Establishment of the regional water balance analysis model based on RS-ET data and current situation analysis

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Abstract: Regional water balance analysis is the foundation that will guarantee the sustainable and scientific use of water resources and the sustainable development of the economy. In this study, the CPSP hydrological model is selected as the regional water-balance analysis tool for Daxing District. The model is validated with the 3 types of data as the runoff data from the Integrated Planning of Water Resource in Daxing District of Beijing, the evapotranspiration data estimated by remote sensing-based model (RS-ET), and the groundwater monitoring data, respectively. The calculated runoff data are basically consistent with that of the Integrated Planning of Water Resource in Daxing District, Beijing. Meantime the dynamic variation of evapotranspiration (ET) and groundwater reserves are better simulated by the CPSP hydrological model. Serving as the basis for this study, the current water resources for 2004 and 2005 are evaluated, in which the water shortages are 0.72×10^8 m^3 and 1.80×10^8 m^3, respectively.

Key words: CPSP hydrological model, regional water balance analysis, RS-ET, groundwater resources

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1 INTRODUCTION

Surface water resources are relatively scarce in Beijing's Daxing District of Beijing, in which groundwater is exploited as the main water resource for the industry, local residents and irrigation. With the fast development of urbanization, both industrial and residential domestic water consumption have increased significantly, causing the regional water table to decline each year, which has created water-use conflicts. The groundwater resource has a limited and non-renewable character. The regional environment is degraded due to the over-exploitation of the groundwater. In order to have sustainable utilization of regional water resources, the regional water balance should be analyzed, which will reveal the current situation of the regional water balance and groundwater over-exploitation. As a result, the main contradictions and internal laws between supply of and demand for water resources are held. Basis of this, a rational plan for regional water resources management and layout is put forward.

Generally, the analysis of the current regional water balance situation can serve as the foundation of water resources management and the precondition of the regional water resources plan as well as the establishment of scientific water resource management measures. Water consumption is the final determination of water resource allocation, based on the regional water balance. The main water consumption is evapotranspiration, which is also an irrigation parameter. Therefore, the effect of water savings is not only evaluated using the irrigation water quantity, but the real water consumption should be used as an important index. Measuring regional ET is very important for the agricultural water management, regional water resource planning and sustainable development of society and economy.

Compared with the traditional method of ET estimation, the main direction for development of the regional ET estimation is based on a remote-sensing technique with space-time continuity and a big region (Sun, *et al*., 2009). Currently, most researchers have concentrated on remote-sensing estimation methods and mechanism analysis. Studying regional water resources management based on RS-ET is still in the exploration stage, in which researchers are focused on water consumption evaluation for short-term current situations (Khan, *et al*., 2008; Li, *et al*., 2008; Teixeira, *et al*., 2009). Valuation of the regional irrigation water use and water consumption has an important guiding significance and reference value for the regional agriculture water management under currently weather condition. Unless the relationship between water consumption and each element of the regional water balance

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Corresponding author: ZHANG Jiyang, E-mail: firizjy@yahoo.com.cn is studied thoroughly, it can not be used to guide regional water resources planning and quota management for agricultural water resources. This relationship mentioned above can be determined using the regional hydrological model. The monitoring data for calibrating the model will be shorted for a big region under the complex surface. When the river flow data are used to calibrate the regional hydrological model, the calibrated results are affected by the choice of the representative outlets, causing uncertainty in the hydrologic process simulation. Temporal and spatial heterogeneity existed in the RS-ET data, which could be used to calibrate the regional hydrological model.

For this reason, the CPSP hydrological model is selected as the regional water balance analysis tool. The real-time agricultural water-use monitoring data and RS land use are selected as the input data for the model. The model is calibrated and validated using ET data and underground water table data. Lastly, the current water resources are evaluated, including water balance and groundwater over-exploitation. The RS-ET data with 30m resolution used in this study are produced by using the ETWatch Model, which is developed by the Institute of Remote Sensing Application of the China CAS. Compared with the data of the estimation value based on the water balance method, the average absolute percentage error is less than 10%, which came from the independent earth verification report on RS ET monitoring in the Beijing region, funded by the GEF Haihe River Basin Project (2010).

2 MODEL CALCULATION PRINCIPLE

The CPSP hydrological model is a district-lumped water-balance analysis tool, which is established by the International Commission on Irrigation and Drainage(ICID) for the project to establish watershed irrigation development and rational water resource distribution in India and China. The CPSP hydrological model is applied and verified. Meanwhile, the CPSP hydrological model is applied successfully to developing irrigation guidelines in countries such as Egypt and Mexico. The water resources are analyzed using the CPSP hydrological model, based on the reasonable exploitation and management of soil and water resources, in which human need for water is considered comprehensively, especially the impact of irrigation development and land-use changes (Gao, 2005). Every hydrological element in the water balance can be calculated using the CPSP hydrological model, including the hydrology variation under the change of land use or agricultural water use.

The CPSP hydrological model can be used to describe surface water balance, groundwater balance, and interaction between surface water and groundwater, as well as the water withdrawal influence on water storage capacity and water consumption. It contains a natural module, a human activities module, a groundwater module, and a water requirement module, among others.

2.1 Water balance

The water balance equation of the CPSP hydrological model is defined as follows.

$$Q_{\text{in}} + P + \Delta s = Q_{\text{out}} + \text{ET} \tag{1}$$

where Q_{in} is the total inflow, Q_{out} is the total outflow, P is rainfall, Δs is the storage change, and ET is evapotranspiration.

$$Q_{\text{in}} = SW_{\text{in}} + GW_{\text{in}} \tag{2}$$

$$Q_{\text{out}} = SW_{\text{out}} + GW_{\text{out}} + R \tag{3}$$

where SW_{in} is the surface water inflow, GW_{in} is the groundwater inflow from other basins, SW_{out} is the surface water outflow, GW_{out} is the groundwater outflow to other basins, and R is the river flow to other basins.

2.2 Groundwater balance

$$\begin{aligned} S_{GW}(i+1) = S_{GW}(i) + C_{GW\text{total}} - \\ WD_{GW\text{total}} - BF \end{aligned} \tag{4}$$

$$\begin{aligned} C_{GW\text{total}} = RC_{\text{P}} + RT_{\text{IR}} + RT_{\text{D IN}} + \\ RC_{\text{R}} + GW_{\text{in}} \end{aligned} \tag{5}$$

$$WD_{GW\text{total}} = WD_{GW\text{IR}} + WD_{GW\text{PC}} + WD_{\text{D IN}} + GW_{\text{out}} \tag{6}$$

where $S_{GW}\,(i+1)$ is the terminal groundwater storage, $S_{GW}\,(i)$ is the initial groundwater storage, $C_{GW\,\text{total}}$ is the total input to groundwater, $WD_{GW\,\text{total}}$ is the total groundwater withdrawal, BF is the base flow, RC_{P} is the groundwater recharge from rainfall, RT_{IR} is the irrigation return to groundwater, $RT_{\text{D IN}}$ is the return to groundwater from industry and domestic use, $WD_{GW\,\text{IR}}$ is the groundwater withdrawal required for irrigation, $WD_{GW\,\text{PC}}$ is the groundwater pumping to canals for meeting surface shortages, and $WD_{\text{D IN}}$ is the groundwater withdrawal for industry and living use.

$$WD_{GW\text{IR}} = (ET_{\text{I}} + DP) / WUE_{GW} \tag{7}$$

$$DP = 90 \times K_{\text{pa}} \tag{8}$$

$$BF = \text{MAX}\left(S_{GW}(i+1) \times REC_{GW}, 0\right) \tag{9}$$

where ET_{I} is the evapotranspiration from irrigation, DP is the deep percolation for paddy, WUE_{GW} is the water use efficiency of groundwater irrigation, K_{pa} is the paddy factor, and REC_{GW} is the recession coefficient for groundwater reservoir.

3 STUDY AREA AND MODEL APPLICATION

3.1 Study area

Daxing District with 14 towns and 2 farms is located in the north-central area of the Haihe Basin, belonging to southern Beijing, between 39°26′N—39°50′N, 116°13′E—116°43′E. Daxing District tilts slightly from northwest to southeast and is 15 m—50 m above sea level and belongs to the Yongding River Alluvial Plain. The area is 1044 km^2. The main soils in the subsurface are sandy soil and sandy loamy soil, and continuous clay can be found in some areas. Winter wheat and summer maize are grown on the agricultural lands.

The warm and continental monsoon climate is fundamental in Daxing District. The yearly mean air temperature is 12°C. The yearly mean evaporation quantity from water in the pan is 1021.0 mm. The yearly mean precipitation is 516.4 mm. The annual average precipitation is 490.5 mm and 364.8 mm, respectively in normal (50% of the theoretic frequency) and dry years (75% of the theoretic frequency). The spatial-temporal distribution of precipitation is uneven, mainly concentrated during the four months of June through September (Peng, Liu, Xu, & Wang, 2008, 2009). Multi-year average annual water resources per capita are less than 300 m^3. The multi-year average water resource consumption rate is 112.8%. The groundwater resources are over-exploited to supply socio-economic, industrial, and agricultural water requirements.

3.2 Model validation

3.2.1 Calculation division and basic data input

The study area is a county and not a closed hydrological unit. In addition, its terrain is a small topography, so the conflux relationship between inflow and outflow for the study area is not clear. In view of this, the watershed river network is extracted using the burn-in method based on the digital elevation model (DEM) data and the vector river networks data from the water system map in study area. After the watershed river network is generated, the watershed is partitioned based on the large closed basin contained in Daxing District.

The overlay analysis is calculated between the partitioned watershed and the Daxing District boundary, in which five sub-basins are acquired, labeled Sub1, Sub2, Sub3, Sub4, and Sub5. The total area of the five sub-basins is 1034.99 km^2, which is 99.1% of the Daxing District area. The CPSP hydrological model is calibrated and validated based on input data such as land use data, monitoring hydrological and meteorological data, and crop parameter data for 2004 and 2005.

3.2.2 Model calibration

The CPSP hydrological model is calibrated based on the available data from 2004. Firstly, RS ET and calculated ET are compared. Next, the groundwater storage variations are determined by comparing monitoring data and calculated results. Monitoring groundwater table data from 30 wells are interpolated using the inverse distance weighted method. For the basis of this calculation, the interpolated groundwater table grid data are calculated based on the five sub-basins, and these results are compared with the calculated results from the CPSP hydrological model. For model calibration, the differences between monitoring data and calculated data are evaluated using the Nash efficiency coefficient and the average error. The value of Nash efficiency coefficient is closer to 1, and the value of the average error is smaller, which indicates that better results can be simulated by means of the CPSP hydrological model. The equations for the Nash efficiency coefficient and average error are as follows (Mou, Tian & Hu, 2009):

$$ENS = 1 - \frac{S^2}{\sigma^2} \tag{10}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{oi} - Q_{si}\right)^2}{n}} \tag{11}$$

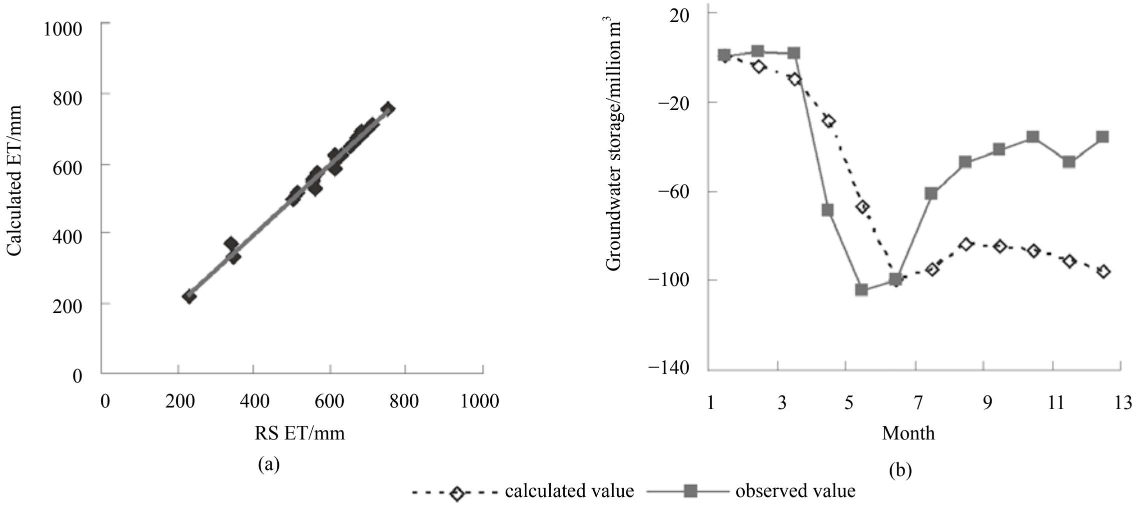
$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_{oi}}\right)^2}{n}} \tag{12}$$

$$M_e = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|Q_{oi} - Q_{si}\right|}{Q_{oi}} \tag{13}$$

where *ENS* is the Nash efficiency coefficient, Q_{oi} is the monitoring data,$\overline{Q_{oi}}$ is the average monitoring data, Q_{si} is the calculated data, n is the monitoring data number, and M_e is the average error.

The relationship between the calculated value and the monitoring value for model calibration is shown in Fig. 1. For ET in 2004, the Nash efficiency coefficient and the average error are 0.99 and 0.02, respectively, indicating that simulated crop ET is better. For the groundwater value in 2004, the Nash efficiency coefficient and the average error are 0.59 and 0.54, respectively, indicating a smaller Nash efficiency coefficient and a larger average error. Compared with the ET value, the simulated groundwater value is accepted and not good. Two causes may have affected the precision of the simulated groundwater value. One is that for model the assumed proportion of groundwater irrigation quantity to total irrigation quantity is the same for different months. In fact, the proportion is different. For example, the proportion of groundwater irrigation quantity to total irrigation quantity should be bigger during the dry season when crop water requirements peak. The other is that the selected study area is not a closed basin, so the inflow data are collected with difficulty. The inflow form other basins is not considered, which affected the precision of the simulated groundwater values. In a word, the simulated precision of the ET value and the groundwater value is accepted, so the calibrated model can be used to analyze the regional water balance.

Based on the calibrated result, the following main parameters of

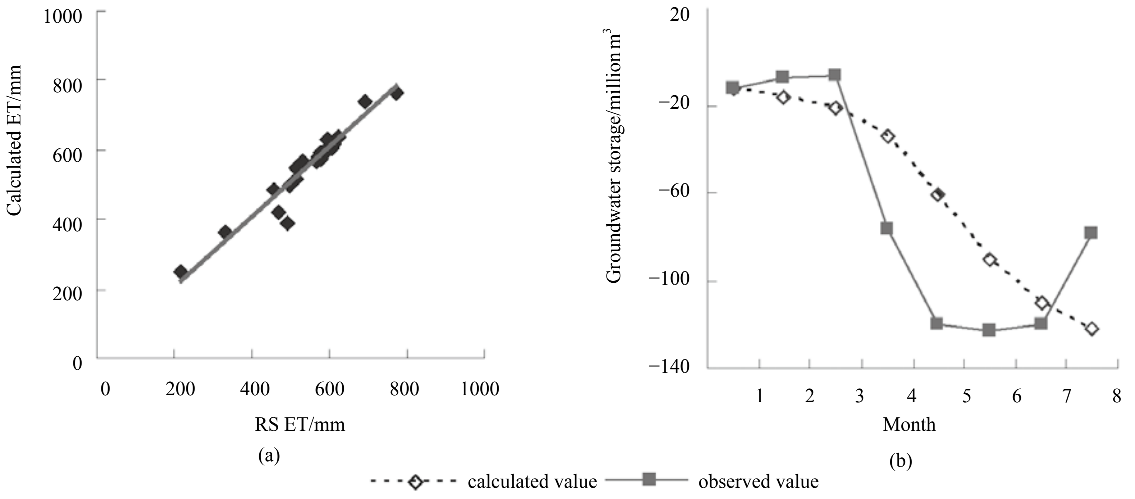


(a)

(b)

Fig. 1 Comparison between the calculated value and the observed value for model calibration

(a) *ENS*=0.99, M_e=0.02; (b) *ENS*=0.59, M_e=0.54



(a)

(b)

Fig. 2 Comparison between the calculated value and the observed value for model validation
(a) ENS=0.93, M_e=0.05; (b) ENS=0.55, M_e=−0.68

the model are adopted. (1) The soil moisture capacity is different for different land uses, such as arbor land 200 mm, winter wheat land 100 mm, other agricultural land 75 mm, and resident land 30 mm. (2) The reasonable outflow and groundwater recharge achieved based on the assumption that 40% of the residual water quantity runs towards surface runoff. (3) The exponential index linking soil moisture availability to the actual ET (*i.e.,* the potential ET ratio) is 0.8. (4) The recession coefficient for the groundwater reservoir is 0.25.

3.2.3 Model validation

Based on the calibrated parameters, the monitoring hydrological and meteorological data in 2005 are selected as an input data. The calculated ET and the calculated groundwater storage value are analyzed. The model is validated by comparing the calculated value with the monitoring value. The relationships between the calculated value and the monitoring value for model validation are shown in Fig. 2. For ET in 2005, the Nash efficiency coefficient and the average error are 0.92 and 0.05, respectively. For the groundwater storage value in 2005, the Nash efficiency coefficient and the average error are 0.55 and −0.68, respectively. Therefore, the simulated crop ET has the better results with the calibrated model. Besides, the simulated precision of the groundwater variation is acceptable. Generally, based on the results of calibration and validation, the hydrological characteristics of Daxing District can be simulated better, which means the water cycle and water use situation in future scenarios can be predicted using the calibrated model.

3.3 Current water situation analysis

3.3.1 Overall water balance

Based on the calibrated and validated model, the current water balance for Daxing District is analyzed, which is shown in Fig. 3. The annual precipitation is 5.12×10^8 m^3 in 2004, close to that of a normal year (50%). The annual precipitation is 3.96×10^8 m^3 in 2005, which is slightly higher than that of dry years (75%). Due to less precipitation, the simulated runoff also is less. The calculated river flow totals for 2004 and 2005 are 0.31×10^8 m^3 and 0.21×10^8 m^3, respectively. The river flow totals in normal years (50%) and dry years (75%) are 0.32 and 0.13×10^8 m^3, respectively, in the Integrated Planning of Water Resources in Daxing, Beijing (2004). Therefore, the calculated river flow total is consistent with that of the Integrated Planning of Water Resources in Daxing, Beijing (2004).

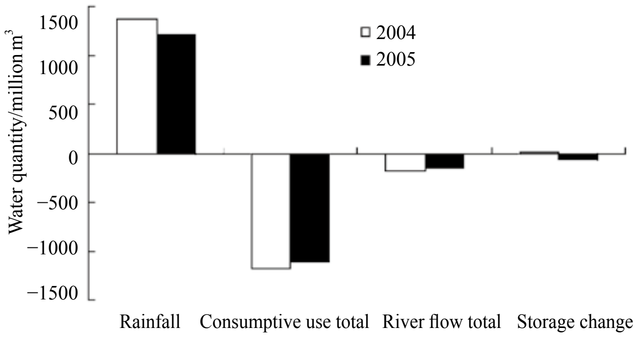


Fig. 3 Overall water balance for current situation in Daxing District

The water withdrawal totals include agricultural irrigation water, industrial water use, and residential domestic water use. The annual irrigation water use totals for 2004 and 2005 are 1.55×10^8 m^3 and 1.78×10^8 m^3, respectively, which are more than 70% of the water withdrawal total. The groundwater withdrawal is more than 90% of the water withdrawal total. The water consumption totals in 2004 and 2005 are 5.53×10^8 m^3 and 5.55×10^8 m^3, respectively. The water consumption of agricultural land is approximately 79% of the water consumption total. The annual rainfall, annual river flow total, and annual water consumption total are analyzed, which showed that the water shortages for 2004 and 2005 are 0.72×10^8 m^3 and 1.80×10^8 m^3, respectively.

3.3.2 Groundwater exploitation

Based on the observed data of the groundwater table, the annual average decreases in the groundwater table in Daxing District for 2004 and 2005 are 0.06 m and 0.61 m, respectively. The groundwater balance for the current situation is shown in Fig. 4. The recharge quantity of groundwater is mainly from rainfall, irrigation water return, and river flow. The withdrawal of groundwater is mainly from irrigation, industry water use, and residential domestic water use, of which irrigation water quantity is the biggest proportion of total groundwater withdrawal. The month variation in the observed groundwater table and the fact of agricultural irrigation are analyzed, which showed that the main reason for the decrease in the groundwater table is irrigation. Therefore, agricultural water management should be strengthened to ensure sustainable utilization of groundwater resources.

4 CONCLUSION

The annual precipitation for 2004 is nearly that of a normal year (50%). The annual precipitation for 2005 is slightly higher than that of a dry year (75%). The calculated river flow totals for 2004 and 2005 are 0.31×10^8 m^3 and 0.21×10^8 m^3, respectively. The river flow totals for normal years (50%) and dry years (75%) are 0.32 and 0.13×10^8 m^3, respectively, in the Integrated Planning of Water Resources in Daxing, Beijing (2004). Therefore, the calculated river flow total is consistent with that of the Integrated Planning of Water Resources in Daxing, Beijing (2004). Based on the results of model calibration and validation, the crop ET and the groundwater storage change can be simulated better using the established model. Therefore, the calculated results based on the model are reasonable.

The serious water shortages for 2004 and 2005 are 0.72×10^8 m^3 and 1.80×10^8 m^3, respectively. In the current situation, the rainfall has been less. Therefore, the recharge water for the groundwater or the surface water from rainfall is less. As a result, surface water is mainly from return water. Meanwhile, the recharge water quantity for the groundwater from the return water could be increased. Compared with the fresh water, the water quality of the returned water is not good. It means that the risks exist, which the water resources quality could be not good with high percentage recharge water from the return water. The calculated results show that the industry water use, the residential domestic water use and the irrigation water use are mainly from groundwater, of which irrigation water quantity is the largest proportion of total groundwater withdrawal. In order to ensure the sustainable utilization of water resources, agricultural water management should be strengthened to reduce ET.

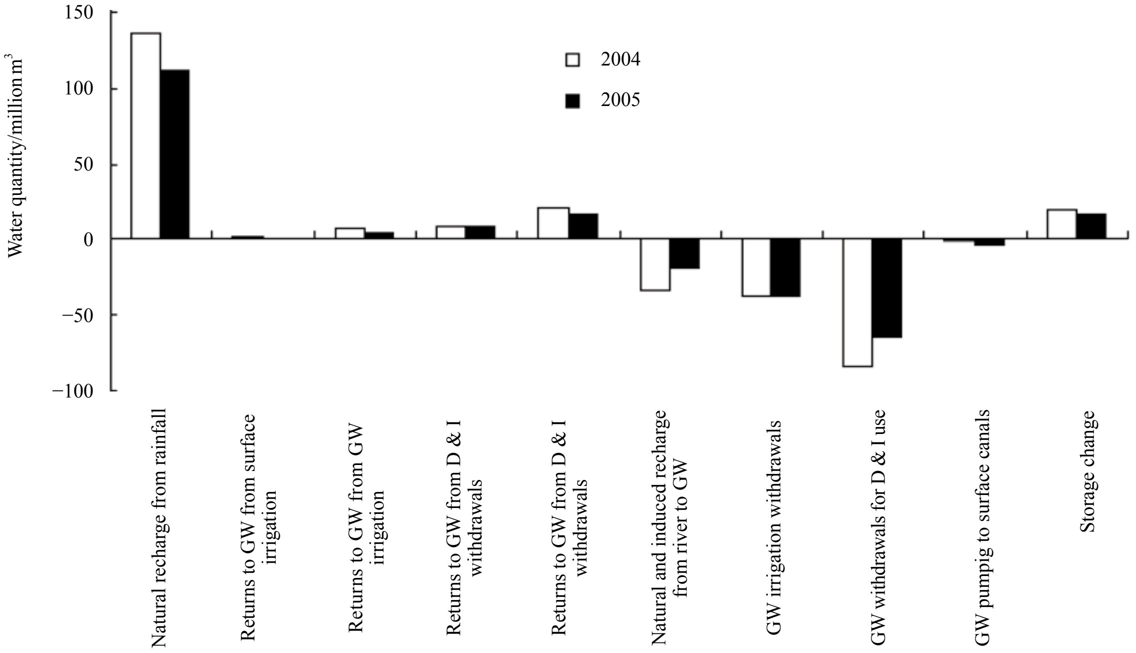


Fig. 4 Ground water balance for the current situation in Daxing District

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基于遥感ET数据的水平衡模型构建及现状分析

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摘　要：区域水平衡分析是保证水资源可持续利用和经济可持续发展的基础。在介绍CPSP模型计算原理的基础上，选择该模型作为北京市大兴区的区域水平衡分析工具。利用《北京市大兴区水资源综合规划》（2004年）中径流量的计算成果、遥感ET及地下水实测数据对模型进行校验结果表明，模型径流计算结果与规划成果基本一致，模型能较好模拟腾发及地下水储量动态变化过程。现状分析表明：2004年缺水0.72亿m^3，2005年缺水1.80亿m^3。

关键词：CPSP模型，水平衡分析，遥感ET，地下水

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1　引　言

北京市大兴区地表水资源相对匮乏，工业用水、居民生活用水及农业灌溉等水源主要来自开采地下水。随着城市化加速，工业及城镇居民生活用水剧增，区域地下水位连年下降，用水矛盾非常突出。地下水具有有限性和不可再生性特点，过度超采致使区域生态环境恶化。为使区域水资源可持续利用，只有加强区域水平衡分析，揭示区域供需耗排及地下水超采现状，掌握区域水资源供需关系的内在规律和主要矛盾，才能对区域水资源规划和管理做出科学且符合实际的安排。可见，区域水平衡现状分析是水资源管理各项工作的基础，是区域水资源规划及制定科学水管理措施的前提。从区域水平衡来说，耗水才是水资源的最终配置。ET是区域用水最主要消耗量，也是灌溉管理的依据，衡量农业节水效果不应简单地仅以灌溉用水量作为标准，而应将真实耗水量作为一项重要指标。因此，ET监测对农业水资源管理、区域水资源规划和社会经济持续发展至关重要。与估算区域腾发量的传统方法相比，遥感监测具有时空连续性及跨度大的特点，是区域ET估算主要发展方向（Sun 等，2009）。目前关于遥感估算ET方法与机理分析较多，而在利用遥感ET数据开展区域水资源管理方面仍处于探索阶段，且现有研究多注重于现状年短期内耗水评价（Li 等，2008；Khan 等，2008；Teixeira 等，2009）；现状年短期内因受降水随机性影响，开展在该降水条件下区域灌溉用水及耗水评价虽对区域农业水管理具有重要指导意义和借鉴价值，但若考虑把该研究成果用于指导区域用水规划及农业水资源的定额管理，仍需研究耗水与区域水平衡各要素的关系，由此才能对未来农业水管理提供更好的决策支持。采用区域水文模型作为技术支持能很好研究区域耗水与各水文要素之间的关系，但因区域下垫面复杂，模型率定的实测数据缺乏；若采用河道流量率定该模型，也

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因河道出口代表性及水文过程模拟的不确定性等因素影响模型率定效果。遥感ET数据能够兼顾时空异质性等特性，可考虑应用遥感ET数据对水文模型进行率定。

为此，本研究选择CPSP模型为区域水平衡工具，以区域用水实测资料及遥感土地利用作为模型基础输入数据，利用遥感ET数据及实测地下水位资料对所构建的区域水平衡分析模型进行率定及验证，以此为基础对研究区水平衡及地下水超采现状进行分析。本研究采用遥感ET数据是基于ETWatch生产的30 m分辨率的腾发量数据，该数据与水平衡法估算值相比，二者间的平均绝对百分比误差小于10%（北京师范大学，2010）。

2 模型计算原理

CPSP（Country Policy Support Programme）是国际灌排委员会（ICID）为在印度和中国实施的“以流域为单位的灌溉发展与水资源合理配置”项目开发的分区集总式水平衡分析模型，这一模型除了在上述项目中得到验证和应用之外，还在埃及和墨西哥等发展中的灌溉大国成功应用。该模型从水土资源合理开发和管理的角度对水资源进行分析，综合考虑了人类对水的各种需要，特别是灌溉发展和土地使用变化的影响（高占义，2005）。模型可用来计算整个土地利用的水循环过程，包括由于土地利用或农业用水改变而引起的水文变化。它可以分别描述地表水平衡、地下水平衡、地表水地下水之间的相互作用以及取水对蓄水量和耗水量的影响，该模型包含自然模块、人类活动模块、地表水模块、地下水模块及需水模块等。

2.1 水量平衡

模型水量平衡方程定义为：

$$Q_{\mathrm{in}}+P+\Delta s=Q_{\mathrm{out}}+\mathrm{ET} \tag{1}$$

式中，Q_{in}为入流总量；Q_{out}为出流总量；P为降水量；Δs为蓄变量；ET为蒸散耗水量。

$$Q_{\mathrm{in}}=SW_{\mathrm{in}}+GW_{\mathrm{in}} \tag{2}$$

$$Q_{\mathrm{out}}=SW_{\mathrm{out}}+GW_{\mathrm{out}}+R \tag{3}$$

式中，SW_{in}为地表水调入量；GW_{in}为其他流域汇入的地下水量；SW_{out}为地表水调出量；GW_{out}为流出到其他流域的地下水量；R为河道出流量。

2.2 地下水平衡

$$S_{GW}(i+1)=S_{GW}(i)+C_{GW\,\mathrm{total}}-WD_{GW\,\mathrm{total}}-BF \tag{4}$$

$$C_{GW\,\mathrm{total}}=RC_{\mathrm{P}}+RT_{\mathrm{IR}}+RT_{\mathrm{D\,IN}}+RC_{\mathrm{R}}+GW_{\mathrm{in}} \tag{5}$$

$$WD_{GW\,\mathrm{total}}=WD_{GW\,\mathrm{IR}}+WD_{GW\,\mathrm{PC}}+WD_{\mathrm{D\,IN}}+GW_{\mathrm{out}} \tag{6}$$

式中，S_{GW}（i+1）为时段末地下水储量；S_{GW}（i）为时段初地下水储量；$C_{GW\,\mathrm{total}}$为地下水总输入量；$WD_{GW\,\mathrm{total}}$为地下水取水总量；BF为河道基流量；RC_{P}为降雨补给地下水量；RT_{IR}为灌溉回归地下水量；$RT_{\mathrm{D\,IN}}$为工业及居民生活用水回归地下水量；$WD_{GW\,\mathrm{IR}}$为地下水灌溉取水量；$WD_{GW\,\mathrm{PC}}$为取地下水到渠道，以补充地表水缺水量；$WD_{\mathrm{D\,IN}}$为工业及居民生活取用地下水量。

$$WD_{GW\,\mathrm{IR}}=\left(ET_{\mathrm{I}}+DP\right)/WUE_{GW} \tag{7}$$

$$DP=90\times K_{\mathrm{pa}} \tag{8}$$

$$BF=\mathrm{MAX}\left(S_{GW}\left(i+1\right)\times REC_{GW},0\right) \tag{9}$$

式中，ET_{I}为灌溉耗水量；DP为水生作物种植时的渗漏水量；WUE_{GW}为地下水灌溉水分利用系数；K_{pa}为水生作物因子；REC_{GW}为地下水退水系数。

2.3 模型参数

模型参数包括4类：植被参数、土壤水分参数、地表水及地下水资源转换参数等（表1）。由上述水平衡方程来看，该模型参数都具有明确物理意义，但

表 1　CPSP模型主要参数及取值依据

参数名	取值依据
作物系数K_c	参考FAO56–灌溉排水指导手册及大兴试验站数据
土壤蓄水能力	取决于土地利用类型，在参考模型缺省值基础上，通过模型率定获取
土壤水分衰减指数	通过模型率定获取
降水补给系数	通过模型率定获取
地下水退水系数	通过模型率定获取
工业及居民生活耗水系数	北京市水资源公报2004年—2005年
灌溉回归水蒸发系数	采用模型缺省值及调查估计获取

在实际应用过程中，受条件限制，特别是大区域范围内不易获取。因此在没有试验数据时，可先依据常规情况对这些参数进行假定，然后利用已有的气象水文观测数据，通过反复模拟分析和参数反演来确定。

3　研究区概况及模型应用

3.1　研究区概况

大兴区地处海河流域中北部，属北京南郊，介于39° 26′ N—39° 50′ N, 116° 13′ E—116° 43′ E之间，共辖14个乡镇和2个农场（图1）。大兴区地势平坦，从西北向东南略呈倾斜，境内无山脉，属永定河冲洪积平原，海拔在15—50 m之间，全区面积1044 km^2。地表以沙性土和沙壤土为主，局部地区出现连续的黏性土；大兴区内农业用地以冬小麦和夏玉米为主。气候为中纬度暖温大陆性季风气候，多年平均气温为12℃，多年平均水面蒸发量1021.0 mm；多年平均降水量516.4 mm，平水年（50%频率）490.5 mm，枯水年（75%频率）364.8 mm，降水量年际变化较大，季节分布不均，主要集中在6月—9月（彭致功 等，2008，2009）。多年人均年占有水资源量不足300 m^3，多年平均水资源利用消耗率达112.8%，靠超采地下水满足社会经济和工农业生产生活需要。

3.2　模型校验

3.2.1　计算分区及基础数据输入

研究区为行政区域，不是封闭水文单元，且地势较为平缓，汇流关系不清楚。鉴于此，结合DEM数据，利用实际手工矢量河网数据采用“burn-in”方法，提取流域河网。流域河网生成后，考虑选择包含大兴区闭合流域为基准进行流域划分，提取后的流域与大兴区边界进行叠加分析，将大兴区划分5个子流域进行研究（图2），各子流域分别为Sub1、Sub2、Sub3、Sub4和Sub5，其面积总和为1034.99 km^2，占大兴区面积的99.1%。分别采用2004年及2005年的土地利用、实测水文和气象资料作为输入数据，对模型进行率定及验证。

3.2.2　模型率定

根据现有的数据资料，以2004年数据对模型进行率定，一方面考虑遥感监测的ET与模型计算的ET相比较；另一方面利用模型计算结果地下水的变化与观测的结果相比较。研究中对30个地下水位观测井月实测数据进行反距离加权插值分析，以此为基础并结合子流域分区划分情况进行统计分析，便于与CPSP模型地下水计算结果进行比较。对于模型率定过程中的模拟值与观测值之间的差距，可采用Nash效率系数ENS及平均误差M_e来评价，Nash效率系数值越接近1，平均误差越小，表明模型模拟效果越好。Nash效率系数计算公式如下（牟丽琴 等，2009）：

$$ENS = 1 - \frac{S^2}{\sigma^2} \tag{10}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}(Q_{oi} - Q_{si})^2}{n}} \tag{11}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_{oi}}\right)^2}{n}} \tag{12}$$

式中，ENS为Nash效率系数，Q_{oi}、$\overline{Q_{oi}}$为实测值及其均值，Q_{si}为模型计算值，n为实测数据个数。

平均误差的计算公式如下（公式中变量含义不变）：

$$M_e = \frac{1}{n}\sum_{i=1}^{n}\frac{|Q_{oi} - Q_{si}|}{Q_{oi}} \tag{13}$$

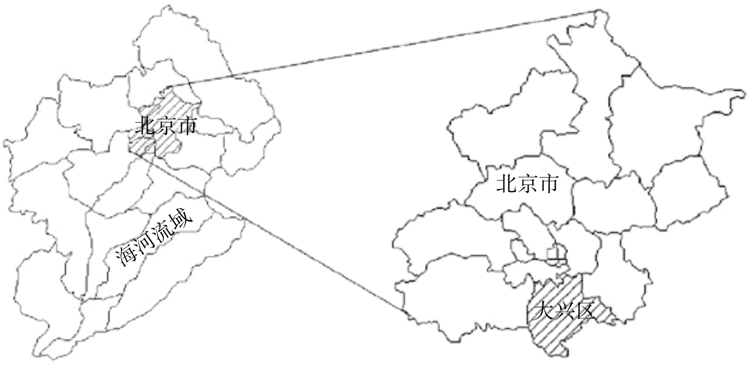


图1　大兴区位置示意图

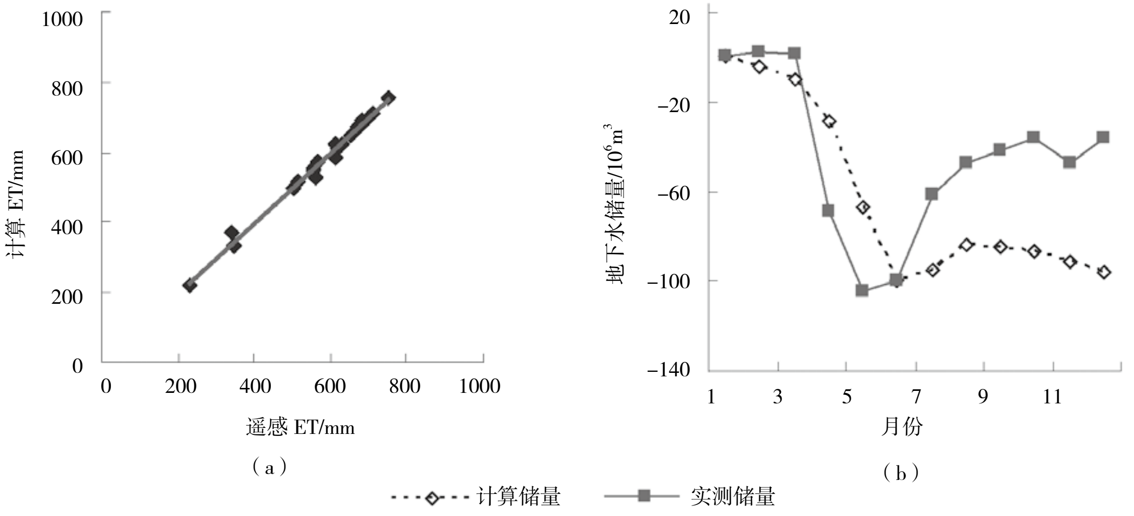
图2　大兴区子流域划分

图3给出了模型率定下计算值与测定值间的关系，其中2004年ET的模拟值与同期遥感ET值的Nash效率系数ENS及平均误差M_e分别为0.99和0.02，表明模型能较好模拟作物腾发过程；而2004年地下水储量的观测值与计算值的年内变化过程中Nash效率系数*ENS*及平均误差M_e分别为0.59和0.54，Nash效率系数较小，而平均误差M_e较大，造成该问题原因可能在于模型设定地下水月开采比例相同，该假定与实际情况存在差异。在实际情况中，干旱季节及作物需水高峰期，地下水开采量比较大。另外，由于项目区为行政区域，不是闭合流域，数据收集不完备，地下水模拟不甚理想。原因可能在于对外来水情况考虑不足。根据模型中ET值及地下水位储量的对比进行整体分析，可认为率定后模型具有一定精度，能适于该区域水量平衡模拟研究。

根据模型率定的结果，采用主要参数为：（1）土壤最大蓄水能力因土地利用差异而不同，乔木绿地采用200 mm，小麦地采用100 mm，其他农业用地采用75 mm，居民地采用30 mm；（2）假设40%的剩余水量产生地面径流，60%的剩余水量补给到地下水，可以得到合理的出流量及补给地下水水量；（3）在ET计算的过程中，腾发量随土壤含水量变化的衰减指数采用0.8；（4）地下水退水系数采用0.25。

3.2.3 模型验证

依据模型率定所采用参数，结合2005年实测气象水文资料作为模型输入，选择模型计算ET及计算地

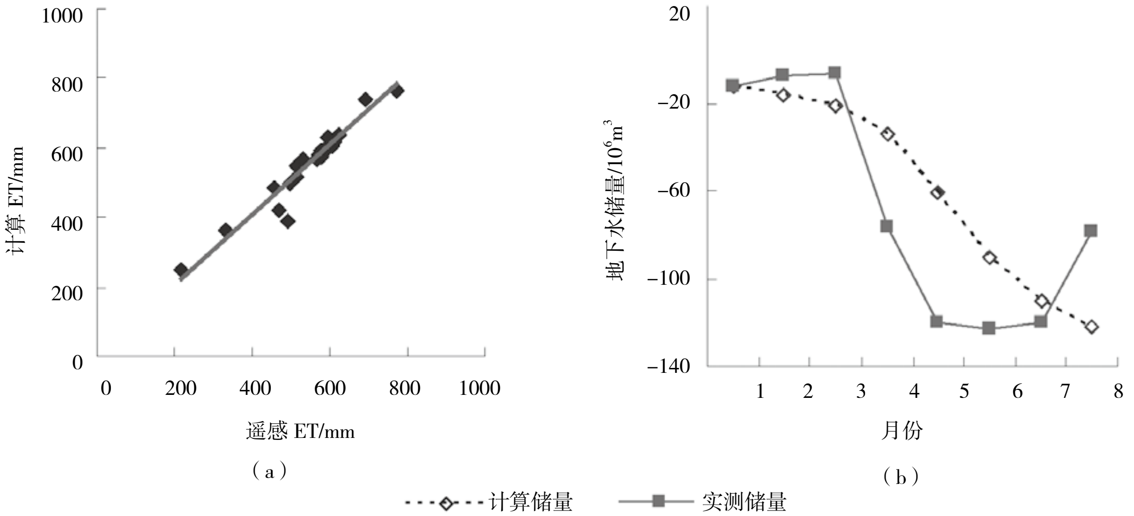


（a）

（b）

图3 模型率定中计算值与测定值比较（2004年）

（a）ENS=0.99，M_e=0.02；（b）ENS=0.59，M_e=0.54



（a）

（b）

图4 模型验证中计算值与测定值比较（2005年）

（a）ENS=0.93，M_e=0.05；（b）ENS=0.55，M_e=−0.68

下水储量为研究对象，通过对二者计算值与同期测定值进行对比分析，以此为基础对率定后模型进行验证。模型率定下计算值与测定值间的关系如图4，其中2005年ET的模拟值与同期遥感ET值的Nash效率系数ENS及平均误差M_e分别为0.92和0.05；而2005年地下水储量的观测值与计算值的年内变化过程中Nash效率系数ENS及平均误差M_e分别为0.55和－0.68。模型验证中表明率定后模型能很好模拟作物腾发过程，同时对地下变化趋势模拟精度基本符合要求。总之，根据模型率定及验证进行分析，可以看出模型能很好地反映出大兴区的水文特征，能用于对大兴区未来情景下的水循环和用水状况进行预测。

3.3 现状分析

3.3.1 供需耗排

通过对所构建的水平衡分析模型进行率定及验证，在此基础上对大兴区水资源的供需耗排及地下水开采现状进行分析。由图5可知，大兴区2004年降水量为5.12亿m^3，接近50%平水年的降水量；2005年降水量为3.96亿m^3，稍高于75%枯水年降水量，因现状降水偏少模拟结果显示径流较小。结合《北京市大兴区水资源综合规划》（2004）成果50%平水年及75%枯水年径流的计算结果分别为0.32亿m^3和0.13亿m^3，而模型计算2004年及2005年径流量分别为0.31亿m^3和0.21亿m^3，反映模型计算结果与《北京市大兴区水资源综合规划》（2004）的结果基本一致。

取水量主要包括农业灌溉用水、工业及居民生活用水。2004年及2005年灌溉用水量分别为1.55亿m^3及1.78亿m^3，占年取水总量的70%以上。取水水源主要来自开采地下水，所占比例接近取水总量的90%以上。2004年及2005年总耗水量分别为5.53亿m^3、5.55亿m^3，其中农业用地耗水占总耗水量的79%左右。通过对现状年降水量、径流量及总耗水量情况进行比较分析可知，在现状条件下大兴区缺水较严重，2004年缺水0.72亿m^3，2005年缺水1.80亿m^3。

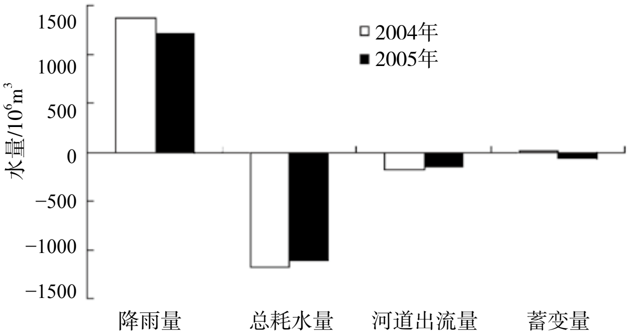


图5 大兴区现状供需耗排状况

3.3.2 地下水开采

地下水位实测数据显示，在大兴区2004年地下水位平均下降0.06 m，2005年下降0.61 m。北京市大兴区地下水平衡模拟结果见图6，地下水的补给量主要来自降水补给、灌溉回归水补给及河流补给；而地下水的支出部分主要来自农业灌溉、工业用水及生活用水，其中农业灌溉所占比重较大。根据大兴区实测地下水位月际变化规律，同时考虑大兴区农业灌溉的实际情况，分析表明地下水位下降主因在于农业灌溉取用地下水，所以应加强农业用水管理以确保地下水资源的持续有效利用。

4 结 论

（1）大兴区2004年降水量接近50%平水年降水量；2005年降水量稍高于75%枯水年降水量。《北京市大兴区水资源综合规划》（2004）成果中50%平水年及75%枯水年径流的计算结果分别为0.32亿m^3和0.13亿m^3，而模型计算的2004年及2005年径流量分别为0.31亿m^3、0.21亿m^3，表明模型径流计算结果与规划成果基本一致；另一方面，结合模型校验分析结果表明模型能较好模拟作物腾发及地下水储量动态变化过程。由此表明，该模型计算结果较为合理。

（2）在当前条件下大兴区缺水形势较为严峻，2004年缺水0.72亿m^3，2005年缺水1.80亿m^3；在当前条件下因降水量较少，降水对地表水及地下水补给都较小，相应来自回归水补给比例增加。由于回归水的水质较其他水质稍差，而大兴区地表水水源主要为回归水，造成地表水质压力非常大；同时也增大了地下水污染的风险。另外，在现状条件下工业用水、居民生活用水及农业灌溉等水源主要来自地下水，其中农业灌溉所占比重较大。为确保区域水资源可持续利用，应加强农业用水管理以加大资源性节水力度。

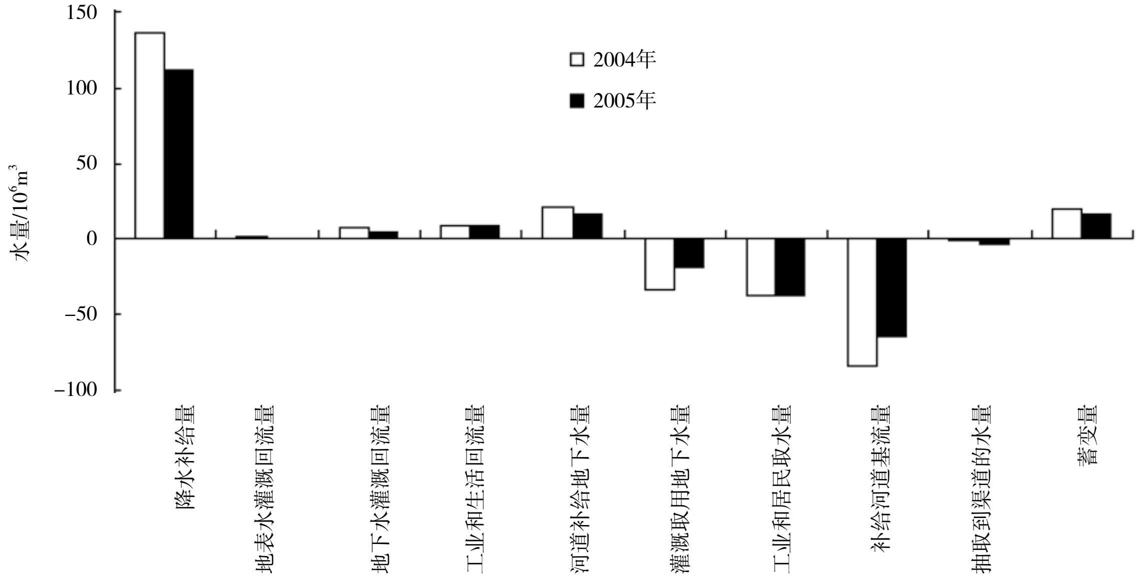


图6 大兴区现状地下水平衡状况

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