Remote Sensing Application for Estimation of Irrigation Water Consumption in Liuyuankou Irrigation System in China

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EXTENDED ABSTRACT

Efficient water use is the key for sustainable management of water resources. The major reason of non-efficient management of water resources, especially in developing countries, is non-availability of reliable hydrological information about the actual water used by different agricultural crops with in a large irrigation system or at the basin scale. Therefore, an estimation of spatially distributed crop water consumption is important and challenging to determine water balance at different scales to promote efficient management of water resources. Remote sensing data can resolve difficulties in determining water balance due to scientific developments in the calculation of spatially distributed actual evapotranspiration. In this study, seven TERRA/MODIS satellite images were used on different dates (April 06, May 31, June 12, July 12, August 23, September 22, and October 24) during the summer cropping season of 2002 over Liuyuankou Irrigation System (LIS) located along the Yellow River basin of China.

There are many remote sensing algorithms for an estimation of spatially distributed actual evapotranspiration and each algorithm has its own merits and demerits. The Surface Energy Balance Algorithm for Land (SEBAL) is the most promising algorithm with the minimum input of ground based variables and it has been widely applied in many countries of the world due to an accurate estimation of actual evapotranspiration. Therefore, SEBAL was applied to MODIS sensor for the estimation of crop water requirement. The actual evapotranspiration (ET_a) was integrated for 24 hours on a pixel-by-pixel basis from the instantaneous evapotranspiration (ET). Later, temporal integration (April–October 2002) was done to get the seasonal actual evapotranspiration (ET_s) map of LIS irrigation district.

Volumes of crop water consumption at different scales were compared through statistical analyses. The comparison provided better decision-making for identifying areas (e.g. fallow lands) that have high non-beneficial evapotranspiration at different spatial scales in an irrigation system. The result showed a unique combination of derived ET_a compared to different MODIS images on different dates (April 06, May 31, June 12, July 12, August 23, September 22, and October 24) for water consumption in the LIS. The results were further compared with the crop potential evapotranspiration (ET_c) calculations at a meteorological station in the LIS system, which showed a deviation of -5% between ET_a and ET_c which is within an acceptable range. However, the accuracy of this comparison of modeled ET_a against measured data of ET_c needs to be considered with respect to scale, and this will be a feature of this paper. Modeled area data was derived from discrete areas of one square-kilometer (spatial resolution of a MODIS pixel for thermal bands) and would therefore contain reflectance attributes from many different physical mediums (mixed spectral signatures) and a resulting combined evapotranspiration rate. The discussion provides the research orientation for ET assessment at different scales and its further implications in applied research for water management aided by satellite images.

1. INTRODUCTION

The world's thirst for water is likely to stay as one of the most pressing resource issues of the 21st century. Agriculture is the largest consumer of water in the Asian region as compared to other sectors i.e. domestic, municipal, industrial, and environmental. However, the water-use efficiency of agriculture is very low and it needs to be improved. The improvement of the water-use efficiency requires the complete understanding of all the terms of the water balances at various scales i.e. farmer's field to basin level. The dominant aspect of water balance is evapotranspiration (ET), which is one of the most difficult parameters to measure in the field. A number of research projects undertaken in the past have estimated reference ET from meteorological data and converted this to actual ET. The major disadvantage of this approach is that most methods generate only point values, resulting in estimates that are not representative of larger areas. These methods are also based on crop factors under ideal conditions and cannot therefore represent actual crop ET.

The use of remote sensing techniques to estimate evaporation is achieved by solving the energy balance of thermodynamics fluxes at the surface of the earth. These 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 (Vidal and Perrier, 1989; and Granger, 1997). 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.

Originally, SEBAL was developed in Spain and Egypt with Landsat 5TM in 1995 by Bastiaanssen (1995). Water consumption of large irrigation systems has been addressed also with NOAA AVHRR in Pakistan (Bastiaanssen et al., 1999). Farah (2001) studied modeling of evaporation under various weather conditions in the Navaisha Basin, Kenya. Combinations of Landsat 7 ETM+ and NOAA are found in Chemin and Alexandridis (2001). Later on, Hafeez (2003) applied SEBAL for the estimation of seasonal actual evapotranspiration using ASTER, MODIS and Landsat sensors in UPRIIS, Philippines.

The main constraint in using remote sensing-based models is that ET_a is calculated only on the satellite overpass days. The limited availability of cloud-free images, and cost, poses major constraints in processing satellite images for daily ET_a estimation. Temporal integration strategies have to be used in order to fill in the missing satellite data and obtain the integrated ET_a information for a season so that ET results can be used in water balance studies.

The primary aim of this study is to calculate the daily actual evapotranspiration in the Liuyuankou Irrigation System (LIS) area, using the SEBAL model applied to a remote sensing TERRA/MODIS sensor. The second objective is to estimate seasonal actual evapotranspiration of the LIS area for the summer season of 2002. These results were integrated with a MODFLOW based water balance of the LIS which will be reported separately.

1.1 Description of the Liuyuankou Irrigation System (LIS)

LIS is located in North West China, in Kaifeng County (Figure 1) and is part of the Hui Ji River system (Huai He River basin). Water for irrigation for crop production is drawn from the channels diverted from the Yellow River, mainly in the northern area of LIS (situated above railway line and hereafter known as "ARL"), as well as by groundwater pumping, in southern area of LIS (situated below railway line and hereafter known as "BRL"). The total area of LIS is 55,512 ha with the net irrigated command area of 40,724 ha. The Liuyuankou major canal is located in the upper part of the irrigation district, and feeds three main canals and fourteen branch canals. Mean annual air temperature is 14.1°C and mean annual precipitation of 627 mm (of which 70 - 80% falls in from June to September period). Mean annual evaporation is 1316 mm. Maximum evaporation occurs from March to August. The major crops include rice, maize, and cotton.

2. MATERIALS AND METHODS

2.1 Satellite Data

MODIS is the key instrument aboard the TERRA satellite, which began operation in March 2000. TERRA/MODIS view the entire earth surface every 1 to 2 days, acquiring data in 36 spectral bands (different wavelengths of electromagnetic radiation). The bands have 250 to 1000 m spatial resolution. An overview of the sensor is provided in Table 1. This study deals with seven MODIS images of the LIS area acquired on different dates (see details in Table 1) to estimate seasonal actual evapotranspiration for the summer season of 2002.

Figure 1. Layout of LiuYuanKou Irrigation System (LIS) in China

Table 1. Overview of TERRA/MODIS sensor and details of satellite image used in the study

Sensor	Satellite Images Used	Sub-systems	Number of bands	Spectral range (μm)	Spatial resolution (m)
TERRA/ MODIS	April 06, 2002 May 31, 2002	VNIR	2	0.62 up to 0.876	250x250
	June 12, 2002 July 12, 2002	SWIR	5	0.459 up to 2.155	500x500
	August 23, 2002 September 22, 2002	SWIR	11	0.405 up to 0.965	1000x1000
	October 24, 2002	TIR	16	3.66 up to 14.385	1000x1000

2.2 Specificity of Porting SEBAL to MODIS

Acquisition of the L1B image (radiometrically corrected) was done through the red hook Eros Data Center Internet web site using the ftppull protocol. Extraction of the binary file was performed for two bands (1 and 2), five short-wave infrared bands (3, 4, 5, 6, and 7) and two thermal bands (31 and 32). A subset image for the study area was created for better visualization. The L1B data was already calibrated for radiometric variations, while geo-referencing was done in the UTM/WGS-84/Zone 50 with a RMSE of less than 1 pixel.

The pre-processing parameters required for SEBAL include the Normalized Difference Vegetation Index (NDVI), emissivity, broadband surface albedo, and surface temperature. The NDVI was calculated from bands 1 and 2 of MODIS, and the broadband albedo was calculated using weighing factors of all visible, near infrared and short wave infrared bands of MODIS (Liang et al. 1999). Surface emissivity of the sensor was calculated from the NDVI of the sensors. Surface temperature of MODIS sensors was calculated from thermal bands 31 and 32 using the split-window technique found in Wan (1999).

2.3 Running SEBAL

Calculation of the net incoming radiation and the soil heat flux were done after Bastiaanssen (1995), while the later development of Tasumi et al. (2000) were incorporated to determine the sensible heat flux. However, to calculate the first temperature difference between air and soil for the “hot” pixel (i.e., where the latent heat flux is assumed null), a first estimation of the air density was required. This was achieved by generalizing meteorological data of relative humidity and maximum air temperature from meteorological station at the time of satellite overpass. Iterations of sensible heat flux were conducted five times. Operational observation showed that this method does not stabilize the air-soil temperature difference as fast as the earlier method found in Bastiaanssen (1995). In SEBAL, manual sampling of hot pixel values of the previous iterations output image files are required before the next iteration can be done which is a practical constraint in the operationalization of this technique. This constraint can be resolved by automation (after hot pixel identification) in the data collection of the results. The sensible heat flux can be improved by repeating the iteration 5 times, but this process is time and space consuming.

The ET is calculated in SEBAL (Hafeez 2003) from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, R_{n24}. 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 (Equation 1).

$$ET_{24} = \Lambda \times \left[R_{n24} \times \left((2.501 - 0.002361 \times T_0) \times 10^6\right)\right] \quad \textit{(mm/day)} \quad \textit{Equation 1}$$

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

The evaporative fraction, Λ, is computed from the instantaneous surface energy balance at the moment of satellite overpass for each pixel (Equation 2):

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\lambda E}{\lambda E + H_0} \quad \textit{(-)} \quad \textit{Equation 2}$$

where λE = latent heat flux (the energy allocated for water evaporation). λ can be interpreted in irrigated areas as the ratio of actual evaporation to crop potential evaporation. 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 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 seasonal ET_a. A larger sample of timely ET observations is necessary to obtain an accurate result and to adjust the daily fluctuation of ET_a for integration of seasonal ET_a. As proposed by Tasumi et al. (2000), missing values of ET_a could be obtained by daily calculation of reference evapotranspiration (ET_o) using the modified Penman-Monteith method. Temporal integration was undertaken in four steps: (i) determination of the period represented by each satellite image, e.g., selecting the April 06, 2002 image to represent the month of April, etc.; (ii) computation of ET_o using the modified Penman-Monteith method for the whole period represented by each image (average monthly ET_o values collected from Hubei meteorological station, is summarized in Table 2); (iii) computation of K_m values for each period as shown in Table 3; and (iv) computation of cumulative seasonal ET_a using the Equation 3:

$$ET_S = \sum_{i=1}^{n} (ET_a)_i \times (K_m)_i \quad \textit{(mm)} \quad \textit{Equation 3}$$

where ET_a = actual daily ET value computed by SEBAL for each pixel of image "i" (mm);
K_m = multiplier for ET for the representative period; n = number of satellite images processed; and ET = seasonal ET (mm).

Table 2: Average ET_o and cumulative ET_o values representing meteorological stations in LIS

ET (mm)	April 06	May 31	June 12	July 12	August 23	September 22	October 24
Cumulative ET_o	97.95	96.77	138.9	117.3	106.33	96.45	72.66
Average ET_o	3.53	4.92	6.16	5.72	4.23	2.23	1.93

Table 3: Values of K_m for summer season 2002 in LIS

	April 1-30	May 1-31	June 1-30	July 1-31	August 1-31	September 1-30	October 1-30
K_m	27.75	19.67	22.55	20.51	25.14	43.25	37.65

3 RESULTS AND DISCUSSION

Daily weather data was collected from the Hubei weather station and used to calculate ET_o using the modified Penman-Monteith equation (Allen et al. 1998). ET_o was converted into potential crop evapotranspiration, ET_c, by multiplying with the crop coefficient K_c ($ET_c = K_c\ ET_o$). Based on the actual cropping calendar, the weighted crop coefficient K_c for different satellite overpass dates were used in this study. The major crop was rice, maize, and cotton in the LIS.

In this study, 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}), estimated ET_o and ET_c from Hubei meteorological station for the summer season of 2002 in LIS as shown in Figure 2. There is a significant difference in ET values obtained from remote sensing and classical techniques, which use weather station data. The former provides spatial distribution results, whereas the latter provides only point values.

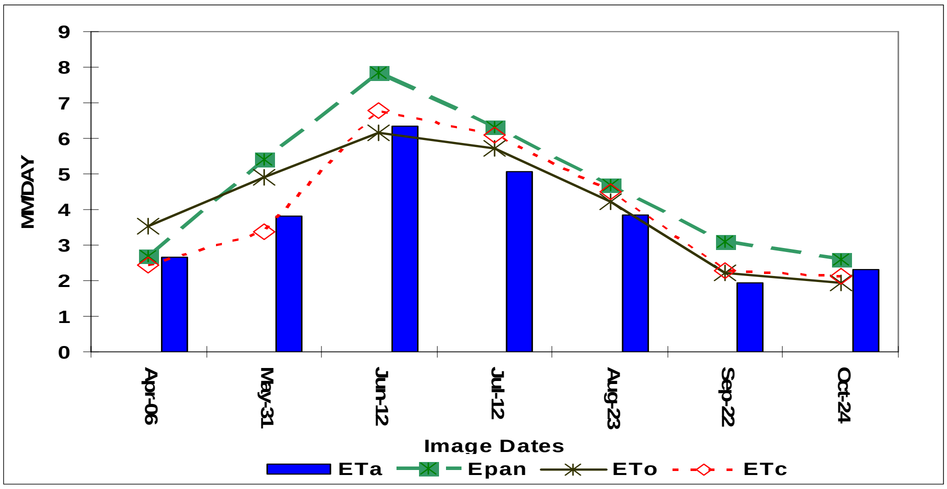

Figure 2. Comparison of ET_a with E_{pan}, ET_o, and ET_c, at Hubei weather station for summer season 2002

As shown in Figure 2, E_{pan} value from Hubei meteorological stations was always higher (on average 26%) than ET_a values for all image acquisition dates. For pixels assumed to be under crop, the estimated ET_a was on average 11% and 5% lower than the average ET_o and ET_c calculated from 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 MODIS, it is difficult to absolutely compare such information with the classical point data from meteorological data, even though Figure 2 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 MODIS pixel for thermal bands) and would therefore contain reflectance attributes from many different physical mediums (mixed spectral signatures from rice fields, bare fields, and roads) and a resulting combined evapotranspiration rate. Comparison between the modeled data and the point-based measured data from class A pans or meteorological stations introduces the possibility of scale related errors. Even though a comparison of ET_a with E_{pan}, ET_o and ET_c does not bring sufficient absolute elements for validation, it does contribute to a consistency cross-checking of the method of ET_a calculation from SEBAL. The comparison show similar trends in ET in the time domain of the summer season 2002.

The integration of daily ET_a raster maps was done using the straightforward method described in the temporal integration part of the previous section. The ET_s map on a pixel-by-pixel basis was produced through integration of all daily ET_a images for the summer season 2002. The statistics of ET_s and volume of water consumption for different areas in the LIS during the summer season 2002 are summarized in Table 3. Results show that ARL has a high volume of water consumption through ET_a than BRL scale. This is mainly due to higher ET from shallow watertables caused by inefficient surface water irrigation and lateral seepage from river. The comparison provided better decision-making for crop water requirement of ARL and BRL areas for this irrigation system.

From a water management perspective, the most important model output of SEBAL was the spatially distributed estimation of the seasonal actual evapotranspiration (ET_s) which was later used with a MODFLOW model of the area. These volumes were cross-validated by the water balance of the LIS provided by Khan et al (2004). For example, Figure 3 depicts a range from 300 mm to 855 mm of ET_s in the LIS region for the summer season of 2002.

Table 3. Seasonal actual evapotranspiration (ET_s) in LIS

Area	Area (ha)	Minimum ET_s (mm)	Maximum ET_s (mm)	Mean ET_s (mm)	Standard Deviation (mm)	Volume (McM)
ARL	27187	300.2	852.8	577.1	160.3	170.9
BRL	28325	327.3	751.3	537.7	124.6	147.6
LIS	55512	300.2	852.8	557.4	160.7	317.3

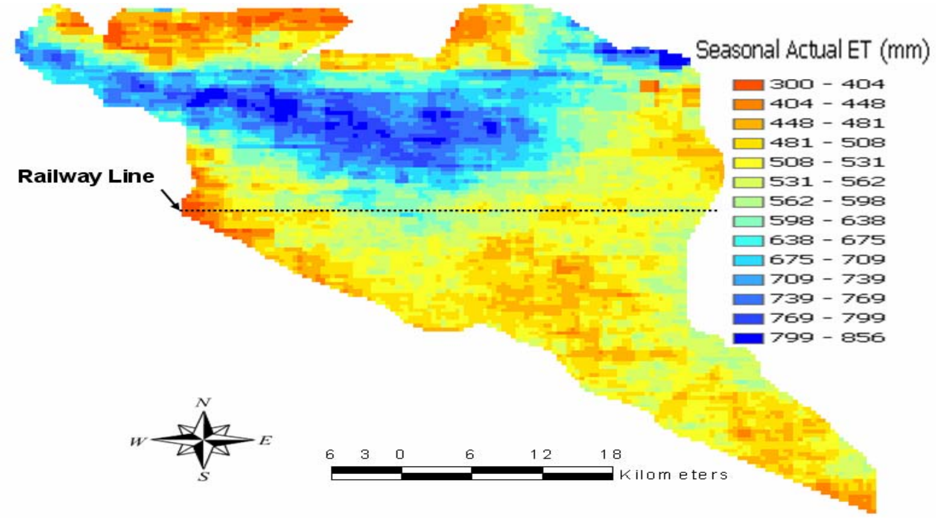

Figure 3. Seasonal actual evapotranspiration map using MODIS sensor for summer season of 2002

Low ET_s is modeled for the bare fields and settlements, 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 darker blue color in Figure 3.

The BRL areas have lower ET_s values because the water table is quite deep and the lack of a surface water irrigation network. Lower ET_s values are indicated by yellow color in Figure 3. The ET_s map further shows a spatial gradient of decreasing evapotranspiration from the Northern (ARL) parts towards the Southern parts (BRL) of the irrigation system The irrigated rice fields (blue color) can be differentiated from the non- irrigated fields (red color) at a spatial resolution of 250 m in Figure 3. The histograms of ET_s for LIS, ARL and BRL from an image representing the summer season of 2002 (April 1 to October 31, 2002) over the irrigation system are shown in Figure 4. The histogram of ET_s show the water consumption pattern has many peaks with the main peak features are 518 mm @ 1531 ha for BRL area, 516 mm @ 1087 ha for LIS area and 745 mm @ 437 ha for ARL area.

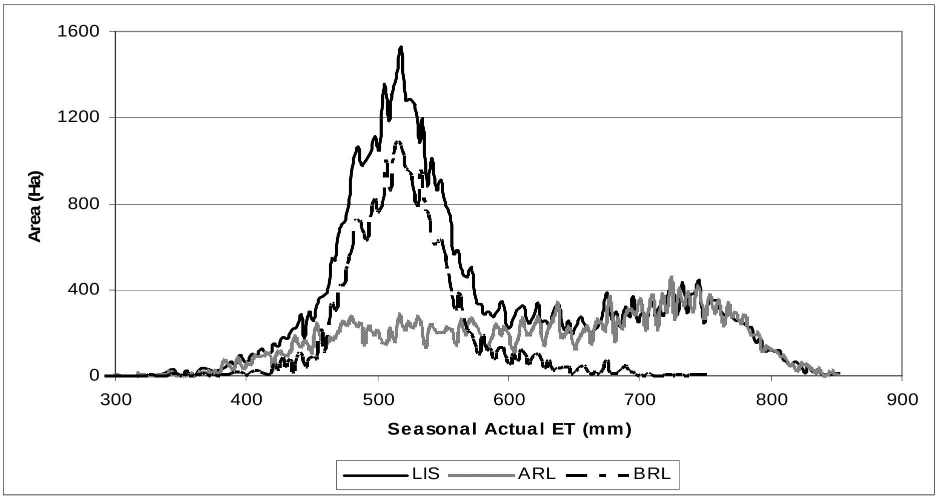

Figure 4. Sensor Histogram of seasonal actual evapotranspiration (mm)

4. CONCLUSIONS

This study focused on the evaluation of multi-temporal MODIS data to calculate actual and seasonal evapotranspiration, applying the SEBAL model. Optical satellite imagery and the SEBAL algorithm provides estimates of spatially distributed ET_a on the days of satellite overpass. The spatial patterns could generally be explained by the cropping patterns observed in the field. The problem of spatially distributed seasonal ET_a estimation can be overcome by integrating daily ET_a from satellite images acquired on different dates in a cropping season with the reference evapotranspiration. The seasonal actual evapotranspiration provides good indicators of crop water consumption throughout the study area. A comparison of ET_a estimated from SEBAL with crop potential evapotranspiration (ET_c) measurements showed a deviation of -5% which is within an acceptable range. The possible reason for deviation of the ET_a estimates using the MODIS sensor is pixel size for small agriculture fields, because the thermal bands MODIS provide surface temperature over one square kilometer size. Estimation of actual ET from remote sensing indicated relatively good accuracy and potential for use in the water balance and water productivity of the LIS. In future, the volume of water consumed for different land use types will be estimated which would provide information about the volume of water lost through fallow land in the LIS. The quantification of non-beneficial ET will help irrigation managers to develop new strategies for water saving from the fallow land, which will lead towards sustainable management of water resources in the LIS area.

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6 REFERENCES

Allen, R., Pereira, L. S., Raes, D. and Smith, M. (1998), Crop evapotranspiration. guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.

Bastiaanssen WGM (1995), 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.

Bastiaanssen WGM, Chemin Y, Ahmad MD, Ali S, Asif S and Prathapar SA (1999), Patterns of crop evaporation in Indus Basin recognized from NOAA-AVHRR satellite. 17th ICID Conference, Switzerland, September 1999, 9p.

Chemin Y and Alexandridis T (2001), Using remote sensing for deriving water productivity indicators in low data environments. A case study for different irrigation unit sizes in Zhanghe Irrigation District, China.

Farah HO (2001), Estimation of regional evaporation under different weather conditions from satellite and meteorological data: A case study of the Navaisha Basin. Doctoral thesis Wageningen University, Den Haag, 170p.

Granger RJ (1997), Comparison of surface and satellite-derived estimates of evapotranspiration using a feedback algorithm. Proceedings of 3rd International Workshop NHRI Symposium 17, NASA, Maryland, USA

Hafeez, M. M. (2003), Water accounting and productivity at different spatial scales in a rice irrigation system: a remote sensing approach. Ph.D. Thesis, University of Bonn, Volume 8.

Khan S, Rana T, Yuanlai C, Blackwell J (2004), Can Irrigation Be Sustainable? 4th International Crop Science Congress Brisbane, Australia, 26 September – 1 October 2004.

Liang S, Strahler AH and Walthall CW (1999), Retrieval of land surface albedo from satellite observations: *Journal of Applied Meteorology.*

Tasumi M, Bastiaanssen WGM, Allen RG (2000), 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.

Vidal, A., & Perrier, A. (1989), Analysis of a simplified relation used to estimate daily evapotranspiration from satellite thermal IR data. *International Journal of Remote Sensing* Vol 10(8): 1,327-1,337, 1989.

Wan, Z. (1999), MODIS Land-surface Temperature algorithm theoretical basis document (LST ATBD). University of California, Santa Barbara