Application and study on evaluation method of the overall effect of water saving efforts in a region based on remote sensing

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Abstract: The efficacy of water saving efforts in a region is often evaluated using only a single index measuring a specific industry or user, seldom examining the overall effect of efforts over the whole of the region. In this paper, a new method, referred to as baseline comparison, is used to evaluate the overall effect of water saving efforts in a region to determine the water utilization rate as well as the level at which water use is sustainable. The method takes target evapotranspiration (ET) and the theoretical change in groundwater level as the evaluation baseline, which is then compared with two evaluation indices: actual regional evapotranspiration (ET) and actual change in groundwater level calculated by remote sensing. This method is applied in Daxing District of Beijing, producing evaluation results consistent with measurements. A new evaluation method of the overall effect of water saving efforts in a region is proposed.

Key words: remote sensing, overall effect of water saving efforts, target ET, change in groundwater level, baseline comparison, evaluation

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1 INTRODUCTION

The city of Beijing suffers from a scarcity of water resources; less than 300 m^3 of water are available per capita, significantly lower than the 1000 m^3 per capita threshold that is globally recognized as signifying a water shortage (Yang & Cui 2005). In recent years, the government has taken a series of measures to urge industrial operations to save water, including economic and policy measures and the deployment of new technology. According to statistics available from the Beijing Water Authority, overall water use in Beijing has dropped each year over the past decade, decreasing from 40.4×10^8 m^3 in 2000 to 35.8×10^8 m^3 in 2009. Recycling of water used by industrial operations has increased 93%, while the efficiency of water used in irrigation has been 63%, However, groundwater depth has dropped from 13.85 m in 2000 to 24.07 m in 2009, which shows that while using a single-industry evaluation index which is useful for evaluating water conservation efforts in a specific domain, it does not provide an accurate understanding of the overall efficacy of efforts throughout the region.

In order to make an overall evaluation of the efficacy of water savings efforts in the region, we chose the district of Daxing as a research area, and then applied the baseline comparison method to evaluate the overall effect of all water saving efforts in the region. This baseline comparison method took the target evapotranspiration (ET) (Qin, *et al*., 2008) and projected change in groundwater level (Gu, *et al*., 2008) as an evaluation baseline, which was then compared with the two evaluation indices: Actual regional evapotranspiration (ET) and actual change in groundwater level as calculated by remote sensing, considering the actual level of water consumption in the region as well as the level at which utilization is sustainable.

2 STUDY AREA AND DATA

2.1 Introduction of the study area

Daxing District is located in the alluvial plain of the Yongding River in the southern part of Beijing. It covers an area 44 km long from north to south and 44 km wide from east to west. Its latitude range is from 39°26′N to 39°50′N while its longitude range is from 116°13′E to 116°43′E, giving Daxing District a total area of about 1030 km^2. The mean annual precipitation is 535 mm, creating 2.623×10^8 m^3 of exploitable groundwater each year, against an actual exploitation amount of 2.914×10^8 m^3. The ground water depth has dropped from 3.07 m in 1980 to 19.28 m in 2009.

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2.2 Data and data processing

In this paper, Terra/MODIS Level 1B data with a resolution of 1 km is used to calculate regional evapotranspiration in the research area from 2007 to 2009. The MODIS data processing (including geographical correction, radiation calibration, atmospheric correction, and cloud detection) was completed using ETWatch (Wu, *et al.*, 2008) a system created by the Institute of Remote Sensing Applications of the Chinese Academy of Sciences which calculates regional evapotranspiration based on remote sensing. The projection type of all MODIS data was an Albers equal-area conical projection whose projection parameters are as follows: Spheroid: Krasovsky; Datum: Krasovsky; Latitude of first standard parallel: 25N; Latitude of second standard parallel: 47N; Longitude of central meridian: 110E; False easting at central meridian: 4000000 m.

Meteorological data from the weather station in Daxing District for 2007 through 2009, including wind velocity, temperature, humidity, and atmospheric pressure, were interpolated to form raster data with the same projection type as the MODIS data. The kriging method (Zhou, *et al.*, 2006) was applied to the wind velocity, humidity, and atmospheric pressure, while the temperature was interpolated using the gradient plus inverse distance squared (GIDS) method (Lin, *et al.*, 2002).

The hydrological data in the research area includes precipitation, runoff coefficient, and specific yield from 2007 to 2009. The precipitation data was again interpolated using the gradient plus inverse distance squared (GIDS) method (Lin, *et al.*, 2002). The multi-year average precipitation was from the data series for 1956 to 2000. The runoff coefficient data and specific yield data were from the monitoring and evaluation report of the Beijing Water Conservation and Irrigation Project funded by the World Bank.

3 METHOD

We applied the baseline comparison method to evaluate the overall effect of water saving efforts in the region. The baseline comparison method took target evapotranspiration (ET) (Qin, *et al.*, 2008) and the projected change in groundwater level (Gu, *et al.*, 2008) as an evaluation baseline, which was then compared with the two evaluation indices: Actual regional evapotranspiration (ET) and the actual change in groundwater level as calculated by remote sensing.

3.1 Calculation method of the evaluation baseline

3.1.1 Target evapotranspiration

Target evapotranspiration (Qin, *et al.*,2008) is the maximum amount of water use which can support the sustainable development of the regional economy and the sustainable utilization of regional water resources in current special development stage, given the basic condition of the region's water resources and the constraints of the region's ecological cycles. Target evapotranspiration, which includes vegetation transpiration, soil or water evaporation and water consumption fixed in the products shipped out of the region.

The process of calculating target evapotranspiration is complicated and involves the distribution model of water resources, the distributed hydrological model, the regional evapotranspiration monitoring model based on remote sensing, and the soil moisture model. Generally, target evapotranspiration is calculated at a basin level first, and then at a provincial level, then a city level and county level. The Eq. (4) for calculating target evapotranspiration (Qin, *et al.*, 2008) is as follows.

$$ET_O=ET_R+W_C=P+W_{in}+W_D-W_{out}-W_{sea}-\Delta W \quad (1)$$

ET_O denotes target evapotranspiration (unit: mm), ET_R denotes regional natural evapotranspiration (unit: mm), W_C denotes the amount of water contained in products shipped out of the region (unit: mm), P denotes the precipitation level per year (unit: mm), W_{in} denotes the annual inflow (units: mm), W_{out} denotes the annual outflow (unit: mm), W_D denotes annual water amount from external regions, W_{sea} denotes the annual water amount flowing into the sea (unit: mm), ΔW denotes the water resource storage variation amount in the region (unit: mm).

3.1.2 Projected change in groundwater level

The projected change in groundwater level is a function of specific yield, precipitation, and surface water resources (Gu, *et al.*, 2008). If the projected change in groundwater level is positive, it shows that the groundwater level should rise in that specific period, with the increase equal to the projected change in groundwater level. If the projected change is negative, it shows that the groundwater level should drop in that specific period, with the drop equal to the absolute value of the projected change in groundwater level. Projected change in groundwater level is calculated as follows in Eq.(2)(Gu, *et al.*, 2008):

$$\Delta H_T=((P_i+W_i)-(\bar{P}+\bar{W}))/(1000\mu) \quad (2)$$

where ΔH_T denotes the projected change in groundwater level (unit: mm), P_i denotes annual precipitation (unit: mm), W_i denotes surface water resources level in the year (unit: mm), $\bar{P}$ denotes the multi-year precipitation average (unit: mm), $\bar{W}$ denotes multi-year average surface water resource amount (units: mm), and μ denotes specific yield (units: m^3/m)

If a region is heavily irrigated, the projected change in groundwater level is calculated by the following Eq. (3) (Gu, *et al.*, 2008):

$$\Delta H_T=(P_i-\bar{P})/(1000\mu) \quad (3)$$

3.2 Calculation method of the evaluation indices

3.2.1 Actual regional evapotranspiration

Because of the limitations of common methods for the calculation of regional actual evapotranspiration (Mao , 2005), the ETWatch system (Wu, *et al.*, 2008), created by the Institute of Remote Sensing Applications of the Chinese Academy of Sciences, is used to calculate the region's actual daily, monthly, and yearly evapotranspiration. This system consists of an operational processing chain starting from data pre-processing to application products, utilizing spatial information on climate, soil type, land use, vegetation cover, digital elevation, and remotely sensed land surface parameters. SEBAL (Bastiaanssen, *et al.*, 1998) and SEBS (Su , 2002)are integrated into ETWatch to estimate surface flux in clear-sky conditions, while Penmon-Monteith is applied to retrieved daily ET based on a surface resistance model, meteorological data and surface parameters from remote sensing data such as TM, ASTER, NOAA, and MODIS. The process flow is shown in Fig. 1 (Wu, *et al.*, 2008):

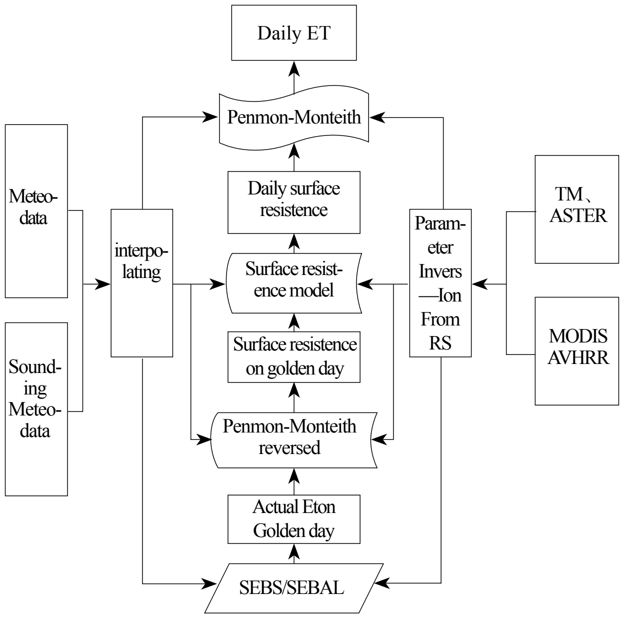

Fig. 1 ETWatch Process Flowchart

3.2.2 Actual change in groundwater level

The actual change in groundwater level can be expressed a function of precipitation, evapotranspiration and surface water resources (Gu, *et al*., 2008). Its equation is shown as follows (Gu, *et al*., 2008):

$$\Delta H_{\mathrm{p}} = \left(\left(P_i \left(1-\alpha\right) + W_i \right) - \mathrm{ET} \right) / \mu \tag{4}$$

where ΔH_{p} stands for the actual change in groundwater level (unit: mm), ET stands for regional evapotranspiration, P_i stands for annual precipitation (unit: mm), α stands for runoff coefficient, W_i stands for surface water resources amount in the year (unit: mm), and μ stands for specific yield (unit: m^3/m)

3.3 Evaluation method

In this paper, we have calculated the efficacy of water saving efforts in the test region by a baseline comparison method comparing projected values with the actual evaluation indices gathered by remote sensing. The actual evapotranspiration in the region was compared with the target evapotranspiration to determine the evapotranspiration evaluation value, expressed as $\mathrm{ET_v}$, while the actual change in the region's groundwater level was compared with projected change in groundwater level to get the change in groundwater level evaluation value expressed as ΔH_{v}.

If the region's actual evapotranspiration value is higher than target value, this will lead to water resource loss, showing that the water saving methods are not reaching the necessary standard of effectiveness and water saving efforts are failing, shown as an $\mathrm{ET_v}$ value equal to −1. If the actual evapotranspiration value is equal to the target value, this will lead to a balance between water supply and consumption in the region, showing that the water saving efforts are succeeding, providing an $\mathrm{ET_v}$ value equal to 0. If the actual evapotranspiration value is smaller than target value, this will lead to a water resource surplus, showing that the water saving efforts are highly successful and providing an $\mathrm{ET_v}$ value equal to 1. This evaluation process can be expressed by the follow Eq. (5):

$$\mathrm{ET_v} = f(\mathrm{ET}, \mathrm{ET_o}) = \begin{cases} 1 & (\mathrm{ET} < \mathrm{ET_o}) \\ 0 & (\mathrm{ET} = \mathrm{ET_o}) \\ -1 & (\mathrm{ET} > \mathrm{ET_o}) \end{cases} \tag{5}$$

As for the variance in groundwater level: If the actual level is higher than theoretical level, then the projected amount of groundwater is smaller than the measured amount of groundwater, showing that the water savings efforts are highly successful, giving a ΔH_{v} value equal to 1. If the actual level is equal to the theoretical level, water use is in balance and ΔH_{v} is equal to 0. If the actual level is lower than the theoretical level, the projected amount of groundwater will be larger than the measured amount of groundwater, showing that the water saving efforts have not reached a successful standard, providing a ΔH_{v} value equal to −1. This evaluation process can be expressed by Eq. (6):

$$\Delta H_{\mathrm{v}} = \varphi\left(\Delta H_{\mathrm{p}}, \Delta H_{\mathrm{T}}\right) = \begin{cases} 1 & \left(\Delta H_{\mathrm{p}} > \Delta H_{\mathrm{T}}\right) \\ 0 & \left(\Delta H_{\mathrm{p}} = \Delta H_{\mathrm{T}}\right) \\ -1 & \left(\Delta H_{\mathrm{p}} < \Delta H_{\mathrm{T}}\right) \end{cases} \tag{6}$$

4 RESULTS AND ANALYSIS

4.1 Results of evaluation baseline

According the report on target evapotranspiration distributed by the Hai River Water Resources Commission (Zhu, *et al*., 2009), the target evapotranspiration for Daxing District during the study period was 542 mm.

There has been no water in rivers in Daxing District since 2000, so the surface water resource level is zero. Runoff levels are negligible. Therefore, only precipitation contributes water to Daxing District. All irrigation is done with groundwater. Therefore, according to Eq. (3), the theoretical annual variance in groundwater level for Daxing County from 2007 to 2009 were respectively –0.19 m, 0.20 m and –1.34 m; that is to say, in 2007 there was a theoretical decline in groundwater level of 0.19 m in Daxing district, a theoretical rise in groundwater level of 0.20 m in 2008, and a decline of 1.34 m in 2009. These results are shown in Table 1.

Table 1 the integrated water saving effect evaluating results in Daxing

year	P_i /mm	$\bar{P}$ /mm	ET /mm	μ /(m^3/m)	$\mathrm{ET_o}$ /mm	ΔH_{T} /m	ΔH_{p} /m	$\mathrm{ET_v}$	ΔH_{v}
2007	532.0		568.3			−0.19	−0.52	−1	−1
2008	559.1	545	511.0	0.07	542	0.20	0.68	1	1
2009	451.5		499.9			−1.34	−0.69	1	1

4.2 Results of monitoring indices

The average values of actual annual levels of evapotranspiration for Daxing District which were calculated by ETWatch form 2007 to 2009 are 568.3 mm, 511 mm and 499.9 mm, respectively.

The actual change in groundwater level for Daxing District, which was calculated by Eq. (4), were −0.52 m, 0.68 m and −0.69 m, respectively. This shows that the groundwater level dropped by 0.52 m in 2007, rose 0.68 m in 2008, and dropped 0.69 m in 2009. These data and results are shown in Table 1.

4.3 Analysis of evaluation results

The values of evapotranspiration (ET_v) calculated by Eq. (5) and the values of change in groundwater level (ΔH_v) calculated by Eq. (6) in Daxing District from 2007 to 2009 are respectively −1, 1, 1 and −1, 1, 1. These results are shown in Table 1.

The evaluation results showed that the net water consumption amount (actual evapotranspiration) of Daxing District in 2007 exceeded the maximum water consumption quota (target evapotranspiration). The actual drop in groundwater level was larger than projected, showing that water was being used a rate faster than it was being replenished; as a result, the water supply and groundwater resources ran at a deficit. In 2008, the net water consumption amount was smaller than the maximum water consumption quota, and the actual rise in groundwater level was bigger than the projected, showing that the groundwater was used less quickly than it was replenished, creating a surplus. In 2009, the net water consumption amount was less than the maximum water consumption quota, and the drop in groundwater level was smaller than projected, leading to a water surplus and a decrease in the rate of groundwater loss.

According to the data from the Beijing Water Resources Bulletin from 2007 to 2009, the groundwater level in Daxing District descended 0.4 m in 2007, ascended 0.3 m in 2008 and descended 0.33 m in 2009. This shows that the evaluated results are in agreement with the measured results from groundwater observation wells.

5 CONCLUSIONS

In this paper, a new method referred to as baseline comparison is proposed to evaluate the overall effect of water-saving efforts in a region for the purpose of regional water consumption control and maintaining the sustainable usage of groundwater. This method takes target evapotranspiration (ET) and projected change in groundwater level as the evaluation baseline, which is then compared with the two evaluation indices: regional actual evapotranspiration (ET) and actual groundwater level as calculated by remote sensing. This method was applied in Daxing District of Beijing. The results showed that:

(1) This method yields satisfactory results. By taking the target evapotranspiration reflecting existing water consumption controls and the projected change in groundwater level reflecting sustainable groundwater utilization as an evaluation baseline, then calculating the actual evapotranspiration in the region and actual change in groundwater level based on remote sensing, and finally comparing the baseline with the corresponding index to evaluate the actual overall effect of water saving efforts in the region, we obtained results commensurate with the measured values.

(2) The overall effect of water saving efforts in Daxing District in 2007 did not meet expectations, leading to an overexploitation of groundwater and a loss of water resources. The overall effect of water saving efforts in Daxing District fared better in 2008 and 2009, with a sustainable usage level of water resources leading to a surplus and increase in groundwater level.

A possible avenue for future study in this field is the method for improving the suitability of this evaluation method under differing rainfall conditions. Rainfall can vary, leading to wet years and dry years, but the target evapotranspiration used as a baseline for this paper reflects the conditions in an average year (Qin, *et al*., 2008), which may lead to inaccurate results in years where rainfall differs significantly from average.

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区域综合节水效果的遥感评价方法研究与应用

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摘　要：区域节水效果的常规评价方法都是利用单项指标评价单一行业的或者单方面的节水效果，不能反映区域综合节水效果。本文从耗水控制水平和地下水可持续利用的角度出发，提出了以目标蒸散量（ET）和地下水位理论变幅为评价基准，利用遥感技术监测区域实际蒸散量和地下水位实际变幅，采用基准比较法评价区域节水综合效果的方法；并以北京市大兴区为例，开展了该区的综合节水效果遥感评价，为区域综合节水效果评价提供了新的思路。

关键词：综合节水效果，遥感评价，目标ET，地下水变幅，基准比较法

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1　引　言

北京市是水资源紧缺的城市，人均水资源占有量不足300 m^3，远远低于世界公认的1000 m^3的缺水下限（杨进怀和崔彩林，2005）。近年来，北京市政府采取了一系列经济、技术、政策等措施来促使各行业开展节水工作，缓解水资源紧缺形势，实现区域水资源可持续利用。据北京市水务部门的统计资料：北京市的用水总量逐年减少，已经由2000年的40.4亿m^3下降到2009年的35.8亿m^3，工业企业用水循环利用率达到93%，灌溉水利用系数提高到0.68；但地下水埋深却逐年下降，已经由2000年的13.85 m下降到2009年的24.07 m，这说明利用单项指标仅能衡量某一方面的节水效果，不能全面地评价区域综合节水效果。为全面地评价区域节水效果，本文以北京市大兴区为研究区，从耗水控制和地下水持续利用的角度出发，以目标蒸散量（秦大庸等，2008）[2384–2385]和地下水理论变幅（Gu等，2009）[499]为评价基准，利用遥感监测区域实际蒸散量和地下水位实际变幅，采用基准比较法评价了区域综合节水效果。

2　研究区与数据

2.1　研究区域概况

大兴区位于北京市南部的永定河冲积平原区，介于39° 26′ N—39° 50′ N, 116° 13′ E—116° 43′ E之间, 南北长约44 km，东西宽约44 km，总面积1030 km^2。该区降水量多年平均值为545 mm，地下水可开采量的多年平均值为2.623亿m^3，地下水实际开采量的多年平均值为2.914亿m^3，地下水埋深由1980年的3.07 m下降到2009年的19.28 m。

2.2　数据

本文采用的遥感数据为研究区2007-01-01—2009-

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12-31晴朗天气的Terra/MODIS Level1B数据，分辨率为1 km。MODIS数据处理主要包括几何纠正、辐射定标、大气纠正和云检测等过程，采用中国科学院遥感应用研究所开发的蒸散量遥感监测系统ETWatch（吴炳方等，2008）来完成相应的处理工作。所有MODIS数据的投影类型都统一为Albers等积圆锥投影(中央经线：110° E；第一割线：25° N；第二割线：47° N；坐标东偏：4000000 m）。

采用的气象数据为研究区气象站点2007-01-01—2009-12-31的日平均气温、风速、湿度和气压等数据，其中风速、湿度和大气压等气象要素的空间插值方法采用克里格方法（Kriging）（周会珍 等，2006），气温的空间插值方法采用梯度距离平方反比法（GIDS）（林忠辉 等，2002），其投影类型与MODIS数据相同。

本文采用的水文数据为研究区2007年、2008年和2009年的降水量、径流系数和给水度等数据。降水量数据的空间插值方法是梯度距离平方反比法（GIDS）（林忠辉 等，2002），多年平均降水量数据采用1956 年—2000年系列的数据。研究区的径流系数和给水度数据来源于“北京市世行节水灌溉项目监测评价报告”。

3 方 法

基于“耗水控制、地下水持续利用、综合评价”原则，本文以反映区域耗水水平的目标蒸散量（Evapotranspiration，简称ET）（秦大庸 等，2008）和反映地下水持续利用水平的地下水理论变幅（Gu 等，2009）[499]为评价基准值，利用遥感技术监测区域实际蒸散量和地下水实际变幅，采用基准值比较法来评价区域的综合节水效果。

3.1 评价基准值确定方法

3.1.1 目标蒸散量

目标蒸散量（秦大庸等，2008）[2384-2385]是指在一个特定发展阶段，以区域的水资源状况为基础条件，以生态环境良性循环为约束条件，满足区域经济社会可持续发展与区域水资源可持续利用的最大可消耗水量（包括植被蒸腾、土壤或水面蒸发以及工农业生产时固化在产品中并运出本区域的耗水）。目标蒸散量是一组值，包括反映区域综合耗水状况的综合目标蒸散量和反映各行业或者土地类型的分项蒸散量（秦大庸 等，2008）[2385-2386]。

目标蒸散量的计算过程涉及水资源配置模型、分布式水文模型、区域蒸散量遥感监测模型和土壤墒情模型等模型或工具，计算过程比较复杂。一般情况下，区域目标蒸散量是先计算流域级的目标蒸散量，然后按照流域、省、市、县的层序等级由高到低逐级分解确定。目标蒸散量的计算式（秦大庸 等，2008）[2385]如下：

$$\mathrm{ET_O}=\mathrm{ET_R}+W_\mathrm{C}=P+W_\mathrm{in}+W_\mathrm{D}-W_\mathrm{out}-W_\mathrm{sea}-\Delta W \quad (1)$$

式中，$\mathrm{ET_O}$表示区域目标蒸散量；$\mathrm{ET_R}$表示区域的自然蒸散量；W_C表示运出区域的工农业产品中含带的水量；P表示区域某一水平年的降水量；W_in表示区域年入境水量；W_out表示区域年出境水量；W_D表示区域的调入水量；W_sea表示区域年入海水量；ΔW表示区域水资源蓄变量。

3.1.2 地下水理论变幅

地下水理论变幅是给水度、降水量和地表水资源量的函数（Gu等，2009）[499]。如果地下水理论变幅为正值，则表示在特定时段内地下水位应上升，且上升的数值等于地下水理论变幅；如果地下水理论变幅为负值，则表示在特定时段内地下水位应下降，且下降的数据等于地下水理论变幅的绝对值。地下水理论变幅的计算如式（2）：

$$\Delta H_\mathrm{T}=\left((P_i+W_i)-(\bar{P}+\bar{W})\right)/(1000\,\mu) \quad (2)$$

式中，ΔH_T表示地下水位理论变幅；P_i表示当年降水量；W_i表示当年地表水资源量；$\bar{P}$表示多年平均降水量；$\bar{W}$表示地表水资源量的多年平均值；μ是给水度（$\mathrm{m^3/m}$），表示单位面积的潜水层降低单位长度时在重力作用下所能释放出的水量。

若一个区域以井灌为主，则地下水理论变幅可以近似地表示为式（3）：

$$\Delta H_\mathrm{T}=(P_i-\bar{P})/(1000\,\mu) \quad (3)$$

3.2 监测指标计算方法

3.2.1 区域实际蒸散量

由于常规方法在区域实际蒸散量（ET）计算中的局限性（毛德发，2005），本文采用中国科学院遥感应用研究所研发的蒸散量遥感监测系统ETWatch（吴炳方等，2008）计算区域实际蒸散量。ETWatch以TM/ASTER和NOAA/MODIS为遥感数据源，采用能量平衡–余项式模型（SEBAL模

型（Bastiaanssen 等，1998）和SEBS模型（SU，2002）和Penman-Monteith模型相结合的方法计算区域日蒸散量、月蒸散量和年蒸散量。ETWatch集遥感数据处理、气象数据处理、蒸散量计算等功能于一体，其流程可以表示成图1（吴炳方 等，2008）。

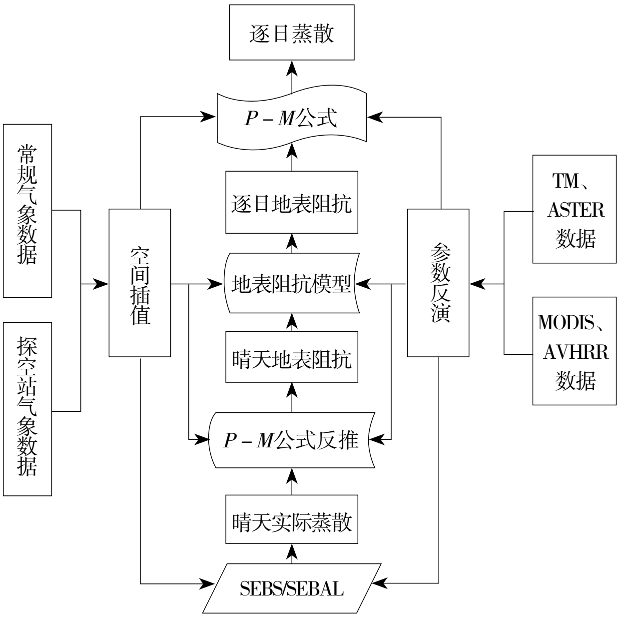

图1 ETWatch模型计算区域实际蒸散量流程图

3.2.2 地下水实际变幅

地下水实际变幅可以表示成降水量、蒸散量和地表水资源量的函数（Gu 等，2009）[499-500]，其计算式可以表示为式（4）：

$$\Delta H_p = ((P_i(1-\alpha)+W_i)-\mathrm{ET})/\mu \quad (4)$$

式中，ΔH_p表示地下水实际变幅（单位：m）；ET表示区域蒸散量；P_i表示降水量，α表示径流系数；W_i表示当年地表水资源量；μ是给水度。

3.3 评价方法

本文采用的评价方法为基准比较法，即将监测指标与相应评价基准进行比较，得出评价值，以评价区域节水效益的完成情况。就本文而言，即将区域实际蒸散量与目标蒸散量比较，得出蒸散量评价值（$\mathrm{ET_v}$）；将区域地下水实际变幅与地下水理论变幅比较，得出地下水位变幅评价值（ΔH_v）。

就区域蒸散量而言：若区域实际蒸散量大于目标蒸散量，这将造成区域水资源亏损，说明节水工作不达标、节水效果差，则蒸散量评价值$\mathrm{ET_v}=-1$；若区域实际蒸散量等于目标蒸散量，则区域水资源恰好实现供耗平衡，说明节水工作基本实现目标，则蒸散量评价值$\mathrm{ET_v}=0$；若区域实际蒸散量小于目标蒸散量，则区域水资源存在盈余，说明节水工作绩效优良，则蒸散量评价值$\mathrm{ET_v}=1$。区域蒸散量的评价过程可用式（5）表示：

$$\mathrm{ET_v} = f(\mathrm{ET},\mathrm{ET_o}) = \begin{cases} 1 & (\mathrm{ET} < \mathrm{ET_o}) \\ 0 & (\mathrm{ET} = \mathrm{ET_o}) \\ -1 & (\mathrm{ET} > \mathrm{ET_o}) \end{cases} \quad (5)$$

就地下水位变幅而言：若地下水实际变幅大于地下水理论变幅，则地下水的开采量小于回补量，地下水得到了补充，说明节水效果优良，地下水位变幅评价值$\Delta H_v=1$；若地下水实际变幅等于地下水理论变幅，则地下水开采与回补实现了动态平衡，节水工作基本实现了工作目标，地下水位变幅评价值$\Delta H_v=0$；若地下水实际变幅小于地下水理论变幅，则地下水的开采量大于回补量，地下水超采了，节水工作没达标，地下水位变幅评价值$\Delta H_v=-1$。地下水变幅的评价过程可用式（6）表示：

$$\Delta H_v = \varphi(\Delta H_p, \Delta H_T) = \begin{cases} 1 & (\Delta H_p > \Delta H_T) \\ 0 & (\Delta H_p = \Delta H_T) \\ -1 & (\Delta H_p < \Delta H_T) \end{cases} \quad (6)$$

4 结果与分析

4.1 评价基准值结果

根据海河流域水利管理委员会分配给各区县的目标蒸散量，大兴区在研究时段内的目标蒸散量为542 mm（朱晓春 等，2009）。

自2000年以来，大兴区内河道基本无水，地表水资源量为零；降雨几乎没有形成径流，降水量全部为有效降水量；农业灌溉用水全部是地下水。因此，根据式（3），大兴区2007年—2009年的地下水理论变幅分别为：–0.19 m、0.20 m和–1.34 m，即大兴区2007年地下水位下降理论值为0.19 m；2008年地下水位上升理论值为0.20 m；2009年地下水位下降理论值为1.34 m（表1）。

表 1　大兴区节水效果评价数据表

年份	P_i /mm	$\bar{P}$ /mm	ET /mm	μ /(m^3/m)	ET_o /mm	ΔH_T /m	ΔH_p /m	ET_v	ΔH_v
2007	532.0		568.3			−0.19	−0.52	−1	−1
2008	559.1	545	511.0	0.07	542	0.20	0.68	1	1
2009	451.5		499.9			−1.34	−0.69	1	1

4.2　监测指标结果

利用ETWatch系统计算的大兴区2007年—2009年的年实际蒸散量平均值分别为：568.3 mm、511 mm和499.9 mm。

根据式（4）计算的大兴区2007年—2009年的地下水位实际变幅分别是−0.52 m、0.68 m和−0.69 m。这说明大兴区2007年地下水位实际下降了0.52 m；2008年地下水位实际上升了0.68 m；2009年地下水位实际下降了0.69 m（表1）。

4.3　评价结果分析

根据式（5）和式（6）计算得出，大兴区2007年—2009年的蒸散量评价值ET_v和地下水位变幅评价值ΔH_v分别为–1、1、1和–1、1、1（表1）。

蒸散量和地下水位变幅评价结果表明：大兴区2007年的水资源净耗水量（即实际蒸散量）超过该区最大耗水限额（即目标蒸散量），而且地下水水位的实际降幅大于理论降幅，说明地下水的开采量大于回补量，从而造成供水亏缺以及地下水资源亏损；2008年的水资源净耗水量（实际蒸散量）小于该区最大耗水限额（即目标蒸散量），且地下水水位实际升幅大于理论升幅，说明地下水的开采量小于回补量，这将形成该区域供水盈余和地下水回补的良好局面；2009年的水资源净耗水量（实际蒸散量）小于该区最大耗水限额（即目标蒸散量），地下水水位的实际降幅小于理论降幅，这将使该区域供水盈余，地下水位虽然也会下降，但下降的速度将减缓。

根据北京市2007年—2009年的水资源公报数据，大兴区2007年地下水位下降0.4 m，2008年地下水位上升了0.3 m，2009年地下水位下降0.33 m。这表明评价结果与地下水观测井的监测结果基本吻合。

5　结　论

从耗水控制和地下水持续利用的角度出发，提出了以目标蒸散量和地下水位理论变幅为评价基准指标，利用遥感监测区域实际蒸散量和地下水位实际变幅，采用基准比较法评价区域综合节水效果的方法；并以北京市大兴区为研究区，开展了该区域的综合节水效果遥感评价。应用结果表明：

（1）以反映耗水控制水平的目标蒸散量和反映地下水持续利用水平的地下水位理论变幅为评价基准指标，利用遥感监测实际蒸散量和地下水位实际变幅，采用基准比较法评价区域综合节水效果的方法是可行的，遥感的评价结果与实际监测结果基本吻合。

（2）大兴区2007年的综合节水效果较差，造成水资源亏缺和地下水超采，不利于水资源持续利用；2008年和2009年的综合节水效果较好，促进了地下水回补，有利于水资源的持续利用。

本研究仍有待改进的地方：目标蒸散量是根据平水年的水资源条件确定的（秦大庸 等，2008），利用该指标评价平水年的综合节水效果较为合理，在非平水年情况下，评价结果可能存在偏差。因此，需要进一步研究在丰水年、枯水年和特枯年等不同降水频率条件下的目标蒸散量计算方法，以增加该评价方法的适用性。

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