying Sparta aquifer. An experimental operation was conducted by USDA-ARS from 4/14/2021 to 7/13/2021 to preliminarily assess the impact of the GTIP project.

Field experiments and measurements are essential to test the feasibility of the project, while numerical modeling is important for the evaluation of potential designs. Therefore, a numerical groundwater model, CCHE3D-GW (Fang et al., 2019), was developed for this pilot project. The modelling domain was chosen based on the spatial distribution of the hydraulic head in the MRVAA (shown as the color map in Figure 1a). The outlines of the modelling domain (Figure 1b) generally followed the hydraulic gradient of the groundwater head to reduce the impact from the lateral boundaries. This domain was approximately 10 × 10 km in the horizontal plane, which was discretized by 141 × 128 non-uniform mesh points. The finest mesh size in the *x*-*y* plane was 5.0 m which was used for the areas near the extraction and injection wells (Figure 2a). The

simulated aquifer was 52.0 m thick, and it was represented by 21 non-uniform layers (Figure 2b). The screen interval of the extraction well was from 6.40 to 21.64 m above the NAVD 88 datum, while the screen interval of the injection well was from 4.57 to 16.76 m above the NAVD 88 datum.

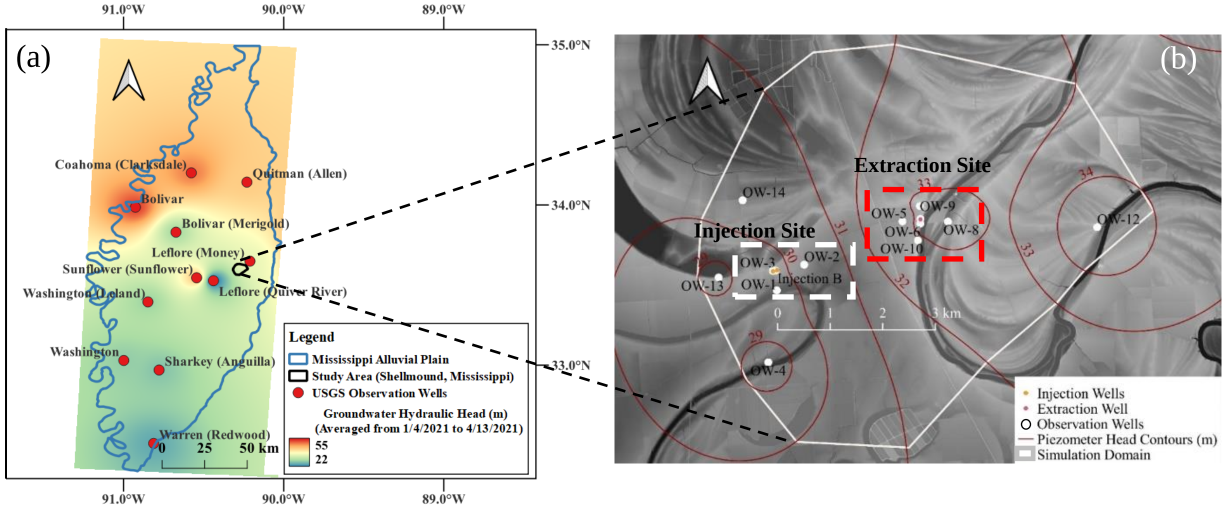


Figure 1. (a) Location of the study site in which the color map represents the spatial distribution of the mean hydraulic head from 1/4/2021 to 4/13/2021 and (b) the detailed layout of the experimental GTIP project at Shellmound, MS.

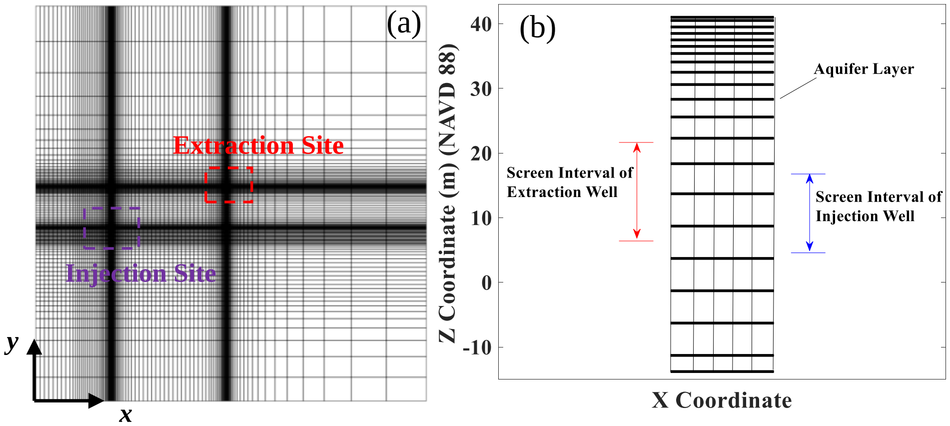


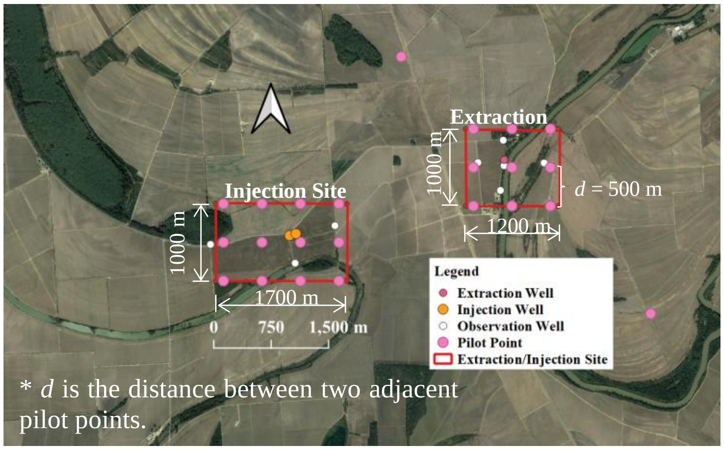
Figure 2. (a) Configuration of the mesh in $x - y$ plane and (b) the setup of the mesh in z direction.

Groundwater modelling results can be substantially affected by the spatial distribution of the aquifer hydraulic properties (Desbarats and Srivastava, 1991; Fogg et al., 1999; Weissmann and Fogg, 1999). However, it is generally impossible to measure the hydraulic conductivity distribution directly. Considering the correlation between the sediment resistivity and the hydraulic conductivity, airborne resistivity data measured by the U.S. Geological Survey (Burton et al., 2020) were incorporated into the groundwater model. An empirical formula from Purvance and Andricevic (2000) was used to translate the resistivity into the hydraulic conductivity, which is written as:

$$K = a \cdot R^b$$

where K is hydraulic conductivity (m/s); R is the measured bulk resistivity (Ω·m); a and b are unknown parameters which were determined by calibrating the numerical model with the measured groundwater heads in the monitoring wells. The calibration period was from April 14 to April 18, 2021.

The spatial distribution of the parameters (a and b) in the empirical formula of Purvance and Andricevic (2000) were considered by introducing pilot points (Figure 3). After obtaining the values of a and b at the pilot points, ordinary kriging was used to interpolate the values at the mesh points. In this study, an exponential variogram was applied in which the sill was set to 1.0, and range was set to 10000.0 m. Although this pilot-points method has been applied to calibrating the spatial distribution of the aquifer hydraulic conductivity using the airborne resistivity data (e.g., Christensen et al., 2017), it is still unclear how many pilot points are needed to obtain the optimal result. Therefore, a set of numerical experiments was conducted in this study. As shown in Figure 3, the distance between two adjacent pilot points is represented by d. By changing the value of d, the number of pilot points varies. Four sets of pilot points were studied, which were (a) one pilot point, (b) d = 500.0 m (23 pilot points), (c) d = 300.0 m (46 pilot points) and (d) d = 100.0 m (343 pilot points). The calibration was done with PEST++GLM (White et al., 2020).



* d is the distance between two adjacent pilot points.

Figure 3. Layout of the pilot points in the simulation domain.

The quality of the calibration, which is the agreement between the simulated and measured groundwater head changes, was evaluated by the coefficient of determination (R^2) and the non-dimensional root mean square error (NRMSE). The NRMSE is computed as:

$$\text{NRMSE} = \frac{\text{Root Mean Square Error}}{\text{Maximum Measured Value - Minimum Measured Value}}$$

It can be seen that the quality of the calibration is generally improved with more pilot points (Figure 4). The best-fit result was obtained when d = 300.0 m. Due to overfitting, the quality of the calibration declines slightly when reducing d from 300.0 m to 100.0 m (Figure 4c and d). It indicates that d = 300.0 m is sufficient to produce the optimal calibration result.

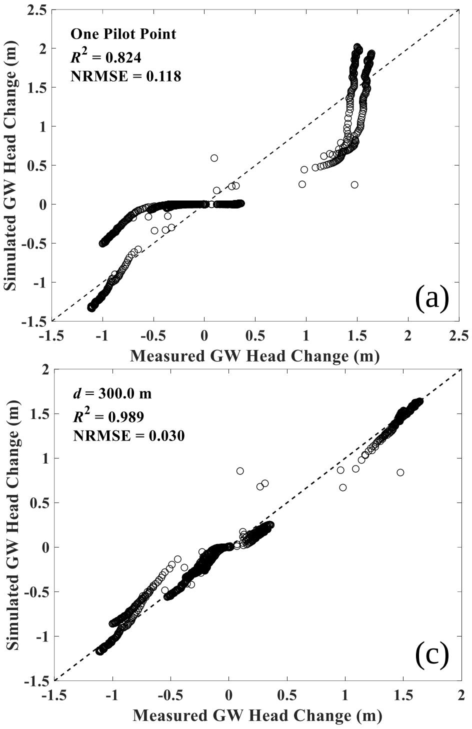


Figure 4. Comparisons between the measured groundwater head changes and the results simulated with (a) one pilot points, (b) *d* = 500.0 m, (c) *d* = 300.0 m and (d) *d* = 100.0 m during the calibration period.

The best-fit calibration model was then validated with the measured data from April 19 to May 22 in 2021. Good agreement can be observed between the simulated and measured groundwater head changes during the validation period (Figure 5), indicating the potential of using numerical groundwater models and airborne resistivity to facilitate the decision-making on the designs of the GTIP project.

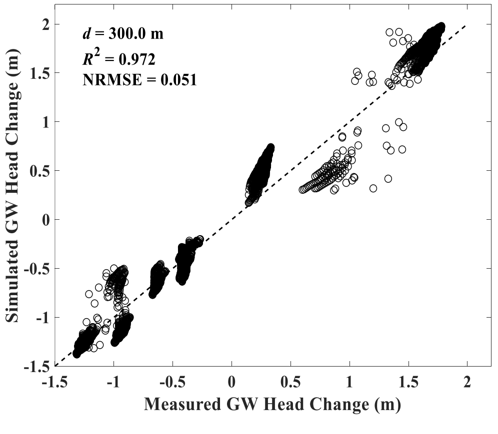


Figure 5. Comparisons between the measured groundwater head changes and the results simulated with the best-fit calibration model during the validation period.

References

Burton, B.L., Minsley, B.J., Bloss, B.R., Kress, W.H., Rigby, J.R., and Smith, B.D., 2020, "Highresolution airborne geophysical survey of the Shellmound, Mississippi area," U.S. Geological Survey Scientific Investigations Map 3449, 2 sheets, https://doi.org/10.3133/sim3449.

Christensen, N.K., Ferre, T.P.A., Fiandaca, G., and Christensen, S. 2017. "Voxel inversion of airborne electromagnetic data for improved groundwater model construction and prediction accuracy," Hydrology and earth system sciences, 21(2):1321-37.

Desbarats, A. J. and Srivastava, R. M. 1991. "Geostatistical characterization of groundwater flow parameters in a simulated aquifer," Water Resources Research, 27:687–698, doi:10.1029/90WR02705, 1991.

Fang, J., Jia, Y., Ozeren, Y., and Rigby, J.R. 2019. "Numerical studies of ground water flow near a partially penetrated well and an alluvial river." Proceedings of the 38th IAHR World Congress, Panama City, Panama, September 1 to 6.

Fogg, G. E., LaBolle, E. M., and Weissmann, G. S. 1999. "Groundwater Vulnerability Assessment: Hydrogeologic Perspective and Example from Salinas Valley, California," American Geophysical Union, Washington, DC.

Purvance, D. T. and Andricevic, R. 2000. "On the electrical-hydraulic conductivity correlation in aquifers," Water Resources Research, 36:2905–2913, doi:10.1029/2000WR900165.

Weissmann, G. S. and Fogg, G. E. 1999. "Multi-scale alluvial fan heterogeneity modeled with transition probability geostatistics in a sequence stratigraphic framework," Journal of Hydrology, 226:48–65, doi:10.1016/S0022-1694(99)00160-2.

White, J.T., Hunt, R.J., Fienen, M.N., and Doherty, J.E. 2020. "Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis," U.S. Geological Survey Techniques and Methods 7C26, 51 p., https://doi.org/10.3133/tm7C26.