Agricultural Water Management 165 (2016) 131–140

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Towards groundwater neutral cropping systems in the Alluvial Fans of the North China Plain

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 6 November 2015
Accepted 7 November 2015
Available online 7 December 2015

Keywords:
Groundwater
North China Plain
Sustainable
Crop rotation
Wheat
Maize
Plastic film mulch
APSIM

ABSTRACT

Groundwater levels in the North China Plain (NCP), the bread basket of China, have dropped more than one meter per year over the last 40 years, putting at risk the long term productivity of this region. Groundwater decline is most severe in the Alluvial Fans where our study site is located. Avoiding a foreseeable systems collapse requires region-wide changes in crop systems management, underpinned by sound environmental policies. Here, we explore the potential of crop system adaptation to remedy the excessive water use and quantify the likely yield penalties associated with more sustainable water use practices. Using simulations with the APSIM cropping systems model we explore production opportunities in an area within the NCP with intensive cropping and no access to irrigation from rivers. We estimate the attainable production levels for wheat and maize if agriculture were made groundwater neutral, through changes in crop sequence, irrigation practices and water conservation technologies (e.g. mulching with plastic film). Total grain production would drop by 44% compared to current practice if agriculture were made groundwater neutral. Water conservation by plastic film could limit this reduction to 21–33% but possible environmental impacts of plastic film need attention. This analysis facilitates a much needed debate on alternative agronomic practices and incentives through a quantitative comparison of adaptation options. Our biophysical analysis needs to be complemented with socio-economic considerations and discussions with all stakeholders. Similar analyses in other parts of the NCP are possible but require more accurate modelling of landscape hydrology and (towards the coast) risk of salt water intrusion.

1. Introduction

Just like many in the western world have been borrowing too much from the bank leading to the recent financial crisis, Chinese farmers in the North China Plain (NCP) are borrowing too much groundwater. A resource built up over hundreds of years is depleted within a few decades, and climate change could greatly influence the water cycle and aggravate the water crisis situation in the NCP (Changming et al., 2001; Qiu, 2010; Tao et al., 2003; Tao et al., 2005; Xiong et al., 2009). Groundwater overexploitation is unsustainable, whether in the NCP or other parts of the world (Giordano 2009; Gleick and Palaniappan, 2010). The current practice will have to come to an end in the foreseeable future. Energy costs for pumping up the water increase with groundwater table depth. On the east coast, overdraft of groundwater already causes seawater intrusion into fresh water reservoirs (Xue et al., 2000). Furthermore, groundwater from deep aquifers can contain toxic levels of fluoride and arsenic (Currell et al., 2012). Health problems may therefore increase as pumping reaches into deeper layers. It is unclear when water extraction will become economically or practically impossible, but this moment is approaching. Once water resources are depleted, there will be no more "life-saving" irrigation possible in

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http://dx.doi.org/10.1016/j.agwat.2015.11.005
0378-3774/

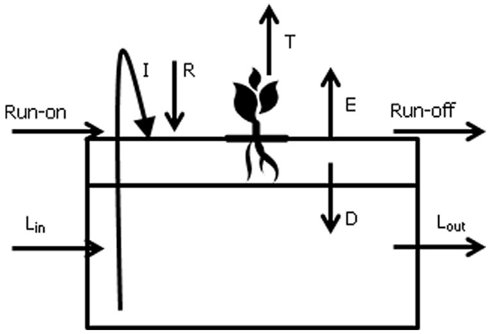

Fig. 1. Water balance. I = irrigation (from groundwater), R = rainfall, T=transpiration, E = evaporation, D = drainage below the rootzone. $\Delta L = L_{in} - L_{out}$ = net lateral inflow underground. Net groundwater recharge is $D + \Delta L - I$.

the dry years, no bank to provide a loan to help us through the dry years. This is especially serious in the context of monsoonal climate variability, which can experience extended periods of drought, as was for instance witnessed in the Sahel region in Africa in the 1970s and 1980s (Shanahan et al., 2009).

Groundwater extraction must be drastically reduced to conserve the aquifers, and this would inevitably cause a large drop in production in the North China Plain (Wang et al., 2008). However, continuation of overusing the groundwater now will affect future generations who would have reduced access to groundwater, possibly none. Even though reductions of ground water use may seem socially and politically unacceptable now, it is critical to think about options to move towards a more sustainable system. Here, we have defined a sustainable system as one that does not deplete the groundwater on average over an extended number of years, i.e. where in the long term groundwater storage does not change.

To calculate the input/output balance of the water resource in aquifers, we consider the water extraction for irrigation (I) as output, and drainage below the root zone (D) and net lateral underground flow ($\Delta L = L_{in} - L_{out}$) as inputs (Fig. 1). The groundwater table remains at the same level (neutral) if $I = D + \Delta L$ and groundwater declines if $I > D + \Delta L$. Run-on, run-off and the difference between soil moisture at the start and end of a simulation are of no significance on longer time scales and are therefore not considered in our study.

The simplest solution to stop groundwater decline is reducing irrigation input (I). But often this also leads to reduced drainage (D) so that the net effect is that groundwater levels keep going down (Kendy, 2003; Kendy et al., 2003, 2004). Hence, irrigation needs to be reduced by a greater amount than the current net extraction from ground water. We therefore consider the full water balance, which includes the rainfall (R), evaporation (E), transpiration (T), run-on, run-off and the difference between soil moisture at the start and end of a 50 years (1961–2011) simulation (Fig. 1).

Another much studied solution to growing water scarcity is improving water use efficiencies (Condon et al., 2004; Fang et al., 2010; Xue et al., 2000; Zhang et al., 1999, 2003, 2006). Increased water use efficiencies are obtained by having a greater share of the water input (I or $I + R$) taken up by the crop (T) and less "lost" through drainage (D) or evaporation (E). However, if at unchanged irrigation input the drainage is reduced, then increased water use efficiencies will actually speed up groundwater decline. Increasing efficiency is therefore not a sufficient solution to the problem of declining water resources (Kendy 2003; Kendy et al., 2003, 2004).

A third possible management option is to not irrigate at all. Zero irrigation would eventually lead to increases in the groundwater table: in wet years part of the rainfall will drain below the root zone, replenishing the aquifer. However, the yield penalties of zero irrigation are very large (Wang et al., 2008). An important question is how much groundwater can be extracted annually while maintaining a neutral or slightly positive, long term downward water flux. Such baseline quantification is essential to determine sustainable irrigation levels. Best use of such irrigation can best be assessed via simulations (Chen et al., 2010a,b; Mao et al., 2005; Wang et al., 2008).

Under zero irrigation with rainfed agriculture, our study area has a small rainfall surplus (rainfall minus ET > 0) and therefore a small lateral discharge to neighbouring aquifers and streams. Pumping decreases lateral discharge, because the hydraulic head at the pumping site becomes lower than that of neighbouring sites (Theis, 1940; Sophocleous, 2000; Bredehoeft, 2002; Devlin and Sophocleous, 2005; Zhou, 2009). The decrease will stop after some time in case of sustainable pumping rates so that a new equilibrium is installed, at which storage remains unchanged. "Sustainable pumping rates" are pumping rates at which groundwater storage remains unchanged in the long run (Devlin and Sophocleous, 2005; Zhou, 2009). Groundwater neutral cropping systems are cropping systems with sustainable pumping rates. The evapotranspiration (ET) differs between each cropping system, therefore each groundwater neutral cropping system has its own and different sustainable pumping rate. Our definition of sustainable pumping rates states that all rainfall received at a particular location may be consumed by evapotranspiration at the same location. As some of the rainfall infiltrates below the root zone in wet years (i.e. becomes gross recharge) we permit some pumping to recapture this part of the rainfall. But nothing more than that. Past pumping has already led to a drop from a net lateral outflow of around 42–53 mm/year to a net inflow of 16 mm/year. This reduction represents the water already captured from nearby aquifers. This deficit accumulated over a longer timespan cannot easily be undone (unless a purely rain-fed cropping system without any irrigation is adopted). At the very least, one should attempt not to further aggravate the situation. Therefore we allowed no further mining of nearby aquifers, something warned for by Sophocleous (2000). Therefore, we imposed the constraint of a constant (=not increasing) net lateral inflow ΔL. With this constraint complex spatio-temporal modelling of groundwater dynamics is not needed and the analysis can be simplified to a simple water balance calculation.

With sustainable pumping rates the long run drainage plus net lateral underground flow equals the irrigation and evapotranspiration equals rainfall plus net lateral underground flow: $\Sigma(D + \Delta L) = \Sigma I$ and $\Sigma(E + T) = \Sigma(R + \Delta L)$. In this paper, we take 50 years as a summation period thus accounting for weather and high frequency climate variability (i.e. ENSO), but not for decadal and multi-decadal climate variability (Howden et al., 2007). Although simulation of climate change effects is not a key objective of this paper, we do include one climate change scenario to assess the sensitivity of our outcomes to future climate change.

The objective of this paper is to construct groundwater neutral cropping systems and compare these in terms of productivity and risk with the current unsustainable practice and with the possible future scenario when irrigation would no longer be possible. Sustainability is a broader concept than "sustainable pumping rates". Sustainability has many environmental and social dimensions, whereas "sustainable pumping rates" are simply those pumping rates at which groundwater storage does not change (Devlin and Sophocleous, 2005; Zhou, 2009). We follow this distinction in this paper. In Sections 2 and 3 we compare 3 cropping systems with current practice (declining water table), 8 cropping systems with sustainable pumping rates and 8 cropping systems with zero pumping rates. In Section 4 we place these in the broader perspective of sustainability.