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Assessing potential water savings in agriculture on the Hai Basin plain, China

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ABSTRACT

The Hai Basin in China exemplifies problems that are observed in many arid environments: excessive water consumption, depletion of aquifers, and damage to eco-systems. Progressively since the 1970s water resources in Hai Basin have been over-exploited, primarily for irrigation, while the water requirements of other sectors have increased. Water tables are falling and outflows to the sea are sporadic and heavily polluted. Current consumption of water in the basin is estimated to exceed the renewable supply from rainfall by $6.25 \times 10^9\ m^3\ yr^{-1}$. Traditional approaches—improving irrigation efficiency through structural works and on-farm technologies such as drip and sprinkler—have failed to restore a balance. Researchers have investigated various on-farm techniques to reduce consumption, including mulching, zero tillage, deficit irrigation, revised cropping patterns, and improved cultivars. We project the results of such experiments for winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and cotton (*Gossypium* spp.) to basin scale to assess their potential in restoring sustainable water consumption. Widespread adoption of mulching, which is the most promising option for farmers, would reduce the over-consumption by 25% ($1.6 \times 10^9\ m^3\ yr^{-1}$). If water quotas are introduced, forcing a reduction in consumption, current production could be maintained while saving $4.1 \times 10^9\ m^3\ yr^{-1}$. Ending the remaining over-consumption of $2.15 \times 10^9\ m^3\ yr^{-1}$ would require reducing grain production by 4–7.8 Mt yr^{-1}.

1. Introduction

Irrigation, especially in countries with limited rainfall, dominates water use, often accounting for 70–80% of total water use. Population growth, improved and diversified diets, industrialisation, and economic development increase the pressure on limited water resources (Peng, 2000). Surface water, being most accessible, is often exploited first, but since the 1970s, when deep tube-wells using submersible pumps became affordable, groundwater has been a major additional source of irrigation. Wada et al. (2012) report that the most significant examples of this unsustainable consumption are in India ($68 \times 10^9\ m^3\ yr^{-1}$ of non-renewable groundwater depletion) followed by Pakistan ($35 \times 10^9\ m^3\ yr^{-1}$), the United States ($30 \times 10^9\ m^3\ yr^{-1}$), Iran ($20 \times 10^9\ m^3\ yr^{-1}$), and China ($20 \times 10^9\ m^3\ yr^{-1}$). These volumes range from 15 to 30% of total irrigation water delivered.

Irrigated agriculture is likely to experience substantial future reductions in water availability. Total consumption by all sectors must be reduced to restore, or at least stabilise, depleted aquifers and damaged ecosystems, and agriculture is often a low priority user of water, such that its share in the aggregate is likely to decline. Nevertheless, irrigation will continue to be a substantial component of water demand (Xu and Kang, 2002), and as such, reducing consumption in this sector will remain a high priority.

The North China Plain is an example of this pattern of development. Traditionally a rainfed, agrarian economy, the area has contributed substantially to national food security. Since the 1970s groundwater tables have fallen substantially as the area under tube well irrigation expanded. Industrialisation and urbanisation have progressed rapidly, and outflows from the river system are now limited and heavily polluted. The area continues to contribute substantially to food security in China. Maintaining production while re-establishing a sustainable, ecologically and environmentally acceptable water regime is a high priority for the government. Achieving this goal will be challenging, and will require careful consideration of the costs and benefits of water use and water saving in the region.

To date, the response to excessive agricultural water use on the Hai Basin plain, which constitutes about 40% of the total area of the North China Plain, has focused on improved infrastructure

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(Gong et al., 2003; Blanke et al., 2007). Since 1980, canal lining and pipeline distribution technology have been introduced on more than 2.7 Mha (37.2% of the irrigated area) in the Hai Basin (Zhu et al., 2008). Drip and sprinkler irrigation have been introduced on 492,000 ha (7% of the irrigated area), largely for orchards and greenhouses (Zhu et al., 2008).

Such investments have been widely promoted as "water saving", because less water needs to be withdrawn from the source to meet the water requirements of the crop.

However, several authors stress the need to evaluate the impacts of changes in irrigation management and technology in the full hydrologic context (Willardson et al., 1994; Seckler, 1996; Jensen, 2007; Perry, 2007; Perry et al., 2009; Crase and O'Keefe, 2009). The common issue they raise is the extent to which "losses" return to useable aquifers or streams. Specifically for the Hai Basin, Kendy et al. (2003, 2004) conclude that improved irrigation technology cannot restore the water balance because the vast majority of "losses" are in fact recovered and reused.

Humphreys et al. (2010) evaluate an array of potential interventions in northwest India—where groundwater is also a major source of irrigation water. The authors conclude that:

> "Reducing deep drainage will not "save water" nor reduce the rate of decline of the water table. In these regions, it is critical that technologies that decrease evapotranspiration (ET) and increase the amount of crop produced per amount of water lost as ET (i.e., crop water productivity) are implemented" (p 157).

Most recently, reflecting the importance of these insights, interventions funded by the World Bank and the Global Environmental Facility[1] focus directly on reducing consumptive use ("evapotranspiration management") rather than pursuing the traditional engineering concept of efficiency.

Complementing this approach, we review research results, in terms of reduced ET at field level and associated changes in crop production, and we identify the most promising interventions. We then project reported water savings and production impacts from research scale to basin scale for the Hai Basin for the main crops grown in the area (wheat, maize and cotton). We also discuss the constraints that will limit the water savings potential of adopting the water management measures described in research findings.

Our analysis is relevant to recent policy statements in China. In Document No. 1 of 2011,[2] the State Council decided to accelerate water reform and development through the "strictest water resources management" and enforcement of the "Three Red Lines" which will reduce water use, restore aquifers and rivers, and increase production per unit of water used.

2. Materials and methods

2.1. The study area

The Hai Basin plain is located between the longitudes and latitudes of 113.2–119.8° E and 35.0–40.4° N. The area is about 131,000 km^2, accounting for about 40% of the total land area of the Hai Basin. The study area belongs to the temperate zone continental monsoon climate. About 80% of the annual precipitation occurs between June and September. Rainfall since 1990 has averaged 557 mm yr^{-1}. The total arable land of our study area is about 81,200 km^2.

We divide the plain of the Hai Basin into eight river-plain districts: Beisi, Luan, Daqing west, Daqing east, Ziya, Heilonggangyundong, Zhangwei and Tuhaimajia. There are several agricultural research stations in the study area (Fig. 1). Among them, Baoding, Luancheng, Wuqiao and Yucheng are major stations. Tunliu, Fengqiu, Luoyang and Shangqiu, are outside Hai Basin plain, but they are located near the border of the Hai Basin plain and have similar agro-climatic conditions.

Research reports usually only state the county name but not the specific location. Therefore we use the county borders to identify the general "experimental regions" where the reported studies took place, as shown in Fig. 1. Winter wheat and maize are grown at all stations. Beijing Xijiao is the only experimental site where cotton was grown.

2.2. Cropping patterns and water use

The crop rotation over the North China Plain in 2010 was derived from the research of Wu et al. (2013). The charge-coupled device on the HJ-1A/B satellite at a resolution of 30 m was used to obtain the training data for classification. A decision tree algorithm was applied to the time series of vegetation indices (NDVI and EVI) to identify areas with different crop rotations. We extracted the crop rotation data for the study area and calculated the crop areas. Major crops were winter wheat (3.67 Mha), spring maize (2.49 Mha), summer maize (2.73 Mha, of which 1.92 Mha follows wheat), and cotton (0.73 Mha).

Winter wheat rotated with maize is the predominant cropping system in the Daqing west, Ziya, Zhangwei and Tuhaimajia river plains, which are the main grain producing regions, accounting for about 46% of the study area, and more than 50% of the basin's total production (53.2 Mt yr^{-1}). Single crop rotations (cotton or maize) are most common in the Beisi, Luan, Daqing east and Heilonggangyundong river plains.

Wu et al. (2014) estimated the incremental consumption of water in the Hai basin due to human intervention at 36×10^9 m^3, of which 6.25×10^9 m^3 is the excess over the sustainable consumption rate that would stabilise aquifers and restore adequate river flows.

Monthly ET data for the study area from 2002 to 2009 were produced by using the remote sensing model-ETWatch, which was validated using the observation data (Wu et al., 2012). The deviation for individual fields on a seasonal basis is 12% and decreases to 6% for an annual cycle, and the deviation is 3% for catchments for an annual cycle. Average crop ET derived from the remote sensing analysis was 333 mm for wheat, 319 mm for maize, and 585 mm for cotton. Wang (2013) used the same remote sensing data to derive the average "natural" ET from the uncultivated landscape for the periods corresponding to the major crops. During the winter wheat season, natural ET was 145 mm, and for the maize season it was 259 mm.

2.3. Reported impact of water-saving techniques

The government of China has supported research on water-saving techniques since the 1980s, involving many specialists and institutions. More than 3000 experimental results have been reported over the last 30 years. Techniques include improved irrigation technology (lining of channels, drip and sprinkler systems), mulching, conservation tillage, deficit irrigation, improved crop varieties, and improved weed control (Zuo, 1997; Blanke et al., 2007; Fang et al., 2010a).

Our empirical analysis is based on existing research on interventions designed to reduce ET and improve crop water productivity (defined as kg m^{-3}) in the conditions of the Hai Basin. The

[1] http://www.worldbank.org/en/results/2013/04/09/china-improving-water-resource-management-pollution-control-in-hai-basin, viewed June 7, 2014.

[2] http://www.china.org.cn/china/2012-02/17/content_24664350.htm, viewed 9 June, 2014.