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HYDROGEOLOGICAL MODELING OF PROCESSES IN INTENSIVELY IRRIGATED AREAS: A CASE STUDY OF THE MALIK AREA

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Abstract
This study presents the results of mathematical modeling of hydrogeological processes in intensively irrigated areas using the Malik experimental site as a case study. The investigated area is characterized by a four-layer hydrogeological structure consisting of cover sandy loams and loams, gravel-bearing sand deposits, low-permeable loam layers, and underlying sandy aquifers. A pumping test conducted at well 2ts and observation wells was used to evaluate the hydrogeological parameters of the aquifer system. Preliminary hydraulic conductivity coefficients were determined using the AquiferTest software package, followed by calibration of a numerical groundwater flow model. During the modeling process, calculated groundwater levels were compared with observed data, and filtration parameters together with storage coefficients were adjusted to minimize discrepancies between measured and simulated groundwater heads. The calibrated hydraulic conductivity values were determined as 0.03 m/day for cover loams, 5 m/day for gravelly sands, 0.02 m/day for dense loams, and 14 m/day for fine-grained sands. The results showed that irrigation infiltration and collector-drainage systems significantly influence groundwater regime formation in intensively irrigated areas. The developed mathematical model can be used for groundwater regime prediction and assessment of meliorative conditions in irrigated lands.

Keywords: Hydrogeological modeling, groundwater flow, pumping test, AquiferTest, hydraulic conductivity, groundwater regime, infiltration, irrigated areas, collector-drainage network, numerical model, Malik experimental site.

Introduction

Groundwater regime formation in intensively irrigated areas is controlled by a complex interaction between irrigation infiltration, evapotranspiration, collector-drainage systems, and regional hydrogeological conditions. In arid and semi-arid regions, irrigation recharge often represents the dominant source of groundwater replenishment and significantly affects groundwater levels, soil salinity, and meliorative conditions of agricultural lands [2,4]. Recent studies have demonstrated the effectiveness of numerical groundwater flow models for assessing aquifer response to irrigation practices and for predicting long-term changes in groundwater regimes [2,4,8].

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Hydrogeological investigations conducted in Uzbekistan have also demonstrated the importance of groundwater filtration assessment for understanding groundwater regime formation and groundwater discharge processes [3].

Hydrogeological modeling based on pumping-test interpretation and numerical simulation has become an important tool for estimating aquifer parameters and evaluating groundwater flow processes. Modern modeling approaches commonly combine pumping-test analysis with numerical groundwater models developed using MODFLOW-based platforms, allowing calibration of hydraulic conductivity and storage parameters using field observations [1,2].

Despite the importance of irrigated agriculture in the Syrdarya region, detailed hydrogeological modeling studies for the Malik experimental site remain limited. Therefore, the objective of this study was to develop and calibrate a numerical groundwater flow model for the Malik experimental site using pumping-test data and groundwater-level observations. Particular attention was given to determining hydraulic conductivity parameters of the multilayer aquifer system and evaluating the influence of irrigation infiltration and collector-drainage systems on groundwater regime formation.

Materials and Methods

The study was carried out at the Malik experimental site located in the Syrdarya district of the Syrdarya region, Republic of Uzbekistan [6]. Malik is an urban-type settlement that received its official settlement status in 2009. The geographical location of the study area within the Syrdarya region is presented in Figure 1.

Figure 1. Map of the Syrdarya region and location of the Malik experimental site

The hydrogeological structure of the study area consists of cover sandy loams and loams, gravel-bearing sand deposits, low-permeable loam layers, and underlying sandy aquifers. Based on lithological and hydrogeological data, the study area was schematized into four model layers.

Hydrogeological parameters were evaluated using data from a pumping test conducted at well 2ts with a depth of 105 m. Groundwater responses were monitored in observation wells 2ts/1n, 5k/2, 5k/3, and 5k/9. Groundwater levels were measured at 6-hour intervals during a 72-hour pumping test using electric water-level meters with ±0.01 m accuracy. Measurements were conducted in four observation wells (2ts/1n, 5k/2, 5k/3, 5k/9) during pumping and recovery phases.

Preliminary hydrogeological parameters, including transmissivity (T), hydraulic conductivity (K), and storage coefficient (S), were estimated using AquiferTest Pro software based on pumping-test drawdown data. The interpretation results served as initial parameter values for numerical modeling.

A three-dimensional groundwater flow model was developed using the Groundwater Modeling System (GMS) with the MODFLOW-NWT numerical engine. The model was solved using the Preconditioned Conjugate Gradient (PCG2) solver with a head convergence criterion of 0.01 m and a flow imbalance tolerance of 0.001 m^3/day. The model domain covered an area of 5.0 × 6.0 km and was discretized into 250 rows and 300 columns with a uniform grid spacing of 20 m. Vertically, the model consisted of four hydrogeological layers corresponding to the geological structure of the study area.

Initial groundwater conditions were assigned using groundwater monitoring data collected during 2023-2024. Variable-head boundary conditions were specified along the northeastern and southwestern boundaries of the model, whereas the southern boundary was considered impermeable. Irrigation canals and collector-drainage systems were represented as third-type (Cauchy) boundary conditions to simulate hydraulic interaction between surface water bodies and groundwater.

Model calibration was performed using a manual inverse modeling approach. Hydraulic conductivity and storage parameters were adjusted iteratively to minimize the differences between observed and simulated groundwater heads. The objective function was defined as the root mean square error (RMSE).

Results and Discussion. The hydrogeological structure of the Malik experimental site is characterized by a four-layer system composed of cover sandy loams and loams, the gravel-bearing aquifer layer QIIIsd, a low-permeable heavy loam interlayer, and the underlying aquifer layer QIIts. Based on these lithological conditions, the study area was schematized into four model layers. The first layer consisted of cover sandy loams and loams with a thickness of 21.6 m, associated with the groundwater table. The second layer was represented by heterogeneous sand with gravel inclusions (28.4 m), the third layer by dense loams (36.5 m), and the fourth layer by fine-grained sands (18.5 m).

To evaluate hydrogeological parameters, a pumping test was conducted at well 2ts with a depth of 105 m. Observation wells 2ts/1n, 5k/2, 5k/3, and 5k/9 were used for groundwater level monitoring during the pumping process. A conceptual and numerical model of the pumping test at the Malik experimental site is presented in Figure 2.

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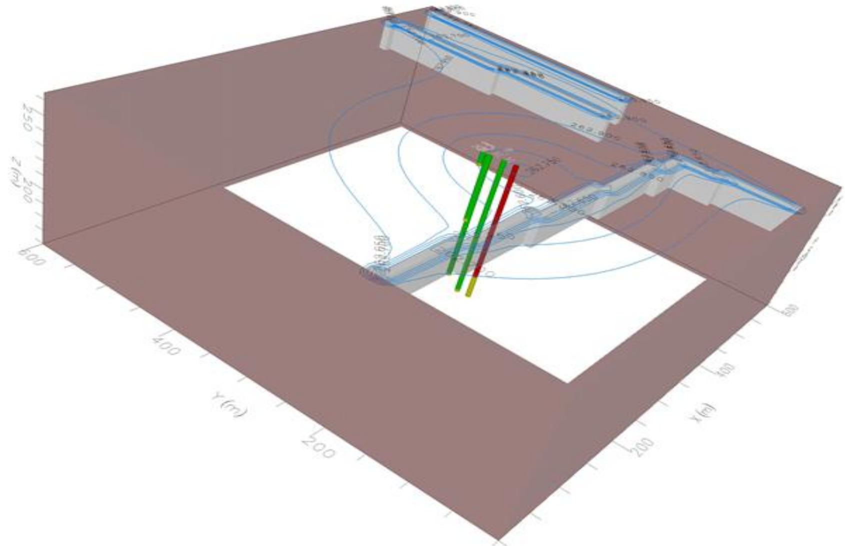

Figure 2. Model of the pumping test at the Malik experimental site

Preliminary hydraulic conductivity coefficients were estimated using the AquiferTest software package based on pumping test data. The obtained hydrogeological parameters are presented in Figure 3.

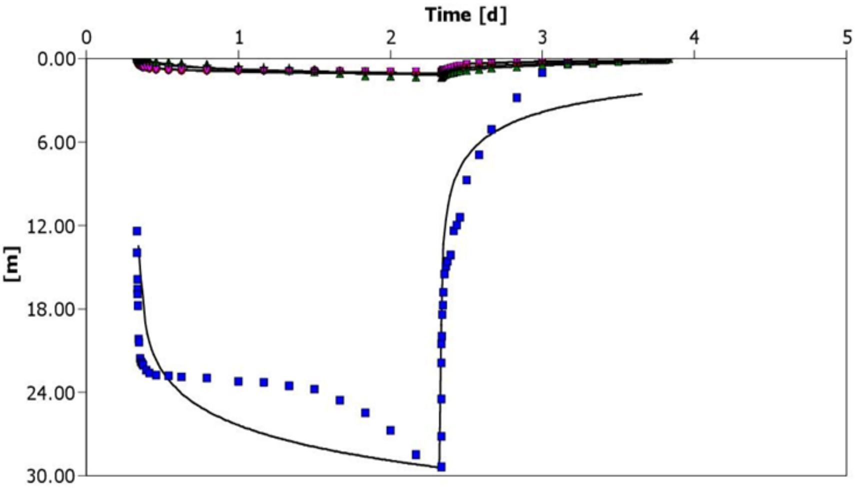

Figure 3. Preliminary estimation of transmissivity, hydraulic conductivity and storage parameters based on pumping-test interpretation using AquiferTest Pro software

Figure 3 shows the results of pumping-test interpretation obtained using AquiferTest Pro software. The estimated transmissivity (T), hydraulic conductivity (K), and storage coefficient (S) were used as initial parameter values for calibration of the MODFLOW groundwater flow model.

During the calibration process, simulated groundwater levels were compared with observed data obtained from the observation wells. Hydraulic conductivity, specific yield, and elastic storage coefficients were adjusted to minimize discrepancies between measured and modeled groundwater heads. Comparative graphs of observed and simulated groundwater levels are presented in Figure 4.

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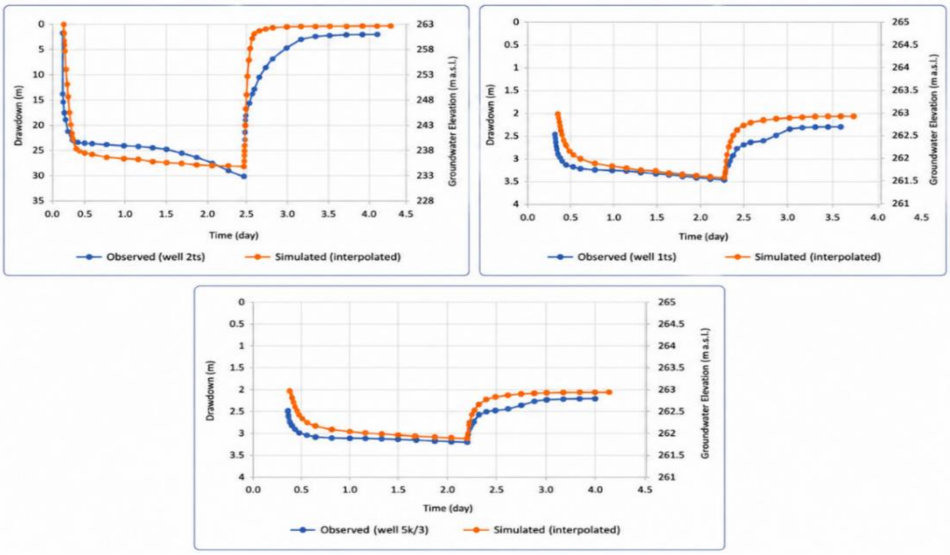

Figure 4. Comparative graphs of observed and simulated groundwater levels for observation wells during pumping test modeling

According to the modeling results, the calibrated hydraulic conductivity coefficients were determined as 0.03 m/day for the first layer composed of cover sandy loams and loams, 5 m/day for the second gravel-bearing sand layer, 0.02 m/day for the third dense loam layer, and 14 m/day for the fourth fine-grained sand layer. These values indicate considerable heterogeneity of the filtration properties within the lithological sequence and confirm the significant influence of geological structure on groundwater flow processes.

Initial groundwater conditions were assigned using groundwater monitoring data obtained from observation wells during 2023-2024. Boundary conditions were defined according to the regional direction of groundwater flow. Variable-head boundaries were specified along the northeastern and southwestern parts of the model domain, while the southern boundary was represented as impermeable. Internal model boundaries included irrigation canals and collector-drainage systems represented by third-type boundary conditions reflecting hydraulic interaction between surface water bodies and the aquifer system.

The numerical model domain covered an area of 5.0 × 6.0 km and was discretized into 250 rows and 300 columns with a grid spacing of 20 m. Vertically, the model consisted of four hydrogeological layers corresponding to the lithological structure of the study area. The obtained results demonstrated that irrigation infiltration and collector-drainage systems are the dominant factors controlling groundwater regime formation in intensively irrigated territories. Scenario analysis indicates that irrigation infiltration contributes approximately 35-55% of total groundwater recharge in the study area, significantly influencing seasonal groundwater level fluctuations.

These processes are closely related to secondary soil salinization problems observed in irrigated lands of the Syrdarya region [7].

Conclusion

The developed numerical model adequately reproduced groundwater flow processes at the Malik experimental site under intensively irrigated conditions. Comparative analysis of observed and

simulated groundwater levels showed satisfactory agreement during model calibration, indicating that the developed model adequately represents groundwater flow conditions of the Malik experimental site. According to AquiferTest interpretation results, the average transmissivity coefficient was 3.02×10^2 m^2/day, the average hydraulic conductivity coefficient was 1.63×10^1 m/day, and the average storage coefficient was 6.29×10^{-2}.
The calibrated hydraulic conductivity values for the model layers were determined as 0.03 m/day for cover sandy loams and loams, 5 m/day for gravel-bearing sands, 0.02 m/day for dense loams, and 14 m/day for fine-grained sands. The obtained results confirmed that irrigation infiltration and collector-drainage systems are the dominant factors controlling groundwater regime formation in intensively irrigated territories. The proposed modeling approach can be effectively applied for groundwater regime prediction and assessment of meliorative conditions in irrigated areas.
The proposed modeling approach can be effectively applied for groundwater regime prediction, assessment of filtration processes, and evaluation of meliorative conditions in irrigated territories. Overall, the obtained results confirmed the reliability of the developed hydrogeological model and demonstrated its applicability for optimizing groundwater management under irrigated conditions. The model reproduced observed groundwater head variations with acceptable accuracy for hydrogeological and engineering applications.

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