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Research papers

Estimation of actual irrigation amount and its impact on groundwater depletion: A case study in the Hebei Plain, China

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ABSTRACT

Irrigation water is an important but missing hydrological cycle component in the region with intensive agricultural irrigation, due to the lack of monitoring facilities. The Hebei Plain, suffering the most severe groundwater depletion in China for agriculture production, provides an ideal background to study historical agricultural water consumption and its dependence on groundwater exploitation. This paper investigated the method of retrieving the spatial-temporal irrigation amount from multiple data sets of different sources and different scales. Comprehensive data including 21 years of satellite-based data, ground-based data, and four years of tracer experiment data are synthesized to implement the soil water balance. We proposed a modified soil water balance framework by relying on as much as possible of easily available data. Our results showed that the multi-mean annual irrigation amount in the Hebei Plain is 317 mm, and mean irrigation-to-evapotranspiration ratio reaches 50.8% in recent two decades. Moreover, the precipitation distribution, plant structure, and agricultural intensity result in significantly spatiotemporal variation in irrigation and irrigation-to-evapotranspiration ratio, while however has not been addressed by previous studies. Deep percolation, ignored by many soil water balance models, was shown to be unneglectable. The estimated actual irrigation amount, together with groundwater level data, are valuable to obtain a further understanding on groundwater depletion. The diverse groundwater depletion situation in the Hebei Plain indicated the importance of recognizing the groundwater utilization patterns at a smaller scale in the regional-scale groundwater resources management. This work showed the feasibility of estimating the irrigation amount using simultaneously different types of data and revealed the spatiotemporal characteristics of agriculture water consumption and associated groundwater depletion in the Hebei Plain.

1. Introduction

Irrigation plays a significant role in increasing crop productivity. It was reported that global crop yield per unit area rose by a factor of 2.3 and the total crop yield increased by a factor of 2.4 in the period from 1961 to 2004 due to irrigation (Oki and Kanae, 2006). In addition, irrigated land which only accounts for 17% of total cropland produces 40% of food worldwide (Abdullah, 2006). Despite the fact that irrigation largely contributes to food production increase, there are many negative influences of irrigation on the environment, such as depletion of surface water and groundwater resource, water pollution and loss of biodiversity. Globally, the contribution of nonrenewable groundwater extraction to irrigation increased from 75 to 234 km^3/yr over the period 1960–2000 (Wade et al., 2012). In the North China, especially the Hebei Plain, it is well acknowledged that agricultural water consumption greatly contributes to groundwater depletion. Currently, 72.67% of total groundwater extraction is consumed by agriculture (Zhang et al., 2012). Long-term groundwater extraction has led to the continuous decline of the regional groundwater table since the 1970s (Duan and Xiao, 2003; Cao et al., 2013). Statistics showed that the decline rate of shallow groundwater table was 0.42 m/yr and that of deep groundwater table was 1.2 m/yr from 1975 to 2000, resulting in a large area of the cone of depression (Duan and Xiao, 2003). Gravity Recovery and Climate Experiment (GRACE) satellite also confirmed the drastic groundwater storage depletion in the North China at the rate of between 2.0 and 2.8 cm/yr from 2003 to 2010 (Feng et al., 2013; Shen et al., 2014; Huang et al., 2015).

Agriculture water consumption consists of livestock and irrigation water use, and the latter is the dominant component in the

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Hebei Plain. The impact of irrigation on groundwater depletion has been investigated in different ways by different researchers. Zhang et al. (2012, 2013a,b) used the statistical data to explore the relationship between groundwater depletion and irrigation in the Hebei Plain, while their study relied on sufficient data including irrigation data, which are difficult to collect for a large-scale and long-term study due to the lack of observation facilities. Besides the traditional statistical investigation, process-based models such as MODFLOW (Modular Three-dimensional Finite-difference Ground-water Flow Model) and APSIM (Agricultural Production System Simulator) were also employed to analyze the influence of agriculture on groundwater reserve (Mao et al., 2005; Chen et al., 2010; Sun et al., 2015). And in their study site-based irrigation was applied as model input. Overall, most researchers have concluded that irrigation significantly aggravated groundwater decline. Two key challenges remain unsolved, however: how to retrieve the large-scale irrigation amount from multiple data sets of different sources and different scales, and what is the spatiotemporal relationship between agricultural irrigation and groundwater depletion? In the Hebei Plain, irrigation amounts are only discontinuously available at few lysimeter-scale or small-scale experimental sites. The need for accurate information on water consumption and especially on actual irrigation applications is also a worldwide problem (van Dam et al., 2006; Karatas et al., 2009; Droogers et al., 2010). In almost no country is there a good measurement and registration system for water use in general and irrigation water use in particular (Döll and Siebert, 2002).

Since the identification of irrigation amount is nontrivial in many applications, it is typically estimated by water balance method. Many existing studies focused on modeling irrigation water requirements but not actual irrigation water use. The net irrigation amount was firstly computed as the difference between the evapotranspiration and the effective precipitation, then gross irrigation amount was obtained by dividing the net irrigation requirement by the so-called "project efficiency of irrigation water use" (Brouwer and Heibloem, 1986; Döll and Siebert, 2002; de Rosnay et al., 2003; Huninka et al., 2015; Peña-Arancibia et al., 2016). The readers may refer to the model proposed by Döll and Siebert (2002), which has successfully modeled the irrigation water requirements at the global scale. However, these studies generally ignored the possible water percolation into the deep soil and simplified the calculation of conveyance loss by introducing project efficiency. It is usually difficult to obtain the project efficiency since it depends on the size of irrigated cropland, irrigation methods, and management strategies. Furthermore, the estimated irrigation water requirement is not necessarily equivalent to the actually irrigated water amount since most croplands are often over-irrigated or deficit irrigated. The actual irrigation amount can be quantified by the above-mentioned water balance model, but actual evapotranspiration is required (Droogers et al., 2010; Ma et al., 2011). It is also possible to derive a more rigorous soil-water-balance model by introducing all the water balance components including precipitation, evapotranspiration, surface runoff and deep percolation (Hassan-Esfahani et al., 2015).

A few earlier studies have been conducted to estimate the actual irrigation amount in the Hebei Plain or elsewhere (Droogers et al., 2010; Yang et al., 2010; Ma et al., 2011; Hassan-Esfahani et al., 2015). There are some apparent weaknesses in these work. Firstly, most of these studies estimated the actual evapotranspiration by introducing crop coefficients. Crop coefficients are usually determined from limited historical observations, and spatially and temporally variable crop coefficients are unlikely to be produced. Thus, it is a difficult task of accurately delineating the spatiotemporally variable actual evapotranspiration by crop coefficient method. Then most work has neglected the deep percolation. But the deep percolation plays an important role in soil water balance.

To overcome these deficiencies, this study proposes an improved and simple framework to estimate the actual irrigation amount. Comprehensive data including 21 years of satellite-based data, ground-based data, and four years of tracer experiment data are synthesized to produce the spatiotemporal map on irrigation amount with a spatial resolution of 0.05° before 2000 and a resolution of 1 km after 2000. Compared with previous work, we consider a more rigorous soil water balance by incorporating satellite-based evapotranspiration model and soil water deep percolation. Unlike the commonly used Penman-Monteith (P-M) model in combination with crop coefficients, actual aerodynamic resistance and bulk surface resistance are employed to avoid the uncertainties and biases in crop coefficients. We attempt to provide a feasible approach relying on as much as possible of existing open data to identify the actual irrigation amount. On the basis of retrieved irrigation data and groundwater level data, the impact of irrigation on groundwater depletion is investigated. Although the overall declining trend of groundwater level has been identified in the Hebei Plain, there is no study, to the best of our knowledge, contemplating the spatiotemporal variability in groundwater depletion and agricultural water consumption, and the relationship between them.

The worth of this study is that based on remote sensing data, tracer experiment data, ground data, and long series of groundwater monitoring data, the time- and space-dependent agricultural water consumption in recent two decades is characterized in the Hebei Plain. The spatiotemporal relationship between agricultural irrigation and the groundwater depletion is investigated to further reveal the negative effect of irrigation on groundwater system.

2. Materials and method

2.1. Study area

The Hebei Plain (HBP), as the primary region of North China Plain, covers the entire plains of Beijing Municipality, Tianjin Municipality and Hebei Province with a total area of 92,543 km^2. Taihang Mountains is located in the west of the study area and Yanshan Mountains in the north. The topography is relatively flat with an average elevation of 45.58 m above the sea level (Fig. 1). The climate is a typically continental, semiarid climate with mean annual temperature of 11.3 °C and mean annual precipitation of 506 mm in 1993–2013 based on the meteorological data from the China Meteorological Administration (CMA, http://data.cma.cn/). The summer monsoon contributes 70–80% of the annual precipitation during June-September. The study area has experienced several droughts in 1997, 1999 and 2002, with annual precipitation of 373 mm, 347 mm, and 377 mm, respectively.

The Hebei Plain is one most important granary of China. There is about 67,000 km^2 cropland, including 17 large irrigation districts and many small-scale irrigated farms. It produces more than 34.5 million ton of food every year, accounting for 6.5% of the total grain yield in China (Zhang et al., 2012). Winter wheat and summer maize are mostly planted in an annual rotation. Besides, cotton, vegetables, and fruit trees cover a large amount of cropland. Due to the uneven distribution of intra-annual precipitation, agricultural irrigation is required, especially for winter wheat during the spring and autumn. Nearly 70% of the total water supply for grain production is supported by groundwater, and 70–80% of groundwater exploitation is used for irrigation (Cao et al., 2013).

2.2. Data collection

Daily meteorological data of 27 weather stations are obtained from CMA. The data include precipitation, maximum, minimum and mean temperature, mean and minimum relative humidity,