Article

Application of a Surrogate Model for a Groundwater Numerical Simulation Model for Determination of the Annual Control Index of the Groundwater Table in China

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Abstract: The Chinese government hopes to implement groundwater table control to realize the sustainable utilization of groundwater resources based on controlling the current groundwater exploitation amount. In this study, a method to determine the control index of the groundwater table is proposed. In the method, the reasonable relationship between the groundwater table and groundwater exploitation amount is ensured using the groundwater numerical simulation model. The operability of the index determination is improved using a surrogate numerical model, and the annual hydrological dynamic is simplified to three scenarios of dry, flat, and wet. To verify this method, the Minqin Basin in Northwest China was chosen as a typical study area. It is assumed that the control index of groundwater exploitation in 2020 is $85,000 \times 10^3 \text{m}^3$. Then, the preset annual water table index is calculated as $[-0.70, 0.62, 1.13, -1.25, 1.36, 3.09] \text{m} [-0.77, 0.53, 1.05, -1.33, 1.27, 2.96] \text{m}$, and $[-0.83, 0.46, 0.99, -1.40, 1.20, 2.85] \text{m}$ for the chosen six monitoring wells, varying over the years with wet, flat, and dry scenarios. This method can ensure high precision, operability, and dynamic management when determining the control index of the groundwater table and satisfy the demand of managers.

Keywords: groundwater management; control index of groundwater exploitation amount; control index of groundwater table; numerical simulation model; surrogate model; Minqin Basin

1. Introduction

Groundwater is an important strategic resource in China. Unfortunately, China has too many people and insufficient water resources, as well as uneven spatial and temporal distribution of the country’s water resources. Groundwater is widely and directly used in the North China Plain, Northeast China, and Northwest China. Unreasonable development and utilization in China have caused a series of serious problems, such as water table decline, water pollution, and water ecological deterioration in recent years. Like other countries with water shortage problems [1,2], the Chinese government has strengthened the management of groundwater to ensure the sustainable utilization of water resources. The government hopes to achieve the restoration of groundwater over mining areas, utilization management, and groundwater conservation by implementing legislation, rules, and regulations. The implementation of groundwater exploitation amount control and groundwater
table control is regarded as the basic principle for strict groundwater management and protection under current regulations.

The groundwater exploitation amount control restricts the groundwater exploitation of different users in a certain area and a certain period, taking the exploitable amount of regional groundwater as the upper limit. The groundwater table control is used to preset the expected value of the groundwater table and limit the changes of the groundwater table to the threshold of the expected value through management activities. The control index of the groundwater exploitation amount is defined as the allowable exploitation amount of regional groundwater, determined through the comprehensive consideration of reasonable economic and social demands. The control index of the groundwater table is regarded as a reasonable control threshold for the groundwater table under different precipitation conditions.

Groundwater exploitation amount control and groundwater table control are consistent in their mechanisms. They are both groundwater management methods that control the input and output of the groundwater system. Their impacts and functions are interrelated and mutually restricted, and jointly reflect the various influences of human management activities on the groundwater system. If we ignore the relationship between these two methods and simply control water exploitation, the groundwater table will change beyond the expected values. There are also differences in management measures. Managers pre-plan the groundwater exploitation amount and directly intervene in groundwater exploitation. Due to the distributive and convert nature of exploitation, it is very expensive to master all types of exploitation in real time [3]. There are some difficulties in the implementation and effect assessment of groundwater exploitation amount control. The groundwater table is easy to monitor, and a comparison between the observed water table and the expected water table reflects the effect of the intervention on groundwater exploitation.

In the United States, Canada, Australia, and other countries, both groundwater exploitation amount control and groundwater table control have been implemented for many years. Taking Arizona (United States) as an example, groundwater management has developed from focusing on the balance of mining and recharge of the basin scale to groundwater level management due to the requirements needed to solve the impact of land subsidence in urban areas [4]. In Australia, the implementation of sustainable yield as an extraction regime has been subjected to different management constraints and practices, depending on zone-specific characteristics such as water level objectives, aquifer dynamics, level of development, water quality objectives, and water pressure objectives [5]. In countries with high water resource marketization, studies on the joint control of the groundwater exploitation amount and water table mostly use Multi-Objective Optimal Management Models. Specific applications in groundwater management can be found in Sreekanth [6], Ataie-Ashtiani [7], Farhadi [8], Roy T [9], etc.

According to China’s water resource management mode, the reasonable groundwater exploitation amount control and groundwater table control mode are as follows: The higher level water resource management department provides control indexes of the groundwater exploitation amount and groundwater table to the lower management departments. Then, the lower management departments further allocate the control index of the groundwater exploitation amount by optimizing the mining layout to ensure that the measured groundwater table at the end of the year conforms to the control index of the groundwater table. In management practice, the Ministry of Water Resources has implemented the total water consumption control indexes, which include a control index of the groundwater exploitation amount. The method to draw up the indexes involves determining the available water resources of the whole country according to the National Water Resources Comprehensive Planning (2010–2030), and then taking the planning indicator method and comprehensive balance method to decompose and calculate indicators from the national level, through the provincial level, to the city and county levels, step by step. Some provinces have also attempted to use a control index of the groundwater table for local groundwater management.

There is still a large gap between the management effects and expectation. The unsatisfied management demands are mainly reflected in the following: (1) Only the groundwater exploitation
amount control is implemented without groundwater table control. The management department needs a high-precision technical method to formulate a water table index that can reasonably and quantitatively express the relationship between groundwater exploitation and the groundwater table. At the same time, the local government hopes to make the specific process of index formulation simple and easy to operate. (2) The index of the groundwater table set by individual provinces are static, without consideration of the impact of hydrological dynamics during the year. Conflicts are caused between the higher government and lower levels when the implementation of indexes is assessed at the end of the year. Therefore, the main purpose of this study is to propose a method to determine the control index of the groundwater table that can meet the requirements of high precision, strong operability, and dynamic management.

Chinese researchers have carried out many studies on how to determine the groundwater table index. The consensus involves defining the index to encompass the resources and environmental and ecological functions of groundwater [10] using the management mode of red and blue lines [11]. Liao [12] systematically introduced three commonly used methods for quantitative determination of the control index of the groundwater table, such as the water balance method, numerical simulation method, and correlation analysis method; the authors then carried out case studies. All these methods are used to build a mathematical model to obtain the predicted groundwater table, with the exploitation amount as the constraint or input. Each method has specific advantages and disadvantages. The water balance method [13,14] is suitable for various hydrogeological conditions, but the setting of its groundwater system is too simple. It is thus difficult to satisfy the requirements of high precision and dynamic management. The numerical simulation method [15–17] can clearly reflect the changes in the input and output of the groundwater system, with the ability to recognize physical significance and easily predict the output changes under different hydrological dynamic conditions. The numerical simulation method meets the requirements of high precision and dynamics, but does not satisfy the operational requirements. The correlation analysis method [18,19] has a simple model structure that can satisfy the operational requirements. However, this model does not fully reflect the clear physical significance nor the influence of the hydrogeological conditions and mining layout in the management area. There are thus deficiencies in satisfying the requirements of high precision and dynamic management.

Research into a surrogate model began with Box’s research based on a polynomial response surface [20]. After decades of development, this method has been used to replace high-precision simulation models for real-time analysis in many disciplines. A surrogate model is defined as a simpler and faster model that emulates the specified output of a more complex model as a function of its inputs and parameters [21]. In the study of groundwater management, a surrogate model is often used as an intermediate process of simulation–optimization models in groundwater management studies [22,23], which can reduce the huge calculation load caused by the multiple calls of the simulation model in the process of iterative solutions. The establishment of a surrogate model for the numerical simulation model, which effectively combines the advantages of the two, has a wide range of application scenarios in groundwater management research [24]. There is currently no study on the establishment of a surrogate model for the numerical model to rapidly and simply determine the index.

The goal of this study is to use the prediction function of the groundwater numerical simulation model to obtain a certain series of data pairs of the exploitation amount and water table in dynamic hydrological scenarios. Then, the Kriging method was chosen to establish a surrogate model for the numerical simulation model. The established surrogate model is used to put forward the annual control index of the groundwater table based on a certain control index of the groundwater exploitation amount. This method is applied to the Minqin Basin, located in the lower reaches of the Shiyang River Basin of Gansu Province in Northwest China. It is expected that the proposed method can improve the management of groundwater in China and satisfy the demands of the relevant management departments. Furthermore, it is hoped that this method can also provide references for other countries to carry out similar management activities.
2. Methods

2.1. Conceptual Model

In a groundwater system, groundwater table is the response of controllable and uncontrollable variables. This relationship is expressed as

\[ h(\hat{x}, t) = \hat{F}(P, S, CI, UI, O) \] (1)

where \( h(\hat{x}, t) \) is the water table at a certain point, \( \hat{x} \), in the management area at time \( t \), (m); \( P \) is the parameters of the groundwater system, including the hydraulic conductivity, specific yield, specific storage, etc.; \( S \) is the structural characteristics of the water groundwater system, which is composed of the spatial distribution and boundary conditions of the aquifer and confining beds; \( CI \) is the controllable input variables of the groundwater system, including the exploitation amount and artificial recharge amount (10³ m³/a); \( UI \) is the uncontrollable input variables of the groundwater system, including precipitation infiltration recharge, surface water infiltration recharge, evapotranspiration, etc. (10³ m³/a); and \( O \) is the output variables of the groundwater system, including the spring flow, base flow, evapotranspiration, etc. (10³ m³/a).

In the near future, the structural characteristics and parameters of groundwater system will be considered in a steady state, but the dynamics of hydrological factors have a very significant impact on the natural recharge and discharge items, \( R \), of the groundwater system, which cannot be ignored when considering the quantitative relationship between the groundwater exploitation amount and the water table. Hydrological dynamics will also affect the changes in water demand and, ultimately, groundwater exploitation. The proportion of agricultural water of the total water consumption in China is maintained at more than 60% according to the Bulletin for China’s Water Resources (2018). Due to the decrease in rainfall and surface water inflow during dry years, farmers need more water for irrigation and exploit more groundwater resources to bridge the gap. In this case, Equation (1) is converted to

\[ h(\hat{x}, t) = f(q(R)_{\text{D/F/W}}, R_{\text{D/F/W}}) \] (2)

where \( [R]_{\text{min}} \) is the dynamic value of the natural recharge and discharge in the year, including \( UI \) and \( O(10^3 \text{m}^3/\text{a}) \), and \( [q(R)]_{\text{min}} \) is the dynamic value of the groundwater exploitation amount without artificial recharge in a certain year that is ultimately affected by hydrological factors(10³ m³/a).

2.2. Hydrological Dynamics

Considering that precipitation infiltration recharge and surface water infiltration recharge (\( R \)) have a great correlation with rainfall, the rainfall amount is taken as the representative factor for hydrological factors. The \( [R]_{\text{min}} \) and \( [q(R)]_{\text{min}} \) will be simplified to three typical characteristic values for reflecting the dry level, flat level, and wet level scenarios, corresponding to a rainfall assurance rate of 75%, 50%, and 25%. Then, Equation (2) is converted to

\[ h(\hat{x}, t) = f(q(R)_{\text{D/F/W}}, R_{\text{D/F/W}}) \] (3)

where \( R_{\text{D/F/W}} \) is the typical recharge and discharge value of the three scenarios of dry, flat, and wet, which is a constant value(10³ m³/a); \( q(R)_{\text{D/F/W}} \) is the corresponding groundwater exploitation amount(10³ m³/a).

2.3. Groundwater Numerical Simulation Model

A groundwater numerical simulation is adopted to solve the function \( f() \) in Equation (3). The three-dimensional flow system of groundwater in the aquifer is expressed as

\[ \nabla^2 h = \frac{S_o \partial h}{K \partial t} \] (4)
where $h$ is the water head (m), $S_s$ is the specific storage (1/m), and $K$ is the hydraulic conductivity (m/a).

In this study, the numerical model was established by the MODFLOW module of the Groundwater Modeling System (GMS). The finite difference method based on a grid is used to describe the groundwater movement.

### 2.4. Data on the Groundwater Exploitation Amount and Groundwater Table

According to the three scenarios of dry, flat, and wet, the respective prediction simulation models for one year can be established based on the hydrogeological parameters ($P$) and aquifer structure characteristic ($S$) obtained by correcting the numerical simulation model. The R values in different scenarios are calculated and used in the prediction models. Equation (3) can be further simplified as follows when considering only the input and output as variables:

$$\hat{f}(\phi, q(i, j)) = h(k)$$

(5)

where $\phi$ represents the constant values of the groundwater system parameters, the initial conditions, and the sources and sinks in the numerical simulation model; $q(i, j)$ is the sampling results of the exploitation amount for each sub management area with relatively independent exploitation conditions in the management area ($10^3 m^3/a$), and $i = 1, 2, \ldots m$, $j = 1, 2, \ldots n$; $h(k)$ is the observed water table variation of multiple groundwater control monitoring wells in the management area (m), $k = 1, 2, \ldots o$.

$q(i, j)$ is a random variable with dimensions of $m \times n$. The quantity of $m$ represents the groundwater exploitation distribution characteristics in a certain management area, and $n$ is the sampling dimension of the feasible pumping internal. The feasible pumping internal of each sub management areas is defined as

$$q^i \in [q_{i1}, q_{i2}], i = 1, 2, \ldots, m$$

(6)

where $q_{i1}$ and $q_{i2}$ are the maximum and minimum exploitable thresholds for each sub management area according to the current groundwater utilization situation and the alternative water source planned for a certain period of time in the future ($10^3 m^3/a$).

The Latin Hypercube Sampling Technique (LHS) [25] is used to sample $q(i, j)$ within the feasible pumping internal. Taking into account the increase in the number of numerical model runs caused by an increase in the sampling dimension, this study suggests that $n \leq 100$; $q^i$ is divided into equal sampling intervals of $n$, and independent random sampling is conducted from each interval. The values extracted from $q^i$ and the values extracted from $q^j$ are then matched randomly (and not repeatedly), and, finally, the $q(i, j)$ of the $m \times n$ dimension is obtained by continuing this process.

$h(k) = (h_1, h_2, \ldots, h_o)$ is a response value of the $o$ dimension. We can obtain a series of $h(k)$ as a response for every $q(i, j)$ in three scenarios, as well as a set of sample pairs of $(q(i, j), h(k))$.

### 2.5. Surrogate Model

A surrogate model can build a functional relationship between $q(i, j)$ and $h(k)$, instead of simulating the internal operational mechanism of the numerical model $f()$. The general formula of the surrogate model based on Equation (5) can be expressed as follows:

$$g(q(i, j)) \simeq \hat{f}(\phi, q(i, j)) = h(k)$$

(7)

Parts of the sample pairs (80–90%) are used to establish an approximate model. This model provides the best agreement with $g(q(i, j))$, and $h(k)$, and can interpolate the response at unknown points. The most widely used method to establish a surrogate model involves Polynomial Regression, Multivariate Adaptive Regression Splines, k-Nearest Neighbor, Response Surface, Kriging, Radial Basis Function, Gaussian Process, Artificial Neural Network, Support Vector Machine, etc.

The Kriging method is a kind of unbiased estimation model with minimum estimation variance, which has the characteristics of local estimation. This method can easily obtain an ideal fitting effect.
when solving problems with high nonlinearity, and provides better approximation accuracy and robustness [26,27]. In this study, the Ordinary Kriging method is used to establish a surrogate model. The common equation of the Ordinary Kriging method [28] can be described as follows:

\[
\hat{y}(X) = \sum_{r=1}^{v} \beta_w f_w(X) + Z(X) = f^T(X)\beta + Z(X)
\]  

(8)

where \( f_w(X) \) includes \( v \) pre-determined primary functions, which are generally in the formation of a polynomial function, and \( f_w(X) \) provides a global approximation for the simulation; \( \beta_w \) is the regression coefficient that can be estimated by the response value; \( Z(X) \) is the statistical stochastic process that provides an approximation for the local deviation of the simulation, and \( Z(X) \) has a zero expected value and a correlation structure that is a function of the generalized distance between the sample data points.

The surrogate model must be verified to confirm that it can truly reflect the relationship between groundwater exploitation and groundwater table variation in the simulation model. Its accuracy in the numerical simulation model also needs to be judged. In this study, the Pearson Correlation Coefficient (CC) was used to evaluate the fitting effect. The correlation coefficient can be determined by the following equation:

\[
r = \frac{\text{cov}(h(k)_n, h(k)_s)}{\sqrt{\text{D}(h(k)_n)} \sqrt{\text{D}(h(k)_s)}}
\]  

(9)

where \( h(k)_n \) is the groundwater table variation for observation well \( k \) from the numerical simulation model \( (m) \), and \( h(k)_s \) is the groundwater table variation for observation well \( k \) from the surrogate model \( (m) \).

The remaining sample pairs are taken as the test sample of the model. The output \( h(k) \) of the surrogate model is compared with the simulation result of the numerical model to calculate the \( r \) value. When \( r \) is close to 1 with a significance level \( (p\text{-value}) < 0.05 \), the surrogate model can meet the requirements.

2.6. Application

The validated surrogate model is saved and provided to local government managers and can be operated by business software, including three files for the three scenarios of dry, flat, and wet. Using this method, it is very simple for managers to obtain the groundwater table index. Local government managers should supply a set of \( q(i, j) \) for each sub management area as an input according to the issued groundwater exploitation index and local development plan. In this way, they can immediately obtain the output of groundwater table variation as the index under different scenarios in the current year. The determined index can be used to guide the management and assessment of groundwater utilization. If the managers think that the groundwater exploitation amount indexes need to be adjusted within the year, they can use this convenient tool to obtain up-to-date water table indexes quickly.

3. Case Study

3.1. Study Area

Minqin Basin in the lower reaches of Shiyang River Basin of Gansu Province, Northwest China, was selected as the study area (Figure 1). This area is a typical desert oasis in the inland river basins of Northwest China. Minqin Basin is on the north of Hongya Mountain–Alagu Mountain, on the south of North Mountain, on the east of Badain Jaran Desert, and on the west of Tengger Desert (Figure 1). The middle part of the basin features alluvial and lacustrine areas of Shiyang River with the edge covered by desert. The total area of the continent is about 4800 km\(^2\). The study area features a typical continental climate with multi-annual precipitation of 42.2–185 mm and annual average precipitation of 110 mm. Shiyang River is the only surface water system entering the study area. After passing through
Hongyashan Reservoir, Shiyang River is divided into the Outer River and Inner River, which have been transformed into the main irrigation channel of the oasis. Surface water is mainly utilized through the canal system for irrigation and recharge to groundwater in the form of infiltration. A small amount of surface water reaches the tail-end of the river named Qingtu Lake. In the study area, human activities are concentrated in the central oasis of the basin. In the later 1950s, the oasis of the Minqin Basin was transformed into the Hongyashan Irrigation Area, which was a large agricultural area with mixed irrigation water forming channel transportation and well pumping.

The Quaternary strata have a thickness of 50–400 m from south to north in the study area, which is the main aquifer for groundwater (Figure 2) [29]. The aquifer is a multi-layer unconfined-confined system. Moreover, along the direction of the groundwater flow, the water yield of the aquifer changes greatly [30].

The surface water in Shiyang River is transported into the irrigation areas through the canal system for irrigation. Canal system leakage, field irrigation infiltration, and well irrigation return recharge are the main sources of groundwater recharge. There is a small amount of precipitation and condensate infiltration in the plain area and boundary lateral seepage recharge. The movement direction of groundwater is from south to north, which is controlled by changes in topography and aquifer lithology. In the south and central areas, the main flow format is runoff. In the Qingtu Lake, the vertical flow starts to become active in a large area, and the depth of the groundwater becomes shallow. In the oasis area, groundwater mainly discharges in the form of exploitation and evapotranspiration, while in the Qingtu Lake, the main method is evaporation.
Due to the exploitation of groundwater and the decrease in surface water volume, the water table continues to decline in the central oasis. This situation finally caused the disappearance of Qingtu Lake, leaving water-loving vegetation, such as reeds, to languish and die. Since 2012, with the development of the comprehensive treatment of the Shiyang River Basin, more water was transported from the upstream Hongyashan Reservoir directly into Qingtu Lake. The surface of the lake can be maintained over a certain area. The amount of groundwater exploitation has thus been reduced to a certain extent.

There is a long history of groundwater utilization in the study area. Groundwater plays a very important role in the total water supply, which accounts for 38% of the total water consumption, 34.8% of agricultural irrigation, and all the industrial and domestic water consumption. In 2010, the total exploitation amount of groundwater in the study area was $281,400 \times 10^3 \text{ m}^3$. Since then, the exploited volume has decreased year by year. By 2018, the total exploitation amount of groundwater was maintained at approximately $85,000 \times 10^3 \text{ m}^3/\text{a}$.

3.2. Data Preparation

The data used in this study were acquired from water resource planning, reports, statistical reports, and monitoring data that were collected from the Gansu Provincial Water Resources Bureau and Minqin County Water Resources Bureau. The data include the monthly water table monitoring data of 26 monitoring wells from 2000 to 2016, the water supply and water consumption of Minqin County in 1980, 1985, 1990, 1995, 2000, 2005, and 2010, the estimated water demand in 2020 and 2030, the measured flow amount in the region from 1980 to 2010 and 2016, the water diversion volume and groundwater exploitation volume of irrigation areas, and the groundwater resource evaluation results carried out in 2013, along with the hydrogeological parameters, etc. The meteorological data on precipitation and evaporation were obtained from the International Cooperation Station of China Meteorological Data Network. The data include daily data for the Minqin ground station from 1953 to 2014.

According to the GIS data provided by the water resource bureau, the oasis in the study area was divided into 13 sub management areas (Y1–Y13). The scope of the sub management areas was combined with the borders of the 13 township regions and the borders of 3 sub irrigation areas. The 13 sub management areas belong to the current three irrigation areas of Baqu (including the sub management areas of Y1, Y2, Y3, Y4, Y5, and Y6), Quanshan (including the sub management areas of Y7, Y8, Y9, and Y10), and Huqu (including the sub management areas of Y11, Y12, and Y13). Six long-term observation wells were selected as the groundwater control monitoring wells in the study area (Figure 3).

3.3. Numerical Simulation

A groundwater flow numerical simulation model was established in the study area. The simulation range was the same as described in the study area, covering an area of about 4800 km$^2$. The aquifer in the simulation range changed from a thick single layer aquifer to multi-layer aquifers along the groundwater runoff direction. The construction of the aquifer was undertaken in Pliocene and Quaternary loose deposits, and the aquifer was vertically transformed from unconfined to confined. There is a clay layer used as an aquitard with a total thickness of about 50 m between the unconfined and confined aquifers. The thickness of the unconfined aquifer changes from 150 m to 120 m from south to north. The unconfined aquifer was selected as the simulated aquifer for the simulation range and generalized as a heterogeneous isotropic aquifer layer with a thickness of 170 m.
The North Mountain and other erosion resistant mountains were defined as the northwest boundary of the model. The watersheds of the Minqin Basin and Changning basin were defined as the west boundary. These two boundaries were treated as an impermeable boundary. The dam foundation of Hongyashan Reservoir was used as the southwest boundary. The edge of Tengger Desert was used as the east and southeast boundary. These two boundaries were treated as the fixed lateral inflow boundary. The Qingtu Lake area was treated as the fixed lateral outflow boundary in the northeast. The upper boundary of the model was the water table, and the bottom of the aquifer was treated as the impermeable boundary. The given initial value of the horizontal permeability coefficient $K$ was $3.0\–14.2\, \text{m/d}$. The change range of the initial value of the specific yield $S_y$ was $0.064\–0.13$. The given initial values of the hydrogeological parameters showed a general decreasing trend from upstream to downstream.

GMS with the finite difference method was chosen for the establishment and solution of the numerical simulation model. This model was divided into 250 rows and 250 columns. The size of each grid was $400 \times 400\, \text{m}$. The simulation period was 2001–2010, with 120 stress periods for 120 months. The initial field was drawn with the observed groundwater table from January 2001 using 48 monitoring wells in the study area.

The source and sink terms of the model included the lateral flow boundary, rainfall recharge, evapotranspiration discharge, surface water leakage from canals, agricultural irrigation infiltration, and artificial exploitation, among others.

3.4. LHS Sampling

Comprehensively considering the local groundwater utilization conditions, the alternative water source planning and ecological restoration planning in the study area, $q_i^s$ ($i = 1, 2, \ldots, 13$), were determined. In 2009, the actual exploitation of groundwater in the Baqu irrigation area was $86,790 \times 10^3\, \text{m}^3$, and the amount in the Quanshan irrigation area was $46,670 \times 10^3\, \text{m}^3$. We chose 5% of the total amount for $q_i^b$ and 18% of the total amount for $q_i^t$ for each sub management area in these two irrigation areas. To promote ecological restoration downstream, a fixed value is taken as the $q_i^b$ and $q_i^t$ limit for the sub management areas in the Huqu irrigation area (Table 1.). The sampling dimension ($n$) is set as 100.
Table 1. Feasible pumping internal for sub management areas (10³ m³/a).

| Sub Management Area | Y1  | Y2  | Y3  | Y4  | Y5  | Y6  | Y7  | Y8  | Y9  | Y10 | Y11 | Y12 | Y13 |
|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| q_i               | 4340| 4340| 4340| 4340| 4340| 4340| 2330| 2330| 2330| 2330| 0   | 0   | 0   |
| q_t               | 15,620| 15,620| 15,620| 15,620| 15,620| 15,620| 8400| 8400| 8400| 8400| 4000| 4000| 4000|

4. Results and Discussion

4.1. Groundwater Simulation Model

A calibrated numerical simulation model in the study area was used to calculate the groundwater flow field at the end of 2010. The calculated groundwater flow field matched the actual flow field reasonably well (Figure 3) and generally reflected the trend of the groundwater flow. The maximum error was no more than 4 m between the actual water level and the fitted values of the typical observation wells, which demonstrates that this model approximately reflects the dynamic groundwater table characteristics of the study area. The groundwater balance calculated by the model also reflects the actual hydrogeological conditions of the study area. The change trend between computed flow field and actual flow field was in substantial agreement in Figure 4. A prediction simulation model was then established based on the calibrated structural model, as well as its parameters and hydraulic conditions. The simulation period of the model was one year, with a stress period of nine months. The initial field was drawn with the water table at the end of 2014.

Figure 4. The contrast diagram of calculation and actual flow field.

The $R_{DFW}$ and $q(R)_{DFW}$ in Equation (3) were calculated and substituted into the prediction model to obtain the groundwater table variation values of the three scenarios (dry, flat, and wet). Frequency reassignment of the historical precipitation was used to determine the precipitation years of the three scenarios. The year 1981 was regarded as the representative year for a 75% guarantee rate and a precipitation of 91.3 mm. The year 1995 was regarded as the representative year for a 50% guarantee rate, with a precipitation of 100.1 mm, and the year 1983 was regarded as the representative year for a 25% guarantee rate, with a precipitation of 135.1 mm. According to the historical evaporation...
data over the past 63 years, the average evaporation was selected for the prediction model without considering the interannual variation, which was represented by the year 2000 with an evaporation amount of 2580.4 mm.

According to the relevant local planning and water demand prediction results, the surface water transmission leakage and irrigation infiltration recharge amount under wet, flat, and dry scenarios were calculated accordingly. The calculated water leakage recharge of the whole area was 49,400 × 10^3 m^3/a in the wet scenario, 44,650 × 10^3 m^3/a in the flat scenario, and 39,840 × 10^3 m^3/a in the dry scenario. The calculated irrigation water demand amount of the whole area was 131,140 × 10^3 m^3 with an irrigation infiltration recharge amount of 22,290 × 10^3 m^3 in the wet scenario. The amount was 124,140 × 10^3 m^3 and 21,100 × 10^3 m^3 in the flat scenario, and 116,940 × 10^3 m^3 and 19,880 × 10^3 m^3 in the dry scenario. The whole area was divided into three leakage recharge areas according to the scope of the three sub irrigation areas of Baqu, Quanshan, and Huqu. These predicted recharge amounts were distributed according to the average proportion of water transmission leakage in the three sub irrigation areas from 2000 to 2010. The distribution percentage was 60%, 21%, and 19% for the prediction model.

4.2. Sample Pairs

The function lhsdesign was applied in mathematics software to sample the exploitation volume of the 13 sub management areas in the feasible region. In total, 100 groups of groundwater exploitation samples (Table 2) were obtained, which were evenly distributed in the feasible pumping interval and covered the whole feasible pumping interval.

| q(i,j) | Y1  | Y2  | Y3  | Y4  | Y5  | Y6  | Y7  | Y8  | Y9  | Y10 | Y11 | Y12 | Y13 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1      | 15,076 | 10,652 | 10,118 | 10,504 | 8314 | 9073 | 3292 | 3228 | 5548 | 4053 | 2746 | 2728 | 2350 |
| 2      | 5593 | 11,900 | 9378 | 5631 | 15,034 | 4847 | 2517 | 5332 | 2553 | 4726 | 2205 | 3567 | 2117 |
| 3      | 9754 | 15,314 | 7554 | 13,490 | 15,272 | 6850 | 6846 | 6864 | 8046 | 3803 | 414 | 1834 | 3044 |
| 4      | 6357 | 6441 | 13,823 | 5115 | 8734 | 10,259 | 7059 | 5707 | 6781 | 5051 | 2822 | 1719 | 3755 |
| 5      | 9375 | 11,617 | 11,661 | 4413 | 5466 | 9675 | 6426 | 7702 | 6216 | 6551 | 2191 | 3382 | 1778 |
| ...    | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 100    | 14,209 | 15,216 | 12,333 | 4977 | 4407 | 7478 | 5812 | 7538 | 7144 | 3320 | 1188 | 897 | 879 |

According to Equation (7), the 100 groups of q(i,j)(i = 1,2…13, j = 1,2…100) data, together with the source and sink results in the three scenarios, were selected as the input for the prediction simulation model. By running the model, the groundwater table variation values of the six groundwater control monitoring wells (h(k)k = 1,2…6) were calculated, corresponding to q(i,j) in the three scenarios.

4.3. Surrogate Model

An Ordinary Kriging model program was compiled in the mathematics software based on Equation (8). The 270 groups of sample pairs of q(i,j)(i = 1,2…13, j = 1,2…90) and h(k)k (k = 1,2…6) in three hydraulic scenarios were mapped using this program. In this way, we obtained three Kriging surrogate models for the three hydraulic scenarios.

The remaining 10 groups of q(i,j) data were used to verify the surrogate model. The data q(i,j) (i = 1,2…13, j = 91,92…100) in the three hydraulic scenarios were substituted into the surrogate models to obtain h(k)k (k = 1,2…6). The CC values between h(k)k and h(k)k were then calculated. The CC value was 0.9957 in the wet scenario, 0.9962 in the flat scenario, and 0.9957 in the dry scenario. Under the three scenarios, p value was less than 0.01. The results show that the accuracy of the surrogate model satisfies the requirements.
4.4. Application

The following are the different applications scenarios using the technical methods for management departments for 2020.

4.4.1. Common Situation

The groundwater exploitation amount index of the study area in 2020 is $85,000 \times 10^3 \text{m}^3$. The index is allocated to 13 sub management areas (Table 3). The groundwater table variation values for the six wells at the end of the year can be obtained by running the surrogate models for the wet, flat, and dry scenarios, respectively. The variation values are the groundwater table index values for 2010. If the hydraulic conditions in the year are wet, the water table index in the six wells will change accordingly $[-0.70, 0.62, 1.13, -1.25, 1.36, 3.09]$ m compared to the same period in the previous year, with an average change value of 0.71 m. If the hydraulic conditions in the year are flat, the index will be $[-0.77, 0.53, 1.05, -1.33, 1.27, 2.96]$ m with an average value of 0.62 m. The index will be $[-0.83, 0.46, 0.99, -1.40, 1.20, 2.85]$ m, and the average value will be 0.55 m if the hydraulic conditions are dry.

Table 3. Forecasting result of control indexes of groundwater exploitation amount and groundwater table for 2020.

| Groundwater Exploitation Amount Index ($10^3 \text{m}^3$) | Groundwater Table Index (m) |
|---------------------------------------------------------|----------------------------|
| **Sub Management Areas**                                | **Dry Scenario** | **Flat Scenario** | **Wet Scenario** | **Groundwater Control Monitoring Wells** | **Dry Scenario** | **Flat Scenario** | **Wet Scenario** |
|---------------------------------------------------------|------------------|------------------|------------------|-----------------------------------------|------------------|------------------|------------------|
| Y1                                                      | 9400             | 9400             | 9400             | OW1                                     | -0.83            | -0.77            | -0.70            |
| Y2                                                      | 9300             | 9300             | 9300             | OW4                                     | 0.46             | 0.53             | 0.62             |
| Y3                                                      | 8900             | 8900             | 8900             | OW6                                     | 0.99             | 1.05             | 1.13             |
| Y4                                                      | 8800             | 8800             | 8800             | OW17                                    | -1.40            | -1.33            | -1.25            |
| Y5                                                      | 9200             | 9200             | 9200             | OW21                                    | 1.20             | 1.27             | 1.36             |
| Y6                                                      | 9400             | 9400             | 9400             | OW24                                    | 2.85             | 2.96             | 3.09             |
| Y7                                                      | 6800             | 6800             | 6800             | N/A                                     | N/A              | N/A              | N/A              |
| Y8                                                      | 6800             | 6800             | 6800             | N/A                                     | N/A              | N/A              | N/A              |
| Y9                                                      | 6400             | 6400             | 6400             | N/A                                     | N/A              | N/A              | N/A              |
| Y10                                                     | 7600             | 7600             | 7600             | N/A                                     | N/A              | N/A              | N/A              |
| Y11                                                     | 1000             | 1000             | 1000             | N/A                                     | N/A              | N/A              | N/A              |
| Y12                                                     | 800              | 800              | 800              | N/A                                     | N/A              | N/A              | N/A              |
| Y13                                                     | 600              | 600              | 600              | N/A                                     | N/A              | N/A              | N/A              |
| **Total**                                               | 85,000           | 85,000           | 85,000           | **Average**                             | 0.55             | 0.62             | 0.71             |

4.4.2. Scenarios for Adjustment of the Exploitation Layout

In this situation, the superior management department deems that the pumping layout of the index formulated by the management department was unreasonable, albeit with a reasonable total amount. It is thus necessary to reduce groundwater exploitation in the main mining areas and allocate that exploitation to other areas. Assuming that the exploitation index of some management sub areas was adjusted by situation (a) (Table 4), a new water table index can be quickly obtained by using the surrogate model.

4.4.3. Resetting during the Year

In this situation, 2020 was assumed to be a dry year with less surface water coming from upstream in this basin during the rainy season. In order to meet the water demands of autumn irrigation, the groundwater exploitation amount index was considered to be $100,000 \times 10^3 \text{m}^3$ for the year with a reasonable increase of $15,000 \times 10^3 \text{m}^3$. In this situation, it is necessary to rapidly reset the water table index to avoid reflecting the assessment at the end of the year. Assuming that the exploitation amount index of management sub areas was adjusted by situation (a) (Table 5), a new water table index can be obtained quickly.
Table 4. Regulative control indexes of groundwater exploitation amount and groundwater table for 2020.

| Sub Management Areas | Groundwater Exploitation Amount Index (10^3 m^3) | Groundwater Table Index (m) |
|----------------------|-----------------------------------------------|----------------------------|
|                      | Dry Scenario                   | Flat Scenario                   | Wet Scenario                   |
| Y1                   | 8200                           | 8200                           | 8200                           | OW1   |
| Y2                   | 8300                           | 8300                           | 8300                           | OW4   | 0.31 | 0.38 | 0.47 |
| Y3                   | 7600                           | 7600                           | 7600                           | OW6   | 1.12 | 1.18 | 1.26 |
| Y4                   | 7500                           | 7500                           | 7500                           | OW17  | −1.46| −1.40| −1.32|
| Y5                   | 8300                           | 8300                           | 8300                           | OW21  | 1.09 | 1.16 | 1.25 |
| Y6                   | 8400                           | 8400                           | 8400                           | OW24  | 2.65 | 2.76 | 2.89 |
| Y7                   | 7700                           | 7700                           | 7700                           | N/A   |
| Y8                   | 7500                           | 7500                           | 7500                           | N/A   | N/A  | N/A  | N/A  |
| Y9                   | 7800                           | 7800                           | 7800                           | N/A   | N/A  | N/A  | N/A  |
| Y10                  | 8000                           | 8000                           | 8000                           | N/A   | N/A  | N/A  | N/A  |
| Y11                  | 2000                           | 2000                           | 2000                           | N/A   | N/A  | N/A  | N/A  |
| Y12                  | 1800                           | 1800                           | 1800                           | N/A   | N/A  | N/A  | N/A  |
| Y13                  | 1900                           | 1900                           | 1900                           | N/A   | N/A  | N/A  | N/A  |
| Total                | 85,000                         | 85,000                         | 85,000                         | Average 0.52 | 0.59 | 0.68 |

Table 5. Regulative control indexes of groundwater exploitation amount and groundwater table for 2020 in dry scenario.

| Sub Management Areas | Groundwater Exploitation Amount Index (10^3 m^3) | Groundwater Table Index (m) |
|----------------------|-----------------------------------------------|----------------------------|
|                      | Dry Scenario                   | Groundwater Control Monitoring Wells | Dry Scenario |
| Y1                   | 11,500                         | OW1   | −1.00 |
| Y2                   | 10,600                         | OW4   | 0.34 |
| Y3                   | 10,000                         | OW6   | 0.87 |
| Y4                   | 10,200                         | OW17  | −1.48|
| Y5                   | 9600                           | OW21  | 1.04 |
| Y6                   | 10,200                         | OW24  | 2.58 |
| Y7                   | 7500                           | N/A   | N/A  |
| Y8                   | 7400                           | N/A   | N/A  |
| Y9                   | 7100                           | N/A   | N/A  |
| Y10                  | 7600                           | N/A   | N/A  |
| Y11                  | 2900                           | N/A   | N/A  |
| Y12                  | 2800                           | N/A   | N/A  |
| Y13                  | 2600                           | N/A   | N/A  |
| Total                | 100,000                        | Average 0.39 |

4.5. Inadequacy

According to the statistics of groundwater exploitation provided by Gansu Provincial Bureau of Hydrology and Water Resources (Table 6), the exploitation amount of the Baqu irrigation area, Quanshan irrigation area, and Huqu irrigation area in 2016 were $50,490 \times 10^3$ m$^3$, $21,120 \times 10^3$ m$^3$, and $13,750 \times 10^3$ m$^3$, respectively, with an accumulative exploitation amount of $85,360 \times 10^3$ m$^3$. The data show that 2016 was a flat year with an annual precipitation of 114.5 mm. The calculated water table index for 2016 is $[-0.82, 0.94, 0.49, -1.54, 0.89, 2.37]$ m under the technical method, with an average increase of 0.39 m compared to the water table at the end of 2015. According to the actual monitoring data of 2016, the average water table of the six monitoring wells at the end of 2016 increased by 0.53 m compared to that at the end of 2015. The variation between the preset index and the measurement value is more than 10%, which indicates that there is a certain deviation in the preset index.
Table 6. Calculated control index of groundwater table of 2016.

| Groundwater Exploitation Amount Index \(10^3\)m³ | Groundwater Table Index (m) |
|-----------------------------------------------|----------------------------|
| Sub Management Areas                          | Dry Scenario               | Groundwater Control Monitoring Wells | Dry Scenario |
|                                               |                           |                                |               |
| Y1                                            | 9480                       | OW1                             | −0.53         |
| Y2                                            | 8650                       | OW4                             | 0.67          |
| Y3                                            | 8220                       | OW6                             | 1.79          |
| Y4                                            | 8340                       | OW17                            | −1.75         |
| Y5                                            | 7360                       | OW21                            | 0.37          |
| Y6                                            | 8440                       | OW24                            | 1.60          |
| Y7                                            | 5410                       | N/A                             | N/A           |
| Y8                                            | 5330                       | N/A                             | N/A           |
| Y9                                            | 5240                       | N/A                             | N/A           |
| Y10                                           | 5140                       | N/A                             | N/A           |
| Y11                                           | 4760                       | N/A                             | N/A           |
| Y12                                           | 4870                       | N/A                             | N/A           |
| Y13                                           | 4120                       | N/A                             | N/A           |
| **Total**                                     | **83,560**                 | **Average**                     | **0.36**      |

This deviation is caused by the difference between the calculated mining layout and the actual mining layout. Limited by the data, this study only collected the groundwater exploitation statistics of three sub irrigation areas without more detailed mining statistics for 13 sub management areas. In the numerical model, the exploitation volume of each sub irrigation area is evenly distributed without considering internal regional disparity. When using the alternative model to determine the index, the process of dividing the total amount index into each sub management area is also not based on the actual mining amount.

Indeed, the groundwater exploitation amount is different in each sub management sub area of the study area. For example, a cone of depression exists in Sanlei town of the Baqu irrigation area and Shuangcike town of the Quanshan irrigation area. The groundwater pumping intensity of these sub management areas is much higher than that of other areas. Furthermore, the change in the mining layout inside the sub management areas will also have a direct impact on the shape of the groundwater flow field. To improve the accuracy of the method, it is necessary to collect more detailed mining data. We have requested the disclosure of statistical data on the groundwater exploitation amount from the prepaid smart meter system in Northwest China.

5. Conclusions

In this study, a method for determining the annual control index of the groundwater table was discussed using the control index of the groundwater exploitation amount in China. According to the groundwater numerical simulation model, data on the groundwater exploitation amount and water table were obtained under different hydrological scenarios. Surrogate models based on the Kriging maps were applied to replace the calculation process of the numerical model. The annual control index of the groundwater table can be calculated quickly by inputting the annual control index of the groundwater exploitation amount into the surrogate model. This method was applied in the Minqin Basin for the case study. Using the case study, we found that:

1. The establishment of a surrogate model for the numerical model is a good method to ensure high precision, operability, and dynamic management to determine the control index of the groundwater table, which satisfies the demands of Chinese managers.

2. It is feasible to determine the control index of the groundwater table by generalizing the annual hydrological dynamics into three scenarios.
Although this study provides a scientific and rapid method for determination of the control index of the groundwater table, the results of the case study showed that the difference in the water table index under different scenarios is not large enough, which affects the application of the index. This could be related to the insufficient accuracy of the source and sink data used in the numerical simulation model. More case studies should be implemented to improve the accuracy of the data to verify the reliability of the method. On the other hand, this study only gives the recommended values for the sampling dimension of the feasible pumping interval. Further study is needed on the variability of the sensitivity of the water table to the sampling dimension, which can not only reduce the calculation amounts of the model, but also ensure the accuracy of the output.

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