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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.

and biological water consumption to determine total water consumption (defined as the amount of water evaporated, transpired, or lost through perspiration, and thus removed from the system) in a basin. ET management distinguishes between controllable and uncontrollable ET, as well as beneficial and non-beneficial consumption.

2.1.1. Total evapotranspiration by solar energy, domestic and industrial water consumption

The largest amount of water consumption in an area is typically due to evapotranspiration as a result of solar energy (ET_{sol}). This includes ET from agriculture (ET_{agr}) and from areas such as forests, grasslands, water surfaces and bare soil (ET_{env}). In addition, water is consumed as a result of mechanical, chemical energy processes that happen throughout the basin (Q_m). Such consumption includes cooking, industrial production, and electricity generation, or occurs when water is embodied in an industrial product. Water consumption from biological energy processes (Q_b) includes perspiration by people and animals.

2.1.2. Uncontrollable and controllable ET

Uncontrollable ET (ET_{unc}) includes ET from the natural environment (woodlands, grasslands and wetlands) as well as from impervious surfaces or soil evaporation from unvegetated areas. The actual ET from such surfaces depends on the precipitation and the characteristics of the surface area.

Controllable ET (ET_{con}) is the evapotranspiration that is or can be affected by human interventions. This category of evapotranspiration includes consumption from residential and industrial land (ET_{res_con}) and agricultural land (ET_{agr_con}). The ET from the residential and industrial land further comprises landscape water consumption, mainly from landscape water surfaces and man-made green areas, direct residential consumption as a result of cooking and washing and direct industrial consumption (Q_m) as power plant and steel factory cooling water loss, and indirect residential and industrial consumption, including evaporation from soil or water surfaces when water used by humans returns does not return to the water system.

2.1.3. Beneficial and non-beneficial consumption

The last important concept for ET management is the distinction between beneficial and non-beneficial consumption. Beneficial consumption is water evaporated or transpired for an intended purpose, while non-beneficial consumption is water evaporated or transpired other than for the intended use (Perry, 2007). For example, transpiration from an irrigated crop and evaporation from a cooling tower are beneficial consumption, while water evaporation from water logged or seepage areas, or from exposed water surfaces are generally non-beneficial consumption.

The distinction between beneficial and non-beneficial consumption often requires judgement. Changes in management (for example to retain water longer in a dam for a different cropping pattern) will induce extra evaporation from the dam which must be accounted for as necessary, though not directly beneficial consumption to achieve the new objective. Differing perspectives of the benefits of preserving a natural landscape compared to developing agriculture for food security can only be resolved politically.

2.2. Four steps in the ET management approach

To achieve sustainable and productive water resources management on a basin-wide scale, ET management focuses on controlling and reducing ET wherever possible, and maximizing beneficial consumption as a proportion of total consumption. ET management comprises four steps: (i) developing a basin scale water consumption balance analysis, (ii) calculating, based on sustainability objectives, the target ET for the basin, (iii) dividing the target ET among different sectors and industries by weighing and comparing the competing water demands from agriculture, industry, domestic use, and social and environmental, and (iv) monitoring and assessing achieved water consumption savings. While the first and last steps involve only a technical analysis of available data, the second and third aspects require input on sustainability objectives and priorities from stakeholders, planners, and policymakers.

2.2.1. Basin scale water consumption balance analysis

Conventional water balances consider the inflow and outflow of water in a given area, taking into account the change in storage. In Wu et al. (2011), a basin scale water balance analysis method was presented based on water consumption. The results of such an analysis can be used to determine whether water consumption in a basin or sub-basin is sustainable, or whether water consumption must be reduced to restore equilibrium.

As described in Wu et al. (2011), the ET based balance analysis equation is as follows,

$$P - \mathrm{ET} - O + I = \Delta \mathrm{gw} + \Delta s \quad (1)$$

where P is basin precipitation, ET is total water consumption (water that leaves the system through evaporation and transpiration); surface water inflow to the area is I; surface water outflow is O (I and O may include inter-basin transfers); Δgw is the change in groundwater and soil water storage in a certain period, and Δs is the change in surface water storage. When groundwater is not overdrafted, Δgw is zero. Because soil water storage generally is assumed not to change over an annual cycle, any change in regional water storage is considered to be mainly the result of a change in groundwater storage. Precipitation data (P) can be measured at observation stations or using remote sensing, while inflow and outflow data are measured at major control point and river sections.

As described in Section 2.1.1, total evapotranspiration (ET) is the sum of evapotranspiration caused by solar energy (ET_{sol}) and the water consumption in industrial and domestic processes, respectively referred to as Q_m and Q_b.

$$\mathrm{ET} = \mathrm{ET}_{sol} + Q_m + Q_b \quad (2)$$

ET_{sol} can be obtained using the ETWatch model, which is an integration of the "Residue Approach" and Penman–Monteith. The model consists of five subsystems and a system database (Wu et al., 2012). The five subsystems include data acquisition, data pre-processing, ET monitoring, ET application, and database management. Since 2008, ETWatch has been installed at the Hai Basin Commission of the Ministry of Water Resources and Beijing Municipal Office of Water Affairs. The input datasets for estimating ET of Hai Basin during the period 2002–2009 are composed of remote sensing data and meteorological data. Remote sensing data include MODIS product files, which are provided by the NASA Goddard Space Flight Center Distributed Active Archive Center. Data can be downloaded from their website (reverb.echo.nasa.gov/reverb). Meteorological data are provided by the meteorological data center of the China Meteorological Administration. Due to cloud cover and satellite overpass intervals, ET datasets often contain large temporal gaps; ETWatch addresses this problem through a Gap-filling algorithm in cloudy days (Wu et al., 2012).

For completeness, we estimate evaporative water consumption by industrial sectors and by humans and livestock. These are best estimates, though probably less accurate than the major flows from vegetation.

Q_m can be divided into water consumption by different industrial sectors and calculated with the following equation:

$$Q_m = \sum_{i=1}^{n} P_i \times Co_i \quad (3)$$

where Q_m is industrial water consumption, i is type of industry, P_i expresses the production of this type of industry, and Co_i is the water consumption coefficient per unit output value of this type of industry.

Wu et al. (2011) discuss the calculation method for water consumption by industry and domestic sectors. Hai basin is a center of coal-fired generating plants, iron and steel enterprises, which are main water consumption enterprises in industrial sector. According to the statistics from National Development and Reform Commission (2006), the water consumption per kWh electricity was 3.5 kg/kWh in 2002, 3.4 kg/kWh in 2003, 3.2 kg/kWh in 2004, and 3.1 kg/kWh between 2005 and 2007. There are many large iron and steel enterprises in Hai basin. Refer to the statistics from Wang (2007), the water consumption of one ton of iron-making process for large iron and steel enterprises was approximately 19–34 m^3/t. The water consumption for steel-making process is difference from enterprise to enterprise, as 4.98 m^3/t in Shougang group, 6.09 m^3/t in Handan iron and steel group, and 4.25 m^3/t in Tangshan iron and steel group. It is difficult to collect all water consumption rate of industrial sector, so the total water consumption of industry is calculated using water consumption rate per production unit and production of main water consumption industrial sectors. For example, the water consumption of a coal-fired plant can be calculated by the total electricity generated in the region and the water consumption rate per unit of electricity, the water consumption for iron-making process can be calculated by the total production and water consumption rate per unit output.

Q_b expresses annual perspiration, which is calculated with the following equation:

$$Q_b = \sum_{i=1}^{n} Q_i \times F_i \quad (4)$$

where Q_i is the number of people or different types of livestock and F_i is the perspiration factor. In general, perspiration of one people is approximately 0.004–0.005 m^3 of water per day in the summer, 0.0008 m^3 per day in the spring and autumn, and 0.0005 m^3 per day in the winter and average annual perspiration is 0.56 m^3 (http://care.39.net/0781/14/92595.html), because of without the perspiration of livestock, this paper uses average annual perspiration of human being as perspiration factor to calculate the perspiration from livestock.

Equation (1) for the observed situation can now be rewritten as:

$$P-(ET_{env\_unc} + Et_{imp\_unc} + ET_{bar\_unc} + ET_{res\_con} + ET_{agr\_con} + Q_m + Q_b)-O+I = \Delta gw + \Delta s \quad (5)$$

2.2.2. From actual ET to target ET

Once the water balance within a basin is established, the same data provide the basis to determine the sustainable ET for the basin, and its components sectorally and spatially. This is a step beyond conventional water balance models which do not account for consumption limitations that will protect ecosystems and stabilise aquifers.

The target ET (ET_{tar}) is defined as the maximum value for total controllable water consumption in the basin that would allow for sustainable water resources management based on the following four principles: (i) groundwater is not overexploited; (ii) natural ecological systems receive enough water to remain healthy; (iii) the environmental flow in the river is preserved, and (iv) the water cycle—the link between ground and surface water—is not broken. Using these four principles and based on formula (1), the target ET can be calculated with the following equation:

$$ET_{Tar} = P + I_{env} - O_{env} - (ET_{env\_unc} + Et_{imp\_unc} + ET_{bar\_unc}) \quad (6)$$

and

$$ET_{Tar} = (ET_{res\_con} + ET_{agr\_con} + Q_m + Q_b) \quad (7)$$

where P, I and O, are basin precipitation, inflows and outflows as before, with I and O redefined to meet environmental criteria for river flow status are met. Et_{unc} is total uncontrollable evaporation and transpiration. Precipitation (P) can again be measured at observation points or from remote sensing data. Environmental flows can be calculated with various observation or simulation methods (Chan et al., 2012; Meijer et al., 2012; Sun et al., 2012; Wang et al., 2012; White et al., 2012), depending on the particular objective for ecosystem protection.

The uncontrolled ET can be determined by combining the various uncontrolled ET losses from the environment (ET_{env_unc}) and human-made impervious surfaces (ET_{imp_unc}) and bare farmland (ET_{bar_unc}). In the case study below, ET_{env_unc} is determined using the ETWatch model and a detailed land use map of Hai basin. The MESMA method (Wang et al., 2011) was used to determine the impervious surface. ET_{imp_unc} and ET_{bar_unc} are calculated with ETWatch based on temperature difference (Liu et al., 2011) and NDVI time series.

2.2.3. Water consumption tradeoffs, competition and feedback

After determining the target ET as the average maximum allowable controlled water consumption to maintain sustainable consumption of water resources, this target value can be allocated among the different water sectors, such as agriculture, industry, domestic use, and social and eco-environmental consumption. In this allocation process, water administrators and policymakers must assess the priorities and trade-offs between different water sectors, and within sectors for specific industries or units. Guiding principles could include: (i) consideration of essential industries and activities (availability of clean drinking water, domestic use, and food production), (ii) national, regional, and local administrative goals and priorities, and (iii) differences in water productivity among competing entities.

By allocating allowable, target ET to sectors, the water savings focus shifts from limiting abstraction to limiting water consumption, and finally to increasing water productivity per unit of ET.

The stages of ET management consist of interventions to reduce water consumption, while increasing productivity per unit of water consumed so as to maintain and if possible enhance production. Such interventions include:

- *Enhancing water security for rain-fed crops*. In the case of rain-fed crops, the variable water supply causes fluctuation in crop yield between years. Under these circumstances, farmers choose risk-minimising, low input strategies. Security is improved by mulching (to retain moisture for productive transpiration while reducing non-productive evaporation), and increasing infiltration to improve soil moisture status. Such interventions will increase WUE, as farmers are encouraged to increase investments when they are sure the needed water will be available, but may also increase local ET to the extent that previous runoff or percolation to aquifers is intercepted.
- *Reducing non-beneficial ET under irrigated conditions with secure water supplies*. When the water supply is reliable, farmers tend to enlarge the area of irrigated land in an effort to further increase

yield, consuming a higher proportion of the irrigation water applied to the crop. At this stage of water management, the aim should be improving WUE through a reduction in non-beneficial ET. In irrigated cropping systems, the relationship between *E* (evaporation of water directly into vapour from wet soil and foliage), *T* (transpiration of water through the plant, with water vapour emitted through the stomata of the leaves), and biomass production is not always straightforward. For standardised climatic conditions, biomass production for most field crops is a linear function of transpiration (see for example Howell, 1990). This suggests that it will normally be beneficial to minimise E and ensure that T is as large as possible. However, as Balwinder-Singh et al. (2011) have reported, for relatively dense crop stands *E* actually contributes to a micro-climate that reduces the evaporative demand on the crop so that the "non-productive" *E* is actually offset by a reduction in *T* required to meet a specific level of production. The physical explanation of this is that biomass production is maximised when *T* is at its maximum *potential* level, which in turn is a function of the vapour pressure deficit experienced by the leaves of the plant. Local *E* reduces the vapour pressure deficit and to that extent allows maximum biomass production at a lower absolute level of transpiration (though $E+T$ remains essentially constant). While foliage is less dense, this effect is not significant—and *E* indeed is non-beneficial consumption.

- *Increasing production under stable ET*. Decreasing ET is important for water savings, but to ensure a healthy environment, the non-beneficial ET cannot be reduced to zero. When non-beneficial ET has been reduced through various appropriate methods, it becomes important to increase crop yield under stable ET, increasing yield (and thus WUE) by using improved crop varieties, fertilizers, and other agricultural inputs.

An additional "source" of water to increase production is to ensure that non-recoverable outflows are minimised: while the change in storage is the balancing item in the equation of water balance, not all changes in storage are of equal value: percolation to fresh aquifers can be recovered by pumping, but if the aquifer is saline (or so deep as to be economically unusable) the impact in terms of lost productivity is the same as non-beneficial ET, and "saving" this water through conventional improvements to irrigation efficiency allows increased production from the same level of water removed from the system.

2.2.4. Monitoring and assessment of achieved water consumption savings

To assess whether water consumption in a basin is sustainable, the final step in the ET management process is monitoring—comparing the total actual water consumption with the target ET. Water consumption will have been sustainable if the total controllable water consumption is less than ET_{tar}. The following formula can be applied:

$$D = \frac{(ET_{tar} - ET_c)}{ET_{tar}} \times 100 \quad (8)$$

In which *D* is an indicator of the level of meeting the ET_{tar}, ET_c is controllable ET and ET_{tar} is the target ET. If *D* is larger than zero, basin water consumption is sustainable. If *D* is less than zero, groundwater is over-exploited and basin water consumption is unsustainable. In that case, measures should be taken to decrease ET consumption.

3. Practical application of ET management to Hai Basin, China

To illustrate the ET management approach described in Section 2, data from Hai Basin in China is used for a water basin analysis, ET target setting, and calculation of the *D* value, where a recent GEF/World Bank funded project in ET management has been successfully applied.

3.1. About Hai Basin

Hai Basin is located in North-East China between 112–120°E and 35–45°N (see Fig. 1). The basin is bordered in the east by the Bohai Sea, in the west by the Taihang Mountains, in the south by the Yellow River, and in the north by the Mongolia Plateau. The region, with a total area of 317,800 km^2, includes 15 sub-basins.

The average annual water resources of Hai basin are 37 billion m^3. The per capita water resources are only 276 m^3. Hai Basin currently experiences the most severe shortage of water resources in China (Wu and Lu, 2011) and because of this has been the focus of several studies on water resources management.

3.2. Water consumption balance analysis for Hai basin

Calculated using formulas (1)–(4), national statistics, ETWatch, and basin water resources data, Table 1 presents the water consumption balance analysis for Hai Basin for 2002–2007. ET data for Hai Basin is at 1 km resolution. From 2002 to 2007 average available water resources, average water consumption, and average outflow were 160.3 billion m^3, 164.6 billion m^3, and 1.9 billion m^3, respectively. The analysis indicates groundwater was seriously overexploited with an average storage change of −6.23 billion m^3.

The analysis shows that of the total water consumption, ET from agriculture (ET_{agr}), environmental ET (ET_{env}), domestic water consumption (Q_b), and industrial water consumption (Q_m) account for 54.3%, 43.4%, 2.2%, and 0.1% respectively. Because environmental ET cannot be controlled, and industrial and domestic water consumption are of high socio-economic priority and only account for a very small part of total water consumption, the data confirm that most attention should be paid to reducing agricultural ET.

3.3. Setting a target ET in Hai basin

To determine a target ET for Hai basin and its sub-basins, Eqs. (6) and (7) was used to determine a sustainable ET based on the available precipitation (*P*), the environmental flows (I_{env} and O_{env}), and the uncontrolled ET from 2002 to 2007. The environmental flow for each sub-basin was determined by taking 23.1% of the average annual surface flow, using the Hai Basin estimate by Li and Zheng (2000).

Uncontrolled ET is the total of ET_{env_unc}, ET_{imp_unc} and ET_{bar_unc}. ET_{env_unc} was determined using ETWatch and a land-use map for Hai Basin; ET_{imp_uc} was determined using ETWatch and human-made impervious surfaces; ET_{bar_uc} determined using ETWatch and MODIS NDVI time series. The ET targets as well as actual measured values for ET (based on remote sensing data and calculations of biological (Q_b) and industrial water consumption (Q_m)) are presented in Table 2.

While the target for controlled ET (ET_{tar}) for total Hai Basin was 32.33 billion m^3, the actual average controlled ET (ET_c) was 39.06 billon m^3, some 6.73 billon m^3, or about 20% above the target, indicating water consumption from groundwater was above the maximum for sustainable development of water resources for the five year period under review. With the residential and agricultural components of the controlled ET contributing the most (respectively 16% and 79% of the total controllable ET), most attention should be paid to reduce residential and especially agricultural ET.

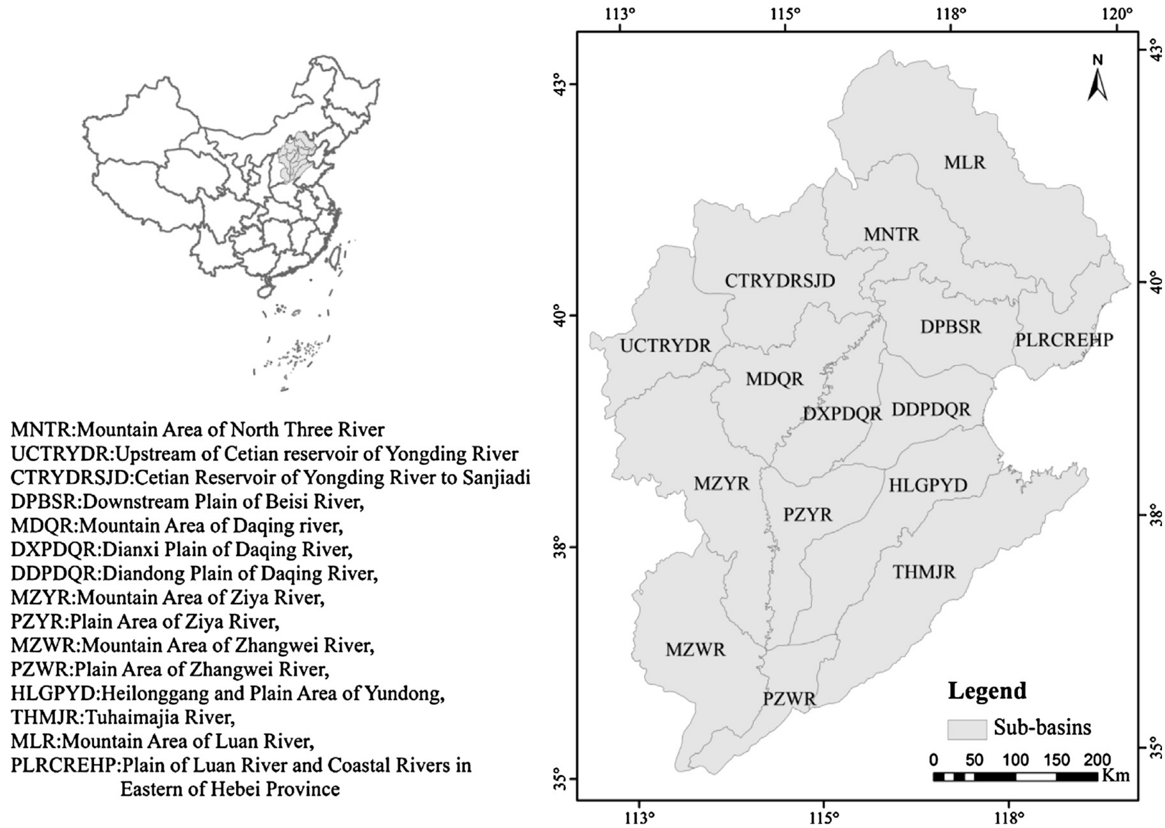

Fig. 1. Location of Hai Basin and its sub-basins.

3.4. Water consumption competition in Hai Basin

Water consumption management in Hai basin is still at an exploratory stage and tradeoff, competition, and control mechanisms have not yet been established. However, it is clear that different water sectors are competing for water resources, resulting in a serious, largely uncontrolled groundwater crisis. Imbalances between supply and demand are not always based on abstraction of river and groundwater: in the Miyun reservoir in Hai Basin, for example, as a result of a forest restoration project, total water consumption upstream of the reservoir in the Chaobai river catchment of the mountain area of north three river (MNTR) (see also Table 2) increased by 6% after 2000 according to monitoring results. Healthier forests intercept and transpire more rainfall than degraded forests. While this increase happened, competing sectors did not decrease their water consumption. Research results (Wu et al., 2011) indicate that from 2002 to 2007 the deficit of water in MNTR was $-8.84 \times 108\,\text{m}^3$, while the groundwater storage change was $-7.4 \times 108\,\text{m}^3$, which meant that the water consumption above ET_{tar} came from groundwater. In another part of the basin, in Hebei province, serious competition for water resources is coming from golf courses: the total water consumption per golf course is 180–240,000 m^3 per year.

3.5. Review and supervision of results: Calculating the D value

Using Eq. (8), the *D* value can be calculated for Hai Basin and its sub-basins. Fig. 2 presents an overview and illustrates the regions with sustainable water consumption when controlled ET is below the target ET (white bars) and unsustainable water consumption when controlled ET is above the target ET (black bars).

The overall *D* value for Hai basin is −21% for 2002–2009, indicating overall water consumption in the basin must fall substantially to achieve the desired equilibrium. The same is true for most

Table 1
Water consumption balance analysis for Hai Basin, 2002–2007 ($10^6\,\text{m}^3$) (Wu et al., 2011).

Item	2002	2003	2004	2005	2006	2007	Average	%
Available water resources ($I+P$)	132,020	189,900	176,480	159,580	144,880	159,040	160,310	100.0
Water inflow (I)	4640	3610	4230	3730	4630	4280	4190	2.6
Precipitation (P)	127,380	186,290	172,240	155,850	140,250	154,750	156,130	97.4
Outflow (O)	180	2180	3710	2490	1390	1710	1940	
Water consumption (ET)	151,150	183,380	166,180	155,660	167,270	163,980	164,600	100.0
Agricultural ET (ET_{agr})	84,220	97,000	91,960	84,380	90,230	88,990	89,460	54.3
Ecological environment ET (ET_{env})	63,750	83,240	70,660	67,100	72,870	70,820	71,410	43.4
Residential water consumption (Q_b)	80	80	80	80	80	80	80	0.1
Industry water consumption (Q_m)	3090	3060	3490	4090	4090	4090	3650	2.2
Water storage change Δs	−19,310	4340	6590	1440	−23,780	−6650	−6230	

Note: ET data is obtained from the ETWatch model; data on precipitation, inflow, outflow, inter-basin water transfer, and sea outflow are obtained from the Hai Basin water resources bulletin; population data from national statistical books and statistical yearbooks; industry data are from statistical year books, Chinese power statistical book, and the Chinese energy statistical book. This water consumption analysis was first presented in Wu et al. (2011).

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Table 2
Target ET and controllable ET in Hai Basin (10^6 m^3), annual average for 2002–2007.

Sub-basins of Hai Basin	*P*+*I*	ETunc	*O*	ETtar	ETsol_c		Q_b	Qm	Total ETc
					ETres_c	ETagr_c			
MNTR	10,986	10,158	524	304	168	844	1	30	1043
UCTRYDR	6625	5058	146	1421	132	599	2	134	867
CTRYDRSJD	10,838	8621	206	2011	194	958	3	104	1259
DPBSR	8235	4525	286	3424	1047	3515	10	303	4875
MDQR	9211	7910	544	757	95	720	1	48	864
DXPDQR	6183	3545	43	2595	883	3685	6	168	4742
DDPDQR	6899	4182	168	2549	718	2671	7	160	3556
MZYR	15,800	11,125	652	4023	238	1691	4	262	2195
PZYR	7634	4215	26	3393	1004	4634	7	264	5909
MZWR	14,827	10,072	585	4170	251	2000	4	224	2479
PZWR	5269	2641	141	2487	484	3232	5	136	3857
HLGPYD	11,973	6743	135	5095	984	6294	6	136	7420
Hai Basin[a]	114,480	78,795	3455	32,230	6198	30,843	58	1969	39,068
Ratio of ET_c					16%	79%	0%	5%	100%

P = precipitation; ETunc = uncontrolled ET; *O* = required environmental outflow; ETtar = target ET; ETsol_c = controlled ET as a result of solar energy; ETres_c = controlled residential ET; ETagr_c = agricultural ET, Q_b = biological consumption; Qm = industrial consumption; Total ETc = total amount of controlled ET.

[a] Tuhaimajia river, mountain area of Luan River, the Plain of Luan River, and coastal rivers in east Hebei Province are not included in this Hai Basin total because not enough data were available.

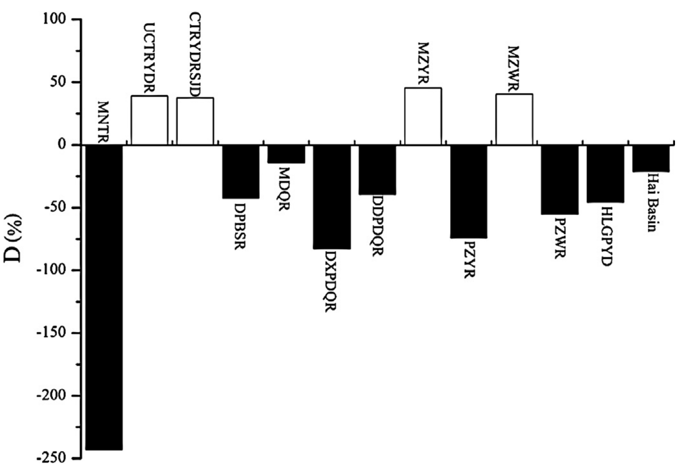

Fig. 2. *D* value in Hai basin and its sub-basins.

sub-basins, in particular the MNTR, while water consumption is sustainable in only four sub-basins.

4. Discussion

A four step approach to sustainable and productive use of water resources, based on ET Management, comprises: (i) assessing the current basin scale water balance, (ii) calculating, based on sustainability objectives, the target ET for the basin, (iii) dividing the target ET among different sectors and industries by weighing and comparing the competing water demands from agriculture, industry, domestic use, and social and environmental, and (iv) monitoring and assessing achieved water consumption savings.

A water consumption balance analysis based on ET data for the Hai basin was compiled for a five year period, and broken down into various elements, distinguishing those elements of the water balance that were uncontrollable, and those where human intervention could change the pattern of use. Major elements of the water balance—evapotranspiration from natural vegetation, irrigated agriculture and from bare soils and impervious surfaces—can be computed from remotely sensed data. Industrial and biological (livestock and human) consumption contribute to total use within a region, but cannot be measured through remote sensing technology and must be calculated based on surveys or empirical relationships. While such uses are currently a small part of total consumptive use, they will increase, making it important to develop a method to improve the accuracy of estimating these elements.

The analysis demonstrated the imbalance between the average availability of water in the Hai basin and showed the average level of excessive groundwater use (6.23 billion m^3) to be some 20% of total controllable consumption. Although the imbalance is significant in comparison with controllable consumption, it is only about 4% of total of annual precipitation, (500–600 mm on an area of 317,000 km^2 or 150 billion m^3).

ETWatch results are consistent with other methods for regional water resources evaluation in the whole basin. Estimates for 2002–2009 were intensively verified at different spatial scales, against field measurement, lysimeter, eddy covariance system, LAS, water balance of the sub-watershed and independent third party estimates (Liu et al., 2011; Jia et al., 2012). The annual deviations are between 3.0% and 9.0% at field scale, 3.8% at sub-basin scale and 1.8% at basin scale. Across landscapes, the annual deviations were 4.0% in mountain areas and 3.8% in plain regions. The water consumption of Hai basin was calculated by using annual ET dataset from 2002 to 2009, the maximum deviation was only 3.8% at sub-basin scale. Independent validation by third party confirmed the accuracy of ET data generated by ETWatch (Jia et al., 2012), concluding that data sets from ETWatch are adequate to guide consumptive water use in the study area.

For the purposes of ET management it is important to note that while the absolute estimate of ET_{sol} is not precise, the relative error across basin is the much smaller. If one area is estimated to consume 10% more water than another area, this ratio is more robust than the absolute estimates of ET in each area because of the standardized method of computation and the same data sources.

However, further development, especially using multi-sources satellite data can improve the ET estimation accuracy and reliability as one of major components of the water balance. The overall average errors of precipitation is 19% in gauge-measured yearly total precipitation over China (Ye et al., 2004); the uncertainty of discharge measurements performed under ideal conditions is 5.6–6.1% (Pelletier, 1988), and the actual error of measuring stream flow is generally higher in less-developed countries and areas (Hirsch and Costa, 2004). For groundwater level measurement, although modern measuring equipment with careful practice can give water level a better than 0.01 m precision, historical data will generally be at least one or two orders of magnitude less precise, and often worse (British Geological Survey, 2013).

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A complete water balance must include consumption in the industrial and domestic sectors. The analysis presented in this paper is at best a rough estimate, but this is adequate to confirm that consumption in these sectors is minimal. For the most part, industrial and domestic sectors are predominantly users rather than consumers of water—which returns to the hydrological system without loss. Furthermore, industrial and domestic uses are higher priority than agriculture so are likely to be protected.

The principles that underly an ET management approach are clear—to achieve a sustainable water balance by properly accounting for outflows from the basin. The practicalities of implementation will always be influenced by local hydrological and geohydrological conditions. The aim is sustainable levels of water consumption, and maximum production within that constraint.

The practical implications of reducing ET, especially in agriculture, will generally be a reduction in production, or at best increased effort and investment by farmers to maintain production. Faced with reduced water supplies, farmers tend to use water more cautiously and productively, but productivity gains are unlikely to fully offset the reduction in available water. This is turn has food security implications as well as social dimensions. Choices about the extent of reductions, the rate at which reductions must be made, and where they should be focused are political trade-off issues that are beyond the scope of this paper. The approach presented in this paper provides the basis for such trade-off choices.

Target level of ET for the controllable component of ET, which would ensure both adequate allocations to sustain the ecological health of river systems and stabilize aquifers was calculated, and distributed across the sub-basins of the Hai River. While the target ET should be the absolute limit in consumption to allow for sustainable water resources management, in regions where groundwater has been over-extracted for many years, the ET target could be phased in over several years.

While the concept of ET management brings a new approach to water resources management, specific challenges need to be overcome to strengthen its practical application. More development should be done to determine how to allocate, trade-off, and allow competition among water using sectors. Once ET quotas are allocated, surplus ET quotas could transfer among sectors or subsectors. In addition, new policies and regulations, along with active monitoring and enforcement, will be necessary to support the competition and trade of ET quotas. This process will require water resource administrators to acknowledge ET is the real water loss within a basin, followed by an improvement in ET monitoring, new laws to address ET management (including ways to penalize sectors for over-consumption), and the development of an ET quotas trade market. Through those measures the different water subsectors and sectors will improve water productivity and reduce water consumption that is above the allocated ET quota.

To effectively manage the water resources, it will also be important for the water sectors to know their allocation. In future developments related to ET target setting attention should be paid to developing a method to transfer ET quotas to water allocation quota. In addition, a water consumption model should be developed to connect the various ET management components by calculating the controllable and uncontrollable ET consumption, determining the target ET for a year, allocating the ET quota for different water users under the restrictions of ET target, evaluating the results (whether the ET target was achieved), converting the ET quota to water allocation quota, and predicting the ET consumption in future.

Finally, while ET management could effectively prevent the further over-extraction of groundwater, it may be difficult to recover ecological health in regions with a long history of groundwater overexploitation. In those cases, new water resources could be brought in to support the area's sustainable consumption. In the case of Hai Basin, with a controllable ET that was 6.73 billion m^3 above the target ET for 2002–2007, the available surface water resources and precipitation are not enough to restore groundwater levels based only on water savings in the basin, so additional water will be required. This water will be supplied by water transfers through the middle route of the South to North Water Transfer (SNWT) Project. Upon completion in 2014, about 4.8 billion m^3 of water will be delivered annually, using the middle route from the Yangtze River to the northern region of the North China Plain (OSC, 2008; Yang et al., 2010).

5. Conclusions

Managing water scarcity has traditionally depended on placing controls on abstractions from rivers and groundwater. For agriculture, the incentive provided by a fixed abstraction quota is to make maximum productive use of the resource—consuming through ET as much as possible of the quota. At the local level (farm or project) such maximization of "irrigation efficiency" has often been seen as a solution to water scarcity. In fact, when viewed at the basin scale, this process often increases water consumption and makes matters worse downstream, or results in still faster depletion of aquifers.

"ET management", by contrast aims to control consumptive use—the difference between water supplied to a farmer, project or town or factory and the water returned as drainage or other treatable effluent. Restricting consumptive use will always release water to other economic uses, to the environment, or to recharge aquifers.

Recent advances in remote sensing technologies provides the basis for such an approach. By distinguishing between controllable and uncontrollable ET as well as between beneficial and non-beneficial water consumption, water resource administrations can take appropriate measures to reduce controllable ET consumption. In water-scarce basins, continued economic growth will put more pressure on water resources and ET management provides a hydrologically sound approach to sustainable water resources management, protecting groundwater resources, the environment and ecosystems.

While the ultimate indicator of sustainable water use will always be empirical observation of streamflows, environmental status and aquifer levels, the ET management approach provides the basis for confirming imbalances and their location as a basis for improved, better focused interventions.

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References

Adamson, D., Loch, A., 2013. Possible negative feedbacks from 'gold-plating' irrigation infrastructure (this issue).
Allen, R.G., Tasumi, M., Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. Journal of Irrigation and Drainage Engineering 133, 380–394.
Anderson, M., Norman, J., Diak, G., Kustas, W., Mecikalski, J., 1997. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. Remote Sensing of Environment 60, 195–216.
Balwinder-Singh, Eberbach, P.L., Humphreys, E., Kukal, S.S., 2011. The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. Agricultural Water Management 98, 1847–1855.
Barnett, T.P., Pierce, D.W., 2008. When will Lake Mead go dry? Water Resources Research 44, W3201.

Bastiaanssen, W., Noordman, E., Pelgrum, H., Davids, G., Allen, R., 2005. SEBAL for spatially distributed ET under actual management and growing conditions. ASCE Journal of Irrigation and Drainage Engineering 131, 85–93.
British Geological Survey, 2013. Errors in groundwater level measurement, http://www.bgs.ac.uk/research/groundwater/datainfo/levels/measuring_errors.html (accessed 30.07.13).
Castellví, F., Snyder, R., 2010. A new procedure based on surface renewal analysis to estimate sensible heat flux: a case study over grapevines. Journal of Hydrometeorology 11, 496–508.
Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M.M., Valentine, E., Patel, S., 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. River Research and Applications 28, 283–301.
Chong, H., Sunding, D., 2006. Water markets and trading. Annual Review of Environment and Resources 31, 239–264.
Connell, D., Grafton, R.Q., 2011. Water reform in the Murray-Darling Basin. Water Resources Research 47, W00G03.
Davis, S., Dukes, M., 2010. Irrigation scheduling performance by evapotranspiration-based controllers. Agricultural Water Management 98, 19–28.
Droogers, P., Immerzeel, W., Lorite, I., 2010. Estimating actual irrigation application by remotely sensed evapotranspiration observations. Agricultural Water Management 97, 1351–1359.
Dugas, W., Fritschen, L., Gay, L., Held, A., Matthias, A., Reicosky, D., Steduto, P., Steiner, J., 1991. Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat. Agricultural and Forest Meteorology 56, 1–20.
Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resources Research 44, W00E04.
Gallopín, G.C., 2012. Five Stylized Scenarios, Global Water Futures 2050, the United Nations Educational, Scientific and Cultural Organization, ISBN 978-92-3-001038-6.
Grafton, R.Q., Chu, H.L., Stewardson, M., Kompas, T., 2011. Optimal dynamic water allocation: irrigation extractions and environmental tradeoffs in the Murray River, Australia. Water Resources Research 47, W00G08.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.
Hirsch, R.M., Costa, J.E., 2004. US stream flow measurement and data dissemination improve. Eos, Transactions American Geophysical Union 85 (20), 197–203.
Howell, T.A., 1990. Grain dry matter yield relationships for winter wheat and grain sorghum—southern high plains. Agronomy Journal 82, 914–918.
Jia, Z., Liu, S., Xu, Z., Chen, Y., Zhu, M., 2012. Validation of remotely sensed evapotranspiration over the Hai River Basin, China. Journal of Geophysical Research 117, D13113.
Ko, J., Piccinni, G., 2009. Corn yield responses under crop evapotranspiration-based irrigation management. Agricultural Water Management 96, 799–808.
Li, L., Zheng, H., 2000. Environmental and ecological water consumption of river systems in Haihe-Luanhe Basins. Acta Geographica Sinica 55 (4), 495–500 (in Chinese).
Liu, S.M., Xu, Z.W., Wang, W.Z., Jia, Z.Z., Zhu, M.J., Bai, J., Wang, J.M., 2011. A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem. Hydrology and Earth System Sciences 15 (4), 1291–1306.
Liu, Y., Tetsuya Hiyama, Tetsuzo Yasunari, Hiroki Tanaka, 2012. A nonparametric approach to estimating terrestrial evaporation: validation in eddy covariance sites. Agricultural and Forest Meteorology 157, 49–59.
Lohmar, B., Wang, J., Rozelle, S., Huang, J., Dawe, D., 2002. Investment, conflicts and incentives: The role of insitutions and policies in China's agricultural water management on the North China Plain. http://publications.iwmi.org/pdf/H029693.pdf
MacFarquhar, N., 2001. Drought Chokes off Iran's Water and its Economy. New York Times.
Margat, J., 2008. Exploitations et utilisations des eaux souterraines dans le monde. UNESCO/BRGM, Paris.
Martin, D., 2010. Evapotranspiration and Watershed Management, Presentation to Task Force , Department of Biological Systems Engineering, University of Nebraska Lincoln http://dnr.ne.gov/LB1057/presentations/ET_WatershedMgt_0610.pdf
McGuire, V.L., 2009. Water-level changes in the High Plains aquifer, predevelopment to 2007, 2005-06, and 2006-07. US Geological Survey Scientific Investigations Report 2009-5019, 9 p, http://pubs.usgs.gov/sir/2009/5019/
Meijer, K., van der Krogt, W.N., van Beek, E., 2012. A new approach to incorporating environmental flow requirements in water allocation modeling. Water Resources Management 26 (5), 1271–1286, ISSN 0920-4741.
Meijninger, W., De Bruin, H., 2000. The sensible heat fluxes over irrigated areas in western Turkey determined with a large aperture scintillometer. Journal of Hydrology 229, 42–49.
Merze, S.K., 2010. Evapotranspiration measurement: informing water management in Australia, Waterlines Report, No. 35. National Water Commission, Canberra.
Motagh, M., Walter, T.R., Sharifi, M.A., Fielding, E., Schenk, A., Anderssohn, J., Zschau, J., 2008. Land subsidence in Iran caused by widespread water reservoir overexploitation. Geophysical Research Letters 35, L16403.
National Development and Reform Commission, 2006. Process in water saving of electric power industry, http://www.sdpc.gov.cn/zjgx/t2006116_93679.htm (accessed 10.07.13).
Norman, J.M., Kustas, W.P., Humes, K.S., 1995. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. Agricultural and Forest Meteorology 77, 263–293.
Office of the State Council for South-to-North Water Diversion Construction Committee, 2008. General Layout of South-to-North Water Diversion. http://www.nsbd.gov.cn/zx/english/20080414
Pelletier, P.M., 1988. Uncertainties in the single determination of river discharge: a literature review. Canadian Journal of Civil Engineering 15 (5), 834–850.
Pengra, B., 2012. The Drying of Iran's Lake Urmia and its Environmental Consequences , UNEP Global Environmental Alert Service (GEAS) Bulletin http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id,79
Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agricultural Water Management 96, 1517–1524.
Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrigation and Drainage 56, 367–378.
Qiu, J., 2010. China faces up to groundwater crisis. Nature 466, 308.
Qureshi, M., Grafton, R., Kirby, M., Hanjra, M., 2011. Understanding irrigation water use efficiency at different scales for better policy reform: a case study of the Murray–Darling Basin, Australia. Water Policy 13, 1–17.
Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002.
Santos, C., Lorite, I., Tasumi, M., Allen, R., Fereres, E., 2008. Integrating satellite-based evapotranspiration with simulation models for irrigation management at the scheme level. Irrigation Science 26, 277–288.
Siebert, S., Burke, J., Faures, J., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F., 2010. Groundwater use for irrigation – a global inventory. Hydrology and Earth System Sciences 14, 1863–1880.
Su, Z., 2002. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. Hydrology and Earth System Sciences Discussions 6, 85–100.
Sun, T., Xu, J., Yang, Z., 2012. Objective-based method for environmental flow assessment in estuaries and its application to the Yellow River Estuary, China. Estuaries and Coasts 35 (3), 892–903.
Van der Gun, J., 2012. Groundwater and Global Change: Trends, Opportunities and Challenges. UNESCO, Paris http://unesdoc.unesco.org/images/0021/002154/215496e.pdf
Wada, Y., van Beek, L.P.H., Bierkens, M.F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resources Research 48, W00L06, http://dx.doi.org/10.1029/2011WR010562.
Wang, H., Wu, B., Li, X., Lu, S., 2011. Extraction of impervious surface in Hai Basin using remote sensing. Yaogan Xuebao – Journal of Remote Sensing 15, 388–400.
Wang, X., Lian, Y., Huang, C., Wang, X., Wang, R., Shan, K., Pedroli, B., van Eupen, M., El Mahdi, A., Ali, M., 2012. Environmental flows and its evaluation of restoration effect based on LEDESS model in Yellow River Delta wetlands. Mitigation and Adaptation Strategies for Global Change 17, 1–11.
Wang, W.X., 2007. The review of puddling technology with blast furnace in China in 2006 , 2007's annual conference of small blast furnace, Zhuhai, China (in Chinese).
Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences of the United States of America 105 (47), 18215–18220 www.pnas.org_cgi_doi_10.1073_pnas.0805554105
White, H.L., Nichols, S.J., Robinson, W.A., Norris, R.H., 2012. More for less: a study of environmental flows during drought in two Australian rivers. Freshwater Biology 57, 858–873.
Willardson, L.S., Allen, R.G., Frederiksen, H.D., 1994. Eliminating Irrigation Efficiencies , USCID 13th Technical Conference, Denver, Colorado, 19–22 October, p. 15.
World Bank, 2012. http://imagebank.worldbank.org/servlet/WDSContentServer/IW3P/IB/2012/12/27/000356161_20121227230933/Rendered/PDF/NonAsciiFileName0.pdf
Wu, B., 2010. Water Balance Analysis Based on Remote Sensing in Turpan Basin , ISPRS Technical Commission VIII Symposium on Networking the World with Remote Sensing, Kyoto, Japan.
Wu, B., Xiong, J., Yan, N., Yang, R., Du, X., 2008. ETWatch: methodology of regional evapotranspiration monitoring with remote sensing. Advances in Water Science 19 (5), 671–678 (in Chinese).
Wu, B., Yan, N., Jiang, L., Chang, S., 2011. A method of water consumption balance and application. Yaogan Xuebao – Journal of Remote Sensing 15, 281–297 (in Chinese).
Wu, B., Yan, N., Xiong, J., Bastiaanssen, W.G.M., Zhu, W., Stein, A., 2012. Validation of ETWatch using field measurements at diverse landscapes: a case study in Hai Basin of China. Journal of Hydrology, 67–80 (436–437).
Wu, B., Lu, S., 2011. Watershed remote sensing: methodology and a paradigm in Hai Basin. Yaogan Xuebao – Journal of Remote Sensing 15, 201–223 (in Chinese).
Xiong, J., Bingfang, W., Nana, Y., Yuan, Z., Shufu, L., 2010. Estimation and validation of land surface evaporation using remote sensing and meteorological data in North China. Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of 3 (3), 337–344.
Yang, Y., Yang, Y., Moiwo, J.P., Hu, Y., 2010. Estimation of irrigation requirement for sustainable water resources reallocation in North China + 5. Agricultural Water Management 97, 1711–1721.
Ye, B., Yang, D., Ding, Y., 2004. A bias-corrected precipitation climatology for China. Journal of Hydrometeorology 5 (6), 1147–1160.
Young, M., 2013. Designing water entitlement regimes for an ever-changing and ever-varying future (this issue).