Modeling Groundwater Behavior for a Chinese Irrigated Perimeter

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Abstract

The groundwater level has persistently dropped during the eighties in an agricultural irrigated perimeter (144.8 km²) located 100 km south of Beijing. The objective of this research is to identify the reasons of such a behavior. Water is primarily used for irrigation. It comes mainly from groundwater and partly from surface water diverted from the nearby Daqing river. The best estimates of the yearly groundwater level were obtained by a simplified regional water balance equation. This model gives good results when considering the water consumption constant over the years, which means that the rainfall is the main factor influencing the yearly groundwater level. The water consumption found (625 mm) for the last years is higher than the water inputs (rainfall 534 mm and surface water diversion 93 mm), resulting in a water deficit (53 mm) that creates on average a slow groundwater level decrease. However, the strong groundwater drop observed in the eighties is mainly due to lower rainfall than usual. In order to assure a stable groundwater level on the long-term, the water deficit needs to be eliminated. Either the water consumption can be diminished or the aquifer can be recharged through additional surface diversion. While considering that the water consumption will be identical in the future, two scenarios of surface water diversion have been considered. First, if the surface water diversion is kept unchanged, the groundwater level will continue to drop 0.34 m per year on the long-term average. Second, additional surface water of 127 mm/year is needed to recharge the aquifer and thus compensate the water deficit to assure future stable groundwater level. The availability of water at the Daqing river is not sufficient to divert sufficient amount of water to compensate the water deficit during dry years. However, on the long-term average, the number of days with flow in the Daqing river is just sufficient for the new diversion needs.

Key words: Water deficit, groundwater simulation, regional water balance, groundwater storage, groundwater recharge

Résumé

Durant les années quatre-vingt, le niveau de l’eau souterraine a régulièrement baissé dans un périmètre irrigué situé à 100 km au sud de Pékin. L’objectif de la recherche est d’identifier les causes de ce comportement. L’eau y est utilisée principalement pour l’irrigation. Elle provient en majorité de la nappe souterraine et partiellement de l’eau de surface dérivée depuis la rivière voisine. La meilleure estimation du niveau annuel de l’eau souterraine est obtenue par une simple équation de bilan régional en eau. Ce modèle donne de bons résultats lorsque la consommation d’eau est considérée comme constante au cours du temps, ce qui signifie que la pluie est le principal facteur influençant le niveau annuel de l’eau souterraine. La consommation d’eau trouvée (625 mm) pendant ces dernières années est plus élevée que les entrées d’eau (pluie 535 mm et...
dérivation d'eau de surface 93 mm), provoquant un déficit en eau (53 mm) qui est responsable en moyenne d'une lente baisse du niveau d'eau souterraine. Cependant, la forte baisse du niveau d'eau observée durant les années quatre-vingt est principalement provoquée par une pluie plus faible que d'habitude. Afin de parvenir à un niveau d'eau stable à long terme, le déficit en eau doit être éliminé. Soit la consommation en eau doit être diminuée, soit l'aquifère doit être rechargé par des dérivations d'eau de surface supplémentaires. Si l'on considère que la consommation d'eau restera constante dans le future, deux scénarios de dérivation d'eau de surface ont été considérés. Premièrement, si la dérivation d'eau de surface reste constante, le niveau de l'eau souterraine continuera de baisser de 0.34 m par an dans le long terme. Deuxièmement, 127 mm/an de dérivation supplémentaire sont nécessaires pour recharger l'aquifère et ainsi compenser le déficit en eau qui assurera un niveau d'eau souterraine stable dans le future. La disponibilité de l'eau dans la rivière n’est pas suffisante pour dériver une quantité d'eau suffisante qui compenserait le déficit en eau pendant les années sèches. Cependant, en moyenne sur le long terme, le nombre de jour avec du débit dans la rivière Daqing est juste suffisant pour les nouveaux besoins en dérivation.

Mots clés : Déficit hydrique, simulation des écoulements souterrains, bilan hydrique régional, stockage d'eau en aquifère, recharge de nappes.

Introduction

In the context of water resources overexploitation, an agricultural perimeter of 144.8 km² was studied from 1994 to 1997. It is located 100 km south of Beijing (see Figure 1) and belongs to the Huang-Huai-Hai river plain, which covers about 320,000 km², and is the major crop producing area of the country.

A persistent drop of the groundwater level was observed during the eighties (see Figure 4). The increasing irrigated surface and grain production (see Table 1) was believed to be responsible of this drop. However, the rainfalls need also to be considered, especially as during that period, rainfalls were lower than usual. The average rainfalls on the project area from 1980 to 1987 were 414 mm/year, whereas the average rainfalls from 1970 to 1996 were 534 mm/year. The understanding of the groundwater behavior and the elaboration of a predictive model are the main objectives of this research. They should lead to some practical proposals to reach a sustainable groundwater level in the project area, with no water deficit.

Table 1. Socio economic data on the project area from 1980 to 1994

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural population</td>
<td>106'600</td>
<td>123'900</td>
<td>125'000</td>
<td>126'500</td>
<td>123'500</td>
<td>124'200</td>
</tr>
<tr>
<td>Irrigated land (ha)</td>
<td>8'770</td>
<td>9'153</td>
<td>9'771</td>
<td>10'157</td>
<td>9'562</td>
<td>11'862</td>
</tr>
<tr>
<td>Grain production (tons)</td>
<td>21'965</td>
<td>57'904</td>
<td>59'462</td>
<td>72'638</td>
<td>79'841</td>
<td>90'035</td>
</tr>
<tr>
<td>Gross industry production (million yuan based on 1990 prices)</td>
<td>39.3</td>
<td>190.4</td>
<td>220.6</td>
<td>285.5</td>
<td>497.2</td>
<td>747.8</td>
</tr>
</tbody>
</table>

In the project area, the population and industries use an estimated 23% of the total water consumption; the 77% remaining are used for irrigation. The most usual crops are winter wheat (October to June) and summer corn (June to September). As 83% of the rainfalls...
occur between June and September, irrigation is needed to allow growing winter wheat and summer corn. An estimated 70% of the project area surface is irrigated. About 80% of the irrigation water come from wells (up to 100 m depth) and the remaining 20% come from canals that bring diverted surface water from the nearby Daqing river. The diversions are not very frequent. Several gates control the river intake at Xingaifang and the distribution in the canals, which mainly bring water to the southwestern part of the project area.

The aquifer under the project area has the typical geological structure of large alluvial plains. It is made of a complex and deep multi-layer system with many lens structures. Soil types include clay to middle coarse sand with no apparent typical homogeneous characteristics.

**Water Balance Approach**

A water balance approach was used to calculate the water deficit on a yearly time step at the project area scale. Figure 2 shows all the possible water movement concerned by the project area.

However, only the following relevant data could be gathered:

- The monthly rainfall from 1953 to 1996 of Xiongxian station (which is considered to be representative of the project area).
- Four sites with reliable historical groundwater levels within the project area from 1974 to 1988.
Figure 2. General water movement concerned by the project area

- 17 reliable groundwater level records every 5 days within the project area from July 1992 to December 1997.
- The average transmissivity of the aquifer that was determined by several pumping tests.
- An estimation of the surface water diverted into the project area from 1970 to 1994.

In Figure 2, only the "(7) Diversion to the project area" and "(8) Rainfall" are known concerning the project area water movement. With those data, it is impossible to calculate the water deficit, which is the difference between all the water outputs and inputs. The following oversimplifications needed to be done according to the available data.

- The total water consumption in the project area (9) (evapotranspiration and domestic uses) is constant each year. This is contrary to the assumption that the drop of the groundwater level is due to an increasing water use. However, no information could quantify this water consumption increase, thus a constant consumption was used as a hypothesis.
- The surface water outflow (10) is neglected. Oral information indicates that water went very rarely out of the project area since 1970.
- The groundwater lateral (13) (14) and vertical flow (15) (deep percolation below 100 m depth) are neglected. Estimation shows that the groundwater lateral net inflow corresponds to only about 1% of the rainfalls.
- The proportion of diverted water reaching the aquifer (called the diversion coefficient) is constant over time.
- The average values of rainfall and groundwater level data available are representative of the overall project area situation.
Consequently, the water movement is much simplified (see Figure 3). The yearly water deficit corresponds to the difference between the output (the water consumption) and the inputs (rainfall and river diversion). Only the inputs are measured values. The output (the water consumption) needs to be determined in a relationship using the groundwater level available. In order to establish this relationship, the cumulated water deficit is computed; it is called the water storage. This value represents the quantity of water that is stored in the underground, expressed in equivalent of mm of water over the project area and not as a direct groundwater level difference. The simplified water balance is based on the following equation, with all values expressed in equivalent mm over the project area (1 mm = 0.001 m x 144.8 km² = 144'800 m³):

\[
WS(t) = WS(t-1)+ R + D*S – C
\]

- **WS (t)**: Water storage at the end of the year (mm)
- **WS (t-1)**: Water storage at the end of the previous year (mm)
- **R**: Rainfalls of the year (mm)
- **D**: Diversion efficiency, fixed value (-)
- **S**: Surface water diversion of the year (mm)
- **C**: Water consumption, fixed value (mm)
- **WI**: Water input (mm) = R + D*S
- **WD**: Water deficit (mm) = C – (R + D*S) = C – WI

Consequently:

\[
WS(t) = WS(t-1) - WD
\]

Then a direct relationship is established between the water storage and the groundwater level. The two unknown fixed values (the water consumption C and the diversion efficiency D) are determined to get the best relationship (highest correlation coefficient R²). Many combinations of C and D values are possible, but only the combination giving the best relationship is selected. This procedure is summarized in Figure 3.

**Figure 3.** Simplified water movement in the project area
The analysis is then done in two steps:

Step 1: The relationship between water storage and groundwater level is established with the available data (1974-1996). The values of C and D are determined to get the best relationship. The relationship is taken as the predictive model used in step 2.

Step 2: The future groundwater level is calculated by using the relationship found under step 1 according to different historical frequency rainfall and diversion values. Some proposals of diversion from Xingaifang are made to reach a sustainable groundwater level in the project area.

Step 1: Relationship between water storage and groundwater level

The best correlation coefficient ($R^2$) for the relationship is found with a constant water consumption of $C = 625$ mm and a diversion efficiency coefficient of $D = 0.42$. The initial water storage has been fixed arbitrarily at 2,000 mm on 31.12.73. This choice has no impact on the analysis, as only the variation of water storage is of interest and not its absolute value.

The relationship between the water storage and the groundwater level is established from 1974 to 1996 (except for 1989-91) which are the only complete available data (see Figure 4). For each year, the new water storage at the end of the year is calculated by adding the previous water storage to the water input and by subtracting the water consumption. The historical trend of the water storage and the groundwater level are found to be very similar (see Figure 4 and 5). The relationship in Figure 5 is expected to be linear, with the slope (15.6%) representing the storage capacity of the aquifer.

Figure 4. Historical trend of the groundwater level (in m a.s.l.) and the water storage
Since 1970, the rainfalls can be considered to be in a homogenous period. From 1970 to 1996, the average rainfall was \( R = 534 \text{ mm} \) and the average diversion was \( S = 91 \text{ mm} \). 42 % (D = 0.42) of the diversion is reaching the groundwater in the project area (D*S = 38 mm). The average water input is then WI = 572 mm \( (R+D*S = 534 \text{ mm} + 38 \text{ mm}) \). From 1970 to 1996, the average water deficit is \( WD = 53 \text{ mm} \) \( (C - WI = 625 \text{ mm} – 572 \text{ mm}) \).

### Figure 5. Relationship between water storage and groundwater level

#### Step 2 : Future groundwater level scenarios and proposals for sustainable groundwater level

The future groundwater levels are estimated by using the predictive model found under step 1. Two management scenarios are considered.

**First scenario : No change in the actual water management**

The first scenario considers that the surface water management at Xingaifang, the rainfalls and the water consumption will be the same in the future as during the 1970-1996 period. The future water deficit will then be on average the same as the 1970-1996 water deficit (53 mm, see step 1). It will create an average yearly groundwater level drop of 0.34 m \( (0.0064 \times 53 \text{ mm}) \), see Figure 5). The average future water deficit indicates the long-term tendency, but each year the water deficit and the yearly groundwater level will vary according to the water inputs (rainfalls and surface water diversions). Table 2 indicates the expected groundwater level variations for different possible situations.

**Second scenario : Proposal for a sustainable groundwater level**

To reach a sustainable or stable groundwater level, the water deficit in the project area needs to be eliminated. One possibility is to diminish the water consumption that is mainly made of agriculture uses, but it also includes evapotranspiration of soil and unproductive plants as well as domestic and industrial uses. The agricultural practices have been studied, with special interest on the irrigation water saving techniques. However, if the present irrigation practices contribute at recharging the aquifer, implementing more efficient irrigation will mainly diminish the aquifer recharge, which will not change much the regional water deficit.
Another possibility is to increase the water input in the project area by modifying the regional surface water management. The amount of surface water diverted from the Daqing river into the project area could be increased, so that this additional water will infiltrate and recharge the aquifer through the existing canals without being used for irrigation. To recharge the aquifer, the diversion events should avoid irrigation period and wintertime with frozen soils.

Table 2 indicates the additional surface water amount to be diverted so that the project area has no water deficit. On average, 127 mm of additional surface water is needed (Table 2). The required quantity is a small proportion of Daqing river’s flow but the flow rate is an important limitation. The maximum flow considered corresponds to the infiltration rate of the canals (2.56 m³/s). The present diversion represents 59 days of diversion at the 2.56 m³/s flow rate. The additional surface water required corresponds to an additional 83 days of diversion. The total diversion should then be of 142 days/year (presently 59 days plus additional 83 days).

As the proposal is to divert more surface water from the Daqing river, the impact on the global water management at Xingaifang needs to be assessed. Table 3 presents the historical water distribution at Xingaifang and the new distribution proposal assuring the long-term sustainable groundwater level in the project area. The required 142 days/year of diversions to the project area means that diversion should occur almost on every day when the upstream Daqing river flows (149 days/year) at Xingaifang. The number of days with flow in the future will depend on the management of the upstream dams that mainly controls the flow of Daqing river. It will depend also on the rainfalls, as the flow has sharply decreased those last years, partly due to the rainfall decrease. The proposal suggest to diminish the water going to Baiyang lake; however the impact on the downstream users still needs to be estimated.

Very different water deficit occurs from year to year (Table 2). The lower the rainfall, the more diversion is needed to eliminate the water deficit, but the less Daqing river flow is available for diversion. In the extreme dry year cases, the infiltration capacity of the canals is not sufficient to compensate the water deficit. It is impossible to compensate the water deficit each year for itself, but the proposal is made based on an average diversion value. This means that if the proposed value is diverted on average every year, the groundwater level will stay stable on the long-term. However, the groundwater level should be maintained in between maximum and minimum acceptable levels.

Discussion of the Results

All previous results are based on some simplifications and hypothesis that could not be clearly confirmed. The following comments and discussion of the results can be made.

- Constant water consumption was the hypothesis used. However, other scenarios with the water consumption increasing over time gave also good results. Surprisingly, it is a 30 mm yearly water decrease since 1992 that gives the best relationship (water storage-groundwater level, R²= 0.9907). Those different trials show that the quality of the data is not sufficient to meaningfully test different water consumption scenarios. This also indicates that the rainfall is the main factor influencing the groundwater level variations and that the water consumption variation has only a minor impact on the overall groundwater behavior.
Table 2. Frequency of the water deficit and its impact on the two scenarios

<table>
<thead>
<tr>
<th>Rain event frequency</th>
<th>95%</th>
<th>90%</th>
<th>80%</th>
<th>50%</th>
<th>20%</th>
<th>10%</th>
<th>5%</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return period</td>
<td>1.05 yr</td>
<td>1.11 yr</td>
<td>1.25 yr</td>
<td>2 years</td>
<td>5 years</td>
<td>10 years</td>
<td>20 years</td>
<td>Values</td>
</tr>
<tr>
<td>Water deficit calculation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rain over the project area (1970-1996) in mm</td>
<td>285 mm</td>
<td>325 mm</td>
<td>378 mm</td>
<td>503 mm</td>
<td>671 mm</td>
<td>782 mm</td>
<td>889 mm</td>
<td>534 mm</td>
</tr>
<tr>
<td>Water diversion to the project area (1970-1996) in mm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>83 mm</td>
<td>172 mm</td>
<td>240 mm</td>
<td>369 mm</td>
<td>91 mm</td>
</tr>
<tr>
<td>Water input (frequency on rainfall + 42% diversion) (1970-1996)</td>
<td>321 mm</td>
<td>390 mm</td>
<td>410 mm</td>
<td>488 mm</td>
<td>822 mm</td>
<td>860 mm</td>
<td>925 mm</td>
<td>572 mm</td>
</tr>
<tr>
<td>Water deficit = C - WI = 625 mm - water input</td>
<td>304 mm</td>
<td>275 mm</td>
<td>215 mm</td>
<td>137 mm</td>
<td>-97 mm</td>
<td>-235 mm</td>
<td>-300 mm</td>
<td>53 mm</td>
</tr>
<tr>
<td>First scenario: No change in the water management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater change (m) = 0.0064 x water deficit (mm)</td>
<td>-1.94</td>
<td>-1.76</td>
<td>-1.38</td>
<td>-0.88</td>
<td>+1.26</td>
<td>+1.90</td>
<td>+1.92</td>
<td>-0.34</td>
</tr>
<tr>
<td>Second scenario: Proposal for a sustainable groundwater level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional water diversion needed = water deficit / diversion coefficient (0.42)</td>
<td>730 mm</td>
<td>660 mm</td>
<td>516 mm</td>
<td>329 mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>127 mm</td>
</tr>
<tr>
<td>Number of days per year with additional diversion needed</td>
<td>477 days</td>
<td>431 days</td>
<td>337 days</td>
<td>215 days</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>83 days</td>
</tr>
</tbody>
</table>

Remarks

All results are expressed in the calendar year and in mm over the project area (144.8 km²). 1 mm = 144,800 m³

* Negative values of a water deficit is a water surplus

** Diversion is supposed to be with an average inflow of 2.56 m³/s. Each day of diversion brings about 1.53 mm of water (2.56 m³/s = 2.21 x 10⁵ m³ during 1 day = 1.53 mm over the project area)
The river surface water diversions into the project area are input data for the model. They are not measured data but estimated values, which are much smaller input values than rainfalls. If surface water is neglected, the values of water deficit using only the rainfalls (S=0) are not very different than with the surface water taken into consideration. The relationships between groundwater level and rainfall \( R^2 = 0.979 \) or including surface water \( R^2 = 0.985 \) are very similar in precision. This shows the predominant influence of rainfalls on the groundwater levels observed.

Several combinations of water consumption (C) and diversion efficiency (D) values can fit the model giving also acceptable relationship. The possible combinations were not further studied because the quality of the available data has shown to be not sufficiently reliable for more precise analysis.

Hydrogeological observations indicate that the groundwater direction has changed over time (see Figure 6), which can be hypothetically explained by two different arguments: First, it might be a consequence of some different water uses in the project area, most probably an increasing water consumption in the northern

### Table 3. Historical and proposed future water management at Xingaifang

<table>
<thead>
<tr>
<th></th>
<th>Historical water management 1980 to 1993</th>
<th>Proposed future water management at Xingaifang</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average discharge at Xingaifang ((3\times10^7 \text{ m}^3/\text{year}))</td>
<td>14.08 \times 10^7 \text{ m}^3</td>
<td>14.08 \times 10^7 \text{ m}^3</td>
</tr>
<tr>
<td>Proportion going to (4)* Baiyang lake (%)</td>
<td>87.2 %</td>
<td>72.9 %</td>
</tr>
<tr>
<td>Proportion going to (5)* the river Daqing (%)</td>
<td>6.7 %</td>
<td>6.7 %</td>
</tr>
<tr>
<td>Proportion going to (6)* the inundation zone (%)</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Proportion going to (7)* the project area (%)</td>
<td>6.1 %</td>
<td>20.4 %</td>
</tr>
<tr>
<td>Average number of days per year with flow at Xingaifang</td>
<td>149 days</td>
<td>-</td>
</tr>
<tr>
<td>Average additional number of days per year when supplementary diversions with 2.56 m/s steady flow are needed into the project area for groundwater sustainability (from Table 2)</td>
<td>-</td>
<td>83 days</td>
</tr>
<tr>
<td>Average total number of days per year when diversions with 2.56 m/s steady flow are needed into the project area for groundwater sustainability**</td>
<td>-</td>
<td>142 days</td>
</tr>
</tbody>
</table>

* Number according to Figure 2
** The previous 91 mm of average diversion takes 59 days with 2.56 m/s steady flow

- The river surface water diversions into the project area are input data for the model. They are not measured data but estimated values, which are much smaller input values than rainfalls. If surface water is neglected, the values of water deficit using only the rainfalls (S=0) are not very different than with the surface water taken into consideration. The relationships between groundwater level and rainfall \( R^2 = 0.979 \) or including surface water \( R^2 = 0.985 \) are very similar in precision. This shows the predominant influence of rainfalls on the groundwater levels observed.

- Several combinations of water consumption (C) and diversion efficiency (D) values can fit the model giving also acceptable relationship. The possible combinations were not further studied because the quality of the available data has shown to be not sufficiently reliable for more precise analysis.

- Hydrogeological observations indicate that the groundwater direction has changed over time (see Figure 6), which can be hypothetically explained by two different arguments: First, it might be a consequence of some different water uses in the project area, most probably an increasing water consumption in the northern
part. This change of water consumption was not noticed in the model with the available data (see point 1). The second possible explanation is linked to the low groundwater level since the end of the eighties. The groundwater movement direction could then be influenced by Baiyang lake that is recharging the aquifer. However, no clear conclusions can be drawn with the available data about the observed change in the groundwater flow direction.

Figure 6. Direction of the general groundwater flow through the project area at different periods

Conclusions

In the context of water resources overexploitation in northern China, the main factors responsible of the groundwater behavior needed to be identified mainly between meteorological factors (variation of rainfalls) and anthropological factors (change in surface water management, irrigation water use increase...). The groundwater level behavior in the studied irrigated perimeter was best reproduced with a yearly relationship between the water storage value and the average groundwater level. The water storage is the cumulated value of the water deficit. The relationship was calibrated for the 1974-1996 values and used as a predictive model. This simplified regional water balance approach gave good results for reproducing the yearly groundwater variations. This approach is appropriate because of the specific conditions defined in this study; they are working at the regional scale, with yearly time steps and with an aquifer responding as a single reservoir.

On average since 1970, the project area is in a water deficit situation that contributes to the drop of the groundwater levels. However, the sharp decrease of groundwater level observed in the eighties is mainly due to a temporal low rainfall period. The groundwater level is mainly influenced by the rainfalls. The diversion of surface water from Daqing river, the possible extension of the irrigated area and the water consumption have only minor influences. The results need however to be taken with precaution as some hypothesis couldn't be confirmed.
Two future water management scenarios were considered. The first scenario states that the actual management practices will be maintained identical in the future and that the rainfalls and the water consumption will stay the same. The water deficit will then be of 53 mm/year that will create an average yearly groundwater level drop of 0.34 m on the long-term. The second scenario proposes to increase the water diversion from Daqing river into the project area to recharge the aquifer and thus reach a no water deficit situation. This would assure a sustainable groundwater level on the long-term. An additional 127 mm/year should be diverted from Daqing river at Xingaifang, which brings the total water diversion to 218 mm/year. This will take 142 days of diversion at a constant flow when the upstream river flows on average only 149 days/year! The limiting factor is more the number of days when the Daqing river flow and the infiltration rate of the canal, than the water quantity available in the Daqing river. Theoretically, the no water deficit situation is possible to be reached in the project area, but it means that water needs to be diverted into the project area all the time when it is available in the river. This new management will have an impact on the other downstream users, topic that was not considered in this project.

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