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PERSPECTIVE

# GROUNDWATER DEPLETION IN THE NORTH CHINA PLAIN: THE AGROHYDROLOGICAL PERSPECTIVE

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**ABSTRACT**

Agricultural production in the North China Plain with rainfall of less than 500 $\mathrm{mm \cdot yr^{-1}}$ has been steadily increasing over the past 40 years, with the groundwater levels decreasing at a rate of over 1 $\mathrm{m \cdot yr^{-1}}$. In this paper, it is demonstrated theoretically that the water level in the aquifer can be expressed as a function of agricultural production and the sum of water added as rainfall and imported from outside the basin. Therefore, the most effective measures to halt groundwater depletion are importing water, decreasing cropping intensity and growing less thirsty crops. Irrigation improvements, mulching and agronomic measures that could increase the yield per unit area have less of an impact on solving the declining groundwater levels.

## 1 INTRODUCTION

Since China started to reform its economy in 1978 by increasing its agricultural production, GDP has grown by nearly 10% per year. In the North China Plain, the increase in agricultural production has been especially remarkable. With less than 500 $\mathrm{mm \cdot yr^{-1}}$ rainfall, groundwater extraction has allowed the cultivation of two crops per year with wheat sown in the autumn and maize in the summer. Currently, the Plain produces 23% of China's grain. However, this remarkable increase in production has come at the expense of water resources. The groundwater table has decreased by over 1 $\mathrm{m \cdot yr^{-1}}$ since double cropping was introduced. It is currently over 30 m deep. Moreover, the depletion was independent of the irrigation applied[1–3].

Ways to reverse this groundwater depletion have been widely researched. A literature search, with the search terms "North China Plain" combined with "irrigation" and "groundwater" in Web of Science (Clarivate Analytics, London, UK), found 288 items in the English language alone. Despite this research, groundwater is still being depleted, suggesting that a fresh look is needed at the relationship between agronomic and irrigation practices and groundwater depletion.

## 2 THE HYDROLOGY OF THE NORTH CHINA PLAIN

To investigate the relationship between agricultural practices and groundwater depletion, we developed a simple conceptual model for the water fluxes in the vadose zone of the North China Plain. The soil profile of the North China Plain consists of sands, silts with interbedded clay, and gravel[4]. Three zones are distinguished. They consist of a root zone, transmission zone and groundwater reservoir[4].

A simplified model in Fig. 1 is a representation of the North China Plain removing the complexities of a transmission zone. Water moves down by gravity, and it is pumped back up for irrigation. Excess irrigation water and rainfall in excess what the root zone can hold, percolates into the transmission zone and moves to the aquifer. The model lacks any lateral flow and assumes that water once it leaves the root zone cannot move back by capillary action. Lateral and upward flows are discussed in detail later.

The water balance (Fig. 1) of the root zone over a period $\Delta t$ is:

$$\Delta S = P + I - E_a - L \tag{1}$$

where, over $\Delta t$, $\Delta S$ is the change of water storage, L is percolation loss from the root zone, $P$ is precipitation, $I$ is irrigation and $E_a$ is the actual evapotranspiration. The loss of water only occurs when the moisture content in the root zone is above field capacity.

The groundwater reservoir water balance over $\Delta t$ is:

$$\mu \Delta h = R - I \tag{2}$$

where $\Delta h$ is the change in the groundwater table, $\mu$ is the drainable porosity and $R$ is the recharge. In Fig. 1, the recharge is equal to the percolation $L$. Combining Eqs. (1) and (2), the notable feature is that the change in the water table only depends on rainfall, evapotranspiration and moisture content in the root zone, and is independent of the irrigation applied, viz.:

$$\Delta h = \frac{\Delta S + P - E_a}{\mu} \tag{3}$$

On a yearly basis, $\Delta S = 0$. Groundwater depletion then only depends on evapotranspiration and precipitation. Thus, for a wheat-maize rotation with annual water use of 690 mm and rainfall of $450\ \mathrm{mm \cdot yr^{-1}}$[5] with a drainable porosity of 0.20, the groundwater declines $120\ \mathrm{cm \cdot yr^{-1}}$ (Eq. (3)) and is independent of the irrigation efficiency.

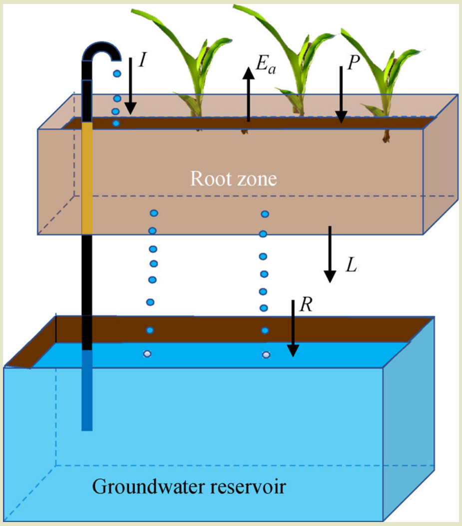

**Fig. 1** Simplified model representing the North China Plain. *I*, irrigation; $E_a$, evaporation; *P*, precipitation; *L*, percolation loss; and *R*, recharge.

## 3 HOW REALISTIC IS THE SIMPLIFIED MODEL?

After considering the down and upward flow in the transmission zone and lateral groundwater flow, it is argued in this section that the simplified model is realistic for the North China Plain.

**Percolation:** Research has demonstrated that water in soils with interbedded coarse and fine-textured layers exhibit funnel flow[6]. Water flows partially sideways above a coarse layer, eventually breaking through and moving downward in preferential pathways (fingers). The wetted finger area, $A_w$, equals the quotient of maximum downward flux and the saturated conductivity, $K_s$[7]. Thus, for a $20\ \mathrm{cm \cdot d^{-1}}$ percolation event, 2% of sand soils ($K_s = 10\ \mathrm{m \cdot d^{-1}}$) is wetted. In sandy loams ($K_s = 4\ \mathrm{m \cdot d^{-1}}$), the wetted area is 5%.

The depth of wetting, $D$, can be calculated as:

$$D = \frac{R}{A_w \theta_d} \tag{4}$$

where $\theta_d$ is the equilibrium moisture content. Thus, for $R$ = 20 cm, the wetting front depth is 100 m in sand ($\theta_d = 0.1$) For a sandy loam ($\theta_d = 0.25$), it is 16 m.

Empirical evidence confirms the existence of preferential groundwater pathways under the North China Plain. Experiments with stable water isotopes showed that following 50 cm of rain over 2 days, the groundwater had the same characteristics as the rain, proving preferential flow. Yang et al.[3] noted too that during a wet year in 1996 with $774\ \mathrm{mm \cdot yr^{-1}}$, the water table at 30 m depth increased the same year. Water velocities of 12–14 $\mathrm{cm \cdot d^{-1}}$ were measured for recharge rates of $1.2\ \mathrm{mm \cdot d^{-1}}$ by Min et al.[8]. All these results can only be explained by a small fraction of soil transporting the water (i.e., preferential flow).

**Lateral flow**: The North China Plain below an elevation of 40 m has a slope of 2 ‰. Therefore, the regional lateral flow is small and can be neglected compared with the irrigation water extracted[9]. Water has been shown to flow along buried faults in the relatively small proluvial fan area with elevations between 40 and 150 m. Upwelling only occurs when the conductivity of the aquifer decreases[10].

**Upward flow:** Theoretically, for groundwater deeper than 3 m, upward movement is restricted because the hydraulic conductivity becomes too small at the matric potential gradients required to move the water upward against gravity. Min et al.[4] experimentally confirmed the absence of upward movement at the Luancheng station because the observed hydraulic potential below 2 m was always positive.

Thus, we conclude that Eqs. (1)–(3) are valid for the North China Plain. The only difference with the simplified model is that the percolation does not reach the groundwater instantaneously but might take a few years.

## 4 YIELD AND GROUNDWATER DEPLETION

To assess the effect of yield on groundwater depletion, we reanalyzed the experimental results of Stewart et al.[10]. We found that crop yield was a function of the ratio of actual evapotranspiration, $E_a$ and that when soil moisture is not limiting, $E_{max}$ (Fig. S1 in the supplementary materials):

$$Y = Y_{max}\frac{E_a}{E_{max}} \tag{5}$$

where $Y_{max}$ is the yield under non-limiting soil moisture conditions.

For ease of argument, in discussing the groundwater depletion, the earlier wheat-maize rotation example is used, covering either part of the region, $A_{crop}$ or all of it, $A_{total}$. Assuming that the fallow land is weed free, and the evaporation is negligible, then based on Eq. (5), the regional evapotranspiration $E_r$ is:

$$E_r = \frac{A_{crop}}{A_{total}}\frac{Y}{Y_{max}}E_{max} \tag{6}$$

**Stopping groundwater depletion:** Combining Eqs. (3) and (6), groundwater is not depleted when:

$$\frac{A_{crop}}{A_{total}}\frac{Y}{Y_{max}}E_{max} \leqslant \overline{P} \tag{7}$$

In the example above, where the entire region is under a wheat-maize rotation ($\frac{A_{crop}}{A_{total}} = 1$) with water use of 690 $\text{mm}\cdot\text{yr}^{-1}$, the average annual precipitation must be greater than 690 $\text{mm}\cdot\text{yr}^{-1}$ for the water table not to decline, which is unlikely even under optimistic climate predictions.

Thus, to prevent groundwater depletion due to agricultural water use, the left-hand term in Eq. (7) has to be less than P. Since $E_{max}$ varies minimally, the ratios of $\frac{A_{crop}}{A_{total}}$ and $\frac{Y}{Y_{max}}$ should, therefore, be reduced. According to Eq. (7), for a well-watered crop $\left(\frac{Y}{Y_{max}} = 1\right)$, the crop acreage should be reduced by 35% of the land (i.e., $\frac{A_{crop}}{A_{total}} \leqslant 0.65$) for the wheat-maize rotation example and 450 mm of rain. Meng et al.[11] showed that this can be achieved by growing one maize crop per year, evaporating around 400 $\text{mm}\cdot\text{yr}^{-1}$. Some of the rotations with two to three crops each two years have similar water uses and can stop groundwater depletion[2,12].

Alternatively, groundwater use can be sustainable by cropping the whole area and implement deficit irrigation that reduces the yield by at least 35% $\left(\frac{Y}{Y_{max}} \leqslant 0.65\right)$. In both cases, food needs to be imported, or diet changed to less meat[13,14].

Retaining current agricultural practice without depleting the groundwater is possible if rainfall can be supplemented with treated wastewater from cities that import water from outside the basin. In the wheat-maize example mentioned above, the difference between annual rainfall and crop water use needs to be imported (i.e., 690–450 = 340 $\text{mm}\cdot\text{yr}^{-1}$ or 3400 $\text{m}^3\cdot\text{yr}^{-1}\cdot\text{ha}^{-1}$).

In the example used, the prevalent wheat-maize rotation was considered. Equations for groundwater table change for several crops are presented in the supplementary material section P1. Although these crops have different $E_{max}$ values, it does not change the general conclusions because the $E_{max}$ of most crops fall within relatively narrow bounds. For example, the water use of pears is 764 $\text{mm}\cdot\text{yr}^{-1}$[5].

Finally, $E_{max}$ and $Y_{max}$ of the wheat-maize rotation is not constant and is affected by agronomic and irrigation practices, as exemplified by the following subset of findings that show that generally, reductions are not in the order of 35% that is needed to stop groundwater depletion. Xu et al.[15] showed that irrigation scheduling, from water applied only at sowing through to fully irrigated, affected the water use per kg of grain by 7% (32 $\text{mm}\cdot\text{yr}^{-1}$). Li et al.[16] observed that per kg of wheat grain, drip irrigation saved 12% water and sprinkler 18% compared to flood irrigation. Mulching with straw can only save a limited amount of water because soil evaporation accounted for only 13% of the total water use in maize production[17], which is consistent with the findings of Qin et al.[18]. Plastic mulch may reduce water use by up to 40%[18] but has the disadvantage of soil pollution. Agronomic factors involving optimum fertilizer use and plant density increase yield but minimally affect water use.

## 5 IMPLICATIONS

In the literature, several indicators have been introduced to show the efficiency of crop water use. For example, the widely-employed water use efficiency (WUE), which is defined as the ratio of crop yield and evaporation, only indirectly affects groundwater depletion. For sustainable groundwater management, a better measure would the ratio of yield and groundwater change. Then based on Eq. (3), the groundwater use efficiency, GWUE, would be calculated as:

$$\mathrm{GWUE}=\frac{Y}{P+X-E_a} \tag{8}$$

where $X$ is the amount of water imported. When GWUE is negative, groundwater declines, and when positive, it increases. With this and other indicators, the problem of accurately measuring evapotranspiration remains.

In summary, groundwater depletion can only be halted in the North China Plain, with an average precipitation of around 450 $\mathrm{mm\cdot yr^{-1}}$, with one or a combination of the following measures: importing water from outside the basin, such as from the Yangtze River to the cities and then treated[19], desalinization of seawater and introducing fallow in rotations reducing cropping frequency to an average of only 1–1.5 crops per year. Agronomic and irrigation practices, perhaps with the exception of plastic mulch, can only partly contribute to stopping groundwater depletion. As with all water projects, the implementation of practices for sustainable groundwater management requires the full participation of farmers and policymakers.

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### Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2021407 contains supplementary materials.

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