Spatial Mapping of Water Productivity in Irrigation System Using Geo-information Techniques

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EXTENDED ABSTRACT

In the context of required increase of food production for rapid population growth, it is critical to improve the productivity of water in the irrigation systems. It may require a lot of field investigations to gather this information at large and especially complex systems like the Liyuankou Irrigation System (LIS), located in located on the right bank of Yellow River in North West China. The use of geo-information techniques such as remote sensing and GIS data has come to override most of the difficulties encountered in collection of large amount of data, especially following the state-of-the-art development on the calculation of actual evapotranspiration.

The Surface Energy Balance Algorithm for Land (SEBAL) has been applied to 13 NOAA-AVHRR 11-12 images in the LIS for the summer season (April-October) of 1994. This analysis was aided by the unsupervised land use classification applied to Landsat 5 TM image at the peak of growing season over the study area. The water accounting and productivity framework was applied to measure both the water use within the system and the water productivity of LIS.

Unsupervised classification (ISODATA clustering algorithm) was applied to Landsat 5 TM image and the results showed that agricultural crop classification has accuracy greater than 81% and the overall accuracy and kappa coefficient associated with classification are 78% and 0.75, respectively. SEBAL results showed that a large amount of water (210 MCM) was lost through non-beneficial ET including from fallow land, bare soil, water bodies and others during 1994. Similarly, a considerable amount of water (125 MCM) was lost through evaporation from fallow land during 1994, which needs to be reduced to improve water productivity of the irrigation system.

The process fraction per unit of depleted water $PF_{depleted}$ is 0.47 for LIS, meaning that 47% of the depleted water is consumed by the agricultural crop and 53% is lost through non-process depletion. The results also prove earlier findings of Khan et al., (2006) that high amount of water is depleted through non-process depletion for LIS. $WP_{irrigation}$ is 0.94 kg/m^3 which show that there is a considerable scope for improvement in our study area by reducing the nonbeneficial outflows from agriculture fields and/or by increasing the yield. Results proved that geo information techniques are providing cost effective way (free NOAA-AVHRR images) for spatial mapping and assessing water productivity factors at different spatial scales, answering to water management for better decision making requirements.

1. Introduction

The lower Yellow River Basin, an important food production area of China, is not particularly well endowed with water yet water has been used as a cheap resource in agricultural production that has caused water shortages in China. Farmers in the basin are under pressure to grow more "crop per drop" (Khan et al., 2007). To address the water scarcity, scientists often recommend a “soft path” to increase overall water productivity (Rijsberman, 2006). However, water productivity estimation at irrigation system level requires a complete understanding of water balance components in a spatio-temporal format. Spatial information on crop water use, crop production and water productivity will play a vital role for water managers to assess where scarce water resources are wasted through a non-beneficial evaporation and where in a given region the water productivity can be improved (Zwart and Bastiaanssen, 2004).

This paper concentrates on Liuyuankou Irrigation System (LIS) where irrigation for crop production is met by surface water drawn from the channels diverted from the Yellow River (YR). However surface water is not enough to supply the whole irrigation system due to high seepage loss from the sandy canals to the underlying permeable aquifers in the northern part of LIS, situated above the railway line and hereafter known as “ARL”. In the southern part of LIS (situated below the railway line and hereafter known as “BRL”) crops are generally grown with water sourced by groundwater pumping. Despite the improved efficiency and the presence of a drainage system, the groundwater table has risen alarmingly in the upstream areas (within 1m of land surface), in the ARL part of LIS (Zhu et al., 2003). As a result, Khan et al., (2006) reported that a significant amount of the irrigation water leaves LIS through fallow evaporation and its reduction is therefore critical to increase water productivity. Currently, information on crop water use and productivity in LIS is only available through traditional hydrological lumped based water balance modeling approaches which does not provide any spatial information about the areas having high non-beneficial evaporation (Hafeez and Khan, 2007). The use of appropriate, reliable and consistent hydrological information at the irrigation system level can improve water management significantly. However, the reduction of fallow evaporation is only possible if we have a reliable spatio-temporal quantification of actual water consumption which will help us to identify areas having high non-beneficial evaporation in LIS. E.g. when indicating the necessary changes for managing the water more beneficially to avoid negative impacts in downstream areas. Recent developments in the remote sensing sciences and their application to water resources management allow now the provision of accurate spatio-temporal quantification about land and water use patterns in large irrigated basin. The use of remote sensing techniques towards the estimation of evaporation is achieved by solving the energy balance of thermodynamics fluxes at the surface of the earth. The use of these remote sensing techniques have become increasing popular since 1990 due to the relatively reported low cost of data collection, \$0.03/ha for irrigated lands. Various methods for the estimation of actual evapotranspiration have been developed by combining satellite images and ground meteorological data for large areas (Hafeez and Khan 2007). Another method estimating actual ET is the Surface Energy Balance Algorithm for Land (SEBAL) by Bastiaanssen (1995). SEBAL is a thermodynamically based model, using the partitioning of sensible heat flux and latent heat of vaporization flux. Remote sensing in combination with water accounting procedure (Molden, 1997) is a power tool to measure water use and water productivity at various spatial scales ranging from farm to irrigation system.

The particular objectives of this study were; a)- to compute spatial distribution of seasonal actual evapotranspiration (ET_s) using NOAA-AVHRR images over LIS during a summer season (April to October) of 1994; b) to quantify the beneficial and non-beneficial amount of water consumption based on land use classes derived from Landsat 5 TM image acquired during the summer season; and c)- to estimate water accounting and productivity based performance indicators to suggest where improvements in water management in the system could be made.

2. Study Area

The LIS is located on the right bank of Yellow River in North West China, more precisely in Kaifeng County (Fig. 1) and is part of the Hui Ji River system (Huai He River basin). The geographic boundary of the LIS rang from 114.35E to 114.78E and from 34.58N to 34.89N.

The LIS has a temperate continental monsoonal climate with cool, dry winters and warm, wet summers. Mean annual temperature is 14.1°C and the frost-free days are 210~240 days. The average annual precipitation for the study area is approximately 627 mm and ranges from 293.6 mm in 1984 to 991.5 mm in 1997. Mean annual evaporation measured through Class A-pan is 1316 mm and the maximum evaporation occurs from March to August. The total area of LIS is 55,512 ha with the net irrigated command area of 40,724 ha and cropping intensity is about 1.43. During recent years, irrigation conditions have become more efficient due to the improvement and maintenance of the hydraulic structures

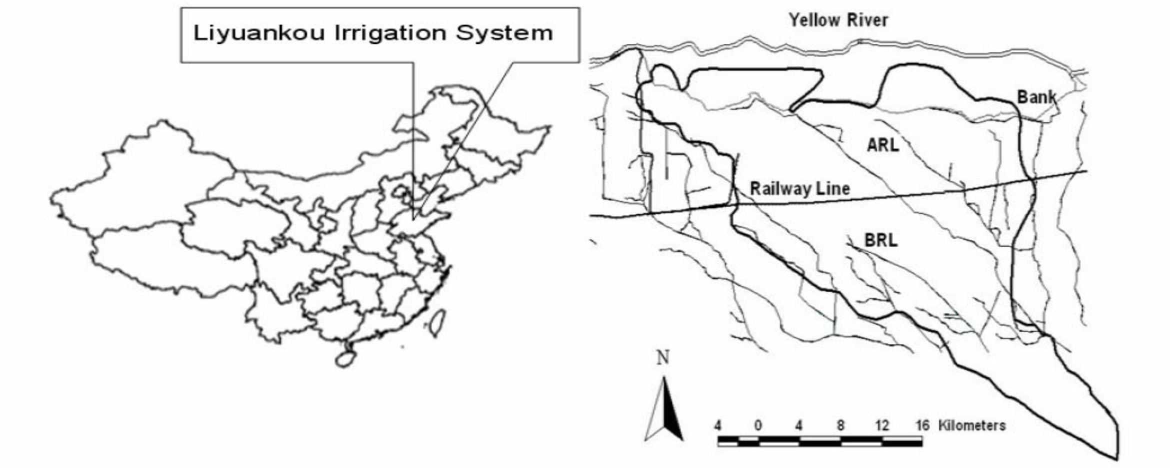

Figure 1: Layout of Liuyuankou Irrigation System (LIS) in China

on the main channels. In spite of this improved efficiency and the presence of a drainage system, the groundwater table has risen alarmingly in ARL and BRL. Due to intensive local groundwater pumping within the BRL area, the lateral outflow of the aquifer is very small compared to lateral seepage into the area. Conversely, in the ARL the groundwater aquifer is already full and there is risk of soil salinisation if hydraulic loading due to rice is reduced, which is mainly responsible for pushing salts down through the aquifer system. Since the overall groundwater outflow from the LIS is very small, this area is a net salt sink and is recycling these salts through the system by groundwater pumping in the BRL area, which could cause substantial yield decline in the future.

3 Materials and Methods

3.1 Water Accounting

The water accounting procedure, based on a water balance approach, was applied to measure water use and water productivity in the LIS system. Water accounting defines the amount of water within the system by classifying inflow, outflow, water depletion through evapotranspiration (process and non-process), and available water among different users with in an irrigation system. The clear understanding of all the components of water accounting will lead to a measure of true water saving. The water accounting and its indicators are presented in the form of fractions and in terms of productivity of water, and are explained in Molden, 1997. All water accounting components, i.e., surface inflow and outflow, rainfall, water pumped from groundwater, storage change, ET_a (agricultural crops and non-agricultural crop), and rice yields were daily measured for 1994 at LIS. Three types of water accounting indicators, which are alternative to the classical irrigation efficiencies, are used in this study: physically based indicators (depleted fractions), beneficial utilization indicators (process fraction) and water productivity indicators (Molden, 1997).

The rainfall data was manually observed and recorded twice a day at Hubei weather station. The volume of rainfall was calculated by multiplying the area with quantity of rainfall. The major canal in LIS is located in the upper part of the irrigation district, and feeds three main canals and fourteen branch canals. The discharge of the main canal was converted to determine the equivalent volume of water by multiplying the discharge with time. The total volume of water was estimated by summing up the discharge of the inflow point for each year. The major crops cultivated in the LIS include maize, cotton, rice and soybean. The yield data were obtained from weekly monitoring activity of the irrigation department at LIS.

3.2 Remote Sensed Parameters

3.2.1 Land use classification

Landsat 5 TM image on August 2, 1994 covering the LIS were used to assess land use at the peak stage of the growing season. A subset of LIS using false color composite (FCC) of satellite image was created after geo-referencing the image in the UTM Zone 51, WGS84 using 40 well distributed ground control points (GCP) with root mean square error (RMSE) of less than 1 pixel size.

The land use classification of summer season 1994 was performed using a series of consecutive unsupervised classification steps. The unsupervised classification has been carried out on the basis of the ISODATA clustering algorithm. Three ISODATA clustering attempts have been performed, using respectively 5, 10 and 20 clusters. The ISODATA clustering with 6 classes has been used to separate bare soil, settlement, fallow land, water, agriculture crops, and unclassified (mainly clouds). A limited ground truth data with 74 records of the major land use classes for the summer season was available through land cover database of the local irrigation department. This database has been used to assign the ISODATA clustering results to land cover classes. The six major land use classes for summer season are bare soil, settlement, fallow land, water, agriculture crops and unclassified. The ground truth data of 47 records were available mainly for fallow land which was used to interpret ISODATA results and assigning pixels for fallow land. Fallow land occurs in summer where salinity exceeds the threshold for summer crops. The farming area in LIS is often around 0.5 ha which is further subdivided into small parcels of land for various farming activities. However, Landsat pixel is around 30 m^2 which is often higher than small parcels of land with in a farm. Therefore, it becomes quite difficult to have accurate land use classification in LIS. To overcome this issue, a percentage of 5% for field canals, 5% for field bunds and 4% for field roads are subtracted from the total area classified as agriculture crops.

3.2.2 Seasonal Actual Evapotranspiration

NOAA AVHRR imagery is one of the most stable sources of information available publicly from Internet. It covers consequent areas (1000 x 3000 Km) while having a spatial resolution (1 x 1 Km) at the merging of climatic and agricultural applications. A set of 13 NOAA AVHRR 11-12 images were downloaded from Internet through the Satellite Active Archive website, which has publicly available satellite imagery archives, covering different time periods of 1994 (April to October) over the study area (see Table 1).

Table 1: Images used in this study

Sensor	Satellite Image Acquisition days
NOAA-AVHRR 11-12	April 04, 1994 April 13, 1994 April 27, 1994 May 10, 1994 May 28, 1994 June 13, 1994 June 26, 1994 July 06, 1994 July 23, 1994 August 02, 1994 August 16, 1994 September 04, 1994 October 09, 1994

Specificity of porting SEBAL to NOAA-AVHRR

A subset image for the study area was created for better visualization, and geo-referencing was done using 40 well distributed ground control points in the UTM Zone 51, WGS84, with a RMSE of less than half pixel size. The pre-processing parameters required for SEBAL include the Normalized Difference Vegetation Index (NDVI), broadband surface albedo, emissivity, and surface temperature. More detailed information about the porting of SEBAL for NOAA-AVHRR can be found in Hafeez and Khan (2006).

SEBAL is a thermodynamically based model which solves energy balance at the time of satellite overpass using the partitioning of sensible heat flux and latent heat of vaporization flux. The Λ, evaporative fraction, is the output of SEBAL and is defined as the ratio of latent heat to maximum net available energy as in Equation;

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\lambda E}{\lambda E + H_0} \qquad (-)$$

where λE = latent heat flux (the energy allocated for water evaporation). λ can be interpreted in irrigated areas as the ratio of actual to crop potential evapotranspiration. It is dependent on the atmospheric and soil moisture conditions equilibrium; R_n = net radiation absorbed or emitted from the earth's surface (radiative heat) (W/m^2); G_0 = soil heat flux (conduction) (W/m^2) and H_0 = sensible heat flux (convection) (W/m^2).

The daily actual ET is calculated in SEBAL from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, R_{n24}. The latter has to be transformed from W/m^2 to mm/day by the T_0-dependent latent heat of the vaporization equation inserted in the main equation.

$$ET_{24} = \Lambda \times \left[R_{n24} \times \left((2.501 - 0.002361 \times T_0) \times 10^6\right)\right]$$

where ET_{24} = Daily ET actual (mm/day); R_{n24} = average daily net radiation (W/m^2); and T_0 = surface temperature (°C)

The ET_a calculation through remote sensing on specific dates provided a good indication of its spatial distribution in the irrigation system. However, this information could not be used directly, as ET_a directly depends upon weather conditions and water availability in the field, which varies from day to day. It was therefore necessary to simulate daily values to get an accurate estimation of ET_s. A larger sample of timely ET_a observations is necessary to obtain an accurate result and to adjust the daily fluctuation of ET_a for integration of ET_s. ET_s was estimated spatially by adding the satellite images together following a daily weight ratio corresponding to the number of days representing each image time period (April 1994 to October 1994) cover over the study area. This method is found in Tasumi et al. (2001), and is a "classical" step approach in the integration of individual values over a certain dimension. Hafeez and Khan (2006) described in detail the procedure of obtaining ET_s.

3.2.3 Classical Crop ET

The reference evapotranspiration (ET_o) was calculated using modified Penman-Montieth method from a climatic data of Hubei weather station (Allen et al., 1998). The crop coefficients of the major crops in the LIS were obtained by knowing the crop development stages for each month. Crop water consumption was obtained by multiplying the respective crop coefficient by ET_o value for each corresponding month.

4 Results and Discussions

4.1 Land Use Classification

Overall, the land use/land covers identified for 1990-91 were: agricultural crops, fallow land, bare soil, settlements, water bodies, and unclassified (Figure 2). Agriculture crops were classified with accuracy greater than 81% and the overall accuracy and kappa coefficient associated with classification are 78% and 0.75, respectively.

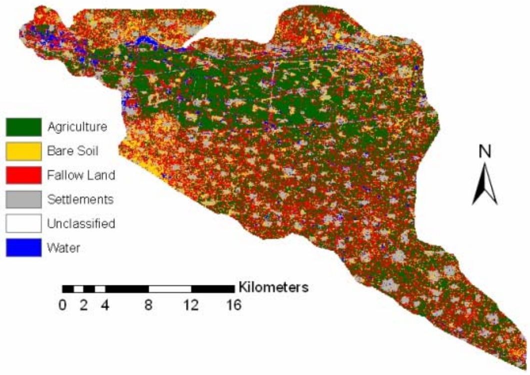

Figure 2: Land use classification map of LIS area using Landsat 5 TM for summer season (April-October) of 1994.

4.2 Seasonal Actual Evapotranspiration

The ET_s map on a pixel-by-pixel basis was produced through integration of all daily ET_a images for the 1994 period (see Fig. 3). Figure 3 depicts a range from 230 mm to 930 mm of ET_s in the LIS region for the season of 1994. Low ET_s is modelled for the bare fields and fallow lands, while the irrigated areas range from medium to high ET_s. The agricultural fields in ARL area have higher ET_s values due to shallow water table, lateral seepage from the yellow river and a leaky network of irrigation canals. Higher ET_s values are indicated by purple and yellow colors in Fig. 4. The BRL areas have lower ET_s values (brownish color) because the water table is relatively deep and there is no surface water irrigation network. The pixel values of ET_a calculated through SEBAL, in the area surrounding Hubei meteorological station, were compared with the measured evaporation through Class A Pan (E_{pan}), and ET_c from Hubei meteorological station for 1994 as shown in Fig. 4. There is a significant difference in ET values obtained from remote sensing and classical techniques which utilize weather station data.

The former provides spatial distribution results, whereas the latter provides only point values.

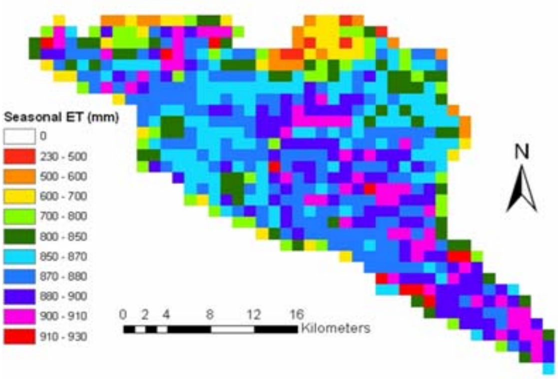

Figure 3: Seasonal actual evapotranspiration map using NOAA-AVHRR sensor for summer season of 1994

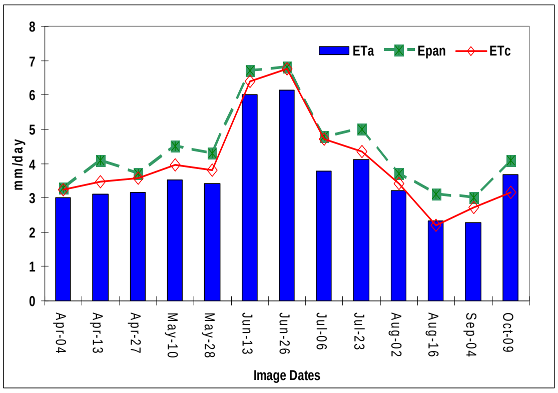

Figure 4: Comparison of ET_a with E_{pan}, ET_o, and ET_c at Hubei weather station for summer season 1994

As shown in Figure 4, E_{pan} values from Hubei weather stations were always higher (on average 22%) than ET_a values for all image acquisition dates. For pixels assumed to be under crop, the estimated ET_a was on average 8% lower than the average ET_c calculated from the weather station. The comparison provides an indication of the amount of confidence that can be given to the values of ET_a derived from the remote sensing images. The ET_a is estimated from all the physical mediums within one pixel, which might have mixed spectral signatures of road, settlement, and rice fields. Due to the large pixel size of NOAA-AVHRR, it was difficult to absolutely compare such information with the classical point data from meteorological data, even though Fig. 4 shows a good trend regarding the accuracy of ET_a derived from the SEBAL.
However, the accuracy of this comparison of modeled against measured data needs to be considered with respect to scale. Modeled area data was derived from discrete areas of one square kilometer (spatial resolution of a NOAA-AVHRR sensor) and would therefore contain reflectance attributes from many different physical mediums (mixed spectral signatures from agriculture fields, bare fields, and roads) and a resulting combined evapotranspiration rate.

4.4 Water accounting and productivity

Results of water performance indicators are summarized in Table 2. The process fraction per unit of gross inflow (PF_{gross}) at LIS is 0.47 which means that 47% of the water is depleted through ET_{crop}. The process fraction per unit of depleted water ($PF_{depleted}$) is 0.51 for LIS, meaning that 51% of the depleted water is consumed by the agriculture crop and 49% is lost through non-process depletion. In our area, there is a big scope to further increase the process fraction of depleted water by reducing non-beneficial evaporation and improving crop management practices through fertilizers and pest management. The results showing a high amount of water is depleted through non-process depletion for LIS is similar to earlier findings of Khan et al., (2006) and Hafeez and Khan (2007). The depleted fraction per unit of available water ($DF_{available}$), interpreted as irrigation system efficiency, is 0.98 at LIS which shows that 98% of the available water is depleted and there is little scope to improve water productivity. The

Table 2: Water Accounting and performance indicators

Description	1994*
Total area (Ha)	52888
Agriculture area (Ha)	22619
Gross Inflow (McM)	468.73
Irrigation	122.97
Rainfall	272.51
Pumping from Ground water	73.25
Storage Change (McM)	-11.59
Net Inflow (McM)	457.14
Total Outflow (McM)	19.92
Lateral Outflow	19.92
Total Depletion (McM)	429.25
Process - $ET_{agriculture}$	218.62
Non Process $ET_{non\text{-}agriculture}$	210.63
Available Water (McM)	437.22
Agriculture Crop Yield (Kg/Ha)	3819
Agriculture Crop Production (Kg)	1.2E+08
Water Productivity (Kg/m^3)	
of Gross Inflow	0.25
of Net Inflow	0.25
of Irrigation	0.94
of ET_{crop}	0.53
Depleted Fraction (-)	
of gross inflow	0.92
of available water	0.98
Process Fraction (-)	
of gross inflow	0.47
of available water	0.50
of depleted water	0.51

* Summer season (April to October)

water productivity per unit of gross inflow is 0.25 kg/m^3. The water productivity per unit of irrigation water ($WP_{irrigation}$) is 0.94 kg/m^3. There is considerable scope for improvement in our study area by reducing the nonbeneficial outflows from agriculture fields (evaporation from the ponded water layer, seepage, and percolation) and/or by increasing the yield. Similarly, the water productivity per unit of crop evapotranspiration is 0.53 kg/m^3 for the cropping season of 1994. Loeve et al., (2003) reported that the $WP_{irrigation}$ ranges from 1.75 kg/m^3 at the first main canal command (28,519 ha) to 2.98 kg/m^3 at the second main canal command (160,206 ha) in Zhanghe Irrigation System (ZIS) in China. The major reason of low water productivity in LIS is high non-beneficial evaporation from the fallow land and there is huge potential of improving water productivity by reducing non-beneficial evaporation.

5 Conclusions

Significant amount of the irrigation water leaves from LIS through fallow evaporation and its reduction is therefore critical to increase water productivity. However, it is only possible after the identification of fallow land through land use classification and then verification of fallow evaporation figures through advanced geo-information tools like remote sensing, which provide a more realistic estimation of ET_a in a spatio-temporal distributed format. Therefore, it was decided to estimate seasonal actual ET by applying SEBAL for 13 NOAA AVHRR 11-12 images over summer season of 1994. Unsupervised classification (ISODATA clustering algorithm) was applied to Landsat 5 TM image and the results showed that agricultural crop classification has accuracy greater than 81% and the overall accuracy and kappa coefficient associated with classification are 78% and 0.75, respectively. SEBAL results showed that a large amount of water (210 MCM) was lost through non-beneficial ET including from fallow land, bare soil, water bodies and others during 1994. Similarly, a considerable amount of water (125 MCM) was lost through evaporation from fallow land during 1994, which needs to be reduced to improve water productivity of the irrigation system.

The water accounting and productivity framework was applied to measure both the water use within the system and the water productivity of LIS. $PF_{depleted}$ is 0.47 for LIS, meaning that 47% of the depleted water is consumed by the agricultural crop and 53% is lost through non-process depletion. $WP_{irrigation}$ is 0.94 kg/m^3 which show that there is a considerable scope for improvement in our study area by reducing the nonbeneficial outflows from agriculture fields and/or by increasing the yield. Results proved that geo information techniques are providing cost effective way (free NOAA-AVHRR images) for spatial mapping and assessing water productivity factors at different spatial scales, answering to water management for better decision making requirements.

6 Reference

Allen R.G., Pereira L.S., Raes D. and Smith M.: Crop evapotranspiration – Guidelines for computing crop water requirement. FAO Irrigation and Drainage Paper 56, Rome, Italy, 1998.

Bastiaanssen, W.G.M.: Regionalization of surface flux densities and moisture indicators in composite terrain, A remote sensing approach under clear skies in Mediterranean climates, Report 109, Agricultural Research Department, Wageningen, The Netherlands, 1995.

Hafeez, M.M. and Khan, S.: Mapping of actual evapotranspiration over regional scale using NOAA/AVHRR satellite data". Paper presented during 13th Australasian Remote Sensing and Photogrammetry Conference (ARSPC), Canberra, November 20-24, 2006, Australia, 2006.

Hafeez MM, and Khan S. (2007) "Spatial Mapping of Actual Crop Water Use in Ground Water Dominant Irrigation System" Australian Journal of Agricultural Research (AJAR), Australia (accepted with minor corrections)

Khan S., Mushtaq S., Luo Y., Dawe, D., Hafeez, M.M., and Rana, T.: Economic assessment of system-level water saving through conjunctive water management options: Examples from Liuyuankou Irrigation System, China, Journal of Irrigation and Drainage 2007.

Khan, S., Rana, T., Yuanlai, C. and Blackwell, J.: Can Irrigation Be Sustainable? Journal of Agriculture Water Management 80:87-99, 2006.

Loeve, R., Barker, R., Dawe, D., Lin, H. and Bin, D.: Growing More Rice with Less Water: An Overview of Research in Liuyuankou Irrigation System, Henan Province, China, 2003.

Molden, D.: Accounting for water use and productivity, SWIM Paper 1, Colombo, Sri Lanka, IWMI, 1997.

Rijsberman, F.R.: Water Scarcity: Fact or fiction? Journal of Agriculture Water Management, 80:5-22, 2006.

Tasumi, M., Bastiaanssen, W.G.M. and Allen, R.G.: Application of the SEBAL methodology for estimating consumptive use of water and stream flow depletion in the Bear River Basin of Idaho through Remote Sensing, EOSDIS Project Report, Raytheon Systems Company and the University of Idaho, USA, 2000.

Zhu, Z., Cai, X., Giordano, M., Molden, D., Hong, S., Zhang, H., Lian, Y., Zhang, X. and Xue, Y.: Yellow River Comprehensive Assessment: Basin Feature and Issues, Working Paper 57, Colombo, Sri Lanka, IWMI, 2003.

Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69, 115-133.