The distribution and driving factors of irrigation water requirements in the North China Plain

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Abstract: In this study, we analyze the spatial and temporal distribution of irrigation water requirements in the North China Plain using soil water balance, precipitation, and evapotranspiration. The soil parameters are taken from 76 sites, the precipitation data is taken from 14 meteorological stations, and evapotranspiration is estimated by using the ETWatch model for the period from 2002 to 2007. We further analyze the quantitative relationships among irrigation water requirement, precipitation and the cultivated crop-area by using multiple regression correlation analysis. The results show an increase in the irrigation water requirements from the coastal to the piedmont regions of the study area. The average annual irrigation water requirements are 172 mm, 238 mm and 282 mm, respectively, in the Taihang Mountain piedmont, the middle plain, and the coastal region. The main driving factors of irrigation water requirements are precipitation and the cultivated areas of wheat and vegetables. In the study area, precipitation is inversely related to the irrigation water requirement. A high irrigation water requirement is found in counties with high cultivated areas of wheat and vegetables. Meanwhile, a low irrigation water requirement is found in counties with high cultivated areas of cotton and soybean.

Key words: North China Plain, ETWatch, evapotranspiration, irrigation water requirement, multiple regression correlation, driving factor

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1 INTRODUCTION

The maximum limiting production factor in the North China Plain (NCP), which is the most important food production zones in China, is the severe conflict between water supply and demand, driven mainly by rapid population and socio-economic growth. Particularly in Hai Basin, total average annual water resources are 41.9 billion m^3, otherwise, per-capita water availability is only 335 m^3, which is less than 1/6 of the national average and 1/24 of that of the world (Liu, 1989; Xia, 2002). Agriculture is the major water user in the area which occupies more than 70% of the available total water resources. With declining groundwater levels and a deteriorating water environment, it is vital to quantify the irrigation requirements in space and time, and to determine the driving factors of irrigation for the effective management the additional external water from the South-North Water Transfer (SNWT) project (Yang, *et al*., 2001; Jia , *et al*., 2002; Wu, *et al*., 2007). The analysis is of ultimate importance for the sustainable management of limited water resources, agricultural production and food security in both the region and the country at large.

Estimation of large-scale irrigation water requirements could be achieved via a combination of statistical analysis of cropping structures and irrigation quotas, crop growth models, the FAO-56 method, or remote sensing technology in hydrology. The FAO-56 method, which is based on reference crop evapotranspiration and crop co-efficiency, has been used widely to estimate crop water requirements (Gunston, *et al*., 1983; Chen, *et al*., 1995; Allen, *et al*., 1998; Liu, *et al*., 2003, 2005). However, the main drawback with the FAO method lies in its simplicity, and therefore, it fails to reflect adequately the specific effects of the environment on irrigation. Crop growth models such as the Clouds and the Earth's Radiant Energy System maize (CERES-maize) model (Jones, *et al*., 1986), the Environmental Policy Integrated Climate model (EPIC)(Thomson, *et al*., 2002), or the World Food Studies model (WOFOST) (Vandiepen, *et al*., 1989) also have been used (locally and internationally) to estimate

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crop water requirements. Though crop growth models run well at the field scale due to the use of a range of field-measured parameters, they are sometime intensive in terms of labor and time because they must be calibrated and validated for each different region of application.

With the rapid development, the remote sensing technology in hydrology increasingly is being used to estimate especially large-scale evapotranspiration. The Surface Energy Balance Algorithm for Land (SEBAL) model is developed by Bastiaanssen, *et al*. (1985) and provides a new way for studying distributed agricultural water consumption. Mohamed, *et al*. (2004) used SEBAL-estimated evapotranspiration in conjunction with National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) RS images to monitor water storage fluctuations in a Nile River wetland. Both SEBAL and the Surface Energy Balance System (SEBS) have been used to simulate evapotranspiration in the North China Plain (Li, *et al*., 2008; Wu, *et al*., 2008; Zhao, *et al*., 2009). In addition to the SEBAL model, other RS-based models have been used to simulate evapotranspiration. For example, Sun (2007) estimated evapotranspiration using the National Aeronautics and Space Administration (NASA) method and field-measured data from the Yucheng Comprehensive Experimental Station of Chinese Academy of Sciences. Mo (2005) used the Vegetation Interface Processes (VIP) model (driven by GIS, RS, and meteorological data) to simulate evapotranspiration of wheat and corn for the period 1951 through 2006.

Though evapotranspiration can be estimated using RS-based models, its impact on water resources is actually different from that of irrigation water requirements. Therefore, a new method for estimating irrigation water requirements is developed in this study based on the combined use of soil water balance and ETWatch-estimated evapotranspiration. The method is used to quantify the spatial and temporal distribution of irrigation water requirements in the North China Plain and to determine the factors driving the distributed irrigation pattern in the region. In this study, we provide an informed background that will assist researchers, decision-makers, and grass-root implementers with improving water resource management in the region and beyond.

2 MATERIALS AND METHODS

2.1 Study area

The study is conducted in the Hebei Plain (in northern NCP) between 114.18°E —117.48°E and 36.03°N —39.34°N. The study area has an average elevation of less than 100 m and covers a total of 84 contiguous counties.

Mainly grown in the study area are winter wheat and summer maize (in a rotational crop system). However, these crops are interspersed widely with such economic crops as vegetables, fruits, cotton, and soybeans.

2.2 Data collection

County-level data for planting and cultivated and irrigated land areas of wheat, maize, cotton, and other crops are obtained from the Statistical Yearbook of Hebei Province (2002—2007). Multiple crop indices are calculated from county-based totals of plantings and cultivated areas.

Evapotranspiration is estimated using the ETWatch model. ETWatch is an operational evapotranspiration processing chain starting from data pre-processing to application products. It utilizes spatial information on climate, soil type, land use, vegetation cover, land surface elevation and other RS-retrieved land surface parameters. The SEBAL and SEBS models are integrated components of ETWatch that facilitate the estimation of surface fluxes for clear-sky conditions. The Penman-Monteith model retrieves daily evapotranspiration via the surface resistance model, meteorological data, and RS-retrieved surface parameters. Details of the method of estimating evapotranspiration by ETWatch are documented in Wu, *et al*. (2008).

Precipitation data are obtained from the 14 weather stations in Hebei Province and are interpolated in GIS using the IDW interpolation method. Soil data used in the model are obtained from 76 sampling sites distributed across the study area. The soil properties are calculated from the soil textures (see Saxto & Rawls, 2006).

The cropped land area for 2002 through 2007 is estimated from the 1:100 000 land use maps. These maps are obtained from the Chinese Academy and Environmental Science Data Resources Center.

2.3 The irrigation water requirement model

In the study, initial soil moisture content (SW_0; mm) is taken at 60% of the soil effective moisture content (SW_h; mm), as it was difficult to measure for the various sites in 2002.

$$SW_0=0.6\times SW_h \tag{1}$$

$$SW_h=h\times(SW_c-SW_w) \tag{2}$$

where h, SW_c and SW_w represent soil thickness (mm) with a model set of 800 mm, field capacity (mm^3/mm^3), and wilting coefficient (mm^3/mm^3), respectively. SW_c and SW_w are calculated from soil texture and organic matter content.

If dry-land and paddy-field areas accounted for over 90% of a pixel, then the pixel is treated as farmland. Irrigation water requirements are quantified using ETWatch-estimated evapotranspiration as follows.

$$SW_{i+1}=SW_i-\mathrm{ET}_i+P_i \tag{3}$$

where i is the i^{th} day, and SW_i, ET_i and P_i represent soil water content (mm), evapotranspiration (mm), and precipitation (mm), respectively. Since the study area (NCP) is a relatively flat terrain, the equation omits surface runoff.

Soil water content is driven by three main conditions, and when $SW_{i+1} > h\times SW_c$, then Dr_{i+1} represents leakage (mm), and the soil water content SW_{i+1} is calculated as follows.

$$Dr_{i+1}=SW_{i+1}-h\times SW_c \tag{4}$$

$$SW_{i+1}=h\times SW_c \tag{5}$$

when $(h\times SW_w+0.4\times SW_h) < SW_{i+1} < SW_c$, soil water is assumed to meet crop need, and the amounts of leakage and RIA are zero. When $SW_{i+1} < (h\times SW_w+0.4\times SW_h)$, the field needed irrigation, and RIA_{i+1} (mm) and RIA are calculated as follows.

$$RIA_{i+1}=h\times SW_c-SW_{i+1} \tag{6}$$

$$RIA=RIA+RIA_{i+1} \tag{7}$$

In this study, required irrigation amount (RIA) refers to the minimum irrigation needed to sustain current levels of agricultural production, which is quantified for the study area using the above chain of equations (Fig. 1).

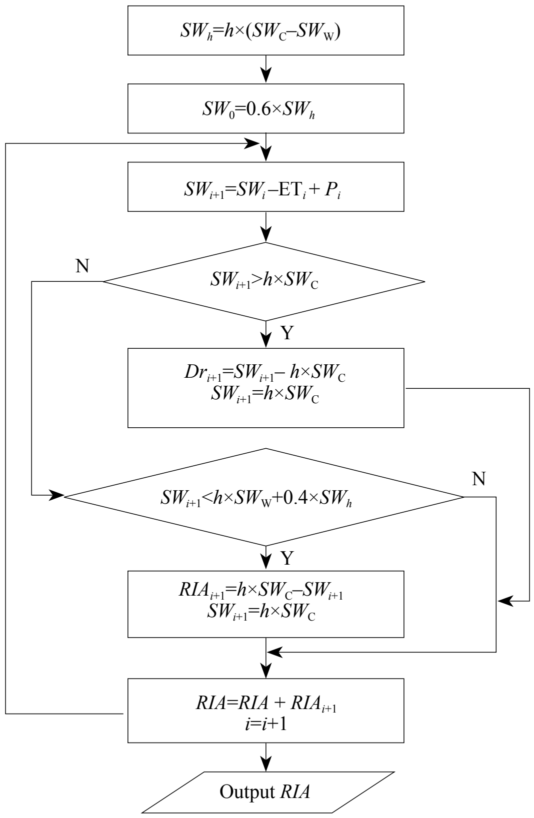

Fig. 1 A schema of irrigation requirement amount computation for the North China Plain study area

2.4 Analysis method

Whereas the evapotranspiration is estimated by the ETWatch model, the pixel/county-based irrigation water requirement is calculated by the above model and correlation coefficient analysis. Irrigation water demand and the relevant driving factors of irrigation are determined through multivariate regression and statistical analysis in Statistical Package for Social Scientists (SPSS).

3 RESULTS AND ANALYSIS

3.1 Spatial distribution of irrigation water requirements based on region

The study shows that the irrigation water requirements for the period of 2002 —2007 are high in the piedmont areas of Taihang Mountain and low in the coastal regions of the NCP. The irrigation water requirement trend gradually decreased from west to east (Fig. 2).

Annual average irrigation water requirements for the piedmont regions of Taihang Mountain, the middle plains and the coastal regions are 282 mm, 238 mm and 172 mm, respectively. The highest irrigation water requirements (300 to 450 mm) are in Xushui, Wangdu, Nanhe, Ren, and Longyao counties. The requirements are lowest (60 to 210 mm) in Huanghua, Cang, Qing, Dacheng, Wen'an, Renqiu and Hejian counties.

3.2 Yearly variation in irrigation water requirements

The range of annual irrigation water requirement in the study area is 178 mm to 308 mm (Fig. 3). A high fluctuation in annual

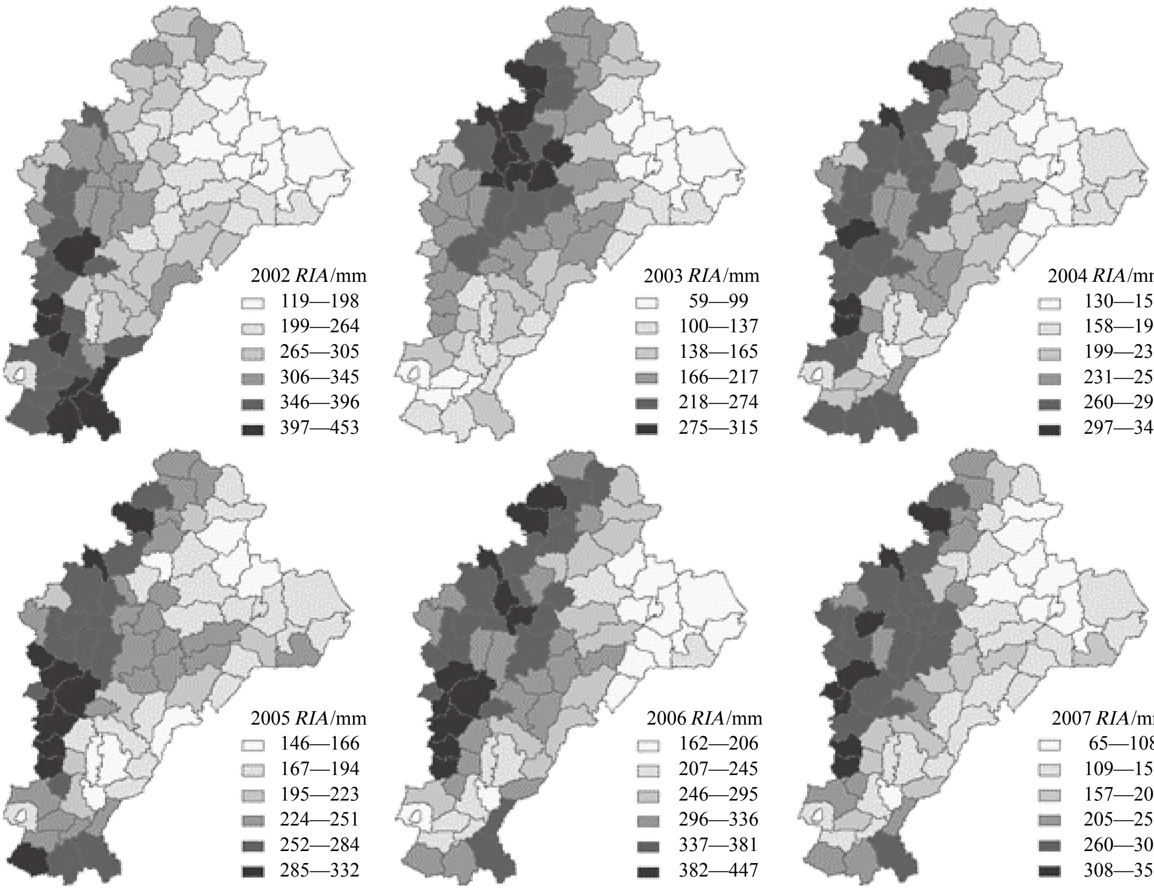

Fig. 2 Distribution of annual required irrigation amount for 2002—2007

irrigation water requirements is seen in the study area for 2002 through 2007.

For the dry years of 2002 and 2006, annual irrigation water requirements are 304 mm and 308 mm, respectively. In other years, the requirements are 177 mm to 229 mm, with an annual average of 211 mm. This shows that annual precipitation significantly influenced irrigation water requirements in the study area.

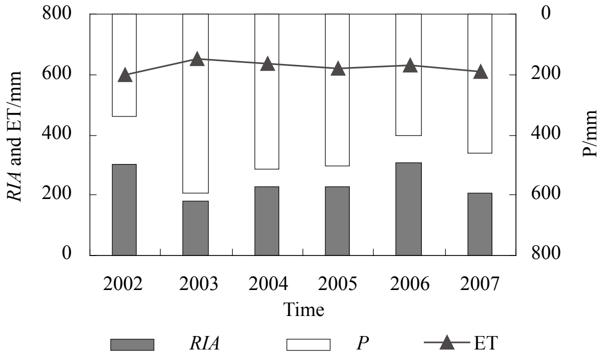

Fig. 3 Comparison of annual required irrigation amount (*RIA*), precipitation (*P*), and evapotranspiration (ET) for 2002—2007

3.3 Spatial distribution of irrigation water requirement based on basin

Table 1 Ratios of cultivated areas of wheat, corn, cotton, and vegetables to total cultivated area, along with multiple crop index (MCI) for 2002—2007 in different basins

	Wheat	Maize	Cotton	Vegetable	Soybean	MCI
eastern Daqing River Plain	0.25	0.33	0.10	0.14	0.05	1.39
western Daqing River Plain	0.33	0.32	0.03	0.13	0.01	1.62
Ziya River Plain	0.36	0.30	0.05	0.16	0.03	1.68
Heilonggang Plain	0.32	0.27	0.20	0.06	0.03	1.46

Fig. 4 shows that the annual average irrigation water requirements in front of Taihang Mountain are higher than in other areas. Annual average irrigation water requirements are 280 mm (11.7×10^8 m^3), 288 mm (22.8×10^8 m^3), 206 mm (26.5×10^8 m^3), and 195 mm (11.0×10^8 m^3), respectively, in the western Daqing River Plain, Ziya River Plain, Heilonggang Plain, and the eastern Daqing River Plain. As seen in Fig. 4 and Table 1, local cropping structure dominated the annual average irrigation water requirements in the study area.

In the Ziya River Plain, wheat planting and vegetable planting areas account for 46% of the total cultivated area, and the multiple crop index is as high as 1.62. In the western Daqing River Plain, wheat planting and vegetable planting areas account for 49% of the total cultivated area, and the multiple crop index is as high as 1.69. The annual irrigation water requirements are lowest in the eastern Daqing River Plain. The lowest annual irrigation water requirements are relative to cropping structure, which is the lower ratio (0.39) of wheat and vegetable, the highest ratio (0.33) of maize, and the lowest multiple crop index (1.39) (Table1).

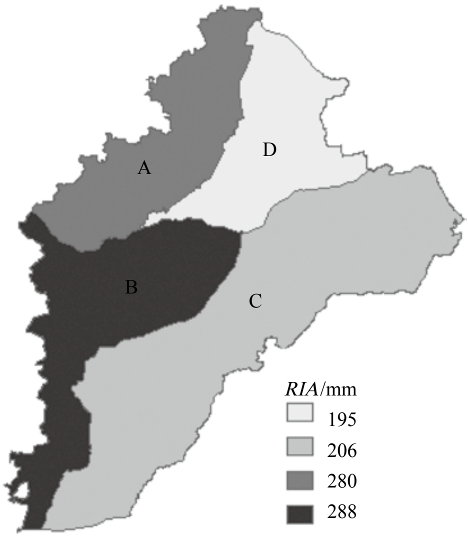

Fig. 4 Annual average irrigation water requirements in different basins (A, B, C, D respectively represent western Daqing River plain Ziya River plain Heilonggang plain eastern Daqing River plain)

3.4 The driving factors of irrigation water requirements

3.4.1 Precipitation

As seen in Fig. 3, precipitation for 2002 to 2007 is 338 mm to 596 mm. While precipitation is lowest for 2002 (338 mm), irrigation water requirements are second highest (304 mm) for that period. The highest precipitation (596 mm) in 2003, coincided with the least irrigation water requirements (178 mm).

In the study area, evapotranspiration is in the range of 597 mm to 651 mm for the period of 2002—2007 fluctuating only slightly for the entire simulation period. Generally, an inverse correlation exists between irrigation water requirements and precipitation. A similar trend exists between the spatially distributed irrigation water requirement and evapotranspiration. While the correlation trends between irrigation water requirement and precipitation are different for different counties in the study area (e.g. Zhao, Ningjin, Baixiang, Ren & Nanhe counties), irrigation is generally high for relatively high precipitation in such counties as Linzhang, Wei, and Daming. Moderate irrigation under high precipitation is found in several of the 84 counties(Fig. 5). The overall linear correlation between precipitation and irrigation water amount is $RIA = 455.08-0.45P$, where *RIA* is annual irrigation water requirement (mm) and P is precipitation.

The $F_{0.01}$ test shows the correlation between irrigation water amount and precipitation is not only significant but inverse, as well ($R^2 = -0.591$). The analysis further shows that spatial variations in irrigation water requirements in the study area cannot be explained entirely by precipitation, suggesting that some other factors influenced irrigation in the study area.

3.4.2 Cropping structure

(1) Temporal trend of cropping structure

Fig. 6 shows a gradual increase in the area of land under maize for 2002 through 2007. Whereas a slight decrease occurred in the area of land under wheat in 2003 and 2004, a rebound to the original cultivated area is observed in other years. Minimal variations are seen in the areas of land under cotton, vegetables, and soybean.

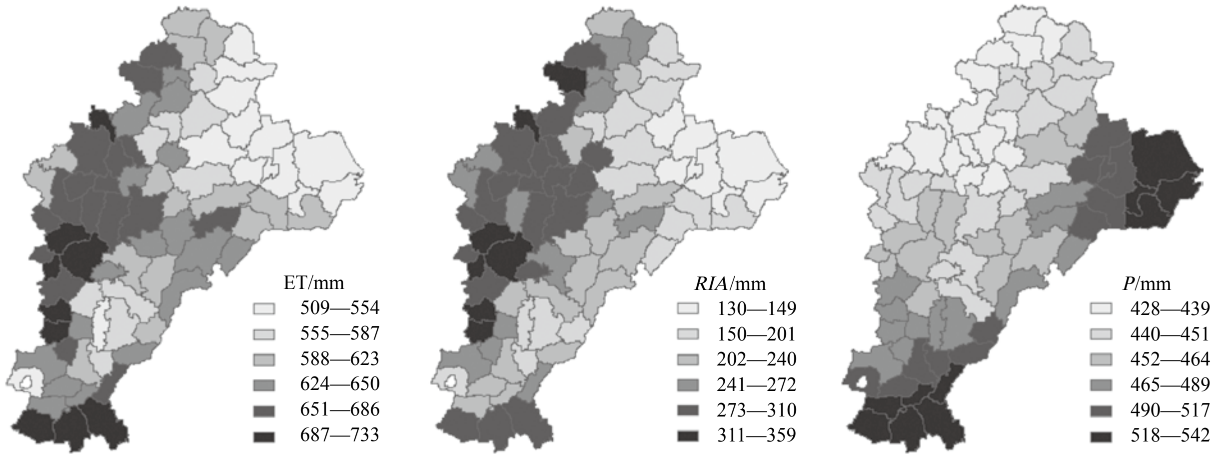

Fig. 5 Plots of distributed annual average evapotranspiration (ET), required irrigation amount (*RIA*), and precipitation (*P*)

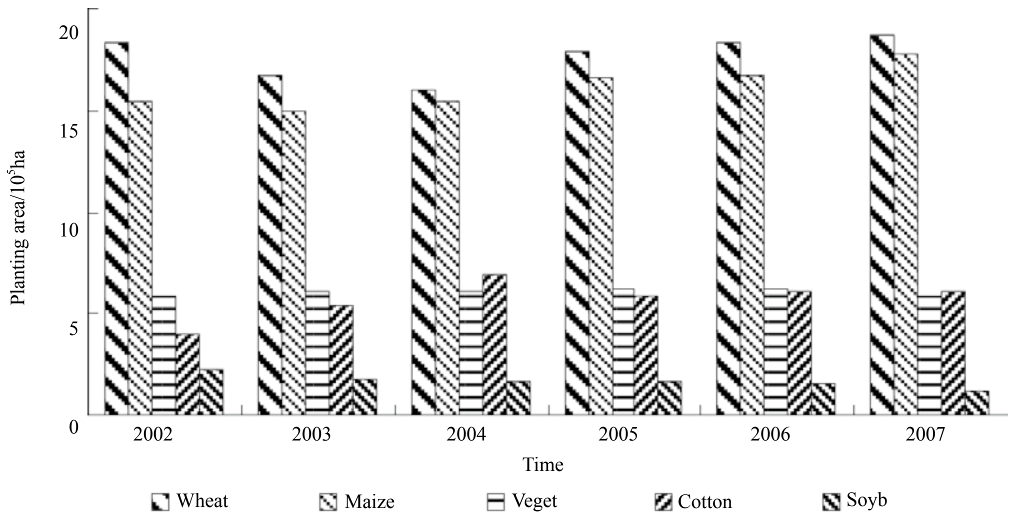

Fig. 6 Variation in cultivated areas of wheat, maize, cotton, vegetables (Veget), and soybean (Soyb) in the study area from 2002 through 2007

(2) Spatial distribution of cropping structure

Wheat dominates in counties located in ten of the piedmont plains, including Wuji, Jinzhou, Ningjin, Baixiang, Ren, Nanhe, Pingxiang, Guangping, Wei and Daming. In these counties, wheat planting area accounts for 43% to 47% of the total cultivated area. A similar spatial distribution exists for irrigation water requirements in the study area. A multi-regression equation including wheat planting area, precipitation, and irrigation water requirements is constructed as $RIA = 327.116-0.442P+238.5W$, where *RIA* is average annual irrigation water amount (mm), *P* is precipitation (mm), and *W* is wheat planting area.

In comparison with the $F_{0.01}$ test, the correlation coefficient ($R^2 = 0.751$) shows a drastic increase. This suggests that the irrigation water requirement is greatly influenced by the wheat planting area. An inverse correlation exists between maize and cotton planting areas. Counties where maize cultivation is relatively high account for 42% to 48% of the study area(Fig. 7). Most of these counties, including Rongcheng, Anxin, Xiong, Dacheng, and Botou, are in the northern region of the study area. On the contrary, counties where maize cultivation is relatively low account for 45% to 61% of the study area. Most of these counties, including Guangzong, Wei, Qiu and Nangong City, are in the southern region of the study area. The low irrigation water requirements in these counties could be explained in terms of the cropping year-to-year mode. Vegetable production takes place largely in metropolitan environs. The main cultivated crops in the northeastern region of the study area are maize, cotton, and soybean. In this same region (including Huanghua City, Cang County, Qing County, Dacheng County, Wenan County, Renqiu City and Hejian City), lower irrigation water requirements are noted. The low multiple crop index for the region is due to the year-to-year cropping mode. The spatial distribution of the high-irrigation water requirement regions is in agreement with that of the high-multiple crop index. This is mainly in the piedmont plains where the winter wheat with summer corn double cropping mode is prevalent.

(3) Driving factors

Precipitation strongly influences irrigation. To illustrate the influence of the various driving factors of irrigation water requirement, the simulation period is subdivided into three different periods: dry period (2002 and 2006), normal period (2003, 2004, 2005 and 2007), and the entire period (2002—2007). A stepwise regression relation among irrigation water requirements, cultivated area (for wheat, maize, soybean, cotton, vegetables, oil crops and rice), and precipitation is developed for the three sub-

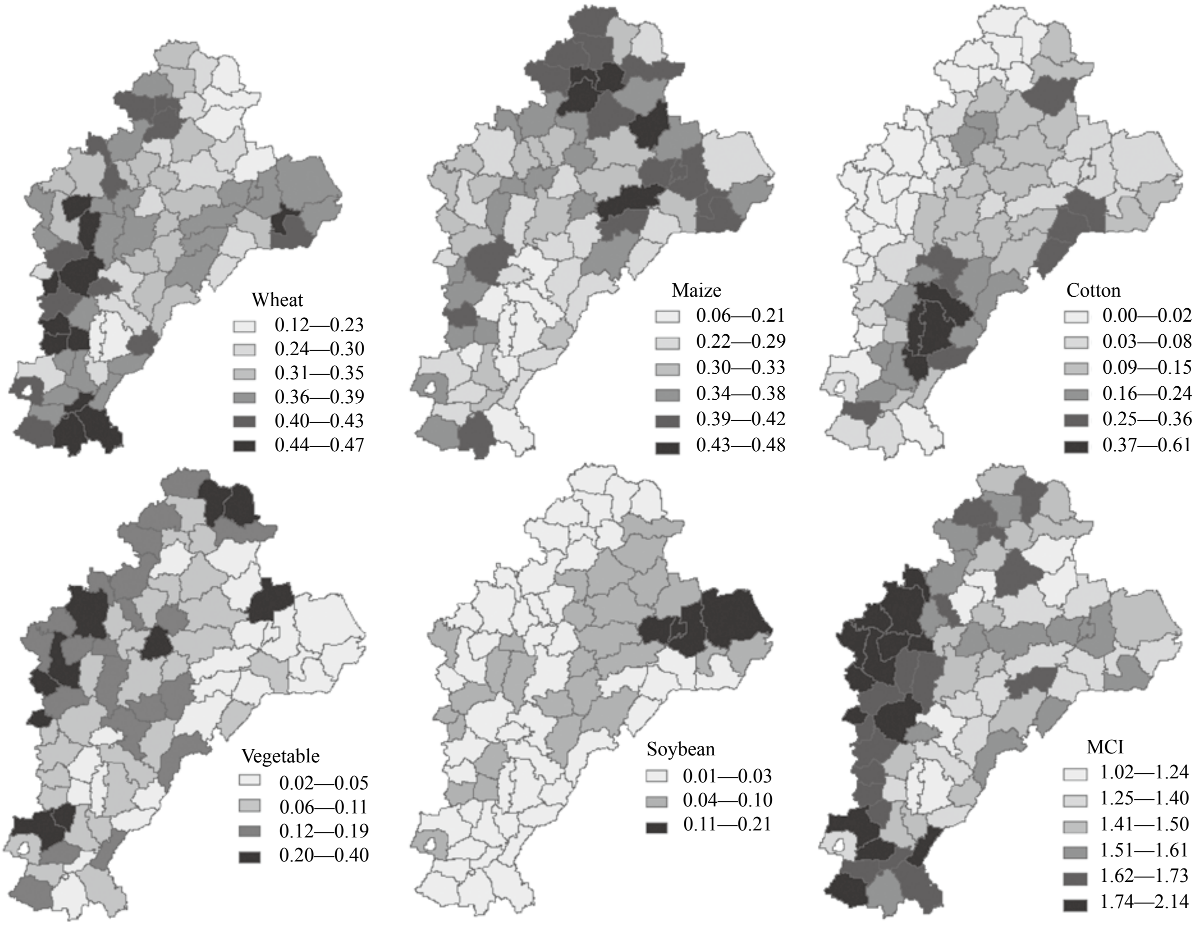

Fig. 7 Ratios of cultivated areas of wheat, corn, cotton, and vegetables to total cultivated area, along with multiple crop index (MCI) for the period of 2002—2007

periods.

The results of the regression analysis indicate a significant positive correlation between irrigation water requirements and planting areas of both wheat and vegetables under normal periods (Table 2). On the other hand, a negative correlation is found among irrigation water requirements, precipitation, and planting areas of cotton, soybean and maize. The planting areas of wheat and vegetables significantly influence irrigation water requirements, as these crops require high irrigation. As most of the other crops are under a single-cropping system, they generally require less irrigation.

Two possible explanations exist for the negative correlation between irrigation water requirement and the planting area of maize. One reason is the large overlapping planting area between maize and wheat, and another is the single cropping practiced in the eastern plain region. For the dry period, the influence of the various factors on irrigation water requirement is similar to that of the normal period. However, an insignificant negative correlation is found between irrigation water requirements and cotton planting area. The probable reason is the high cotton irrigation water requirements during dry periods. The degree of influence (standard coefficient) of various factors on irrigation water requirements differed from year to year. Based on the standard regression coefficient for normal periods, it can be seen that the degree of the influence on irrigation water requirement declines in the listed order: the wheat planting area, cotton planting area, precipitation, maize planting area, soybean planting area and the vegetable planting area. During the dry periods, the degree of influence declines in the listed order: wheat planting area, precipitation, soybean planting area, and maize planting area.

Table 3 shows the measures of the identified driving factors of irrigation water requirements and the correlations among the factors. Based on the correlations among the irrigation water requirements and the various driving factors, significant positive correlations are found among irrigation water requirements, planting areas of wheat, maize, vegetables, and multi-cropping index, which are 0.482, 0.261, 0.237 and 0.434, respectively. The positive correlation between irrigation water requirements and maize planting area is driven by the high correlation between the planting areas of maize and wheat. The main cropping mode is the winter wheat and summer maize rotation system, and the correlation coefficient between the planting areas wheat and maize is as high as 0.616. The correlation coefficient between wheat planting area and multi-cropping index is also as high as 0.772. The correlation between irrigation water requirements and maize planting area indicates an increasing influence of multi-cropping index on irrigation water requirements.

Multi-regression analysis shows a negative correlation between maize planting area and irrigation water requirements (Table 2).

Table 2 Results of multi-regression analysis of the effect of the driving factors of irrigation on required irrigation amount

Dependent Variable		Regression Equation and Standard Coefficient	Adjusted Determination Coefficient	Significance	Sample Number
RIA_1(W、P、S、M、V)	Equation	RIA_1=390W −0.50P−561S −123M+79V +353	0.637	0.000	156
	Sc	W:0.752 P:−0.429 S:−0.311 M:−0.231 V:0.164			
RIA_2(W、P、V、C、S、M)	Equation	RIA_2=190W −0.28P+35V−147C −376S −115M+347	0.517	0.000	312
	Sc	W:0.479 P:−0.368 V:0.079 C:−0.369 S:−0.203 M:−0.248			
RIA_3(P、W、S、V、M、C)	Equation	RIA_3=−0.43P+260W−417S +44.528V−139M−109C+401	0.630	0.000	468
	Sc	P:−0.555 W:0.506 S:−0.191 V:−0.082 M:−0.240 C:−0.215			

ps: sc: standard coefficient, driving factors P, W, V, S, M, C represent precipitation and planting areas of wheat, vegetables, soybeans, corn, and cotton.

Highly significant negative correlations are noted among the planting areas of soybean and cotton and irrigation water requirements, which are −0.162 and −0.348, respectively. Two reasons are found for the negative correlation. One reason is that soybeans and cotton are grown during the rainy season (during which irrigation water requirements are lowest) and are harvested in autumn. Another is increased planting areas of soybeans and cotton along with decreased planting areas of wheat and vegetables (which are water-intensive crops). This is very much supported by Fig. 3 and Fig. 4. Except for very dry periods, irrigation water amounts are low for Nangong, Guangzong, Wei and Qiu counties, where cotton planting areas are relatively large.

Table 3 Results of correlation analysis of required irrigation amount and planting area of crops and crop indices

Variable	Wheat	Maize	Soybean	Cotton	Vegetable	Crop index	RIA
Wheat	1						
Maize	0.616**	1					
Soybean	−0.002	0.048	1				
Cotton	−0.463**	−0.658**	−0.273**	1			
Vegetable	0.081	0.134**	−0.159**	−0.331**	1		
Crop index	0.772**	0.560**	−0.071	−0.431**	0.545**	1	
RIA	0.482**	0.261**	−0.162**	−0.348**	0.237**	0.434**	1

** Highly significant reached 0.01.

4 CONCLUSIONS

In this study, the spatial and temporal distributions of irrigation water requirements are calculated using the ETWatch-driven irrigation water requirement model. Next, the driving factors of irrigation are analyzed via such statistical methods as multi-regression and partial regression analysis.

A decreasing tendency of irrigation water requirements is noted from the western to the eastern regions of the study area. Irrigation water requirements are high in the piedmont regions of Taihang Mountain and low in the coastal areas. The annual average irrigation water requirements in the piedmont regions of Taihang Mountain, the middle plains, and the coastal areas are 282 mm, 238 mm and 172 mm, respectively. The annual irrigation water requirements ranged from 177 mm to 308 mm, with a large year-to-year fluctuation. During 2002 and 2006, when precipitation is low, the average irrigation water requirement was 211 mm. For all the other years in the study area, the average was 306 mm.

The main driving factors of irrigation water requirements are precipitation and the cultivated areas of wheat and vegetables. Precipitation is negatively related to irrigation requirements. Higher irrigation water requirements are found in counties with relatively high cultivated areas of wheat and vegetables. On the other hand, counties with relatively high cultivated areas of cotton and soybean had low irrigation requirements.

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华北平原灌溉需水量时空分布及驱动因素

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摘　要：采用华北平原14个气象站点2002年—2007年的降水资料、76个站点的0—80 cm厚度的土壤参数以及ETWatch系统计算的蒸散发量数据，运用水分平衡原理计算了灌溉需水量的空间分布；利用相关及多元逐步回归分析方法，定量分析了研究区灌溉需水量的主要驱动因素。结果表明：从山前平原到滨海平原，多年平均灌溉需水量分别为282 mm（36.1×10^8 m^3）、238 mm（37.2×10^8 m^3）和172 mm（9.3×10^8 m^3），有逐渐降低的趋势。降雨量、小麦和蔬菜种植面积是影响灌溉需水量的主要驱动因子，降雨量多的年份灌溉需水量显著减少，小麦和蔬菜种植面积较多的区域灌溉需水量较高，而棉花和大豆种植面积较大的区域灌溉需水量较少。

关键词：华北平原，ETWatch，蒸散发，灌溉需水量，多元逐步回归，驱动因子

中图分类号：TP79/S127　　**文献标志码**：A

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1 引　言

华北平原是中国重要的农业生产基地，同时是中国水资源供需矛盾十分突出的地区。特别是北部的海河流域，多年平均水资源总量419×10^8 m^3，人均水资源占有量仅为335 m^3，不足全国的1/6，世界的1/24（刘昌明，1989；夏军，2002）。灌溉用水在该区耗水量最大，占用水总量的70%以上。在地下水位下降严重、水环境恶化和南水北调工程输水的形势下（杨永辉 等，2001；贾金生和刘昌明，2002；吴光红 等，2007），如何量化灌溉需水量，分析灌溉需水量的时空变化特点，并找出影响灌溉水空间分布的驱动因素，对保证该区域水资源安全、农业可持续发展以及保障中国粮食安全具有重要意义（高占义和王浩，2008）。

农田需水量的估算方法主要有传统的基于作物种植结构和灌溉定额的农业统计法、FAO法、作物模型法和遥感法等。FAO法（FAO Irrigation and Drainage paper 56）是通过参照腾发量和作物系数的乘积来估算作物需水量，这种方法的优点是简单实用，曾被许多学者用来估算当地的农田蒸散量（Allen 等，1998；陈玉民 等，1995；Gunston和Batchelor，1983；Liu 等，2003，2005）。缺点是机理过于简单，仅一个作物系数不足以反映作物具体栽培环境对耗水的影响。国内外研究者利用作物模型如CERES（Clouds and the Earth’s Radiant Energy System）模型（Jones和Kiniry，1986）、EPIC（Environmental Policy Integrated Climate）（Thomson 等，2002）、WOFOST（World Food Studies）模型（Vandiepen 等，1989）模拟农田需水量，取得了很好的研究结果。但作物模型是基于站点的模型，在小范围的大田尺度运行良好，在较大区域上的应

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用存在一定缺陷，如空间上参数的获取和区域上的验证等。

随着遥感技术的发展，利用遥感技术估算区域蒸散量得到广泛应用。Bastiaanssen等人（1998a，1998b）开发的SEBAL模型为研究区域农业耗水的空间分布提供了可能。Mohamed等人（2004）根据SEBAL模型，采用NOAA/AVHRR遥感影像研究了尼罗河上游湿地的蒸发和蓄水变化；许多学者利用SEBS或SEBAL模型模拟了华北平原的蒸散量（Li等，2008；吴炳方 等，2008；赵静 等，2009）。除SEBAL模型外，其他遥感模型也在华北平原有广泛的应用，如Sun等人（2007）利用中国科学院禹城综合实验站的蒸散实测数据，提出了在NASA方法上提高MODIS16产品估算蒸散精度的方法。莫兴国等（2005）在GIS、RS和气象数据的基础上建立了VIP（Vegetation Interface Processes model）模型，模拟了华北平原小麦玉米1951年—2006年间的蒸散发量。上述遥感模型的主要输出结果都是蒸散发，这与水资源研究的灌溉用水或者灌溉需水有一定差异，因此，本文在吴炳方等（2008）开发的ETWatch系统的基础上，探讨了根据土壤水分平衡原理，由区域蒸散发量计算农业灌溉需水的方法；在此基础上分析了灌溉需水量时空分布的主要驱动因素，目的是为区域水资源管理决策提供参考。

2 资料与方法

2.1 研究区概况

研究区为华北平原北部的河北平原，包括区域内海拔低于100 m的78个县市。经度范围为114.18° E—117.48° E，纬度范围为36.03° N—39.34° N。冬小麦-夏玉米一年两熟是该区域的主要的种植模式，蔬菜、林果、棉花和大豆是该区主要的经济作物。

2.2 数据来源

各种作物的种植面积、耕地面积和有效灌溉面积等数据由《河北农村统计年鉴》（2002年—2007年）获得，复种指数根据各县的总播种面积和耕地面积计算得到。

蒸散发量数据由ETWatch系统生成，时间分辨率为日，空间分辨率为1000 m，时间为2002年—2007年。ETWatch系统是以Penman-Monteith公式为基础建立的下垫面表面阻抗估算方法，利用逐日气象数据与遥感反演参数，采用能量平衡余项法获得连续的蒸散量，详细介绍参见文献吴炳方等（2008）。

降水量数据：利用河北省14个气象站的降雨量数据进行IDW插值，得到整个研究区的降雨量。

土壤数据：根据76个土壤测站的土壤质地测定数据、有机质含量数据计算土壤饱和含水量、田间持水量和萎蔫系数等（Saxton 和 Rawls，2006）。

土地利用数据：由于农田面积变化不大，因此利用2000年1：100000土地利用图来估算2002年—2007年的农田面积。此数据由中国科学院资源环境科学数据中心提供。

2.3 算法

土壤初始含水量的计算：由于2002年各站点的初始土壤含水量（SW_0）数据难以获得，故设土壤含水量的初始值为土壤有效含水量（SW_h）的60%。

$$SW_0=0.6\times SW_h \tag{1}$$

$$SW_h=h\times(SW_c-SW_w) \tag{2}$$

式中，h为土层厚度（模型中设为800 mm），SW_c为田间持水量，SW_w为萎蔫系数，根据土壤质地和有机质数据计算得到。

将所有旱地和水田面积所占比例大于90%（0.9 km^2）的像元设为农田。灌溉需水量根据ETWatch中的农田蒸散量（ET）计算。首先计算土壤含水量：

$$SW_{i+1}=SW_i-\mathrm{ET}_i+P_i \tag{3}$$

所有变量中下标i表示i天；SW_i为土壤含水量；ET_i为蒸散量；P_i为降水量；由于华北平原地势较平坦，假设地表径流为零，即公式中忽略地表径流项。

模型将根据土壤含水量的3种情况进行判断，当$SW_i>h\times SW_c$时，渗漏量Dr_{i+1}和土壤含水量SW_{i+1}为：

$$Dr_{i+1}=SW_{i+1}-h\times SW_c \tag{4}$$

$$SW_{i+1}=h\times SW_c \tag{5}$$

当（$h\times SW_w+0.4\times SW_h$）< SW_{i+1}< SW_c时，土壤水能满足农作物需要，无渗漏量无需灌溉；当SW_{i+1}<（$h\times SW_w+0.4\times SW_h$）时，农田需要灌溉$RIA_{i+1}$为：

$$RIA_{i+1}=h\times SW_c-SW_{i+1} \tag{6}$$

$$RIA=RIA+RIA_{i+1} \tag{7}$$

RIA为灌溉需水量，根据上述原理，依次在计算时期内循环，具体计算流程如图1：

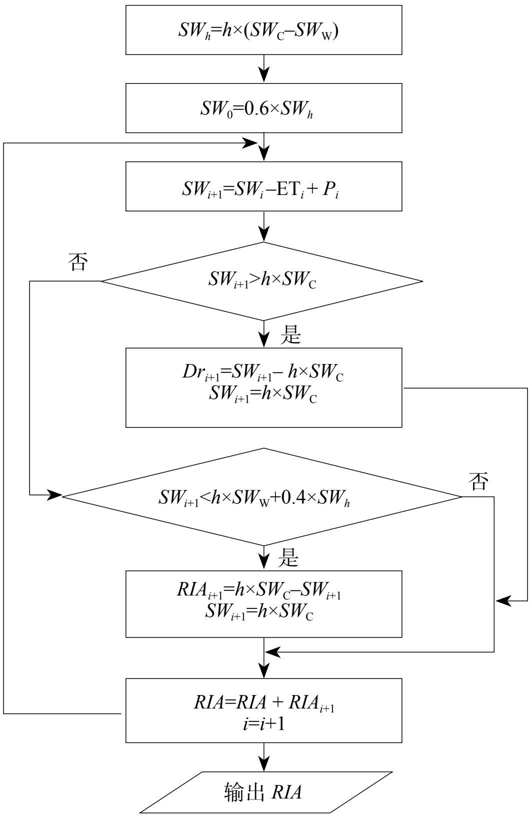

图1 灌溉需水量计算流程图

2.4 分析方法

本文由ETWatch获得蒸散数据，通过模型进一步计算研究区各像元和各县（市）灌溉需水量。利用SPSS for Windows软件进行多元统计分析获得统计数据的相关系数以及灌溉需水量与相关驱动因子的逐步回归统计结果。

3 结果与分析

3.1 灌溉需水量空间分布

通过对2002年—2007年灌溉需水量的分析发现：华北平原山前平原一带灌溉需水量较高；滨海及东部区域灌溉需水量低，灌溉需水量由西向东呈逐渐降低的趋势（图2）。山前平原区、中部平原和滨海区多年平均灌溉需水量分别为282 mm（36.1×10^8 m^3）、238 mm（37.2×10^8 m^3）和172 mm（9.3×10^8 m^3）。6年中，灌溉需水量最高的5个县市分别为徐水县、望都县、南和县、任县和隆尧县，灌溉需水量为300—450 mm，灌溉需水量较低的县为黄骅市、沧县、青县、大城县、文安县、任丘市及河间市，灌溉

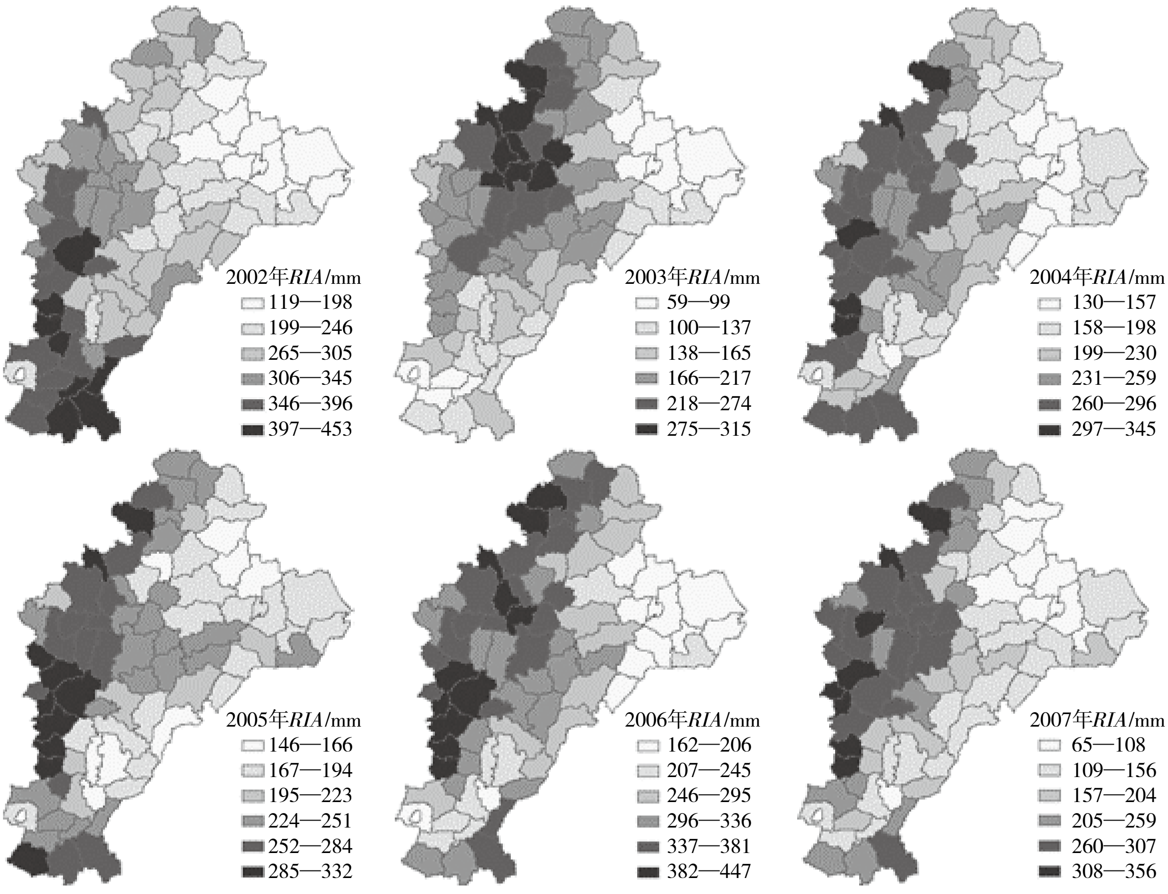

图2 2002年—2007年灌溉需水量的空间分布

需水量为60—210 mm。

3.2 灌溉需水量年际间变化

研究区年平均灌溉需水量在178—308 mm（58.4×10^8—98.8×10^8 m^3）之间（图3）。灌溉需水量年际间波动较大，在枯水年份2002年和2006年，年均灌溉需水量分别为304 mm（95.8×10^8 m^3）和308 mm（98.8×10^8 m^3）；在其他年份灌溉需水量在177—229 mm之间，平均值为211 mm（67.3×10^8 m^3）。说明年际间降雨量变化影响灌溉需水量。

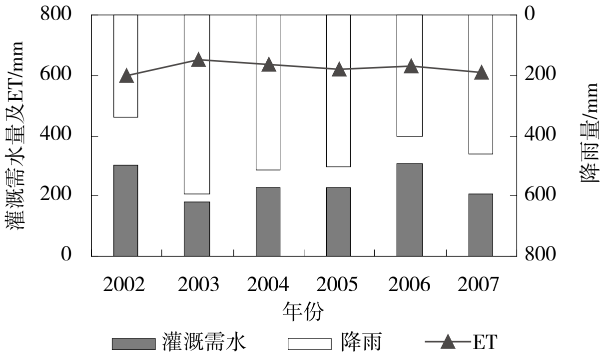

图3　不同年份年均灌溉需水量、降雨量和蒸散发量的比较（2002年—2007年）

3.3 灌溉需水量的空间格局

表1　各流域作物种植面积占总种植面积的比例及复种指数

平原	小麦	玉米	棉花	蔬菜	大豆	复种指数
大清河淀东	0.25	0.33	0.10	0.14	0.05	1.39
大清河淀西	0.33	0.32	0.03	0.13	0.01	1.62
子牙河	0.36	0.30	0.05	0.16	0.03	1.68
黑龙港及运东	0.32	0.27	0.20	0.06	0.03	1.46

由图4知，山前区域灌溉需水量较高。大清河淀西平原、子牙河平原、黑龙港及运东平原和大清河淀东平原多年平均灌溉需水量分别为280 mm（11.7×10^8 m^3）、288 mm（22.8×10^8 m^3）、206 mm（26.5×10^8 m^3）和195 mm（11.0×10^8 m^3）。通过图4与表1分析，各流域的灌溉需水量与当地的种植结构有关。子牙河平原与大清河淀西平原的灌溉需水量较另外两个流域高，其高耗水作物小麦和蔬菜种植面积比例分别高达0.46和0.49，复种指数也高达1.62和1.69。大清河淀东平原年均灌溉需水量最低，该区高耗水作物小麦和蔬菜种植面积比例较低，为0.39；流域内相对耗水较低作物玉米种植比例最高，为0.33；复种指数最低，仅为1.39（表1）。

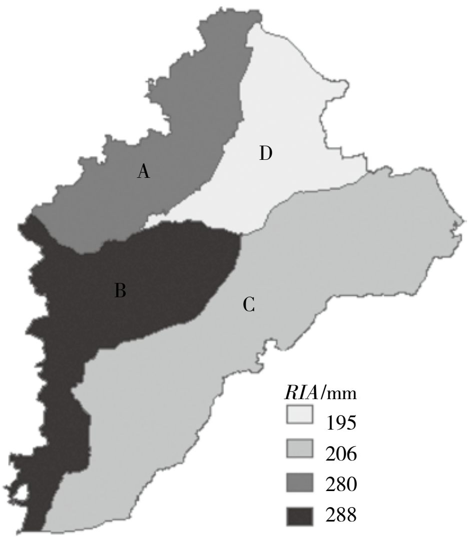

图4　各流域年平均灌溉需水量（A、B、C、D分别代表大清河淀西平原、子牙河平原、黑龙港及运东平原和大清河淀东平原）

3.4 灌溉需水量驱动因素分析

3.4.1 降水影响

由图3可知，2002年—2007年期间年均降雨量为338—596 mm，其中2002年为6年中降水最少的年份，年均降雨量仅为338 mm，灌溉需水量高达304 mm；2003年年均降雨量为596 mm，为降雨量最多的年份，灌溉需水量仅为178 mm。蒸散发量在597—651 mm之间，各年间基本持平，并没有显著性的变化。灌溉需水量与降雨量形成此消彼长的趋势。在空间上，灌溉需水量与蒸散发量变化趋势一致。灌溉需水量与降雨量变化趋势有一定差异性，在赵县、宁晋县、柏乡县、任县和南和县灌溉需水量最多，降雨量并不是最少；临漳县、魏县和大名县灌溉需水量较多，降雨量最多（图5）。降水量与灌溉需水量之间线性相关关系如式（8）：

$$RIA=455.08-0.45P \tag{8}$$

式中，RIA为年均灌溉需水量，P为降水量。对式（8）进行F0.01检验表明，灌溉需水量与降雨量之间呈显著负相关，其可决系数为0.591。同时表明，降雨量不能完全反映空间上灌溉需水量的变化，需考虑多重因子对灌溉需水量的影响。

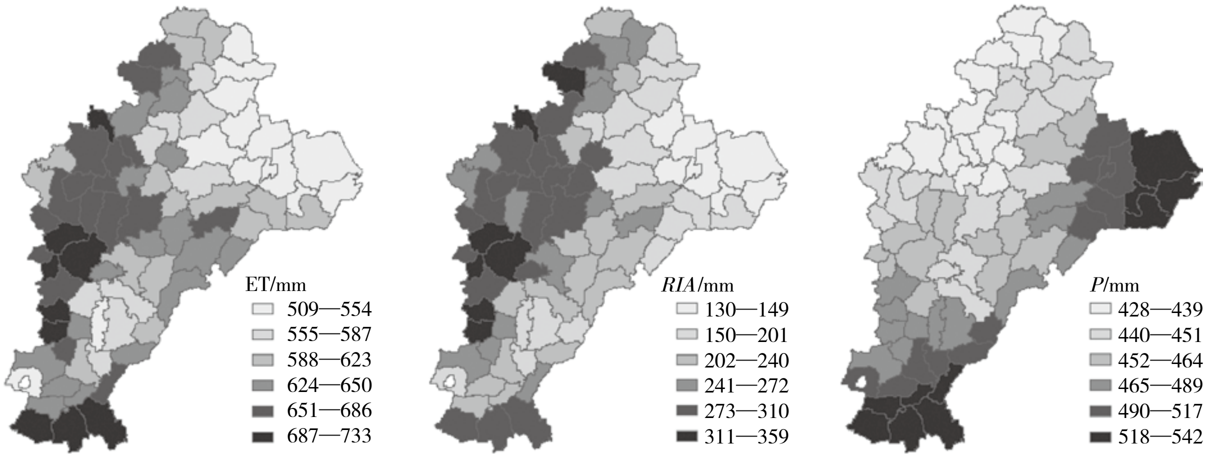

图 5 多年平均蒸散发量（ET），灌溉需水量（RIA）和降雨量（P）

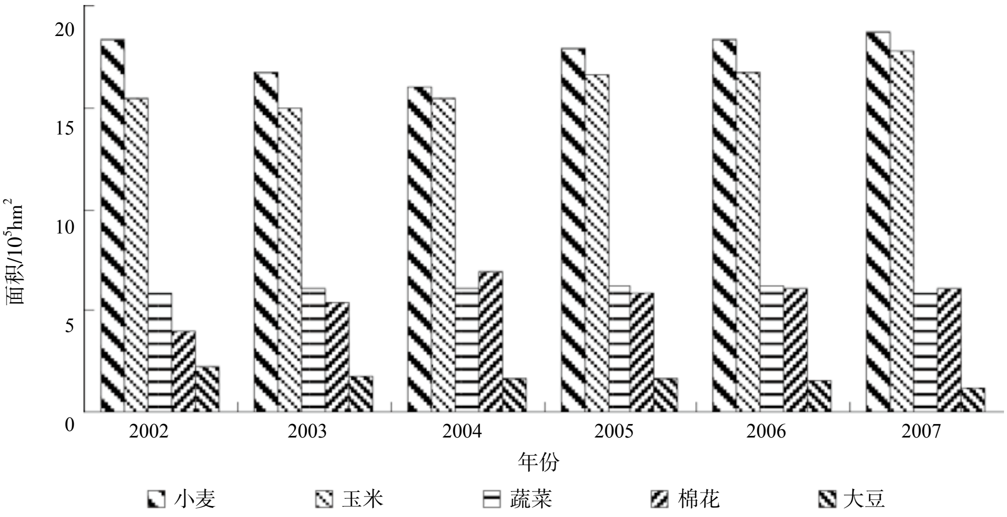

图6 2002年—2007年作物种植面积图

3.4.2 农作物种植结构的影响

（1）作物种植结构年际间变化

由图6可以看出，在2002年—2007年，玉米播种面积呈缓慢增加的趋势，小麦播种面积除2003年和2004年略有下降外，其他年份变化不大。棉花、蔬菜和大豆的播种面积在此期间变化也不大。

（2）作物种植结构的空间分布

小麦种植面积较多的县集中在太行山山前平原区，其中太行山沿线无极县、晋州市、宁晋县、柏乡县、任县、南和县、平乡县、广平县、魏县和大名县小麦播种面积占农作物总播种面积的0.43—0.47。这与图2历年来灌溉需水量较多的县吻合较好。通过对2002年—2007年小麦种植面积，降雨量和灌溉需水量进行多元回归得到如下方程：

$$RIA = 327.116 - 0.442P + 238.5W \tag{9}$$

式中，RIA为年均灌溉需水量，P为降水量，W为小麦种植面积。该公式通过F0.01检验，与式（8）比较，可决系数骤然增到0.751，说明小麦的种植面积对灌溉需水量的影响较大。

玉米与棉花的种植在区域上呈现互补性，玉米种植面积较多的县多集中在研究区北部的榕城县、安新县、雄县、大城县和泊头市，占总播种面积的比例在0.42—0.48之间（图7）。相反，玉米种植面积较少的县（即棉花种植较多的地方）多集中在邢台地区的南宫市、广宗县、威县和邱县（0.45—0.61），这些区域对应的年灌溉需水量较少，这与棉花种植区一年一作较为节水的方式相关；蔬菜种植面积大的区域多分布在大城市周边；研究区域的东北地区主要种植玉米、棉花和大豆，复种指数较低，一年一作比较普遍，这与图2、图5灌溉需水量较低的黄骅市、沧县、青县、大城县和文安县任丘市及河间市吻合；山前平原区复种指数高，小麦玉米一年二作比较普遍，与灌

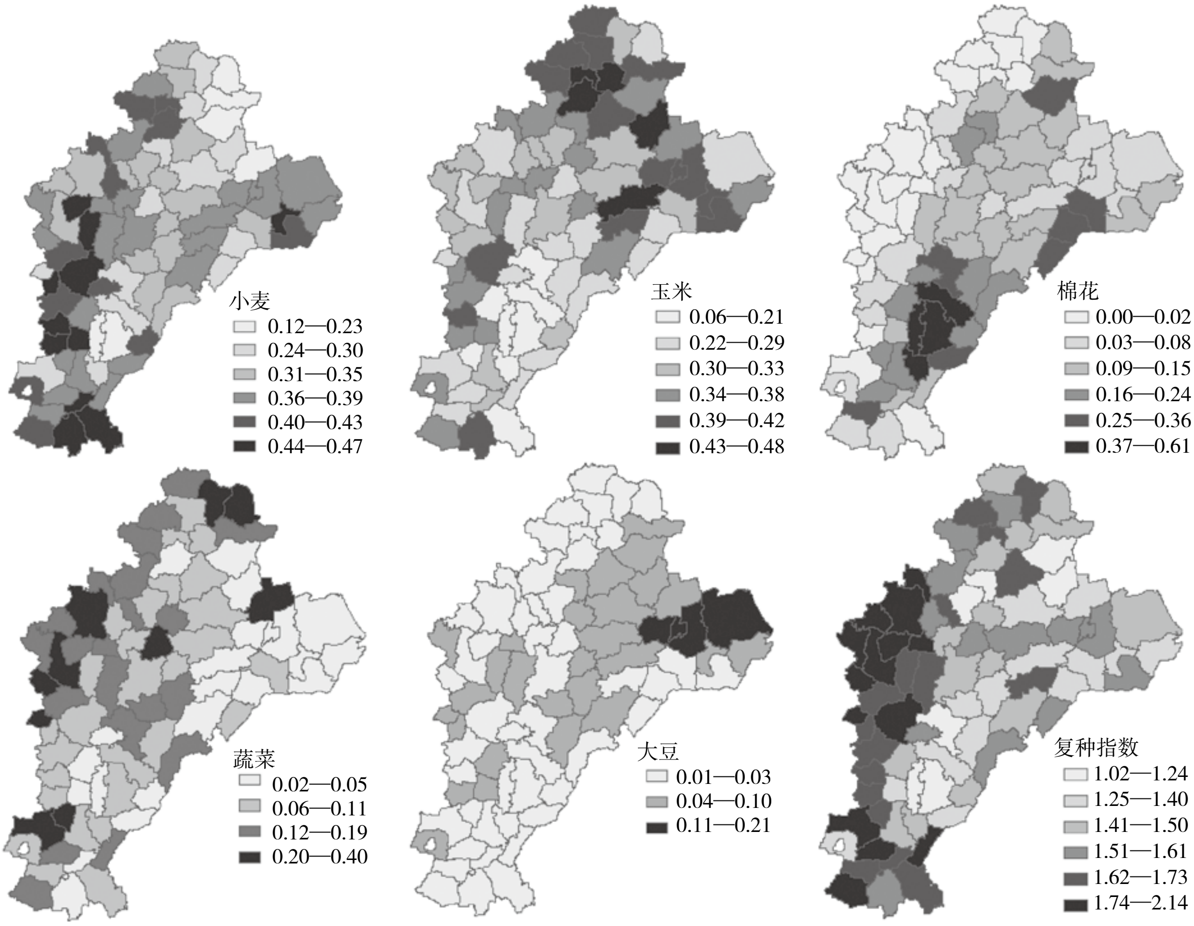

图7 各县作物种植面积占总种植面积的比例及复种指数分布图(2002年—2007年)

溉需水量高值区域相吻合。

（3）驱动因素分析

鉴于自然降水对灌溉需水影响较大，为进一步明晰各因子对灌溉需水的影响程度，将研究期内各年度分为降水较少的2002年和2006 年（RIA_1）类、正常降水的2003年、2004年、2005年和2007年（RIA_2）类和所有年型即2002年—2007年（RIA_3）类，对灌溉需水量和小麦、玉米、大豆、棉花、蔬菜、油料作物、水稻种植面积以及降雨量各因子的影响（由于复种指数受当地热量、土壤、水利、肥料、劳力和科学技术水平等条件的综合影响且复种指数是由农作物种植面积相加得到的，故未引入回归方程）进行逐步回归。

逐步回归结果表明（表2），在正常年份，小麦和蔬菜的种植面积对灌溉需水量都是极显著的正相关关系，而棉花、大豆、玉米种植面积和降雨量呈负相关关系，表明小麦和蔬菜是灌溉需水较多的作物，对灌溉需水影响明显，其他大部分作物由于为一年一作，灌溉量明显减少。玉米与灌溉需水呈负相关，一方面是因为它本身与小麦种植面积重合较多，另一方面是在东部平原地区有一定的一年一作玉米。在少雨年份，各因素对灌溉需水的影响与正常年份基本一致，但棉花对灌溉需水负作用变的不显著，这与少雨年份棉花需要的灌溉量也比较大有关。各驱动因子对灌溉需水量的贡献率（标准系数）在不同年份有所不同。从降雨正常年份（RIA_2）的回归方程标准系数来看，各因子对灌溉需水的贡献率从大到小依次为小麦种植面积、棉花种植面积、降雨量、玉米种植面积、大豆种植面积和蔬菜种植面积。而在少雨年份，贡献率从大到小依次为小麦种植面积、降雨量、大豆种植面积和玉米种植面积。

表3显示各驱动因子单独对灌溉需水的影响，以及各因子之间的相关关系，灌溉需水量与各驱动因素的相关关系可以看出，灌溉需水量和小麦、玉米、蔬菜的种植面积和复种指数呈极显著的正相关关系，相关系数分别为0.482、0.261、0.237和0.434。灌溉需水量和玉米呈正相关关系的原因是玉米和小麦播种面积的高相关性。冬小麦-夏玉米轮作是本研究区域主要的种植制度，玉米与小麦的相关系数达到0.616，与

表 2 灌溉需水量（*RIA*）与驱动因子的多元回归关系

因变量及入选因子		回归方程及因子标准系数	调整的决定系数	显著性	样本数
RIA_1(*W*、*P*、*S*、*M*、*V*)	方程	RIA_1=390*W* −0.50*P*−561*S* −123*M*+79*V* +353	0.637	0.000	156
	标准系数	*W*:0.752 *P*:−0.429 *S*:−0.311 *M*:−0.231 *V*:0.164			
RIA_2(*W*、*P*、*V*、*C*、*S*、*M*)	方程	RIA_2=190*W* −0.28*P*+35*V*−147*C* −376*S* −115*M*+347	0.517	0.000	312
	标准系数	*W*:0.479 *P*:−0.368 *V*:0.079 *C*:−0.369 *S*:−0.203 *M*:−0.248			
RIA_3(*P*、*W*、*S*、*V*、*M*、*C*)	方程	RIA_3=−0.43*P*+260*W*−417*S* +44.528*V*−139*M*−109*C*+401	0.630	0.000	468
	标准系数	*P*:−0.555 *W*:0.506 *S*:−0.191 *V*:−0.082 *M*:−0.240 *C*:−0.215			

注：驱动因子*W*、*V*、*S*、*M*和*C*分别表示小麦、蔬菜、大豆、玉米和棉花的种植面积，*P*表示降雨量

复种指数的相关系数达到0.772。所以灌溉需水量和玉米的相关性更多地体现出复种指数的增加对灌溉水的影响。而在多元回归的情况下玉米对灌溉需水量的贡献为负值（表2）。大豆和棉花的种植面积和灌溉需水量的相关系数为负值，分别为－0.162和－0.348，且达到极显著的水平。大豆和棉花为秋收作物，主要的生长季节在雨季，需要的灌水量较少。另一方面，大豆和棉花面积的增加会相应地减少高耗水作物小麦和蔬菜的种植面积，所以大豆和棉花的种植面积与灌溉需水量呈负相关关系。这一结论在图3和图4中得到印证，除降雨特别少的年份外，种植棉花较多的4个县南宫县、广宗县、威县和邱县的灌水量较小。

表 3 灌溉需水量与各种作物种植面积以及复种指数的相关分析

	小麦	玉米	大豆	棉花	蔬菜	复种指数	灌溉需水
小麦	1						
玉米	0.616**	1					
大豆	−0.002	0.048	1				
棉花	−0.463**	−0.658**	−0.273**	1			
蔬菜	0.081	0.134**	−0.159**	−0.331**	1		
复种指数	0.772**	0.560**	−0.071	−0.431**	0.545**	1	
灌溉需水	0.482**	0.261**	−0.162**	−0.348**	0.237**	0.434**	1

** 代表达0.01极显著水平

4 结 论

本研究在遥感模型ETWatch估算的区域蒸散的基础上，建立了灌溉需水量的估算模型，分析了研究区灌溉需水量的时空分布特征，并用相关及多元逐步回归方法对影响灌溉需水量空间分布的驱动因子进行了分析。

研究区域太行山山前平原一带灌溉需水量较高；滨海及东部区域灌溉需水量低，灌溉需水量由西向东逐渐降低的趋势；山前平原区、中部平原和滨海平原多年平均灌溉需水量分别为282 mm（36.1×10^8 m^3）、238 mm（37.2×10^8 m^3）和172 mm（9.3×10^8 m^3）。

年际间灌溉需水量波动较大，在178 mm—308 mm之间，其中降雨较少的2002年与2006年平均灌溉需水量为306 mm，其他年份年均灌溉需水量为211 mm。

降雨、小麦种植面积和蔬菜种植面积是影响灌溉需水量的主要驱动因子，降雨量增多可显著减少灌溉需水量，小麦和蔬菜种植面积较多的县灌溉需水量较高，而棉花和大豆种植面积较大的区域灌溉需水量较少。

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