Rational allocation of water resources based on ecological groundwater levels: a case study in Jinghui Irrigation District in China

H Li 1,2, W B Zhou 1,2,3, Q G Dong 1,2, B Y Liu 1,2 and C Ma 1,2
1 College of Environmental Science and Engineering, Chang'an University, Xi'an 710054, China
2 Key Laboratory of Subsurface Hydrology and Ecological Effect in Arid Region of Ministry of Education, Chang'an University, Xi'an 710054, China

Email: zwbzyz823@163.com

Abstract. Aimed at the hydrogeological environmental problems caused by over-exploitation and unreasonable utilization of water resources in Jinghui Irrigation District, this paper discusses the ecological groundwater level of the study area and establishes a three-layer optimal allocation model of water resources based on the theory of large scale systems. Then, the genetic algorithm method was employed to optimize the model and obtain the optimal allocation of crop irrigation schedule and water resources under the condition of a 75% assurance rate. Finally, the numerical simulation model of the groundwater was applied to analyze the balance of the groundwater on the basis of the optimal allocation scheme. The results show that the upper limitation of the ecological groundwater in Jinghui Irrigation District ranged from 1.8m to 4.2m, while the lower limitation level ranged from 8m to 28m. By 2020, the condition of the groundwater imbalance that results from adopting the optimal allocation scheme will be much better than that caused by current water utilization scheme. With the exception of only a few areas, the groundwater level in most parts of Jinghui Irrigation District will not exceed the lower limitation of ecological groundwater level.

1. Introduction
Water resources are of great importance to the development of economies human society and ecosystems. Due to the increasing demand for water resources caused by urbanization, industrial growth, climate change and human activity, China is experiencing severe water shortages. Therefore, how to allocate water resources becomes an important issue.
So far in the literature, ample researches have been conducted on water allocation, and most researchers have taken the three principles of equity, efficiency and sustainability into consideration when planning water allocation schemes. For example, a multilayer model of water resource allocation was built by E Romjin (1983)[1]. This model considered the relationship between the utilization and benefit of water resources, as well as reflecting the facts of the multi-objective and multi-bending in the water resource system. Carlos et al. (1997) took maximum synthetical economic benefit as the objective function and created a multi-resources management model of surface water, sewage and groundwater[2]. Rosegrant et al. (2000) optimized the allocation of water resources on the basis of combining a hydrological model with economic benefits in order to improve water utilization efficiency[3]. Reca et al. (2001) established an economic optimization model for water resource management in a deficit irrigation system[4]. Mohammed et al. (2007) established a coupled hydrologic-economic spreadsheet water allocation model that could be applied to both agricultural and environmental sectors with various policy scenarios[5]. Dedi Liu (2010) presented a model that was comprised of four modules for the optimal allocation of water resources in a saltwater intrusion area[6].

However, as groundwater plays an important role in northwestern irrigation areas in China, the impact of groundwater must be taken into account when studying optimal allocation of water resources. Aimed at such an issue, scholars have produced many researches and achievements. For example, Yang (2003) proposed a scheme of groundwater utilization in Hetao irrigation district in Inner Mongolia on the basis of analyzing groundwater recharge and reasonable exploitation[7]; Zhou (2006) used the multivariate nonlinear method to forecast groundwater levels and analyzed the reasonable irrigation water ratio of wells to canals[8]; Yue (2011) established an optimal allocation model of water resources by adopting groundwater level as a constraint condition[9]; He (2011) developed a groundwater stochastic-determination model and optimized the allocation of water resources in Jinghui Irrigation District[10]; Dai and Cai (2012) set up 10 kinds of water-saving irrigation simulation scenarios to simulate the change of the groundwater level according to the actual situation of agricultural irrigation, and studied a suitable irrigation water ratio of well to canal through groundwater equilibrium analysis[11].

In conclusion, most of the current studies have redistributed water resources on a macro level and the optimal allocation of crop water requirements was sketchy. While some other studies took the groundwater level, irrigation consumption and economic benefits into account when optimizing the allocation of water resources, researches that discuss the groundwater equilibrium on the basis of water resource optimal allocation have been much less common.

Jinghui Irrigation District is located in the semi-arid region in northwest of China. In the past few years, because of over-exploitation, the groundwater level in Jinghui irrigation district has been declining, which has caused a series of hydrogeological problems. Against the issue, this paper first discusses the upper and lower limitations of ecological groundwater level based on observation data from 1981-2012, then optimizes the allocation of crop irrigation schedule and water resources on the basis of large scale system theory. Finally, changes to the groundwater budget based on the water utilization scheme were simulated by the groundwater numerical simulation model. The results may provide a useful basis for the sustainable development of groundwater in Jinghui Irrigation District.
2. Study area
Jinghui Irrigation District is located in the middle of Guanzhong Plain of Shaanxi Province, and its west, south and east sides are surrounded by the Jinghe River, Weihe River, and Shichuanhe River. The total area of Jinghui Irrigation District which governs four counties and two administrative districts is 1180km². It is a typical well-canal combined irrigation district that owns a well-functional irrigation system (figure 1). In Jinghui Irrigation District, about 50%~60% of groundwater recharge is from canal leakage and irrigation infiltration, and the average annual precipitation and evaporation are 540mm and 1212mm, which presents a character of high evaporation and precipitation in summer, as well as a character of low temperature and precipitation in winter. Jinghe River and groundwater in the area are the main irrigation water resources. Since the 1980s, due to the increasing demand of water resources and decreased runoff of Jinghe river, groundwater in the Jinghui Irrigation District was over-exploited and the irrigation water ratio of well to canal increased from 0.3 in 1981 to 1.3 in 2012. As a result, the groundwater level sharply dropped and formed regional groundwater depressions (figure 2).

Figure 1. Distribution map of canal system in Jinghui Irrigation District.
3. Discussion on ecological groundwater level

The ecological groundwater level is defined as a level interval that not only can meet the need of ecological environment, but also will not lead to ecological environment exacerbation. It plays an important role in maintaining the sustainable development of the groundwater ecological environment.

3.1. Upper limitation of groundwater level

Increasing the groundwater level, which is caused by consuming a large amount of surface water irrigation, may lead to secondary salinization problems in irrigation districts. Therefore, the upper limitation of groundwater level is supposed to be the minimum groundwater level that does not cause salt accumulation in soil, which could affect crop growth. This paper discusses the upper limitation of groundwater level with a vital index of preventing soil salinization, height of capillary water rise and mainly active layer thickness of crop roots. The calculation formula is as follows:

\[ h = h_p + Z \]  

where \( h \) represents the upper limitation of the groundwater ecological level; \( h_p \) represents the height of capillary water rise; and \( Z \) represents the mainly active layer thickness of crop roots.

The height of the capillary water rise varies with soil texture, and the mainly active layer thickness of crop roots varies with the type of crops. The soil texture types in the study area are similar to part of the soil texture types in the study area of reference [12]. Thus, the height of the capillary water rise can be determined by the experimental results of literature [12]. The mainly active layer thickness of crop roots can be read in reference [13]. Then, the upper limitation of ecological groundwater level was calculated by formula 1 and the Kriging spatial interpolation method was employed to obtain the contour map of the upper limitation of the ecological groundwater level (figure 3). As can be seen...
from figure 3, the upper limitation of the ecological groundwater level in Jinghui Irrigation District ranged from 1.8m to 4.2m, and it increased from south to north, which presented a good similarity with the distribution of aquifer media. The reason why this makes a difference is that the aquifer media in the southern part of the study area is mainly composed of medium-coarse sands, so the heights of the capillary water rise in such regions are low and the mainly active layer thickness of crop roots are thin. The aquifer media in the southern part of the study area is composed of silty clays and clays, so the heights of the capillary water rise in this region are high and the mainly active layer thickness of crop roots are thick.

Figure 3. Upper limitation of ecological groundwater level.

3.2. Lower limitation of groundwater level
As described above, Jinghui Irrigation District is located in a semi-arid region in the northwest of China, where precipitation is concentrated in summer and groundwater level changes greatly in the wet season and dry season. In the wet season, the water table is high and the evaporation loss is great. However, in the dry season, the water table is low. When the water table is lower than the limited level of groundwater evaporation, the groundwater ecological environment may be destroyed. Therefore, in this paper, it is considered that the lower limitation of groundwater level should be the limited level of groundwater evaporation, that is, the level where the evaporation of groundwater is zero[14-15].

The limited level of groundwater evaporation was calculated by the dynamic data correlation methods based on data from 49 observation wells. The result of the calculation has shown that the limited level of groundwater evaporation in Jinghui Irrigation District ranged from 7.8m to 21.4m. However, as mentioned above, due to long term over-exploitation, the groundwater level in the study area has sharply decreased, and two obvious depressions were formed, as shown in figure 1. Therefore, it is unrealistic to recover a healthy environment of groundwater in a short period. Based on this, in order to gradually improve the conditions of this groundwater imbalance, this paper modified the lower limitation of groundwater on the basis of the limited level of groundwater evaporation and the practical situation of groundwater level in the study area. The modified lower limitation of ecological groundwater level is shown in figure 4.
4. Optimal allocation of water resources

With the development of society, many complex issues have become difficult to describe by simple mathematical models. Sometimes, even though a model could be established, the result was very difficult to obtain. Therefore, under the conditions of many constraints and effect factors, the optimization theory of the large scale system was appeared as a burgeoning theory that had more advantages to solve such problems. The large scale system contains several subsystems; the upper systems play a role of coordination while the lower systems are used to decompose the upper systems. The main decomposition purpose of the lower systems is to make the complex issues simple and find out an optimized solution for each simple problem. Meanwhile, the main purpose of the coordination of upper systems is to link up all the subsystems in order to ensure their correlations and find out the optimal solution of the whole system[16-18].

As described earlier, Jinghui Irrigation District is a large irrigation area that consists of six administrative regions, and the main supplying water resources are surface water and groundwater. Therefore, the water utilization system in Jinghui Irrigation District is complex. Under these circumstances, this paper adopted the theory of large scale systems to establish a three-layer structure model of optimal allocation of water resources. Then, the Genetic Algorithm Method was employed to obtain the solution of the model. The final results give the optimal irrigation schedule of crops and optimal allocation of different water resources under the condition of a 75% assurance rate (P=75%), common drought year, because Jinghui Irrigation District is located in semi-arid zone).

The estimation of crop water requirements was calculated by multiplying the estimated hectare by the net water requirement (m³/ha) of each crop. The required meteorological data (P=75%) were obtained from the local weather station, while other required data for calculation were collected from the Administration Bureau of Jinghui Irrigation District. The six administrative regions were considered to be the subareas, and wheat, corn and cotton were considered as the main crops. Thus, the structure of the three-layer model based on the theory of large scale can be built (figure 5).
4.1. Water Optimal Allocation Model in Jinghui Irrigation District

4.1.1. Water Optimal Allocation Model of Single Crop in Different Growth Stages

- **Objective Function**

  The Jensen model is a multiplicative model that takes the ratio of the real yield per unit area \( Y_a \) to the maximum yield per unit area \( Y_m \) as the goal and assumes that the crop will not yield if the crop evaporation at certain stages is zero. This model is widely used in arid and semi-arid areas because it takes interactions of different growing stages into account and has a high sensitivity to gross product. Therefore, the objective function was established by the Jensen model:

  \[
  f^* = \max \left( \frac{Y_a}{Y_m} \right) = \max \prod_{i=1}^{n} \left( \frac{ET_a}{ET_m} \right)^{\lambda_i}
  \]

  where \( ET_a \) represents the real evaporation of the crop; \( ET_m \) represents the maximum evaporation of the crop; \( \lambda_i \) represents the sensitivity coefficient of the crop; and \( n \) represents the growth period of the crop.

- **Constraints**
  
  a. **Constraints of Irrigation Water in the Growth Period**

     The water that is allocated to the crop in its whole growth period cannot exceed the maximum water that is supplied by the water resources:

     \[
     \sum_{i=1}^{Y} m_i \leq Q; \quad 0 \leq m_i \leq q_i
     \]

     where \( m_i \) represents the irrigation water in each stage of the growth period; \( Q \) represents the distributable irrigation water per unit area in the whole growth period of the crop; and \( q_i \) represents the distributable irrigation water at the beginning of each stage.

  b. **Constraints of evaporation in the growth period**

     The evaporation of the crop in each stage of the growth period cannot exceed the maximum evaporation of the crop:
\( (ET_a)_i \leq (ET_{\text{max}})_i \) \hspace{1cm} (4)

where \((ET_a)_i\) represents the evaporation of the crop in \(i\) stage of the growth period; \((ET_{\text{max}})_i\) represents the maximum evaporation of the crop in \(i\) stage of the growth period.

4.1.2. Water optimal allocation between different crops

There are several crops in the irrigation district, and the sensitivity degree of reduction of each crop in its growth period is different. Once the cultivated area of each crop and the amount of supply water are certain, the benefits change with the allocation of irrigation water between different crops. Therefore, how to allocate the irrigation water reasonably between different crops in order to reach maximum economic benefits is the goal of the optimal calculation of this layer.

- Objective function

Considering the maximum economic benefits as the objective function:

\[
\max \sum_i^N x_i = \sum_j^M f_{ij}(Q_{ij}) \cdot S_{ij} \cdot C_j
\] \hspace{1cm} (5)

where \(i\) represents the number of subsystems; \(j\) represents the number of crops; \(f_{ij}\) represents the yield per unit area of \(j\) crop in \(i\) subsystem; \(Q_{ij}\) represents the irrigation water consumption per unit area of \(j\) crop in \(i\) subsystem; \(S_{ij}\) the cultivated area of \(j\) crop in \(i\) subsystem; and \(C_j\) represents the unit price of \(j\) crop.

- Constraints

The sum of crop water consumptions in the subsystem should be less than or equal to the amount of water that is distributed by the irrigation district:

\[
\sum_j^M Q_{ij} \cdot S_{ij} \leq V_{si} \cdot \eta_x + V_{gi} \cdot \eta_g
\] \hspace{1cm} (6)

where \(V_{si}\) represents the amount of surface water allocated by \(i\) subsystem; \(V_{gi}\) represents the amount of groundwater allocated by \(i\) subsystem; \(\eta_x\) represents the utilization coefficient of surface water; and \(\eta_g\) represents the utilization coefficient of groundwater. The means of \(Q_{ij}\) and \(S_{ij}\) are the same as the means of the variables in equation[5].

4.1.3. Water optimal allocation between different subsystems

In this layer, the available supply water of the whole area was distributed to the subsystems of the second layer. In each subsystem, the optimal allocation of irrigation water between different crops and the economic benefits of each subsystem were determined by the optimal water allocation model between different crops. Then, the formerly calculated results should be fed back to the upper layer. Finally, the optimal allocation scheme of water resources that could reach the maximum economic benefits was obtained through the coordination of each layer.

- Objective function

Considering the maximum economic benefits of the whole irrigation districts as the objective:
\[
\max \ Z = \sum_{i=1}^{6} z_i(w_i) - y_g \sum_{i=1}^{6} Q_{gi} - y_s \sum_{i=1}^{6} Q_{si}
\]

where \( Z \) represents the economic benefits of the whole area; \( z_i \) represents the economic benefits of \( i \) subsystem; \( w_i \) represents the amount of irrigation water distributed by the irrigation district; \( y_g \) represents the price per cubic meter of groundwater; \( Q_{gi} \) represents the amount of groundwater irrigation of \( i \) subsystem; \( y_s \) represents the price of per cubic meter of surface water; and \( Q_{si} \) represents the amount of surface water irrigation.

- Constraints
  a. The sum of the supply water in the canal system of each subsystem should be less than or equal to the amount of water in the whole irrigation canal system:

\[
\sum_{i=1}^{6} W_{si} \leq W_{st} \cdot \eta_{st}
\]

where \( W_{si} \) represents the amount of water in whole irrigation canal system and \( \eta_{st} \) represents the water utilization coefficient of canal system.

b. The sum of the groundwater consumption in each subsystem should be less than or equal to the allowable groundwater exploitation:

\[
\sum_{i=1}^{6} Q_{gi} \leq U_i \eta_{gi}
\]

where \( U_i \) represents the allowable groundwater exploitation and \( \eta_{gi} \) represents the groundwater utilization coefficient of the canal system.

c. The ratio of canal-well water utilization should be in a reasonable range.

\[
1 \leq Q_{si} : Q_{gi} \leq 2
\]

The means of \( Q_{si} \) and \( Q_{gi} \) are the same as the means of the variables in equation (7).

4.2. Optimization technique

This paper employed the Genetic Algorithm method (GA) to work out the three-layer model. The procedures of the solution are as follows. First, distribute the total surface water and groundwater to the second layer at a certain proportion, which is taken as an initial value. Secondly, taking the initial value into each subsystem and allocating the irrigation water to the crops in each subsystem and optimizing the allocation of irrigation water of a single crop in each growth stage by the Genetic Algorithm method (GA)[19-20]. Thirdly, calculating the economic benefit of the whole district according to the output of crops, which was obtained by the optimal allocation scheme of water resources. Finally, judging whether the solution is the optimal solution; if not, returning to the upper layers in turn. The calculation will not stop until the optimal solution is received or the maximum number of iterations is reached. The optimal processes of the GA method are shown in figure 6a and 6b, and the results of the optimal allocation are shown in table 1 and table 2.
Figure 6a. Changing process of fitness by GA.

Figure 6b. Changing process of individual average distance by GA.

Table 1. Optimal allocation of crop irrigation schedule in m$^3$/ha.

| crop     | growth stage | Jingyang | Sanyuan | Gaoling | Lintong | Yanliang | Fuping |
|----------|--------------|----------|---------|---------|---------|----------|--------|
| wheat    | winter irrigation | 1006.4   | 1000.2  | 1031.6  | 1012    | 998.3    | 942.4  |
|          | elongation    | 864.6    | 760.1   | 839.7   | 841     | 847.3    | 838.2  |
|          | earing        | 745.1    | 740.2   | 761     | 783.8   | 768.8    | 775.4  |
|          | elongation    | 727.1    | 735.3   | 719.7   | 658.3   | 688.3    | 705.1  |
| corn     | earing        | 706.8    | 700.4   | 721.8   | 711.9   | 689.6    | 658.8  |
|          | flowering     | 603.1    | 615.3   | 593     | 600.5   | 610.2    | 633.6  |
| cotton   | pre-sowing    | 734      | 719.3   | 706.6   | 723.7   | 747.2    | 739.2  |
|          | squaring      | 606      | 641.4   | 603.2   | 619.6   | 614.3    | 626.6  |
|          | florescence   | 536      | 562.4   | 531.9   | 526.8   | 544.3    | 515.8  |
Table 2. Optimal allocation of different water resources in $/10^4 \text{m}^3$.

| District | Water resource | Wheat | Corn | Cotton |
|----------|----------------|-------|------|--------|
|          |                | Winter irrigation | elongation | earing | elongation | earing | flower | Pre-sowing | Squaring | florescence |
| Jingya   | canal          | 963.91 | 699.25 | 778.12 | 689.45 | 923.52 | 795.13 | 357.54 | 327.51 | 343.45 |
|          | well           | 858.23 | 582.98 | 653.64 | 519.82 | 798.58 | 699.81 | 249.32 | 234.22 | 236.87 |
| Sanyuan  | canal          | 598.17 | 493.49 | 577.31 | 449.87 | 540.54 | 461.12 | 290.03 | 273.47 | 255.23 |
|          | well           | 509.58 | 401.45 | 465.89 | 321.56 | 437.12 | 377.65 | 182.86 | 181.49 | 179.58 |
| Gaolingt | canal          | 639.39 | 572.56 | 575.37 | 462.56 | 553.19 | 491.59 | 283.29 | 278.24 | 264.56 |
|          | well           | 549.71 | 458.91 | 460.63 | 358.91 | 466.76 | 407.94 | 195.77 | 181.45 | 183.64 |
| Lintong  | canal          | 556.15 | 484.56 | 491.84 | 385.85 | 405.78 | 355.68 | 297.89 | 283.56 | 181.35 |
|          | well           | 479.36 | 407.28 | 405.78 | 273.46 | 318.95 | 263.45 | 206.91 | 199.68 | 209.23 |
| Yanling  | canal          | 459.12 | 365.17 | 375.15 | 263.56 | 358.51 | 297.85 | 224.33 | 181.63 | 178.78 |
|          | well           | 338.79 | 247.65 | 264.79 | 204.77 | 277.84 | 223.56 | 131.67 | 122.75 | 121.57 |
| Fuping   | canal          | 209.64 | 187.45 | 201.89 | 186.12 | 198.43 | 176.14 | 158.96 | 142.75 | 146.36 |
|          | well           | 144.97 | 126.77 | 135.47 | 130.52 | 131.92 | 121.78 | 92.25  | 95.13  | 93.45  |

5. Numerical simulation of groundwater

In order to study the impact of the optimal allocation scheme of water resources on groundwater balance, a numerical simulation of groundwater was developed.

5.1. Modeling

As the aquifer in Jinghui irrigation district is of large thickness and the hydraulic gradient is relatively slow, the groundwater in this area can be generalized as a two-dimensional unsteady flow, while the hydrogeological model is isotropic and heterogeneous in type. The northern boundary is considered to be the second type of recharge boundary because it receives lateral recharge from the Loess Platform region. As mentioned earlier, the west, south and east sides of Jinghui irrigation district are surrounded by Jinghe River, Weihe River, and Shichuanhe River, they are the main discharge area of groundwater,
they only recharge groundwater in the flood season, and the amount of recharge is small [21]. Therefore, they are set as the river boundary. Meanwhile, the canal seepage is set as the line source, the irrigation water and precipitation are set as the area source, and the evaporation is set as the area sink [22]. Because there are about 20,000 wells in the study area, the exploited wells are also set as the area sink. According to the above conditions, a mathematical model is established as follows:

\[
\frac{\partial}{\partial x} \left[ K(h - z) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K(h - z) \frac{\partial h}{\partial y} \right] + \mathcal{W} = \mu \frac{\partial h}{\partial t}, (x, y) \in \Omega, t > 0
\]

\[
h(x, y, t) = h_0(x, y), \quad (x, y) \in \Omega, t = 0
\]

\[
K(h - z) \frac{\partial h}{\partial n} = q(x, y, t), \quad (x, y) \in \Gamma_2, t > 0
\]

where \( h \) represents the groundwater level (m); \( K \) represents the permeability coefficient of the aquifer (m/d); \( z \) represents the lower bed level of the aquifer (m); \( \mu \) represents the specific yield; \( h_0 \) represents the initial groundwater level (m); \( q \) represents the inflow or outflow per unit area of the second type of recharge boundary (m³/d·m²); \( \mathcal{W} \) represents the source or sink term (m³/d); \( \Gamma_2 \) represents the second type of recharge boundary; \( \Omega \) represents the calculation area; \( x, y \) represent the x and y coordinate axis respectively; and \( t \) represents time.

5.2. Model identification and verification

According to the spatial structure and parameter features, the aquifer of Jinghui irrigation district was divided into a series of grids in 300*150 and also into seven hydrogeological subdivisions (figure 7). The initial values of the parameters were obtained by pumping tests. The groundwater level of January, 2009 was regarded as the initial flow field, and the observation levels of groundwater from January 2009 to December 2010 were used to identify the model, while the observation levels of groundwater from January 2011 to December 2012 were used to verify the model. The relative error of the calculation results ranged from 3% to 7% by comparing the calculated values and the measured values (figure 8). Thus, the results showed that the established model was reliable, the simulation results could reflect the characteristics of the groundwater flow field of Jinghui Irrigation District, and the model can also be used for numerical analysis. The final hydrogeological parameters of the model are shown in table 3.

Figure 7. Map of hydrological subdivisions of the study area.
Table 3. Model parameters of each hydrogeological subdivision.

| Hydrogeological Area | Permeability Coefficient $K$ (m/s) | Specific Yield $\mu$ |
|----------------------|-----------------------------------|---------------------|
| IA                   | $2.90 \times 10^{-6}$            | 0.04                |
| IB                   | $1.00 \times 10^{-4}$            | 0.1                 |
| IIA                  | $1.74 \times 10^{-4}$            | 0.07                |
| IIB                  | $1.16 \times 10^{-5}$            | 0.06                |
| IIC                  | $7.9 \times 10^{-6}$             | 0.11                |
| IIBI                 | $1.01 \times 10^{-5}$            | 0.01                |
| IV                   | $4.4 \times 10^{-6}$             | 0.045               |

5.3. Result analysis of numerical simulation

The irrigation infiltration and groundwater exploitation were calculated on the basis of optimal allocation of the crop irrigation schedule and water resources. Then, the results were substituted into the established model in order to forecast the groundwater level and water balance in 2020. Finally, the forecasted water balance and level that resulted from adopting the optimal allocation scheme were compared with the level and balance condition caused by the current water utilization scheme. Also the forecasted level should also be compared with the ecological groundwater level that was discussed previously. The results are shown in table 4, figure 9a and figure 9b.
Table 4. Comparison of water balance under different scenarios in the year 2020 $10^4$ m$^3$/a.

| Scheme    | Precipitation | Canal leakage | Irrigation | Weir | Lateral Inflow | Exploitation | Evaporation | Outflow | Total Budget |
|-----------|----------------|----------------|------------|------|----------------|---------------|-------------|----------|--------------|
| Present   | 6498.8         | 6342.5         | 1788.6     | 3852.5 | 1987.2         | 22589         | 2365        | 1893.1   | -6377.5      |
| Optimized | 6589.4         | 7189.3         | 2978.9     | 3218.7 | 1895.7         | 19000         | 2658        | 1893.8   | -1679.8      |

Figure 9a. Difference between forecasted level and upper limitation level.

Figure 9b. Difference between forecasted level and lower limitation level.

As shown in table 4, the situation of the groundwater imbalance was greatly improved by the optimal allocation scheme of water resources. By the year 2020, the groundwater level will be lower
than the upper limitation of the groundwater ecological level, that is, the phenomenon of soil salinization will not appear in Jinghui Irrigation District, which is as shown in figure 9a. Additionally, according to figure 9b, the groundwater level in 2020 will not exceed the lower limitation of the groundwater ecological level in most areas in Jinghui Irrigation District, only in a few areas will the level be deeper than that value.

6. Conclusions
The ecological groundwater level was obtained according to the limited level of groundwater evaporation, the height of capillary water rise and the mainly active layer thickness of crop roots. The results have shown that the upper limitation of the ecological groundwater level in Jinghui irrigation district ranged from 1.8m to 4.2m, and the lower limitation of the ecological groundwater level ranged from 8m to 28m.

A three-layer optimal allocation model of water resources on the basis of the theory of large scale systems was established. The model applied economic benefits as the objective function and took the ratio of canal-well water utilization, the supply capacity of different water resources, the water requirements and other conditions as constraints. Then, the optimal allocation of the crop irrigation schedules and water resources under the condition of a 75% assurance rate was calculated through the GA method. The results of optimal allocation indicate that the amount of canal irrigation water is $2.17 \times 10^8$ m$^3$ while the amount of well irrigation water is $1.69 \times 10^8$ m$^3$, and the ratio of canal-well water utilization is 1.28:1.

The groundwater balance based on the optimal configuration of the crop irrigation schedule and water resources was simulated by a numerical simulation model. The simulation results indicate that the imbalance condition of the groundwater will be greatly improved by adopting the optimal allocation scheme. By 2020, the groundwater level will be lower than the upper limitation of the ecological groundwater level and will not exceed the lower limitation ecological groundwater level in most areas of Jinhuai Irrigation District, although the level in some areas will be deeper than the lower limitation level. The results show that the optimizing allocation scheme of water resources is able to realize the sustainable utilization of water resources and gain good integral benefits.

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