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Basin-wide evapotranspiration management: Concept and practical application in Hai Basin, China

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ABSTRACT

As the demand for water resources continues to grow, the current "demand management" approach often fails to deliver the expected results in terms of reduced water consumption, release of water to other uses, or improved environmental conditions. Recognizing that evapotranspiration (ET) represents the dominant consumptive use of water in the hydrologic cycle, this paper describes an approach to basin-scale water resources management based on ET. The ET management approach comprises four stages: (i) a basin-scale water consumption balance; (ii) determination of a target ET consistent with sustainable water consumption; (iii) identification of water consumption tradeoffs, competition and feedback among different water sectors (agricultural, industrial, domestic, and socio-environmental); and (iv) basin-wide monitoring of sustainable water consumption. Continuous, basin-wide ET data obtained from the ETWatch models are combined with estimates of water consumption as a result of mechanical, chemical, and biological energy to assess the water consumption balance, and set targets. On this basis, water resource managers can identify opportunities to achieve sustainable, productive use of water resources by (i) reducing non-beneficial ET; (ii) converting non-beneficial ET to beneficial ET; and (iii) increasing the productivity of beneficial ET. Irrigated agriculture is usually the largest controllable contribution to ET in a basin, so meeting the target ET for agriculture is key. A water balance analysis for Hai Basin and the implementation of ET management in the Basin are presented to illustrate the ET management approach.

1. Introduction

Approaches to managing water resources have changed over time, depending on the sources and uses of water, the supply/demand balance, and available technologies. At first, users simply took the water they needed from the natural river flows and shallow groundwater aquifers that were recharged each year. Later, more organized water resources management focused on supply management—increasing the water supply through the construction of water diversion, transfer and storage projects. As development continued to meet ever-increasing demand, competition for water among industrial, agricultural, domestic and ecological uses led to serious environmental problems, such as a decrease in natural flows, declining aquifers, habitat destruction, and water pollution (Barnett and Pierce, 2008; Qureshi et al., 2011).

As global demand for water resources continues to rise in parallel with social and economic development and population increases, the fourth World Water Development Report by the UN Educational, Scientific and Cultural Organization has warned that the world's water resources are under pressure (Gallopín, 2012). Groundwater in particular is often overexploited in arid and semiarid regions where surface water resources are inadequate to meet demand. The global groundwater abstraction rate has at least tripled over the last 50 years and is still increasing at an annual rate of between 1% and 2% (Van der Gun, 2012). According to recent estimates at country level (Margat, 2008; Siebert et al., 2010), the world's aggregate groundwater abstraction in 2010 is approximately 1000 km^3, of which about two-thirds is abstracted in Asia, with India, China, Pakistan, Iran, and Bangladesh as the major consumers (Van der Gun, 2012). Wada et al. (2012) estimate that 20% of this abstraction is not replenished by natural recharge, with China among the four countries most affected.

Often, the most productive agricultural areas in semi-arid and arid regions are most at risk from groundwater crises. In the Indus River plain, for example, groundwater depletion between 2002 and 2008 has been equivalent to a net loss of 109 km^3 of water, which is double the capacity of India's largest surface-water reservoir (Rodell et al., 2009). From pre-development up to 2007, the average decline of ground water levels in the High Plains of the United States has been 4.34 m, with some zones where groundwater levels have

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dropped by up to 60 m (McGuire, 2009). In the North China Plain, groundwater levels dropped by about one meter per year between 1974 and 2000, forcing continual deepening of wells to access fresh water (Qiu, 2010). In Iran, decades of unrestrained groundwater extraction have resulted in widespread land subsidence (Motagh et al., 2008), with Lake Hamoun, formerly the largest freshwater body in Iran, disappearing (MacFarquhar, 2001) and Lake Urmia, the largest salt body in Iran, experiencing a rapid decline in water level, salt storms, and other environmental problems (Pengra, 2012).

With supply-enhancing options leading to unsustainable use of water resources, the demand management approach was adopted. Water demand management focuses on controlling and limiting water demand in a variety of ways: specification of water quotas and entitlements; reducing losses by improving irrigation efficiency and water use efficiency[1]; charging for water; and reallocating water (either by markets or by fiat) away from lower value uses. Such interventions have sometimes contributed to a slower increase in water use. Demand management, however, has not provided all of the ecological and other benefits that were anticipated.

Demand management is not simple: water availability is unpredictable over time and space; demand, especially for irrigation, tends to be highest when supplies are lowest; and persuading water users to invest their time and resources in "saving" water so that the saved water can be transferred elsewhere is not easy. Water, especially in aquifers, is prone to the "tragedy of the commons" (Hardin, 1968) where each individual user's incentive is to maximize use rather pursue a lower, "sustainable" rate of use that would benefit the community (or the environment) in the long run.

This paper addresses a specific issue that affects several of the interventions adopted to implement demand management: failure to assess water resources on a basin wide scale or across the complete water cycle (including the flow of surface water to ground water), leads to interventions that appear to "save" water locally while actually contributing to an increase in water consumption when assessed at the basin scale. In particular, local increases in irrigation efficiency bear no necessary relationship to impacts at the basin scale (Perry, 2007; Perry et al., 2009; Ward and Pulido-Velazquez, 2008; Adamson and Loch, this issue; Young, this issue) and local water "saving" measures, taken without considering the hydrologic connection between upstream and downstream or between surface and groundwater systems, may have unforeseen and perverse consequences.

Approaches to water demand management that limit abstraction[2] do not necessarily control the consumption of water—if a farmer changes from flood irrigation to drip, for example, the proportion of water applied to the field that is *consumed* by crop transpiration increases even if less water is *applied* (Willardson et al., 1994; Perry, 2007). Since farmers generally wish to expand irrigated areas, increase the cropping intensity, or plant high water consumption crops, they will exploit the opportunity to do so if improved technology minimises outflows from their land and allows increased cropped area. This trend has been documented in the North China Plain (Lohmar et al., 2002), where gross abstractions from groundwater have fallen over recent decades while the irrigated area has increased and aquifers have declined as fast or faster than before.

Improved on-farm irrigation efficiency also has the effect of making abstraction financially more profitable and hence more difficult to control. Experiences from a recent World Bank project in Yemen (World Bank, 2012), where the profitability of pumping water from very deep aquifers was substantially increased by technical improvements to the distribution system highlighted precisely this problem.

In sum, the focus on demand management, through on-farm water savings applications (Qureshi et al., 2011), infrastructure improvements (Connell and Grafton, 2011), agronomic and biological measures (Evans and Sadler, 2008), and economic and policy instruments (Qureshi et al., 2011) has not always led to the expected and desirable release of water to other uses. Even countries such as the United States and Australia with mature water rights trading markets experience water resources depletion if proper provisions are not in place to limit actual consumption (Chong and Sunding, 2006; Connell and Grafton, 2011; Grafton et al., 2011).

Because, from the perspective of a river basin, the dominant water outflows are consumption by evapotranspiration (ET) and (usually to a lesser extent) water discharged to the sea, demand management must focus on water consumption, not just water abstraction. Managing ET becomes the most important aspect for basin-scale water resources management (Martin, 2010; Perry et al., 2009). Understanding and mapping basin-wide ET is the essential first step, and reducing ET, especially in irrigation projects will usually be the first priority. This is especially true for the arid and semi-arid river basins where ET from irrigated agriculture represents the major consumptive use of water. In Australia, for example, approximately 90% of total rainfall returns to the atmosphere through ET (Merze, 2010) and in China, 98% of total water resources in the Hai Basin and 99% of water resources in the Turpan River Basin were consumed as ET (Wu, 2010; Wu et al., 2011).

ET data have been widely used, in the design of irrigation projects and as the basis for agricultural irrigation scheduling (Davis and Dukes, 2010; Droogers et al., 2010; Ko and Piccinni, 2009; Santos et al., 2008). In small areas, ET could be measured and monitored using various approaches such as lysimeters, surface renewal systems, heat pulse velocity, Bowen ratio techniques, eddy covariance analysis, and large aperture scintillometers (Castellví and Snyder, 2010; Dugas et al., 1991; Meijninger and De Bruin, 2000). However, these techniques are not practically applicable for understanding the wider impact of interventions at project or catchment scale, or for resolving interstate water conflicts. Measuring and monitoring ET at these scales requires continuous spatial and temporal datasets at project, catchment and basin scales (Wu et al., 2012). Meanwhile, satellite sensor technologies and remote sensing applications have developed since the 1980s, and various methods for estimating regional or catchment scale ET from thermal infrared imagery have been developed, such as Liu (Liu et al., 2012), Alexi and Disalexi (Anderson et al., 1997; Norman et al., 1995), SEBS (Su, 2002), SEBAL (Bastiaanssen et al., 2005), METRIC (Allen et al., 2007), and ETWatch (Wu et al., 2008, 2012; Xiong et al., 2010). Some of methods can be used to map ET time series and enable basin-scale ET management.

Building on these developments and available data, this paper describes an approach for basin scale water resources management based on ET. The next section introduces the main concepts and methodology, followed by the application of the approach to the Hai Basin, China. The final section presents the results of the analysis.

2. The ET management approach

2.1. Relevant concepts

The ET management approach uses high resolution, continuous remote-sensing based ET data along with estimates of industrial

[1] Throughout this paper, "irrigation efficiency" implies a dimensionless ratio, for example water delivered to the field divided by water diverted from a dam. "Water Use Efficiency" is a productivity term relating the quantity or value of crop produced (kg or dollars, for example) to the water consumed by the crop.

[2] For simplicity, "abstraction" is used to refer to any augmentation of the naturally available water to an area, including pumping from aquifers, diversion from rivers, or utilisation of water from storage reservoirs.