A method of water consumption balance and application

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Abstract: The basin level water balance analysis is the core of water resource evaluation and rational management. A method of basin level water consumption balance is presented in this paper, based on evapotranspiration estimated by remote sensing and combining statistic data. In a case study, we analyzed the water consumption balance in the Hai Basin from 2002 to 2007 and found the average water storage change to be –6.23 billion cubic meters. The agriculture sector is one of the biggest consumers of water resources, accounting for 54.3% of the total water consumption, although the inter-annual change ranges are lower (–5% to 8%). The water resource problems are discussed in this paper based on the analysis of changes in water storage and the evapotranspiration structure, and some suggestions for region water source management and water-saving society construction are proposed.

Key words: water consumption balance, remote sensing, Hai Basin, evapotranspiration, industrial water consumption, living water consumption

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1 INTRODUCTION

Water balance is the expression of the mass conservation principle in the water cycle process. It is calculated as the difference between its income (I) and expenditure of water (O) and is equal to the change of water storage (Δs) within a certain area and period. Water balance is the basis for studying hydrological phenomenon and the hydrological process, as well as the basis for calculating and assessing both the quantity and quality of water resources. The water balance equation can be used to determine the relationships among precipitation, evaporation, and runoff, and to study the water resources quantity and overexploited ground water. (UNESCO, 1978; CAS Committee, 1981)

The water balance expression for a basin is expressed in the following Eq. (1):

$$P–E–R = \Delta s \quad (1)$$

where P, E, R, and Δs are basin precipitation, total evaporation, the total runoff, and water storage change in a certain period, respectively. Precipitation data can be measured from observation station, and runoff data usually are measured at the major control point and river sections. However, measurement of evaporation and water storage change is complicated, so the two variables are not routine measurement data and often are estimated due to the high cost of measurement.

In the early 20th century, empirical hydrologic models (Sherman, 1932; Nash, 1957) were used to analyze water balance by studying the relationship between precipitation and runoff. In the period of the 1960s to the 1980s, the lumped hydrologic model was proposed from the view of the running-off generation and routing theory, with model parameters calibrated according to the flow observation data of rivers, and representative models are Stanford, Tank, and Xinanjiang, among others. Hu, *et al*. (2007) used the improved monthly water balance model to simulate the monthly runoff and evapotranspiration process in the sub-basin controlled by the Tong County station in the Beiyun River. Due to complicated topography and land surface, spatial differences of the variables are obvious, but the lumped hydrologic model did not reflect the relationship between hydrological variables. Since the 1980s, researchers have paid more attention to the development of the distributed hydrological model based on physical process, and some of the representative models are TOPMODEL (Beven, *et al*., 1979), SHE (Abbott, *et al*., 1986), SWAT (Arnold, *et al*., 1995), and WEP (Jia, *et al*., 2005). The distributed hydrologic model integrates the process of runoff, soil water, ground water, and evaporation and considers the spatial differences of variables. Zhu (2005) built a distributed hydrological model of the Hai Basin on the AVSWAT 2000 platform and used it to analyze the water balance of the Hai Basin. Kavvas, *et al*. (2010) analyzed the water balance of the Tigris-Euphrates River Basin by using the regional hydrologic model RegHCMTE. With the increase in human activities, the study of the water recycling process driven by the "Nature-Human" dual mode is in the limelight, and hydrological projects like reservoirs, dams, canals, impounds, water diversion, and inter-basin water transfer make the water cycle process more complicated. The impact of

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the human on water cycle has become more and more significant. Wang, *et al*. (2006) proposed the dual model, which integrates the WEP, ROWAS, and DAMOS models, and applied the model when analyzing the water balance in the Hai Basin after model calibration (Jia, *et al*., 2010).

With the development of studies and application, researchers who use the hydrological models face many difficulties and limits. The prominent problems are with the following three aspects:

(1) Model uncertainty. First is the randomness of hydrological variables and parameters. Second, the model result may not be the same in a different space and time using the same parameters due to many assumptions in the model.

(2) The impact of the changing environment. Human activities have an impact on the water cycle process to a large extent. For example, since 1950, experts have built 1967 reservoirs (Hai River Record, 1998), a river and rubber dam, and control sluices in the Hai Basin, and all of these structures could influence the dynamic process of the water cycle. Grain for green, farmland terracing, a series of soil and water conservation project, and urban development have changed the land surface, which strengthens the spatial variability of hydrological parameters; for example, the soil water infiltration capacity could change in the same soil type because of human activity. The large-scale hydrologic model is not adaptive to a changing environment, but it lacks the detailed information of the land surface for the small-scale hydrologic model, so this undoubtedly increases the model uncertainty.

(3) The limit of basic materials. Whatever the model at different temporal scales or different spatial scales, it needs a long-time series of basic data, including hydrological observation data, land coverage, and soil structure information. However, the weakness of data sharing mechanisms restricts the model application. In addition, the model accuracy can be compared only with limited measuring data, which may not be sufficient.

At present, the model is based on water balance and focuses on runoff generation and routing theory to ensure simulating the flood peak in order to avoid and reduce flood disasters. However, more urgent problems are the unsustainable water resources and ecological deterioration caused by ground water in the water resources shortage region.

With the development of remote sensing technology, different scales and multiple sources of remote sensing information provide land surface information from the angle of vegetation, roughness, and surface topography, among other information. This information may reflect the spatial variability of the regional land surface characteristics. A range of remote sensing evapotranspiration models were developed in the 1980s (Bastiaanssen, *et al*., 1998; Su, 2002; Allen, *et al*., 2007; Wu, *et al*., 2008). Using land surface parameters that were deduced by remote sensing, regional evapotranspiration was calculated based on energy balance. Due to large monitoring areas, more available information, and the ability to avoid much basic observational data, evapotranspiration by remote sensing provides a new data source for water balance analysis from the view of water consumption. Therefore, in this study, we focused on the following two aspects:

(1) Facing basin water resource problems, the regional water consumption balance analysis method based on water balance principle would be presented.

(2) The methods were applied to analyze the process of water consumption, to discuss basin water storage change trends, and to provide support for water resource management decisions.

2 MATERIALS

2.1 Study area

The Hai Basin is located at 112.0°E to 119.8°E and 35.0°E to 42.8° N, with a total area of 318000 km², accounting for 28% of China's total land area. The basin mountain area is 189000 km², accounting for 60% of the total area, while the basin plain area is 129000 km², accounting for 40% of the total area. It belongs to a temperate zone continental monsoon climate with an average annual rainfall of 535 mm. The spatial distribution of precipitation has an obvious character of zonal, seasonal, and inter-annual differences. The area is dry, with rare rainfall in the spring while remaining hot and rainy throughout the summer. Approximately 80% of the annual precipitation is concentrated in the flood season from June to September, with characteristics of drought in the spring and flooding in the autumn. Inter-annual changes of precipitation are large, with a variation of continuous abundance or continuous dry. The average annual temperature is 1.5℃ to 14℃, and average annual evaporation is 1100 mm. Evaporation increases as temperature rises. The Hai Basin includes three major river systems, which are the Hai River, the Luan River, and the Tuhaimajia River. The Hai River is made up of the Jiyun River, the Chaobai River, the North Canal, the Yongding River, the Daqing River, the Ziya River, the Zhangweinan Heilonggang River, and the main stream of the Hai River. Data from 1956 to 2000 show that, for many years, the basin's average annual runoff amount was 21.61 billion cubic meters, and the average annual runoff depth was 67.5 mm.

2.2 Data

Precipitation, inflow and outflow data, inter-basin water transfer, and sea outflow are from the water resources bulletin of Hai Basin (2002—2007).

The evapotranspiration dataset of the Hai Basin with 1 km spatial resolution and for the period from 2002 to 2007 are provided in monthly frequency, using Albers projection and in a TIFF data format. The data were calculated using ETWatch (Wu, *et al*., 2008).

The land use dataset of the Hai Basin with 250 meter spatial resolution and for the period of 2004 and 2006 is provided in Albers projection and an Arcshape data format. The MODIS data was used to interpret land use maps by supervision classification and visual interpretation according to the classification system.

Population data is from the national statistical books and statistical yearbooks of eight provinces. Industry data are from the statistical yearbooks of eight provinces, the Chinese power statistical book, and the Chinese energy statistical book.

The water consumption data per electricity generation used average value of basin received from the National Development and Innovation Committee (2006). The data was 3.5 kg/kwh in 2002, 3.4 kg/kwh in 2003, 3.2 kg/kwh in 2004, and 3.1 kg/kwh between 2005 and 2007.

Water consumption of one ton of iron used average level data received from the Chinese Metal Academy (2007). Water consumption per ton of iron of key steel enterprises was approximately 34 m^3/t, new water consumption per ton of iron was about 19 m^3/t, while 0.5 m^3/t is the standard level at present. The following water consumption data per ton came from energy statistics: 4.98 m^3 in Shougang, 6.09 m^3 in Handan, and 4.25 m^3 in Tangshan.

People perspire approximately 0.004 m^3 to 0.005 m^3 of water per day in the summer, 0.0008 m^3 per day in the spring and autumn, and 0.0005 m^3 per day in the winter(Sanjiu Health Net, 2009). Average annual perspiration is 0.56 m^3.

3 METHOD

The water balance in the basin is expressed in the following Equation:

$$P–E–R = \Delta s \tag{2}$$

where P, E, R, and Δs are basin precipitation, total water consumption, the total runoff, and water storage change in a certain period, respectively. On an average, Δs has been equal to zero for years, and R is the change between outflow (O) and inflow (I). Soil water storage generally does not change in an annual cycle; therefore the regional water storage change will be groundwater storage change.

The precipitation and flow data was retrieved from an observation station, and the key of water balance is the calculation of total water consumption. The total consumption is the sum of three parts, based on the source difference of the water evaporation process, as calculated in the following Equation:

$$E = \mathrm{ET} + Q_m + Q_b \tag{3}$$

where ET is regional evapotranspiration from the solar source, which can be estimated by remote sensing and taking into consideration the land surface evapotranspiration process, such as agriculture, forest, water surface, and bare soil. The agriculture water consumption is a major sector in the Hai Basin, so ET is divided into agriculture ET (ETagri) and environment ET (ETenv). An evaporation process also takes place in mechanical energy, chemical energy, and heat energy. For example, in oil and coal combustion, energy is emitted when chemical changes occur, and water consumption is Q_m; the perspiration energy of people or animals is acquired when the body's biological energy transforms into chemical energy or mechanical energy, and water consumption is Q_b.

Industrial water use is measured using a water meter. One part is used to produce industrial products; the other part is drainage. Most domestic water consumption returns to the basin water cycle through urban and rural drainage systems, while only a small amount of water returns to the atmosphere through evaporation. The water quantity used in industry and living often is measured, while water consumption is not measured. Available data for industry are water quantity, product output, and product water consumption rate, and for domestic water use are the population and the number of livestock. Due to a limitation of materials, we calculated only the three types of water consumption for industry, and living water consumption includes only the perspiration of people and animals.

The water consumption in industry is calculated with the following Equation:

$$Q_m = \sum_{i=1}^{n} P_i \times Co_i \tag{4}$$

where Q_m is industrial water consumption, i is certain types of industries within the region, P_i express the production of this type of industry, and Co_i is the water consumption coefficient per unit output value of this type of industry. Due to absence of industrial water consumption statistical data, limited water consumption rate and product yield information of main industrial water consumption were collected. For example, the water consumption of a power station can be calculated by the total electricity generated in the region and the water consumption rate per unit of electricity. The iron water consumption can be calculated by the products and water consumption rate per unit output.

The Equation for determining perspiration from people and livestock is as follows.

$$Q_b = P \times Co \tag{5}$$

where Q_b expresses annual perspiration, P is the number of people or livestock, and Co is the perspiration factor. Lacking Co information of livestock, this part was substituted by using annual perspiration per capita.

Combining Eq. (2) with Eq.(5), the water consumption balance equation is expressed as Eq. (6).

$$\Delta s = P + I – O – \mathrm{ET}_{\mathrm{agr}} – \mathrm{ET}_{\mathrm{env}} – \sum_{i=1}^{n} P_i \times Co_i – P \times Co \tag{6}$$

In this paper, the inter-basin water transfer is included in the inflow, and the sea outflow is included in the outflow.

4 RESULTS

4.1 Basin-level water balance

Based on the remote sensing data, rainfall and flow statistics, the Hai Basin water balance analysis from 2002 through 2007 was carried out by applying the water balance equation above. The results are shown in Table 1. Annual water resource in this region is 160.3×10^9 m^3, average evapotranspiration is 164.6×10^9 m^3, the basin water income and expenditure obviously are unbalanced between 2002 and 2007, and a deficit has been observed in the regional water resources. The regional water resources come mainly from precipitation, which accounts for 97.4%, and annual changes of precipitation are in the range from –18% to 19% of average value. Evapotranspiration estimated by remote sensing is the greatest part of basin water consumption, accounting for 97.7%, with a change range from –8% to 12% from 2002 through 2007, which is less than the annual change of precipitation. The proportion of industrial consumption and people-livestock consumption in the total water resource consumption is very low, accounting for only 2.3%. Therefore, the average perspiration factor and water consumption factor have little impact on this water balance analysis.

Using ET results inverted by remote sensing and land use maps, evapotranspiration of different land use types was calculated. The farmland evapotranspiration accounted for 54.3% of total, with an inter-annual change from –5% to 8%. Due to irrigation of farmland, the difference between years is far less than precipitation. Environment and ecological evapotranspiration is the evapotranspiration value of other land use, excluding farmland evaporation and including evapotranspiration of forest, shrub, and grass, which accounted for 80% of the environment ecological evapotranspiration, with an inter-annual change from –11% to 19%.

Regional water storage change is equal to the storage change of surface water, groundwater and soil water, but mostly it is groundwater storage change. Therefore, the change of water storage can reflect the changing conditions of the basin groundwater level. A positive value indicates groundwater recoveries, while a negative value expresses that the groundwater level drops. Annual storage change of the total region decreased on an average of 6.23×10^9 m^3 overall between 2002 and 2007, while average annual basin-wide groundwater overdraft was up to 5.02×10^9 m^3 in 1985 to 1998 (Hai River Record, 1998). The groundwater level continues to drop, and the extent of the decline is increasing, so the development and utilization of water resources are in an unsustainable status.

The interannual change fluctuation of regional water storage change was large during the period from 2002 to 2007. The regional storage increased by 12.37×10^9 m^3 during the period from 2003 to 2005, which did not compensate for the deficit of 19.31×10^9 m^3 in 2002. The average storage change dropped by 1.88×10^9 m^3 in the period from 2002 to 2005, while the water balance analysis based on the distributed model of SWAT established by Zhu, *et al*. (2008) showed that average water storage change in the Hai Basin dropped by 1.78×10^9 m^3 during the period from 2002 to 2005. Therefore, the relative error of these two methods is 5.6 %, and the variation trends of regional storage change are consistent, so the application of ET estimated by remote sensing to the basin water balance analysis is feasible. Water storage dropped continually during the period from 2006 to 2007 because of continuous drought.

Table 1 Water balance analysis of the Hai Basin, 2002—2007 ($\times10^8$ m^3)

Item	2002	2003	2004	2005	2006	2007	Average	%
Available Water Resources *I+P*	1320.2	1899.0	1764.8	1595.8	1448.8	1590.4	1603.1	100.00
Water inflow *I*	46.4	36.1	42.3	37.3	46.3	42.8	41.9	2.60
Precipitation *P*	1273.8	1862.9	1722.4	1558.5	1402.5	1547.5	1561.3	97.40
Outflow *R*	1.8	21.8	37.1	24.9	13.9	17.1	19.4	
Water Consumption *Q*	1511.5	1833.8	1661.8	1556.6	1672.7	1639.8	1646	100.00
Agricultural ET	842.2	970.0	919.6	843.8	902.3	889.9	894.6	54.30
Ecological environment ET	637.5	832.4	706.6	671.0	728.7	708.2	714.1	43.40
Living water consumption Q_b	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.10
Industry water consumption Q_m	30.9	30.6	34.9	40.9	40.9	40.9	36.5	2.20
Water Storage Change Δs	–193.1	43.4	65.9	14.4	–237.8	–66.5	–62.3	

The average agriculture water consumption in the basin was 89.46×10^9 m^3, accounting for 54.3% of the total water consumption. Agriculture remains a large sector of water resources consumption in the basin. The controlled part of agricultural water consumption, such as evapotranspiration caused by irrigation and crop planting area increasing, is the key point to proposing the development of water saving irrigation and water-saving agriculture construction. However, the evaporation caused by precipitation and soil water cannot be controlled in the fallow land.

4.2 Sub-basin level water balance

Using statistics data and evapotranspiration estimated by remote sensing, regional water resources storage change was analyzed for the nine sub-basins to determine the water resource problems. Due to the absence of materials, we simplified some of the water balance analysis. Firstly, the proportion of industrial and domestic water consumption is low, and the data were provided for each administration region, so this part could be ignored in the sub-basin analysis. Secondly, the outflow does not include the sea outflow in the sub-basin analysis because of absence of inter-basin water transfer data. Thirdly, the inflow and outflow data were not collected for the period 2002 to 2005. The water balance for all sub-basins is shown in Table 2; as seen in Fig. 1, much spatial difference exists in regional storage change. Surplus water resources are seen in the Zhangwei River, the Ziya River, and the Yongding River, and other regions are in a water-deficit state.

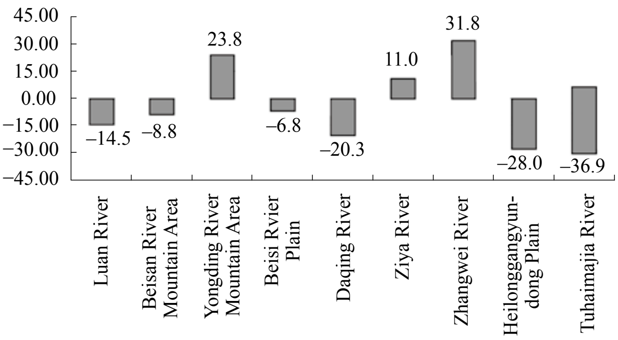

Fig.1 The average water surplus and deficit chart of sub-basins (10^8m^3)

Table 2 Water surplus and deficit analysis of the Hai sub-basins, 2002—2007 ($\times10^8$ m^3)

Sub–basin	2002	2003	2005	2006	2007	Average
Luan River	–25.28	–9.27	10.91	–39.12	–9.82	–14.51
Beisan River Mountain Area	–14.26	–16.83	–5.74	0.07	–7.44	–8.84
Yongding River Mountain Area	38.77	7.01	31.71	19.97	21.55	23.8
Beisi River Plain	–19.47	–7.55	0.03	–4.39	–2.4	–6.76
Daqing River	–14.74	–36.6	–8.12	–38.62	–3.32	–20.28
Ziya River	0.06	20.45	11.35	12.27	11.12	11.05
Zhangwei River	–13.53	73.37	48.74	20.71	29.95	31.85
HeiLongGangyundong Plain	–49.06	9.58	–29.58	–33.64	–37.18	–27.98
TuHaimajia River	–103.58	26.75	–10.3	–56.44	–41.04	–36.92

Based on the water resources plan of the Hai River, the inter-basin water transfer data in 2007 was collected to calculate the water balance of 2007 for the sub-basins (the transfer water of the Yellow River is presented separately in order to make a distinction from Table 2). Table 3 shows the water balance analysis results of the sub-basins. The water storage change is consistent with the water surplus and deficit result, except for the TuHaimajia River sub-basin, so the change of the latter reflects the change in regional water storage.

The TuHaimajia River sub-basin is about 3.2 km², with an average precipitation of 17.44×10^9 m^3 and a total evapotranspiration of 21.16×10^9 m^3. The regional water deficit is most serious in all sub-basins, which is up to 3.7×10^9 m^3. Because it belongs to the main agricultural base of Shandong Province, the largest proportion is farmland evapotranspiration, accounting for 78.8%. Most rivers in the region are seasonal, with no water during dry periods and small runoff during normal periods (Zhai, 2009). Table 2 shows that a surplus of water (2.675×10^9 m^3) appears only in 2003, when water was abundant. Rainfall and runoff cannot meet the needs of two-crop rotation planting. The water diversion projections from the Yellow River are in the TuHaimajia River, the north of Yu, the HeiLongGangyundong Plain and Tianjin, and the water transfer of the Yellow River changed from 3.34 to 6.68×10^9 m^3. The water transfer of the Yellow River to the TuHaimajia River was 3.992×10^9 m^3 in 2007, accounting for 93% of the total water transfer (Integrated Plan, 2010) and reversing the water deficit situation. Therefore, the transferred water compensated for the 3.7×10^9 m^3 shortage. Experts must pay attention to the development of high-efficiency and water-saving agriculture and must strictly control agricultural water consumption. Water savings in high flow years can be used to recharge the groundwater for ecologic environment improvement.

Table 3 Water balance analysis of the Hai sub-basins, 2007($\times10^8$ m^3)

Item	Luan River	Beisan River Mountain Area	Yongding River Mountain Area	Beisi River Plain	Daqing River	Ziya River	Zhangwei River	Heilonggang yundong Plain	Tuhaimajia River
Available Water Resources *I+P*	253.0	108.7	176.4	97.2	239.3	239.9	206.4	93.6	177.1
Water inflow *I*	1.9	8.4	1.5	9.9	2.1	4.7	12.8	1.0	1.9
Precipitation *P*	251.1	100.3	174.9	87.3	237.2	235.3	193.5	92.6	175.3
Water diversion of Yellow River	0.0	0.0	0.0	0.0	0.0	0.2	2.5	0.3	39.9
Outflow *R*	8.1	2.5	0.9	11.6	3.3	0.0	0.0	3.5	7.6
Water Consumption *Q*	254.8	113.6	154.0	88.0	239.3	228.8	176.4	127.2	210.6
Agricultural ET	55.5	16.7	86.0	58.0	123.5	124.6	98.4	99.5	165.9
Ecological environment ET	199.3	97.0	68.0	30.1	115.8	104.2	77.9	27.7	44.7
Water Storage Change Δ*s*	–9.8	–7.4	21.6	–2.4	–3.3	11.1	30.0	–37.2	–41.0
Outflow *R*	–9.8	–7.4	21.6	–2.4	–3.3	11.3	32.4	–36.9	–1.1

In the HeiLongGangyundong Plain, the average water deficit of 2.798×10^9 m^3 was the second to the TuHaimajia River. The water consumption balance in 2007 shows that the total water consumption was 3.46×10^9 m^3 larger than precipitation, and the outflow was larger than inflow at the same time. The water diversion of the Yellow River is only 0.03×10^9 m^3 and cannot compensate for the water deficit. Based on the above data, The HeiLongGangyundong Plain had the most serious water shortage in the sub-basin. The ratio between agriculture and ecological environment is 3.6:1, and the agriculture water consumption exceeded the precipitation. The supply from other water resources is not enough for sustainable utilization of water resources.

In the Beisi River Plain, the average water deficit was 0.676×10^9 m^3. The water consumption balance in 2007 showed that the total water consumption was well-matched with precipitation. The agriculture water consumption accounted for 65.8%, and the ratio between agriculture and ecological environment was 2:1. These statistics are similar to those of the HeiLongGangyundong Plain, but the water resources pressure of agriculture development is far smaller than in the latter. Agriculture water consumption should be controlled tightly in irrigation water management. Experts should pay attention to the water usage requirements of industry and living and to what extent this usage causes pressure on water resources. More detailed industry and living data is needed to analyze this situation further.

The ZhangWei River sub-basin, with an area of 35000 km², had the most surplus water in the sub-basin, with up to 3×10^9 m^3. The average precipitation for six years in the sub-basin was 21.1×10^9 m^3, while the total evapotranspiration is up to 18.11×10^9 m^3. A water shortage of 1.353×10^9 m^3 occurred only in 2002, a drought year, while in the high flow year of 2003, a water surplus of 7.34×10^9 m^3 appeared. The water consumption balance in 2007 shows that precipitation was higher than total water consumption, and the water storage is 3.241×10^9 m^3 when the water diversion of the Yellow River is included. Agriculture evapotranspiration accounted for 55% of total water consumption, while ecological evapotranspiration of grass and forest was up to 41%. Although the water resources are at a surplus, the groundwater seriously is overexploited, so experts should focus on the construction of an infrastructure. Surface water should be use for irrigation in order to reduce groundwater exploitation. The integrated water-saving measures of agriculture are being developed continually in order to restore the water level gradually. The Ziya River sub-basin and mountainous are of the Yongding River are similar to the ZhangWei River sub-basin.

The Daqing River sub-basin, with area of 45000 km², includes a mountainous area and the plain area of the Daqing River. Average precipitation for six years was 21.03×10^9 m^3, while the total evapotranspiration is up to 23.01×10^9 m^3. Water shortages amounted to 2.1×10^9 m^3. Although the water consumption structure in this sub-basin is similar to the Zhangwei River sub-basin, the evaporation capacity of the two regions is not equal. The reference evaporation calculated by Penman-Monteith method is used as the expression of evaporation capacity. The average annual reference evaporation in the Daqing River sub-basin is 44.04×10^9 m^3, while it is 32.8 in the Zhangwei River. The actual evaporation in the Daqing River sub-basin was greater than the Zhangwei River sub-basin under the same precipitation conditions, and the runoff produced by rainfall decreased, so an increase in farmland irrigation water could have caused the water shortage. Water resources have been in shortage from 2002 to 2007. The regional water storage would decrease because of unbalance of water income and expenditure, and then the groundwater level has been declining continuously without water diversion. The water consumption balance in 2007 shows that agricultural evapotranspiration accounted for 51.6% of total water consumption, and ecological evapotranspiration of grass and forest accounted for 33%. The irrigation in the plain mainly relies on groundwater, and overexploited areas are found in the east and west of the Daqing River (Yu, 2009). Therefore, the focus of agriculture water management should develop water saving measures such as field mulching to reduce soil evaporation and adjusting crop planting structures to reduce agriculture evapotranspiration.

The Luan River sub-basin, with a total area of 54000 km^2, includes the Luan River mountainous area, the Luan River Plain, and Jidongyanhaizhuhe. The average precipitation for six years was 25.02×10^9 m^3, while the total evapotranspiration is up to 26.21×10^9 m^3. Water shortages are in the amount of 1.56×10^9 m^3. The water consumption balance in 2007 shows that the agriculture evapotranspiration accounted for 21.8% of total water consumption, while ecological evapotranspiration of grass and forest was 70.5%. Therefore, the main development direction in the sub-basin should be ecological construction. The Beisan River Mountain sub-basin is similar to the Luan River sub-basin the sub-basin. The focus should be on developing water-saving measures while ensuring ecological construction in these two sub-basins. The input and output of cultivated areas should be analyzed to propose a rational crop-planting structure.

5 DISCUSSION

The water consumption balance analysis shows that the average water shortage is 6.23×10^9 m^3, and the reduction of water consumption is the only method to compensate for the deficit. If the total water consumption is reduced by 6.23×10^9 m^3, the water balance status quo will be maintained but groundwater recovery will not take place. Therefore, an annual water consumption balance analysis should be implemented to understand the water consumption inter-annual change trend and to ensure the dynamic balance over a long period of time in order to reduce groundwater overdrafts and to realize sustainable utilization of water resources.

Water consumption is divided into agriculture, ecological environment, industry, and living water consumption. This consumption can be further divided; for example, industry water consumption can be divided into water consumption by different sectors, and living consumption can be divided into urban, rural, human, and livestock water consumption. The fine classification of water consumption would be helpful for water consumption management. With the further development of society and the economy, water consumption in both industry and living will increase continually, and the increasing trend is in conformity with the principle of community water use priority and maximization of economic benefits in water resource integrated management (Yang, 2009). The improvement of the ecological environment is a necessary trend and has caused an increase in water consumption. Therefore, decreasing groundwater overdraft can be realized only by the reduction of agriculture water consumption. The average agriculture water use from 1980 to 2007 was 27.98×10^9 m^3, which accounted for 70.3% of total water use (Haihe River Record, 2010), and agriculture water consumption was 89.46×10^9 m^3, which accounted for 54.3%. Water storage of 6.23×10^9 m^3 amounted to 7% of agriculture water consumption. The uncontrolled part of agriculture water consumption is caused by precipitation, which occurs whether or not irrigation is used, so reduction of water use is not equal to water consumption savings. If the agricultural water consumption without irrigation and crop planting is equivalent to that of grass, the average ET is 380.3 mm, and the available savings ET is 163.7 mm, which accounts for 30% of agriculture water consumption. Therefore, only 30% of agriculture water consumption is controlled. In order to compensate for a water deficit of 6.23×10^9 m^3 in the Hai Basin, 23% of the area must be fallow. However, the basin is the main food production region of China, accounting for 10% of China's total food, and is one of the grain production bases. A crop-planting area reduction will have a direct effect on the yield of grain, which will have a large impact on food security (Water Resource Plan, 2003), making this an unfeasible program and showing the necessity for the south-north water transfer project.

The water consumption balance can be achieved in different spatial scales, from global to basin to sub-basin. Because water consumption is closely combined with the social economy, the water consumption balance can be analyzed for an administrative unit, such as for a county, a region or a province. The evapotranspiration estimated by remote sensing can provide water consumption data of arbitrary units and make water balance analysis possible.

Regarding the water consumption balance, attention should be given to three aspects of water resource management. Firstly, the water consumption balance analysis should be made continually, with reasonable controls in drought years and rigorous control of water consumption in high-flow years to ensure the surplus water recharges the groundwater. In addition, the water storage changes maintain a certain fluctuant range in order to keep a dynamic balance of water consumption over a long period of time. The change range of water resources is not in accordance with water consumption, and water consumption changes are less than precipitation. The annual water balance analysis would be a new method for adjusting the basin water storage to realize reasonable utilization of precipitation in a year or between years.

Secondly, agriculture fallow can solve the water deficit of the basin, but the influence on social security cannot be evaluated. Improvement of water productivity is a core to realize the agriculture high efficiency water use. However, the criterion for developing water saving agriculture is not increasing irrigation areas but is the reduction of agriculture evapotranspiration, which can alleviate the declining groundwater trend.

Thirdly, for a long time, experts in water resource management have paid attention to the water use of both industry and living, but they have ignored the measurement of water consumption data. People should realize water savings for each process in water resource shortage regions, especially the "draft-transfer-use-recharge" process.

The evapotranspiration estimated by remote sensing reflects only the evaporation process caused by solar radiation. The collected data were used to estimate water consumption by other sources. The water consumption of industry and living should not be ignored, especially in water-saving society construction. Large water consumption of industry should be managed based on water consumption to realize water-saving goals. The industry and living data were difficult to obtain because of the management mode of supply-requirement. Goverments should strengthen to collect and measure the water consumption from the view of water consumption.

6 CONCLUSION

Aimed at the water resources problems, a method of water consumption balance analysis is proposed, based on water balance principles that use evapotranspiration estimated by remote sensing and the spatial geo-statistical method. The water consumption of different energy sources was calculated. Regional evapotranspiration with remote sensing includes the natural and human impact on complicated surfaces. Industrial and living water consumption includes evaporation caused by mineral and biological energy. The water consumption results provide spatial information and researchers avoid studying runoff generation and routing theory of natural-human dual water cycle and large amounts of basic data. The water shortage results of the Hai Basin from 2002 to 2005 were estimated, and the relative error is 5.6% using the hydrological model. Therefore, high consistency exists between the two methods at the basin level, and the water consumption balance analysis is feasible.

The ET, precipitation, inflow, and outflow data were used to estimate the water storage of the Hai Basin from 2002 to 2007. The average annual water storage change was -6.23×10^9 m^3, while average annual groundwater exploitation was 5.02×10^9 m^3 in the basin between 1985 and 1998. Therefore, groundwater levels decreased continuously, with the extent of decline increasing over ten years. The utilization and development of water resources has been unsustainable. Agricultural and ecological environment water consumption shows that the agricultural evapotranspiration accounted for 54.3% of the evapotranspiration estimated by remote sensing, with a range of –5% to 8%, and agriculture production remains the main sector of water consumption. A 23% increase of fallow areas in agriculture can compensate for the water deficit of 6.23×10^9 m^3. The criterion for developing water-saving agriculture is the reduction of agricultural evapotranspiration, not increasing the irrigation areas.

The basin-level water consumption balance analysis provides a new method for water resources management. In a region in which groundwater is overexploited and water resource problems are very serious, the annual water consumption balance analysis can be implemented to ensure a dynamic water balance over a long period of time and to realize the sustainable utilization of water resources.

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流域耗水平衡方法与应用

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摘　要：流域水量平衡分析是水资源现状评价与水资源合理调度研究工作中的一个核心。本文基于遥感技术估算的蒸散，结合监测统计数据，提出了流域耗水平衡方法，以海河流域为例进行了2002年—2007年流域及子流域的耗水平衡分析，流域多年平均蓄变量为-62.3亿m^3，其中农业生产是流域水资源消耗的主要因素，占耗水总量的54.3%，年际变动范围较小（-5%—8%）。通过流域蓄变量变化和流域蒸散结构的分析，揭示海河流域存在的水资源问题，为流域水资源管理和节水型社会建设耗水控制和节水方案提出建议。

关键词：耗水平衡，遥感，海河流域，蒸散发，工业耗水，生活耗水

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1 引　言

水量平衡的基本原理是质量守恒定律。地球上某一区域在某一时段内，收入的水量（I）与支出的水量（O）之差等于该区域内时段始末的蓄水变量（ΔS），即$I–O=\pm\Delta S$，系统的空间尺度大到全球，小至一个区域。水量平衡是水文现象和水文过程分析研究的基础，也是水资源数量和质量计算及评价的依据，利用水量平衡方程式可以确定降水、蒸发、径流等水文要素间的数量关系，估计研究地区的水资源数量、分析地下水的超采量等（中国科学院《中国自然地理》编辑委员会，1981；UNESCO，1978）。

对于流域水循环系统，水量平衡方程式为：

$$P–R–E=\pm\Delta S \tag{1}$$

式中，ΔS为流域蓄变量，P为降水量，R为径流量，E为蒸散发。降水通过地面观测获得，径流量通常只在主要控制点和断面测量，蒸散发和蓄变量测量最为复杂，高昂的测量成本使其不能成为常规测量要素，多采用估算方法。

早在20世纪初，经验性水文模型（Sherman，1932；Nash，1957）通过降雨径流关系的研究开展水平衡分析，20世纪60年代—80年代集总式模型的提出从流域产汇流出发建立模拟模型，并根据河流的观测流量值率定模型的参数，代表性的有Stanford模型、Tank模型和新安江模型等。胡庆芳等人（2007）利用改进的月水量平衡模型，模拟了北运河通县站控制流域的1980年—1991年月径流和蒸散发过程。由于流域内地形地貌、下垫面的复杂，各个要素存在着空间差异，集总式模型无法提供流域内水文变量的关系，从80年代以后基于物理过程的分布式水文模型的研究与发展逐渐受到重视，如TOPMODEL（Beven 等, 1979)，SHE模型（Abbott 等, 1986)，SWAT（Arnold 等, 1995）模型, WEP（贾仰文 等，2005），综合了产汇流、土壤水、地下水运动及蒸发过程，考虑了水文变量的空间变异问题。朱新军等（2005）在AVSWAT2000平台上构建海河流域分布式水文模

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型，并利用所建立的分布式SWAT模型对海河流域水平衡关系进行分析。Kavvas（2010）应用区域水文模型RegHCMTE在Tigris-Euphrates流域开展了水平衡分析。随着人类活动的增强，“自然–人工”二元驱动力下的水循环过程研究受到瞩目，水库、闸坝和人工运河等水利工程的建设，蓄水、引水和跨流域调水等使得水循环过程更加复杂，而其中人工侧支循环的影响越来越显著，王浩等人（2006）提出了由分布式流域水循环模型（WEP）、水资源合理配置模型（ROWAS）和多目标决策分析模型（DAMOS）3个模型耦合而成的二元模型，并应用该模型对海河流域进行了分析计算与模型验证（贾仰文人 等，2010）。

随着研究和应用的拓展，水文模型在应用中遇到了各类难题和瓶颈，其中最为突出的表现为三个方面：

（1）模型的不确定性，首先水文变量与参数具有很大随机性，模型中各种假设条件的存在，使同样的参数在不同空间和时间下模型计算结果可能存在差别。

（2）变化环境对模型的影响，人类活动的影响很大程度地影响着流域水循环过程。以海河流域为例，1950年以来已经建有大中小水库共计1967座（海河志，1998），河流堤坝、橡胶坝和河流大大小小的控制闸等，都将影响水循环的动力学过程；退耕还林还草、坡改梯等一系列的水土保持治理工程以及城市化的发展等都使得下垫面发生变化，水文参量与参数的空间变异性大大增强，如同一种土壤类型由于人为原因土壤入渗能力发生变化。在变化环境下的大尺度水文模型不再适用，而小尺度的模型又缺乏详细的资料来描述下垫面的变化，这无疑进一步增加了模型的不确定性。

（3）基础资料的限制，无论是不同时间尺度的模型，还是不同空间尺度的模型，都需要长时间序列的基础数据，包括水文要素观测数据以及详细的地表覆盖和土壤结构信息等，中国在气象、水文和土壤监测数据上的共享机制环节的薄弱限制了水文模型的应用。另外，模型的精度只能通过有限的实测数据与模型计算结果的对比分析，受观测资料的限制，模型难以得到充分检验。

目前，现有基于水量平衡原理的模型，更多的关注流域产汇流机制，可以更好地模拟洪峰以确保防洪减灾。而在水资源短缺地区面临的更大问题是水资源消耗不可持续和地下水超采导致的一系列生态问题。

随着遥感技术的发展，不同尺度的多源遥感信息从植被、粗糙度和地形等角度提供地表信息，可以反映区域下垫面的空间变异性特征。80年代发展的一系列遥感蒸散模型（Allen 等，2007；Bastiaanssen 等，1998；Su 等，2002，吴炳方 等，2008），利用遥感反演的地表参数，基于能量平衡原理进行区域蒸散发的计算。遥感蒸散发监测范围大，信息量大，且摆脱了大量基础观测数据，这为从耗水角度的水量平衡分析提供了一个新的数据源。

因此，本文面向流域水资源短缺问题，提出基于水量平衡原理的耗水平衡分析方法，分析流域水资源消耗的过程，揭示流域蓄变量变化的趋势，为水资源管理对策提供支持。

2 研究区和数据

2.1 研究区

海河流域位于112.0° E—119.8° E, 35.0° N—42.8° N，总面积约31.8万km^2，占中国陆地面积的3.3%。流域山地面积18.9万km^2，约占60%，平原面积12.9万km^2，约占40%。该区域属于温带大陆型季风气候，多年平均降雨量535 mm，降水时空分布呈明显的地带性、季节性和年际差异，春季干旱少雨，夏季炎热多雨，全年降水量80%集中在汛期6月份—9月份，具有春旱秋涝的特点。降水量年际变化大，存在连丰或连枯的变化规律。流域年平均气温在1.5℃—14℃。年平均水面蒸发量1100 mm，蒸发量随着气温上升而增加。海河流域包括海河、滦河、徒骇马颊河三大水系。海河水系由蓟运河、潮白河、北运河、永定河、大清河、子牙河、漳卫南运河、黑龙港水系和海河干流组成。1956年—2000年的资料表明，流域多年平均年河川径流量为216.1 亿m^3，折合流域多年平均年径流深67.5 mm。

2.2 数据

（1）降雨量和出入境流量

降雨量，出入境流量，外调水量和入海水量数据来源于海河流域水资源公报（2002年—2008年）。

（2）蒸散发数据

海河流域蒸散发数据集，空间分辨率为1 km×1 km，

时间2002年—2007年，频次为月，统一为 Albers投影，TIFF格式存储。该数据采用基于能量平衡原理构建的ETWatch系统（吴炳方 等，2008）计算。

（3） 土地利用数据

海河流域土地利用图，空间分辨率为250 m×250 m，时间为2004年和2006年，统一为Albers投影，Arcshape格式存储。该数据是应用MODIS 250 m可见光和近红外数据，按照国家土地利用一级分类系统，采用监督分类和目视解译法完成。

（4）工业产值和人口数据

人口数据主要来源于全国统计年鉴和8个省的统计年鉴。工业数据主要来源于8个省统计年鉴、中国电力统计年鉴和中国能源统计年鉴。

（5）耗水数据

单位发电量耗水量2002年为3.5 kg/kWh，2003年为3.4 kg/kWh，2004年为3.2 kg/kWh，2005年—2007年为3.1 kg/kWh（国家发展改革委，2006）。

吨生铁耗水量数据来自于中国金属学会“2006年中国高炉炼铁技术评述”的数据：重点钢铁企业吨铁耗水量在34 m^3 / t左右，吨铁耗新水在19 m^3 / t左右，目前先进水平在0.5 m^3 / t（中国金属学会，2007）。吨钢耗水量数据来自于能源统计数据：首钢吨钢耗新水4.98 m^3，邯郸钢铁吨钢耗新水6.09 m^3，唐山钢铁吨钢耗新水4.25 m^3。

一天时间内，人从皮肤的汗腺排出的水分，盛夏时一个人平均1 d的排汗量可达4×10^{-3}—5×10^{-3} m^3；春天及秋天，1 d的排汗量是8×10^{-4} m^3左右；冬天出汗量不大，但也要排出5×10^{-4} m^3。平均1 a排汗量为0.56 m^3（三九健康网，2009）。

3 方 法

流域采用陆地外流区的水量平衡表达式：

$$P-E-R=\Delta s \quad (2)$$

式中，P，E，R，Δs分别为流域任意时段内降水量，总耗水量，径流量和蓄变量。R表达为流域出入境的变化量，即出境（O）与入境（I）的差值；对于多年平均而言s=0。通常以一年为周期土壤蓄变量近似不变，那么区域蓄变量相当于地下水蓄变量。

其中降水和径流通过观测站的数据可以得到，关键是区域总耗水量的计算。根据水汽由液态到气态过程能源的不同，总耗水量可以表达为三项之和：

$$E=\mathrm{ET}+Q_m+Q_b \quad (3)$$

式中，ET为区域蒸散发，为太阳能源引起的蒸发，这部分可以通过遥感估算得到，即仅考虑自然状态下地表的蒸散发过程，包括农田、森林、水面和裸露地表的蒸发。在海河流域农田耗水量最大，为了分析农田耗水的变化及影响，结合土地利用图将ET分解为农田蒸散发（ET_{ari}）和生态环境蒸散发（ET_{env}）。而流域内机械能、化学能和热能等能源也存在蒸发过程，像石油和煤的燃烧以及炸药爆炸等是在发生化学变化时候所放出的能量，这部分耗水量就是Q_m；人或动物的排汗能量是储存在体内的生物能转化为化学能或机械能得到的，耗水量是Q_b。

工业水表计量的取水量除用于生产后，一部分循环利用回到生产系统，还有一部分排放出来或经过处理后排放。生活用水中的大部分水通过城市和农村排水系统进入流域水循环，只有少部分水量通过蒸发方式进入大气。工业和生活一般计算用水量，很少会计算耗水量，工业一般可获取的资料是用水量、产品产量和产品耗水率等信息，生活可获取的资料是人口数和牲畜数。由于耗水率和产品资料获取的局限性，工业耗水主要计算流域内3个主要耗水产业的耗水量，生活耗水量中计算人和牲畜的排汗量。

工业生产中的耗水量计算方法采用如下公式：

$$Q_m=\sum_{i=1}^{n}P_i\times Co_i \quad (4)$$

Q_m表示工业类耗水，i表示区域内的某类工业，P_i为该类工业的产量，Co_i为该类工业单位产值的耗水系数。由于资料获取的局限性，只搜集了流域内主要耗水产业的耗水率和产品产量信息。如火电厂的耗水量，可以利用各省市发电量和单位发电耗水量，计算通过消耗煤等能源将水从固态转变为气态时产生的蒸发量。钢铁行业的耗水量，利用各省市钢和铁的产量和单位产量耗水量，可以计算矿物能产生的蒸发量。

生活耗水量的计算公式如下：

$$Q_b=P\times Co \quad (5)$$

Q_b表示年排汗量，P为人或动物的数量，Co为排汗系数。由于缺乏牲畜排汗相关资料，其排汗量按人均年排汗量计。

因此，联合公式（2）—（5），耗水平衡分析公式表达为：

$$\Delta s=P+I-O-\mathrm{ET}_{agr}-\mathrm{ET}_{env}-\sum_{i=1}^{n}P_i\times Co_i-P\times Co \quad (6)$$

海河流域存在跨流域调水和入海流量，为方便分析这两部分分别归并在入境和出境流量中。

4 结　果

4.1 流域水平衡结果

基于遥感数据、降雨和径流的统计数据，应用上述水量平衡方程，进行了海河流域2002年—2007年的耗水平衡分析，结果如表1所示。海河流域2002年—2007年平均水资源量为1603亿m^3，平均蒸发量为1646亿m^3，2002年—2007年流域水量收支明显不平衡，流域水量处于亏缺状态。

流域水资源量主要来源于降水量，占97.4%， 降水量的年际变动在平均降水量的−18%—19%变化。流域水资源消耗量以遥感估算的蒸散量为主，占97.7%。2002年—2007年遥感估算的蒸散量在多年平均蒸散量的–8%—12%变化，比降水年际变化波动小。工业耗水量、人和牲畜耗水量占水资源消耗总量的比重很低，占2.3%，因此采用平均水平的排汗系数和耗水系数来估算耗水量对水平衡分析影响不大。

利用遥感反演的ET结果和土地利用分布图，采用面积加权的方式估算了不同土地利用类型的蒸散量。农田蒸散占遥感蒸散量的54.3%，年际变动在–5%—8%，农田由于人工灌溉的原因，使其变化幅度远远小于降水。环境生态蒸散量为除农田蒸散之外的其他用地蒸散量，包括林地、灌木和草地的蒸散发，占环境生态蒸散量的80%，年际变动在–11%—19%。

流域蓄变量相当于地表水、地下水和土壤水的蓄变量，年蓄变量主要表现为地下水的蓄变量，因此通过蓄变量的变化可以反映流域地下水位变化状况，正值表示地下水回升，负值说明地下水位下降。2002年—2007年海河流域年蓄变量平均减少62.3亿m^3，而1985年—1998年海河流域地下水平均年超采量50.2亿m^3（海河志，1998），流域地下水位呈现持续下降的趋势，且下降幅度增加，流域水资源开发利用方式处于不可持续发展的态势。

2002年—2007年流域蓄变量年际间变化波动较大，2003年—2005年流域蓄变量增加123.7亿m^3，无法弥补2002年流域水资源量193.1亿m^3的亏缺，2002年—2005年多年平均蓄变量下降18.8亿m^3，而朱新军等（2008）基于SWAT分布式模型的水平衡分析结果表明：2002年—2005年海河流域的多年平均蓄变量下降17.8亿m^3，相差5.6%，且两者区域蓄变量变化趋势一致，说明本文中遥感估算ET应用到流域水平衡分析中是可行的。2006年—2007年的连续干旱使得流域区域蓄变量继续减少。

表 1　2002年—2007年海河流域水平衡分析表/亿m^3

名称	2002年	2003年	2004年	2005年	2006年	2007年	平均	%
水资源量I+P	1320.2	1899.0	1764.8	1595.8	1448.8	1590.4	1603.1	100.00
地表水流入量I	46.4	36.1	42.3	37.3	46.3	42.8	41.9	2.60
降水量P	1273.8	1862.9	1722.4	1558.5	1402.5	1547.5	1561.3	97.40
出流量R	1.8	21.8	37.1	24.9	13.9	17.1	19.4	
实际耗水量Q	1511.5	1833.8	1661.8	1556.6	1672.7	1639.8	1646	100.00
农田蒸散	842.2	970	919.6	843.8	902.3	889.9	894.6	54.30
环境生态蒸散	637.5	832.4	706.6	671	728.7	708.2	714.1	43.40
生活耗水量Q_b	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.10
工业耗水量Q_m	30.9	30.6	34.9	40.9	40.9	40.9	36.5	2.20
区域蓄变量Δs	−193.1	43.4	65.9	14.4	−237.8	−66.5	−62.3	

农田（农业区）的流域水资源消耗量仍然最大，多年平均耗水量894.6亿m^3，占总耗水量的54.3%。农田的耗水量中部分是可控的，如灌溉引起的蒸散量是可控的，种植作物增加的耗水量是可控的，这也是水管理中提出发展节水灌溉技术、建立节水型农业的主要原因。但农田休耕时降水和土壤水的蒸发量是无法控制的。

4.2 子流域耗水平衡

利用公报统计资料和遥感估算的蒸散发量，以9个子流域为单元分析区域蓄变量的差异，揭示区域水资源的问题。由于各子流域资料缺乏，在水平衡分析

计算中做了如下简化：（1）工业和生活耗水量比重很低，且工业和人口数据大多按照行政区统计，这里忽略这部分耗水量的计算；（2）出境水量中包括子流域入海流量，由于缺乏跨流域调水数据，子流域入境水量的计算中没有考虑外流域调水。（3）2002年—2005年缺乏各子流域的出入境资料。按照水平衡分析方法计算得到子流域的各个分项（表3），得到各个子流域的2002年—2007年水分盈亏分析结果（图1，表2）。由图可以看出9个子流域的蓄变量存在较大的空间差异，除漳卫河、子牙河和永定河区域表现为水量盈余，其他子流域均表现为水量亏缺。

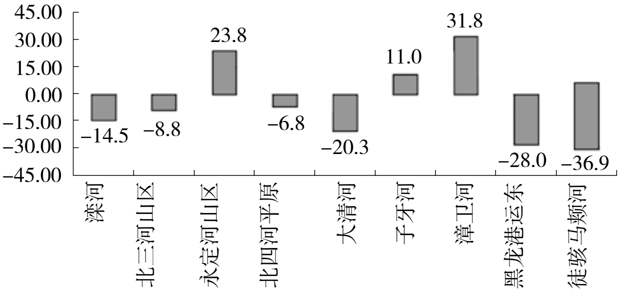

图1 海河子流域多年平均水分盈亏柱状图/亿m^3

表 2 2002年—2007年海河子流域水分盈亏分析表/亿m^3

名称	2002年	2003年	2005年	2006年	2007年	平均
滦河	−25.28	−9.27	10.91	−39.12	−9.82	−14.51
北三河山区	−14.26	−16.83	−5.74	0.07	−7.44	−8.84
永定河山区	38.77	7.01	31.71	19.97	21.55	23.8
北四河平原	−19.47	−7.55	0.03	−4.39	−2.4	−6.76
大清河	−14.74	−36.6	−8.12	−38.62	−3.32	−20.28
子牙河	0.06	20.45	11.35	12.27	11.12	11.05
漳卫河	−13.53	73.37	48.74	20.71	29.95	31.85
黑龙港运东	−49.06	9.58	−29.58	−33.64	−37.18	−27.98
徒骇马颊河	−103.58	26.75	−10.3	−56.44	−41.04	−36.92

以2007年为例，根据海河水资源规划，补充了2007年的跨流域调水量（为区别于表2结果，将引黄水量单独列出），如表3为海河流域各子流域的水平衡分析表。海河南系除徒骇马颊河子流域外，各子流域蓄变量的变化与水分盈亏量一致，水分盈亏量的变化反映了区域蓄变量的变化。

徒骇马颊河子流域3.2万km^2，平均降水量174.4亿m^3，总蒸散为211.6亿m^3，为所有区域水量亏缺最为严重的区域，达37亿m^3。该区域是山东省主要农业基地，农田蒸散比例最大，占78.8%，区域内河流多数属季节性河流，枯水期基本无水，平水期径流量较小（翟志杰，2009），如表2只有在丰水年（2003）出现水分盈余（26.75亿m^3），因此依靠降水量不能满足两季作物生长。海河流域内引黄工程为鲁北徒骇马颊河、豫北地区、河北省黑龙港运东平原以及天津，自1980年以来，引黄水量在33.4—66.8 亿m^{3}变化。根据2007年统计数据表明，徒骇马颊河地区引黄水量为39.92亿m^3，占到引黄总水量的93%（海河流域综合规划，2010），扭转了该子流域水分极度亏缺的局面。因此，由于外调水源的补充，弥补了该地区多年平均近37亿m^{3}水量的亏缺。该区域关注的是发展高效节水农业，严格控制农田水资源消耗量，丰水年节约的水资源量能用于地下水回补，改进生态环境。

表 3 2007年海河子流域水平衡分析表/亿m^3

名称	滦河	北三河山区	永定河山区	北四河平原	大清河	子牙河	漳卫河	黑龙港运东	徒骇马颊河
水资源量	253.0	108.7	176.4	97.2	239.3	239.9	206.4	93.6	177.1
地表水流入量	1.9	8.4	1.5	9.9	2.1	4.7	12.8	1.0	1.9
降水量	251.1	100.3	174.9	87.3	237.2	235.3	193.5	92.6	175.3
引黄水量	0.0	0.0	0.0	0.0	0.0	0.2	2.5	0.3	39.9
出流量	8.1	2.5	0.9	11.6	3.3	0.0	0.0	3.5	7.6
实际耗水量	254.8	113.6	154.0	88.0	239.3	228.8	176.4	127.2	210.6
农田蒸散量	55.5	16.7	86.0	58.0	123.5	124.6	98.4	99.5	165.9
环境生态蒸散	199.3	97.0	68.0	30.1	115.8	104.2	77.9	27.7	44.7
水分盈亏量	−9.8	−7.4	21.6	−2.4	−3.3	11.1	30.0	−37.2	−41.0
区域蓄变量	−9.8	−7.4	21.6	−2.4	−3.3	11.3	32.4	−36.9	−1.1

黑龙港运东平原多年平均水分亏缺量为27.98，仅次于徒骇马颊河子流域。2007年的耗水平衡分析结果表明，该区域实际耗水量大于降水量34.6亿m^3，出境也大于入境流量，引黄水量只有0.3亿m^3，这使得该区域蓄变量成为流域亏损最为严重的地区。该流域总耗水量中，农田与生态环境蒸散的比例为3.6：1，仅农业耗水量已经超出该地区的降水量，其他水资源量补给不足使得该区域水资源使用表现为不可持续的状态。

同样是平原区的北四河下游平原，多年平均水分亏缺量为6.76亿m^3。2007年的耗水平衡分析结果表明，该区域降水量与实际耗水量相当，农田耗水量占总耗水量的65.8%，农田与生态环境蒸散的比例为2：1。情况类似于黑龙港运东平原，该区域仅农业发展对水资源的压力远不如后者，但是也需要对农业耗水进行严格的控制。同时我们还需要关注工业和生活用水的需求，这部分耗水量引起多大程度的水资源供应压力，需要详细的工业和生活数据进行进一步分析。

漳卫河子流域面积3.5万km^2，是所有子流域中水量盈余量最大的区域，达30亿m^3。漳卫河子流域多年平均降水量211亿m^3，总蒸散为 181.1亿m^3，该子流域只有在枯水年（2002年）出现13.53亿m^3的水分亏缺，丰水年（2003年）盈余73.4亿m^3。2007年的耗水平衡分析表明降水量大于总耗水量，加上引黄水量，区域蓄变量为32.41亿m^3。该区域总耗水量中农田蒸散占55.8%，林冠草植被区生态蒸散占41%。尽管水资源量盈余，卫河平原和漳河背风坡河流上游仍然存在地下水超采情况（于翚 等，2009）。因此该区重点是加大基础设施建设，灌溉水以地表水径流为主，减少地下水开采，开展农业节水综合措施，逐渐恢复地下水位。子牙河子流域和永定河山区与该区情况类似。

大清河子流域面积4.5万km^2，包括大清河山区和平原区。年平均降水量210.3亿m^3，总蒸散量为230.1亿m^3，有21亿m^3的水量亏缺。虽然区域蒸散的耗水结构与漳卫河子流域类似，然而两个区域的蒸发能力不同，以参照蒸散表达蒸发能力，大清河子流域多年平均参照蒸散为440.4亿m^3，漳卫河子流域为328亿m^3，同样的降水条件下，大清河实际蒸发量会大于漳卫河区域，因此在大清河子流域降雨形成径流减少，蒸发量大，农田灌溉水量相应增加，导致区域整体水量亏缺。2002年—2007年该流域均为水分亏缺，在没有外调水量的情况下，区域蓄变量减小，地下水位将呈持续下降趋势。2007年的耗水平衡分析结果表明，子流域内农田蒸散占51.6%，林冠草植被区生态蒸散占33%，农业在该区域耗水量最大。平原区灌溉以地下水为主，在大清河淀西和淀东都有超采区（于翚 等，2009）灌溉，因此该区域重点是开展地膜覆盖等节水措施以减少土壤无效蒸发，同时开展作物种植结构调整以减少区域农田的年蒸散量。

滦河子流域面积5.4万km^2，包括滦河山区和滦河平原及冀东沿海诸河。多年平均降水量250.2亿m^3，多年平均总蒸散量262.1亿m^3，水量亏缺15.6亿m^3。2007年耗水平衡分析结果表明，子流域内农田蒸散占21.8%，林冠草植被区生态蒸散占70.5%，该区以生态建设为主。北三河山区与该区情况类似。两个子流域的水资源问题着重是在保障生态建设的同时，开展农业节水措施，分析现状农田的投入产出效益，提出合理的作物种植结构。

5 讨 论

耗水平衡分析结果表明解海河流域多年平均的水资源亏缺量是62.3亿m^3，要弥补这一亏缺量，只有通过降低流域水资源消耗量的方式实现。如果将流域的耗水量降低62.3亿m^3，也只能维持现状的耗水平衡，还不能实现地下水的逐渐恢复。因此减少地下水超采量，实现流域水资源的可持续利用，必须要实施年度耗水平衡分析，以掌握流域年际间耗水量的变化趋势，确保耗水量在长时间序列尺度的动态平衡。

流域的耗水量被粗略分成农业、环境生态、生活和工业耗水量，当然还可以细分，如将工业耗水量分成不同部门的耗水量，生活耗水量也可以分成城市和农村、人与牲畜耗水量等，流域耗水量的细划将有利于有的放矢地进行耗水管理。随着社会经济发展和人民生活水平的提高，工业耗水量、生活耗水量将不断增加，这也是合理的，符合水资源一体化管理的公益用水优先和经济效益最大化原则（杨立信，2009）。生态环境的改善也是必然的趋势，由此也会导致耗水量的增加。因此，想要减少地下水的超采量，只有减少农田耗水量。海河流域农业用水量1980年—2007

年平均为279.8亿m^3，占总用水量的70.3%（海河流域综合规划，2010），而海河流域农田耗水量为894.6亿m^3，占流域总耗水量的54.3%，多年平均超采量62.3亿m^3水相当于农业耗水量的7%。农业耗水量中有相当一部分的耗水量是由于降雨引起的，是不能控制的，不管是否灌溉，不管是否种植作物都会引起蒸散，因此农业用水量的节约量并不意味着同等程度的耗水节约量。假设不灌溉和不种作物的农田耗水量与荒草地相当，多年平均ET为380.3 mm，也就是说农田不种作物不灌溉可节约ET为163.7 mm，只相当于农田耗水量的30%，也就是说农田耗水量中的30%是可控的。如果想补偿流域多年平均亏损量62.3亿m^3，流域内需要休耕23%的农作物种植面积。然而海河流域是中国的粮食主产区，粮食总产量占全国的10%，是中国三大粮食生产基地之一，农作物种植面积的缩减，将直接影响到小麦和玉米主要粮食的产量，对中国粮食安全有较大影响（海河流域水资源规划简介，2003），这种方案并不可取，这也从另一方面说明了南水北调工程的必要性。

耗水平衡可以在不同的空间尺度进行，大到全球，小至一个流域、子流域。耗水平衡与社会经济的紧密结合，因此耗水平衡也可以以行政区为单元进行，如一个县的耗水平衡，一个地区、一个省的耗水平衡，由于采用遥感方法估算耗水数据，可以统计得到任意单元的耗水数据，从而使得不同单元耗水平衡成为可能。

从耗水平衡的角度，水资源管理应在以下3个方面应当重视：一是在水资源管理中需要持续的开展动态水平衡分析，在枯水年对水资源消耗量进行合理控制，在丰水年严格控制流域的耗水量，确保有盈余的水资源量能够回补地下水，有的放矢让区域蓄变量在可控制范围内波动，流域耗水过程在一个长时间序列上达到动态平衡。流域水资源量和水资源消耗量波动范围不一致，耗水量变化波动远小于降水量的变化幅度，年度耗水平衡分析将为调节流域蓄变量提供新的方法，实现在年际间和年内合理利用降水资源。二是尽管农业休耕可以解决流域水量亏缺的问题，但是对社会安全的影响是不可估量的。以提高水分利用效率和产出效益为核心，采取工程措施与非工程相结合的策略，逐步实现农业高效用水的方针不变，但是流域发展节水农业首要衡量标准不能以灌溉面积扩大为标准，应该以有没有降低流域农田蒸散量为标准，只有农田蒸散量降低才能减缓地下水下降的趋势。三是长期以来，水资源管理中重视工业和生活的取用水量，忽略对工业和生活耗水数据的计量。在水资源问题地区争取实现方方面面的节水，不可忽视“取-输-用-退”过程中的消耗。遥感估算的蒸散发只反映了太阳辐射能产生的蒸发，本文利用收集的资料对流域其他能源的耗水进行了粗略估算。工业和生活耗水数据在流域水平衡分析过程中是不可忽略的部分，特别是在开展节水社会建设过程中，更需要关注城市和生活的耗水量，针对性地对耗水量大的行业进行耗水控制管理，达到节水目标。工业和生活耗水量数据很难获取，这与长时间开展水资源供需管理有关，从耗水管理角度，需要加强工业和生活耗水量的收集和观测。

6 结 论

本文利用遥感技术，结合空间统计方法，面向流域水资源短缺问题，提出了基于水量平衡原理的耗水平衡分析方法。从能量角度提出了不同能量来源的区域耗水量计算方法，区域蒸散发的遥感估算技术综合考虑了自然和人工双重影响下的复杂下垫面变化，工业和生活耗水量计算考虑了矿物能和生物能引起的蒸发，估算得到具有空间面信息的水分消耗，避开了流域自然水循环-人工侧支循环复杂的产汇流机制研究以及对于大量基础数据的需求。应用该方法估算的海河流域2002年—2005年蓄变量结果，与水文模型SWAT结果对比，两种方法相对误差5.6%，在流域尺度上有很好的一致性，说明基于水量平衡方程的耗水平衡分析方法是可行的。

利用2002年—2007年的遥感ET数据，以及降水和出入境资料，估算了2002年—2007年海河流域的蓄变量。流域多年平均蓄变量为–62.3亿m^3，而1985年—1998年全流域地下水平均年超采量50.2亿m^3，流域地下水位在近十年间呈现持续下降的趋势，且下降程度增加，因此流域水资源开发利用不可持续发展。利用遥感的蒸散发估算了农业、生态和环境的耗水量，结果表明流域农田蒸散占遥感蒸散量的54.3%，年际变动范围较小（–5%—8%），农业生产仍然是流域水资源消耗的主要因素。如果农田采用休耕的方式，补偿区域62.3亿m^3水的亏损，需要农田休耕面积缩减23%。流域发展节水农业应该以有没有降低流域

农田蒸散量为标准，避免以节水换取灌溉面积扩大的现象。

流域耗水平衡分析方法为流域水资源管理提供了新的手段。在流域地下水超采严重，水资源问题突出的地区，可以实施年度耗水平衡分析，保证耗水量在长时间序列尺度的动态平衡，进而实现水资源的可持续利用。

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