Exploring the relationship between irrigation water requirements and potential yield in the Huang-Huai-Hai plain

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ABSTRACT

By using the GIS technologies, we interpolate the site-based meteorological data into climatic surface data, which are the main input parameters for the CropWat model, used to estimate the reference evapotranspiration (ET_0). And then by combining the ET_0 with the information on share of cultivated land decoded from the Landsat TM/ETM digital imagines covering the entire case study area, the Huang-Huai-Hai plain, we estimate the amount of irrigation water requirements (IWRs) in the years of 1991 and 2000. We then introduce the potential yield (PY) of cultivated land estimated from the Estimation Model for the Agricultural Productivity Potential (EMAPP) to explore the relationship between the IWRs and the PY . By conducting GIS-based spatial overlay analyses, we explore the positive correlation relationship between the IWRs and the PY of cultivated land. Finally, we conclude that the IWRs is now a constrain factor on the PY of cultivated land in the Huang-Huai-Hai plain in those areas with the irrigation water constrains. The result has offered a scientific basis for the decision makings in the exploitation and utilization of resources and energy as well as the land use planning, protection of the potential yields and the managements of irrigation water at the regional level.

Key words: Reference evapotranspiration; Maximal evapotranspiration; Penman–Monteith model; CropWat model; Irrigation water requirements; Crop coefficient; Potential yield; Cultivated land; Spatial overlay analysis; Huang-Huai-Hai plain

1. INTRODUCTION

Irrigation water requirements (IWRs) is one of the most important components for regional water budget and one of the key terms and measurements for the planning and managements of water resources. It is of significance to estimate the amount and changes of IWRs especially for those areas where the conflicts of water demands and supply are serious. While the estimation of IWRs in the plot level can be done with a traditional survey inventory based approach, but for a large area of cropland, we need to implement some more advanced hydrological approaches. In common sense, the latter approach is more efficient and accurate [1]. The Penman-Monteith model presented by Monteith is in common used for calculating reference evapotranspiration (ET_0) [2-3], which is one of the key components for the estimations of IWRs.

The amount of water available for irrigation use in the Huang-Huai-Hai plain has recently become critical. The irrigation water is supplied by the Yellow River, the Huaihe River and the Haihe River in this area. The climate of Huang-Huai-Hai plain is semi-humid with an average annual rainfall varies from 500mm in the south to 800mm in the north region. However, this rainfall is distributed unevenly both temporally and spatially, and the distribution is not optimal for the growing seasons of various crops. Therefore, water shortages are frequent, especially during the dry seasons. Additionally, competition in the water uses between agriculture and other sections has been intensified due to rapidly accelerated population growth, industrialization and urbanization. To effectively and efficiently use the available but limited water sources to meet the possible variation of cropping pattern, estimations of IWRs are with a crucial meaning in the Huang-Huai-Hai plain.

Agricultural Potential Yield (PY) is determined by interaction between soil, water, plant, and atmosphere as a continuum system. Simulation of plant growth stages and consequently forecasting the crop yield permits better planning and more efficient management of crop production processes[4-5]. Among different models for crop growth and yield

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simulation, Paz et al. used a soybean model, and showed that yield variability correlated with variability of simulated water stress[6]. In its simple model, crop yields can be obtained by multiplication of total dry matter production by harvest index H_I. However, the H_I was reported to be dependent on transpiration[7].

Even there are some relevant researches completed within the same field by a large majority of experts in these fields [8-11], there are still quite a lot of research topics left and under study. Along with the rapid developments of GIS, remote sensing, remote detecting and computer technology, the researches with the topics of IWRs and the PY have made some progress in both theoretic development and field validation in China[12-14]. But there are still few kinds of studies with specific motivation to explore the relationship of IWRs and PY at a regional scale, though it is important for the decision makings on the management of water resources.

Without access to quality data from traditional statistical databases, we rely on methods that use Landsat TM/ETM data to decode the information on the share of cultivated land. We develop and use the one area percentage data model to track land conversion in the period between 1991 and 2000. Using this data model, we can easily identify how some certain of land use converted into other uses and how much of cultivated land are transferred into non-agricultural use of land and at the same time how big of the unused land or other uses converted to cultivated land. All these kinds of conversions will definitely lead to the spatial and temporal changes of IWRs.

Current methods used to calculate point-specific ET_0 are mainly from site-based meteorological observation stations. With the support of GIS technology, it is possible to extend these methods to get spatially distributed ET_0 over space. By conducting a GIS-based spatial overlay analyses, we explore the relationship between the IWRs and the potential yield of cultivated land which is calculated based on the EMAPP model, we find that the IWRs is now a one of the main constrain factors for the improvement of potential yield of cultivated land in the Huang-Huai-Hai plain. The result lays the scientific basis for the decision makings in the utilization of resources and energy as well as the land use planning, projections of potential yields and the managements of irrigation water at the regional level.

The purpose of this study is to illustrate an approach to estimate the IWRs of cultivated land in the Huang-Huai-Hai plain and explore the coupled relationship between IWRs and PY for the Huang-Huai-Hai plain in the period between 1991 and 2000. We use the FAO Penman-Monteith methods included in the CropWat model to estimate ET_0. And then we estimate the maximal evapotranspiration, ET_m, and then by using the ET_m and the estimated share of cultivated land, we estimate the IWRs. By developing and using the model of EMAPP, we at the same time estimate the PY. And then we explore the coupled relationships between IWRs and PY and describe the spatial variability of the coupled relationship over the space in the period between 1991 and 2000 for the entire Huang-Huai-Hai plain.

The rest of this paper is organized as follows. Section 2 introduces the data needed and methodology used in this study. Section 3 and 4 analyze temporal and spatial characteristics of IWRs and PY in the Huang-Huai-Hai plain, 1991 and 2000. Section 5 explores the relationship between IWRs and PY. The final section concludes.

2. DATA AND METHODOLOGY

2.1 Data

The meteorological data are derived from China Meteorological Administration, with the records including air temperature, solar radiation, rainfall, relative humidity, wind velocity etc. we collect the crop pattern data from Statistical Yearbook of China and the get the crop coefficient data from IIASA (International Institute of Applied Systems Analysis). We use the daily records for all these meteorological observations. The share of cultivated land, which is decoded from the remote sensing data, is used in this paper. The share of cultivated land has been aggregated into the 1 by 1 grid cells [15]. And the values of each 1 by 1 square kilometer grid identify the area of the cultivated land.

We interpolate the meteorological data using Kriging method, and set the grid resolution of all these meteorological data as 1 by 1 square kilometer. And then we translate the Geographic Projection to the Albers Conic Equal Area Projection, the same projection as the DEM, through the projection transformation. Then all of parameters are with the consistent projection and the spatial and temporal resolutions.

The study is with a specific focus in the Huang-Huai-Hai plain, China (latitude from 32.0° to 41.0°N and longitude from 113° to 123°E), which includes 16 agricultural ecological zones (Fig. 1).

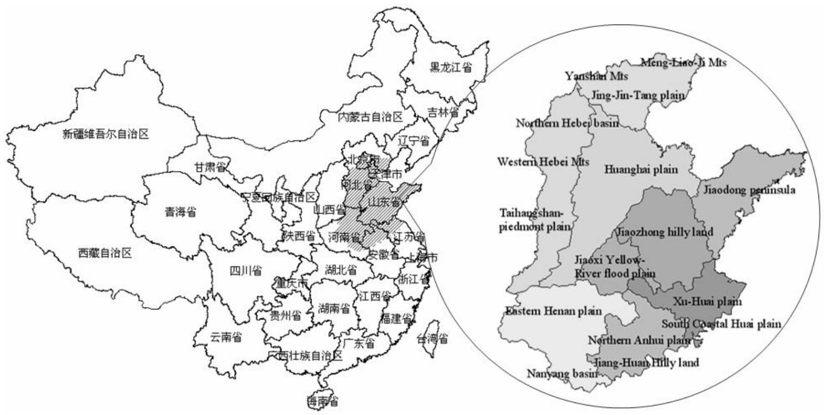


Fig. 1 Location and agricultural ecological zones of the Huang-Huai-Hai plain

2.1 Methodology

The procedures to calculate IWRs included in three steps. First, using the site-based meteorological data, we calculate ET_0 in according to the CropWat model. In order to calculate ET_0, the site based climatic observatory records has been interpolated into the climatic surface data. The meteorological variables, near surface air temperature, air humidity, solar radiation and wind velocity, are supplied by the National Climatic Data Center. Secondly, we calculate ET_m of each grid cell. Crop coefficients are used to estimate ET_m for specific crops in according to the estimated ET_0. And the crop coefficient tables are used to provide a crop coefficient at each grid cell based upon land cover/land use data. Finally, we estimate IWRs of cultivated land by multiplying the share of cultivated land at each one by one grid cells.

Prior to calculating the ET_0, we need to define the reference crop. Following the definition in FAO56[16], we here define the reference crop as *a hypothetical crop with an assumed height of 0.12^m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered.* So the calculation of ET_0, i.e., the rate of evapotranspiration from a hypothetic reference crop with an assumed crop *height of 12cm , a fixed canopy resistance of 70 m s $^{-1}$ and an albedo of 0.23* (closely resembling the evapotranspiration from an extensive surface of green grass), is calculated according to the Penman-Monteith equation illustrated in equation (1) [17-18].

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 denotes the crop reference evapotranspiration (mm day^{-1}); R_n the net radiation at crop surface (MJ m^{-2} day^{-1}); G the soil heat flux density (MJ m^{-2} day^{-1}); T the mean daily air temperature at 2 m height (°C); u_2 the wind speed at 2 m height (ms^{-1}); e_s the saturation vapour pressure (kPa); e_a the actual vapor pressure (kPa); $e_s - e_a$ the saturation vapor pressure deficit (kPa); Δ the slope vapor pressure curve (kPa °C^{-1}); γ the psychometric constant (kPa °C^{-1}). The above variables can be observed or estimated from set of meteorological data (Fig. 2)[2,3,11].

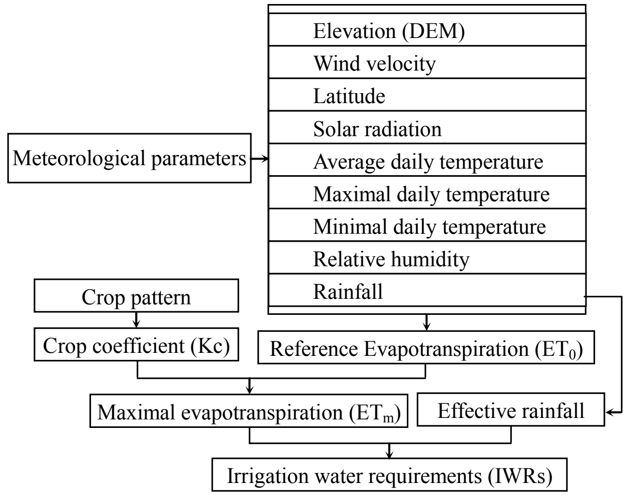


Fig. 2 Scheme to estimate IWRs of cultivated land

According to equation (1) and the meteorological data (Fig. 2), we estimate the average daily ET_0. And then by multiplying it with 365, we calculate the values of annual ET_0 for each grid cells.

In order to estimate the IWRs, we need to estimate the maximal evapotranspiration (ET_m) during the growth period of crops. Theoretically, ET_m is affected by the meteorological parameters, soil water conditions and the biologic characteristics of crops and could be specifically calculated from the following equation:

$$\mathrm{ET_m} = \alpha \times \mathrm{Kc} \times \mathrm{ET_0} \tag{2}$$

Where α is a coefficient to correct the soil water. We, herein, evaluate it as 1, in the condition of enough water for the soil. *Kc* means crop coefficient, which is affected by seasons, crop species and the growth structure of the crops.

There are two methods to generate *Kc* layers. One is the land use /cover data source and the other is the information on crop coefficients from the statistical book. We choose the latter method to obtain *Kc*. According to statistical and survey data, we find that wheat and corn are the predominant crops in the Huang-Huai-Hai plain, and are planted in numerous agricultural ecological zones. The growth months for wheat are January, February, March, April, May, June, October, November, December (9 months in all), the growth months for corn are May, June, July, August, September (5 months in all). So we can use the following equation to generate the maps of annual *Kc*.

$$Kc = \frac{\sum_{i=1}^{6} Kc_{wheat(i)} + \sum_{j=10}^{12} Kc_{wheat(j)} + \sum_{k=5}^{9} Kc_{corn(k)}}{14} \tag{3}$$

The IWRs is estimated as the difference between ET_m and effective rainfall. ET_m is evaluated as the product of ET_0 and the crop coefficient, while the ET_0 is calculated via the FAO Penman–Monteith method. Annual effective rainfall is estimated from total yearly rainfall according to the method developed by the USDA Soil Conservation Service (equation 4). In this paper, we estimate IWRs of the cultivated land by using the following equations.

$$\begin{cases} \mathrm{Pe} = \mathrm{R} / 125 * (125 - 0.2 * \mathrm{R}) & (\mathrm{R} < 250\,\mathrm{mm}) \\ \mathrm{Pe} = 125 + 0.1 * \mathrm{R} & (\mathrm{R} > 250\,\mathrm{mm}) \end{cases} \tag{4}$$

Pe denotes the yearly effective rainfall; *R* the total yearly rainfall.

$$\mathrm{IW}R = \mathrm{ET_m} \times C\mathrm{r} - \mathrm{Pe} \tag{5}$$

Where *Cr* denotes the ratio of the cultivated land, the value of each 1 km^2 grid means the area of the cultivated land.

3. TEMPORAL AND SPATIAL CHARATERISTICS OF IWRS

As mentioned in section 2, we estimate the IWRs of cultivated land in the Huang-Huai-Hai plain for 1991 and 2000 (Fig. 3a). In accordance to the estimations, we can illustrate the temporal and spatial characteristics of IWRs in the Huang-Huai-Hai plain for the year 1991 and 2000.

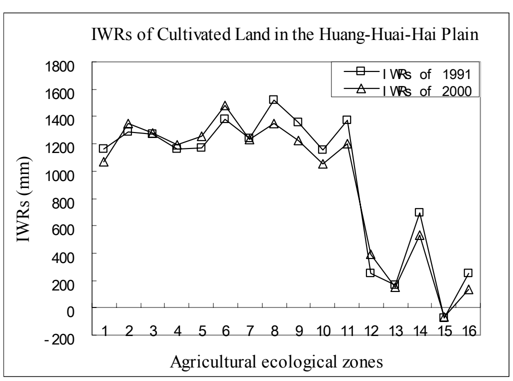
The negative coefficients between IWRs and PY in *Jiaodong peninsula* and Northwest of the Huang-Huai-Hai plain disclose that, theoretically, there are no extra irrigation water requirements for the agricultural production in these area given that there are enough rainfalls and at the same time with less cultivated land. Given this, these areas can develop rainfed agriculture. Besides, *Northern Hebei* basin is also with the negative value, too. So these areas can also develop the rainfed agriculture.

When we compare the IWRs of 1991 and 2000, we can find the there are temporal differences between the year of 1991 and 2000. We find that the IWRs in 2000 is less than those in 1991 for most area in the northern Huang-Huai-Hai plain (include *Jing-Jin-Tang plain, Meng-Liao-Ji Mts, Yanshan Mts* and *Western Hebei Mts*) and the southern Huang-Huai-Hai plain (*Xu-Huai plain, Northern Anhui plain, Eastern Henan plain, South Coastal Huai plain, Jiang-Huan Hilly land*). Among these regions, the values of the IWRs in *Yanshan Mts and Western Hebei Mts* decline dramatically in the periods between 1991 and 2000, with the higher percentage change rates of 47.2% and 23.9% respectively. *Northern Hebei basin, Jiang-Huan Hilly land* and *Northern Anhui plain* decreased by 12.4%、12.3% and 11.3% respectively. The percentage changes for the rest regions are lower than 10%. The IWRs for the middle plains (*include Huanghai plain, Taihangshan piedmont plain, Jiaodong peninsula, Jiaozhong hilly land* and *Jiaoxi Yellow River flood plain*) increased, but the percentage changes of all these regions are small (<10%). The IWRs of *Nanyang basin* which is in the south of the Huang-Huan-Hai plain increase dramatically, with an increase rate as high as 55.7%. In sum, the demand of the water in most of the regions shows a decreasing trend, which is relative to the changes of climatic conditions and the patterns of land uses. Research result also shows that, along with the increase of the CO_2 density, the rainfall in the Huang-Huai-Hai plain is increasing[19]. Furthermore, Along with the rapid development of urbanization, the conversion process of cultivated land to other uses has been accelerated[20], which directly result in the decrease of the cultivated land, as one of the reasons that further led to the decrease of the IWR.

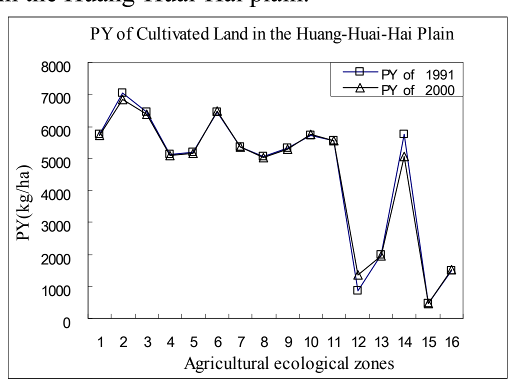
4. CHANGES OF PY ON SPACE

PY of cultivated land reflect the potential ability of persistently grain production on some specific condition. It is restricted by radiation, heat, water, soil and the biologic characteristics of crop[21], and shows prominent difference in spatial scale. In this paper, we utilize the EMAPP model and calculate the potential yields of cultivated land in the Huang-Huai-Hai plain, 1991 and 2000 (Fig. 3b).

The PY has the same spatial characteristics with IWR. But the change in the period between 1991 and 2000 is inconspicuous. *Huanghai plain* and *Jiaoxi Yellow River flood plain* shows the high value of PY, with an amount of 7000 kg/ha while. the value of PY in the *Nanyang basin* and *Northern Hebei basin* are relatively small, about 1000 kg/ha. On the whole, the PY has the same fluctuation trend with the IWRs in the Huang-Huai-Hai plain.



(a)



(b)

Fig. 3 IWRs (a) and PY (b) of cultivated land in the Huang-Huai-Hai plain,1991 and 2000
Agricultural ecological zones: 1 Jing-Jin-Tang plain; 2 Huanghai plain; 3 Taihangshan piedmont plain;

4 Jiaodong peninsular; 5 Jiaozhong hilly land; 6 Jiaoxi Yellow River flood plain; 7 Xu-Huai plain;
8 Northern Anhui plain; 9 Eastern Henan plain; 10 South Coastal Huai plain; 11 Jiang-Huan Hilly land;
12 Nanyang basin; 13 Meng-Liao-Ji Mts; 14 Yanshan Mts; 15 Northern Hebei basin; 16 Western Hebei Mts.

5. COUPLED CHANGES BETWEEN IWRs AND PY

Then we will try to explore the relationship between IWRs and PY. On the whole, the results show that the region with higher IWRs will have high potential yield, or in other words, the amount of IWRs can reflect the situation of the PY of cultivated land. For example, from Fig. 3a, we can find that areas with the high value of IWR, which means that the demand of irrigation water are dramatic, are located in *Huanghai plain* (1286 mm) *Taihangshan piedmont plain* (1271 mm) and *Jiaoxi Yellow River flood plain* (1376 mm). And their corresponding PYs (Fig. 3b) are high, e.g. the values of 7026 kg/ha in *Huanghai plain* , 6455 kg/ha in *Taihangshan piedmont plain* and 6448 kg/ha in *Jiaoxi Yellow River flood plain*. On the contrary, in *Nanyang basin, Northern Hebei basin* and *Western Hebei Mts*, both the IWRs and PY are low. In other words, except for some abnormity regions (such as *Yanshan Mts*), most of the regions support the conclusion that the IWRs and PY of the cultivated land are positively correlated. The same patterns are illustrated in Fig. 3b for the year of 2000, which further proved the existence of the positively correlated relationship between the IWRs and PY.

We go further to compare the percentage change of two year's IWRs and PYs. For those areas with marginal changes of changes of IWRs, their corresponding percentage changes of PYs are also small. For example, the percentage changes of the IWRs for the middle plains (*include Huanghai plain, Taihangshan piedmont plain, Jiaodong peninsular, Jiaozhong hilly land* and *Jiaoxi Yellow River flood plain*) are as low as 10%, and their corresponding percentage changes of PYs are also as low as 3%. This illustrates that the changes of PYs are consistent with those of IWRs in the Huang-Huai-Hai plain.

6. CONCLUDING REMARKS

By using Penman-Monteith formula and GIS technology, we calculate and explore the temporal and spatial characteristics of IWRs in the Huang-Huai-Hai plain for the year 1991 and 2000. We find that the characteristics of variability of the IWRs over space and time. Generally speaking, the IWRs for the *Jiaodong peninsular* and Northwest of the Huang-Huai-Hai plain is lower, which further illustrate we could develop rainfed agriculture in these area. When comparing the IWRs for the year 1991 and 2000, we find that the IWRs in 2000 is less than those in 1991 in the northern as well as the southern areas of the Huang-Huai-Hai plain. The IWRs for the middle plains, however, increase, but the percentage changes of all these regions are marginal, as lower as less than 10%. There is a decreasing trend for the IWRs between the periods of 1991 and 2000.

The IWRs and PY of the cultivated land are positively correlated, which means areas with higher values of IWRs is also with higher values of PY. By clarifying positively correlated relationship between IWRs and PY, we can easily delimit those regions constrained by the supply of irrigation water while with high potential yields at present as well as find other issues closely related with water resource management. The research result has lay the scientific basis for the decision makings in the utilization of resources and energy as well as the planning on land uses, projections of potential yields and the managements of irrigation water at the regional level.

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