Numerical studies on groundwater-grassland relations in an inland arid region in China

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Abstract. In this study, a 2-D numerical model was developed to assess the impacts of groundwater on grassland ecology in the Hulun Lake Basin. An extreme dry climate scenario and water resource management scenario and their interactions in the Hulun Lake Basin were designed, and their influence on groundwater was evaluated. The results show that the grassland ecology is heavily dependent on groundwater, and a distribution of groundwater with a depth of 8 m correlates well with the distribution of grassland. Under the water resource management scenario, the groundwater level will increase to a maximum value of 2.5 m after 15 years around Hulun Lake. The groundwater level will decrease dramatically under the extreme dry climate scenario, thus affecting the environment.

1. Introduction

Covering approximately 3.98 million km² in China, grasslands play an important role in economic development and the environment [1]. Grasslands are usually groundwater-dependent all over the world, especially in arid or semi-arid regions where rainfall is seasonally variable and significantly lower than the evaporation rate [2]. Groundwater-dependent grassland will be at risk if groundwater levels are reduced. An understanding of groundwater-grassland relations is of great importance to maintaining a healthy grassland ecology [3]. Available and adequate water supplies are essential for maintaining grasslands, and thus water resources management is critical to meet the water demands of grasslands, especially during record drought conditions. As the fifth largest lake in China, the Hulun Lake has suffered from the drawdown of groundwater levels and degradation of grasslands around the lake in the past few decades due to excessive groundwater exploitation [4]. To protect and restore grassland ecosystem function, water resources management projects, including water transfer projects within the basins and from adjacent basins, and groundwater extraction control measures should be drafted by the local government. The objectives of this paper are to develop a numerical model using the FEFLOW software [5], a commonly used groundwater modeling system, to quantitatively assess the impacts of groundwater on grasslands and explore the extent to which the potential water resource management project may impact the grassland. In this study, the groundwater depth across the Hulun Lake Basin will be forecasted so that a risk assessment can be performed, aiming to assess the sensitivity of grasslands to groundwater.
2. Methods

2.1. Study area
Located in the northeastern part of the Inner-Mongolia Autonomous Region of China, the Hulun Lake Basin (115°30'-115°30' E, 47°40'-49°50' N) has an approximate drainage area of 34299 km². The study area can be divided into two parts, mountainous in the west and high plains in the east. The elevation ranges from 560 m in the east to 900 m in the west (figure 1). The main rocks types are Paleozoic metamorphic rocks, Mesozoic volcanic rocks and the Yanshan Period granites in the west, and whereas they are Cainozoic sandstone or clayey breccia in the east. The rock type in the central area is mostly sandy loam derived from sedimentary river and lake environments. Study area has a mean minimum yearly temperature of -42.7°C and a mean maximum yearly temperature of 40.1°C, whereas the mean annual rainfalls are approximately 275 mm.

![Figure 1: Map of the study area.](image)

2.2. Conceptual model
The study area is chosen to be the model area. According to the characteristics of the aquifer formation and the hydrological conditions in the Hulun Lake Basin, hydrogeological models were developed. Considering the complex rock types in the phreatic aquifers in the study area, the local media are assumed to be heterogeneous. Due to a scarcity of data, interpolated Digital Elevation Model (DEM) values can be acquired using the Kriging method in the SURFER software. Both the western boundary and southern boundary are assumed as Neumann boundary conditions, and the flux of water flow through the boundary is estimated to be 10⁻⁵ m/d. The northern boundary is regarded as a no-flux boundary. The eastern boundary is represented by a flux boundary with very low flow rate. The relation between the Hulun Lake and groundwater is a very important part in this model. The Hulun Lake will recharge the groundwater when the lake level is greater than the groundwater level, and vice versa. Therefore, the lake is represented by a transfer boundary, and the exchange capacity can be calculated by using Darcy’s Law. The initial conditions of the groundwater system are estimated from a steady-state groundwater flow simulation with the average recharge rate. The model is two-dimensional and was developed using the FEFLOW software.

2.3. Data collection

2.3.1. Grassland coverage. Remote sensing imagery of the Hulun Lake area from the Landsat TM dataset for the year 2000 was used to identify the grassland coverage. Land use maps were collected.
for assisting the interpretation of the remote sensing images. The land use types in the study area can divided into three types, (1) high coverage grassland, (2) moderate coverage grassland, and (3) low coverage grassland, by using ERDAS IMAGINE 8.4 and ArcGIS 9.2 software in combination with the field observations of the spatial distribution of land-use in the Hulun Lake Basin. The high coverage grassland is closely related to the water body and mainly distributed near Hulun Lake, the Wuerxun River, the Kherlen River and the marshland that located to the east of Hunlun Lake. The moderate coverage grassland is widely distributed over highland regions. The low coverage grassland overlays the western hilly region. Saline-alkali land is mostly distributed in the high plain area.

2.3.2. Hydrogeology and observational data. 23 monitoring wells are distributed in the study area (figure 1) and the water-level data from the observation wells are listed in table 1. Based on a geological map of China at a scale of 1:2500000 (http://ngac.org.cn/onemap/index.html), the study area is divided into 20 zones. From hydrogeological reports and pumping tests, the hydraulic conductivities vary from 0.1 m/d to 12.5 m/d, and the porosity ranges from 0.03 to 0.15. The Kherlen River and Wuerxun River are the two main rivers that interact with groundwater in study area. The exchange flux can be calculated by FEFLOW automatically based on the corresponding parameters (e.g., stream stage and groundwater level). Statistical data show that the average level of groundwater exploitation and the return flow are approximately 68.01 million m³ per year and 1.39 million m³ per year, respectively.

### Table 1. Water-level data from observation wells in 2009.

| Month | Water level for each observation well (m) |
|-------|------------------------------------------|
|       | S002 | S004 | S007 | S024 | S069 | S098 | S100 | S142 |
| May   | 582.39 | 576.58 | 575.46 | 621.72 | 651.59 | 574.91 | 568.48 | 643.04 |
| Jun.  | 582.37 | 576.46 | 575.42 | 621.67 | 651.49 | 574.99 | 568.29 | 642.96 |
| Jul.  | 582.53 | 576.60 | 575.80 | 621.72 | 651.55 | 574.97 | 568.27 | 642.94 |
| Aug.  | 582.77 | 576.86 | 576.23 | 621.88 | 651.66 | 574.73 | 568.52 | 643.18 |
| Sep.  | 583.09 | 577.23 | 576.33 | 622.01 | 651.60 | 574.61 | 568.70 | 643.22 |

| Month | Water level for each observation well (m) |
|-------|------------------------------------------|
|       | S154 | S155 | S162 | S165 | S174 | S198 | S200 | S203 |
| May   | 554.44 | 536.80 | 626.38 | 566.28 | 570.20 | 534.24 | 537.49 | 533.60 |
| Jun.  | 554.42 | 536.75 | 626.32 | 566.26 | 570.13 | 534.20 | 537.41 | 533.51 |
| Jul.  | 554.50 | 536.81 | 626.24 | 566.30 | 570.13 | 534.23 | 537.47 | 533.52 |
| Aug.  | 554.59 | 536.95 | 626.40 | 566.40 | 570.24 | 534.32 | 537.70 | 533.72 |
| Sep.  | 554.58 | 536.95 | 626.50 | 566.41 | 570.28 | 534.37 | 537.77 | 533.68 |

| Month | Water level for each observation well (m) |
|-------|------------------------------------------|
|       | S205 | S206 | S214 | S218 | S223 | S227 | S244 |
| May   | 544.92 | 547.20 | 570.08 | 547.12 |
| Jun.  | 544.85 | 547.14 | 570.00 | 547.07 | 537.41 | 541.46 | 697.90 |
| Jul.  | 544.79 | 547.11 | 570.01 | 547.12 | 537.36 | 541.38 | 697.77 |
| Aug.  | 545.02 | 547.33 | 570.20 | 547.31 | 537.59 | 541.66 | 697.91 |
| Sep.  | 545.10 | 547.70 | 570.23 | 547.26 | 537.63 | 541.69 | 698.01 |

2.4. Evaluation of groundwater-grassland relations

Groundwater-grassland relations are evaluated by analyzing the relation between the depth to groundwater and the area of the grassland coverage. The depth to groundwater is simulated using the FEFLOW software, and the suitable depth for grass growth was assumed as ecology water level.
3. Results of model evaluation

The model area is discretized into 3374 nodes and 6482 elements in total. The sedimentary period is set from January to December of 2009. The calibration targets are observed groundwater levels. The period for the observation is from May to September of 2009. The comparison of observed and simulated hydraulic head is shown in figure 2. Relative error is defined as the ratio of the absolute difference between the simulated and observed water level to the observed results. The correlation between observed and simulated values illustrates that the relative errors are less than 2%, which means that the simulated results are basically coincident with the observed results.

3.1. Groundwater balance analysis

The results reveal that the annual precipitation infiltration is 0.45 billion m$^3$, which accounts for 98.70% of the total recharge. The annual groundwater evaporation is approximately 0.38 billion m$^3$, accounting for approximately 82% of the total discharge. Groundwater abstraction is approximately 15% of the total discharge. The yearly water supply is 0.46 billion m$^3$.

3.2. Distribution of groundwater depth and its relation with the grassland

Figure 3(a) shows the map of depth to groundwater, where a depth of less than 4.1 m (the darkest color), less than 8 m (the darker color) and less than 40 m (the gray color) are represented by different colors. The depth to groundwater is within 8 m near the Wulannuor and the Wuexun Rivers, where the distribution essentially coincides with the remote-sensing images of land-use and shrub growth. Thereinafter, a groundwater depth of 8 m is assumed to be the ecology water level.

Figure 2. Comparison of observed and simulated hydraulic head.

Figure 3. Distribution of the groundwater depth for the base scenario (a), the change in the groundwater depth (b) between the base scenario and the management scenario, and (c) that between the base scenario and the extreme dry climate scenario.
4. Discussions
For fulfilling environmental protection in the study area, a water resources management project for the Hulun Lake Basin is proposed. Two scenario are set: a base scenario and a management scenario. In the base scenario, the water level of Hulun Lake is 541.87 m, and the streamflow rate of the Kunduleng and Ganzhuhua Rivers is 0.679 and 0.735 billion m$^3$/a, respectively; whereas in the management scenario, the water level of the lake is 544.51 m, and the streamflow rate at the two stations is 0.552 and 0.606 billion m$^3$/a, respectively. Based on the groundwater balance analysis, precipitation infiltration is the major recharge to groundwater and thus has an important influence on the groundwater level. An additional scenario is added with an extreme dry climate with an annual precipitation of 247.5 mm under the management scenario. This scenario is aimed at revealing the sensitivity of grasslands to precipitation infiltration. The simulation duration is set as 15 years.

The simulated results under the management scenario and extreme dry climate scenario show the change in the groundwater depth (figures 3(b) and 3(c)). The numbers denote the change of groundwater depth between the base scenario and the management scenario, as well as that between the base scenario and the extreme dry climate scenario, and positive values mean that the groundwater table rises. The results show that the maximum increase in groundwater level around Hulun Lake is 2.5 m, mainly due to the rising of Hulun Lake water levels. Thus, the lake will recharge the groundwater, and the grassland ecological function will be further restored. The results show that, with the decline of precipitation infiltration, the depth to groundwater will decrease at a rate of 5 to 10 m over 15 years in the high plain zone compared with the management scenario, thus affecting the ecological environment to a great extent (figure 3(c)).

5. Conclusions
Groundwater-dependent grasslands are very important to the environment. A numerical model was developed to assess groundwater-grassland relations and their changes under a water resource management scenario and an extreme dry climate scenario in the Hulun Lake Basin. Climate, hydrology, digital elevation maps and geological maps, in conjunction with boreholes and monitoring wells, were used to construct the numerical model. Model calibration was carried out and the simulated results have a strong correlation with the observations. The results also show that precipitation infiltration is the main recharge source for the groundwater system and that a distribution of groundwater with a depth of 8 m correlates well with the distribution of grasslands. The results under the management scenario and the extreme dry climate scenario show that groundwater levels will be increased to a maximum value of 2.5 m after 15 years around Hulun Lake after the rising of the Hulun Lake level and that extreme dry weather will cause the decline of groundwater levels and the degradation of grasslands.

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