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The use of medium resolution remote sensing data to compare spatio-temporal variation of irrigation performances and water consumption

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Abstract: Precise information on irrigation performance and water consumption at field or canal command level is important to irrigation managers and policymakers to make appropriate decisions on water management. Use of irrigation performance indices cum water consumption are the tools make such decisions. Calculate those figures are a challenging task for the past cropping years, that essential to make correct decisions especially in data-scarce regions of Asia and Africa. Similarly, calculation of these above at field or canal command level over large irrigation schemes are laborious, costly, timely inefficient and less accurate. The necessity for these figures is rapidly increasing due to the need to make the correct decisions with the continually rising population and food demand cum declining water availability parallel to climatic change issues.

Accordingly, well established surface energy balance algorithm (SEBAL) technique has been employed in large irrigated areas in Punjab, Pakistan, as a tool to estimate actual evapotranspiration (ET_a), i.e., water consumption for the cropping years of 2004/05 and 2006/07. Freely available medium resolute daily MODIS images and hydrometeorological data were used as inputs for the ET_a calculation. Under this study irrigation performance indices of equity and adequacy were calculated using actual evapotranspiration and evaporative fraction.

Results show that annual ET_a varies from less than 100 mm/year in desert/barren areas to 1,650 mm/year over large water bodies. For cropped areas, the variation ranges from 400 to 1,200 mm per year for both cropping years. In rice-wheat area of Punjab, average ET_a of the cropping year 2004/05 is 896 mm, and 971 mm for cropping year 2006/07. In lower and southern Punjab, ET_a is low and varies from 805 to 870 mm during 2004/05 and 2006/07, respectively. ET_a was further analyzed in depth on a seasonal and canal command basis for a better understanding and shows that an average of 9% more water has been consumed by crops during the *Kharif* 2007 season while 10% higher consumption was observed for the *Rabi* 2006/07 season than in the previous 2004/05 cropping year. ET_a of the Thal Canal has increased by 44% in the *Kharif* 2007 season followed by Lower Jhelum Canal with 28%. ET_a of Upper Jhelum Canal has also increased by about 20% while that of Panjnad Canal has increased by 22% in the *Rabi* 2006/07 season. Equity of water consumption in 2006/07 has improved considerably compared to 2004/05 in many canals, especially Central Bari Doab, Bahawal, Thal, Chashma Right Bank, Muzaffargarh and Panjnad, which figured as 2, 12, 11, 7, 8 and 8%, respectively. Similarly, adequacy has also improved in many canal commands in the 2006/07 cropping year when compared to 2004/05.

This study demonstrates how a remote sensing based estimation of water consumption and water stress can be combined to provide a better estimation of system and irrigation performance at a variety of spatial and temporal scales that would assist water managers and policymakers.

Key Words: *Irrigation performance, Water consumption, Actual Evapotranspiration, Evaporative Fraction, Equity, Adequacy*

1.0 INTRODUCTION

Optimum food production with scarce water resources can be achieved through the best irrigation management and monitoring/evaluation practices. In order to achieve better management practices, the performance of the past seasons must be calculated and this accounting procedure is extremely important. Accountability of the performance and field level assessment is a laborious and stressful task, especially when infrastructure is poor and the monitoring/evaluation area is large (Ahmad and Gamage 2008). Therefore, the performance evaluation process continuously develops from the last three decades on various aspects, i.e., irrigation efficiency, performance indicators and framework of accounting and productivity. The paucity of reliable information to evaluate the irrigation performance can be overcome with readily available remote sensing data with its various advantages (Bastiaanssen and Bos, 1999). Accordingly effort was taken to calculate crop water consumption and irrigation performances over large contiguous canal command in Punjab using actual evapotranspiration and evaporative fraction derived from remote sensing data.

2.0 METHODOLOGY AND STUDY AREA

2.1 Surface Energy Balance Algorithm (SEBAL)

SEBAL is a remotely sensed image processing model which computes a complete radiation and energy balance along with the resistances for momentum, heat and water vapor transport for each pixel (Bastiaanssen et al. 1998). SEBAL is a well-tested and widely used method to compute ET_a (Bastiaanssen et al., 1998, 2005; Tasumi et al., 2003; Ahmad et al., 2006). From the reflectance and radiance measurements of the bands, first land surface parameters such as surface albedo (Liang 2000; Liang et al., 2002), vegetation index, emissivity (Van de Griend and Owe, 1993) and surface temperature are estimated (Tasumi, 2003). The evaporation is calculated from the latent heat flux from the instantaneous surface energy balance at satellite overpass on a pixel-by-pixel basis:

$$\lambda E = R_{\mathrm{n}} - \left(G_0 + H\right) \qquad (1)$$

Where: λE is the latent heat flux R_{n} is the net radiation, G_0 is the soil heat flux and H is the sensible heat flux. The latent heat flux describes the amount of energy consumed to maintain a certain evapotranspiration rate. Then, instantaneous latent heat flux, λE, is the calculated residual term of the energy budget, and it is then used to compute the instantaneous evaporative fraction Λ (-):

$$\Lambda = \frac{\lambda E}{\lambda E + H} = \frac{\lambda E}{R_{\mathrm{n}} - G_0} \qquad (2)$$

The instantaneous evaporative fraction Λ expresses the ratio of the actual to the crop evaporative demand when the atmospheric moisture conditions are in equilibrium with the soil moisture conditions. The instantaneous value can be used to calculate the daily value, if the evaporative fraction tends to be constant during daytime hours, although the H and λE fluxes vary considerably. The difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24-hour integrated energy balance is often marginal and may in many cases be neglected (Brutsaert and Sugita (1992), Crago (1996), Farah (2001)). For time scales of 1 day, G_0 is relatively small and can be ignored, and net available energy (R_{n} - G_0) reduces to net radiation (R_{n}). At daily timescales actual evapotranspiration, ET_{24} (mm/day), can be computed as:

$$ET_{24} = \frac{86400 \times 10^3}{\lambda\, \rho_{\mathrm{w}}} \Lambda\, R_{\mathrm{n}24} \qquad (3)$$

Where: $R_{\mathrm{n}24}$ is the 24-h averaged net radiation, λ is the latent heat of vaporization, and ρ_{w} is the density of water. For timescales longer than 1 day, actual evapotranspiration can be estimated using the relation proposed by Bastiaanssen et al. (2002). The main assumption is that Λ specified in equation (3) remains constant over the entire time interval between capture of each remote sensing image so that:

$$ET_{\mathrm{int}} = \frac{\mathrm{d}t \times 86400 \times 10^3}{\lambda \, \rho_{\mathrm{w}}} \Lambda R_{\mathrm{n24t}} \qquad (4)$$

Where: ET_{int} is the time integrated actual evapotranspiration, R_{n24t} average R_{n24} for the time interval dt measured in days. R_{n24t} is usually lower than R_{n24} because R_{n24t} also includes cloudy days.

2.2 Irrigation performance indices

A wide range of irrigation and water use performance indicators are available (Bastiaanssen and Bos 1999; Bos et al., 2005) to assist in achieving efficient and effective use of water by providing relevant feedback to the scheme/river basin management at all levels. Seasonal and annual ET_{a} calculated based on SEBAL is directly used as a representative figure of water consumption in this study. *Equity* and *adequacy* were selected to evaluate the performance of irrigation systems. Equity is considered here as uniformity of the water consumption and to understand equity of water consumption mean of seasonal ET_a and their spatial coefficient of variation (CV) were calculated over the pixels representing cropped areas within each canal commands. Adequacy defined as measure of sufficiency levels of water use in an irrigation system over the growing season. Adequacy of water supplies to cropped area can be assessed using the evaporative fraction maps, as they directly reveal the crop supply conditions (Alexandridis *et al*., 1999; Bastiaanssen and Bos, 1999). Accordingly, *adequacy* is defined as the average seasonal evaporative fraction.

2.3 Study area and data

The study covers the entire canal irrigation system of the Indus Basin (approximately 8.5 million ha of cropped area) of the Punjab Province (Figure 1). There are two dominant cropping seasons, *Rabi (November to April)* which is during the winter season, *Kharif (May to October)* which is during the summer season, when temperatures rise up to 46~50°C in June-July. Mean annual precipitation varies from 125 mm in the southern part of the study area to 650 mm in the northern part. The elevation difference from south to north is minimum and onset of the southwest monsoon is anticipated to reach Punjab by the end of May and continue until July-August. Almost 75% of the annual rainfall occurs during the monsoon season from mid-June to mid-September. Due to scanty and erratic rainfall, successful agriculture is only possible with irrigation from surface water and groundwater. Rice, cotton, sugarcane and forage crops dominate the *Kharif* season whereas wheat and forage are the major crops in the *Rabi* season (Gamage et al. 2007).

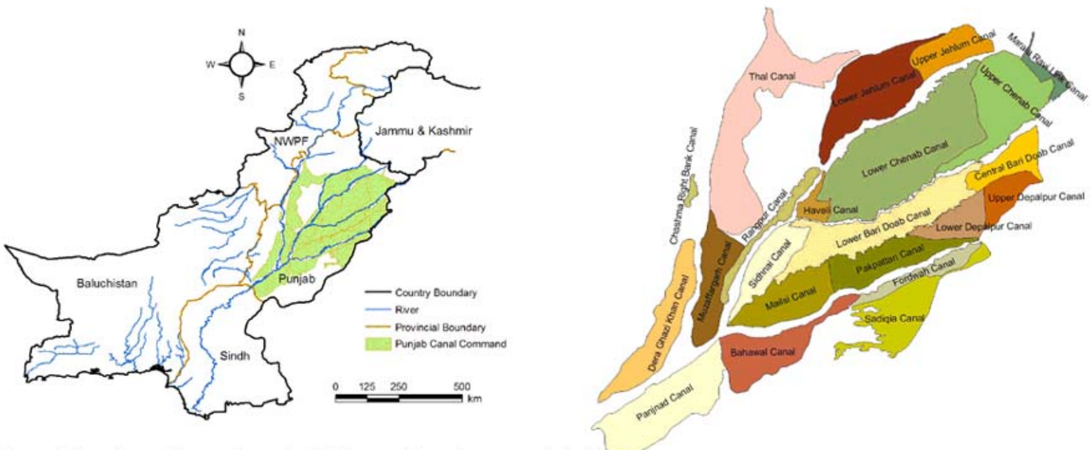

Figure 1 Location of the studyarea in Pakistan and canal commands in Punjab

The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. In addition to satellite images, the SEBAL model requires the following routine weather data parameters (wind speed, humidity, solar radiation and air temperature) and collected from the Pakistan Meteorological Department (17 stations in Punjab). Data were collected to represent two cropping years, October 2004 to November 2005 (Cropping year 2004/05) and October 2006 to November 2007 (Cropping year 2006/07). Further, 39 cloud-free MODIS images, covering the whole Punjab, were downloaded to represent both cropping years from Earth Observing System Data Gateway (EOSDG) of NASA. These level 1B calibrated radiance data of MODIS terra are readily available at NASA Goddard Space Flight Center website (http://ladsweb.nascom.nasa.gov/data/search.html). There first seven bands were used to calculate albedo followed by Liang (2000), band 31 and 32 to calculate surface temperature following Tasumi (2003).

3.0 DISCUSSION

3.1 Spatio-temporal variation in annual ET_a

The annual ET_a varies from less than 100 mm/year in desert/barren areas to about 1,650 mm/year over large water bodies in the processed images covering entire canal commands of Punjab. The annual ET_a from *cropped* areas ranges between 400 to 1,200 mm/year (Figure 2). Due to heterogeneous cropping patterns and medium data resolution, it is difficult to identify pure pixels for particular crops (one pixel corresponds with 100 hectares). However, for the Punjab rice-wheat area (mainly northern part) the annual average ET_a is 896 mm in the cropping year of 2004/05 while it is 971 mm in 2006/07. Generally, in the Lower Punjab this is much lower (i.e., 766 mm/year in Panjanad) because of lower cropping intensity, less water-intensive crops and possible effects of salinity. The average ET_a over all canal commands is about 805 mm in 2004/05 and 870 mm in 2006/07, an increase of nearly 65 mm. Typically, irrigated areas close to the main canals or river have higher ET_a due to better access to canal water and groundwater for agriculture albeit in both cropping years ET_a gradually decreased towards the tail end.

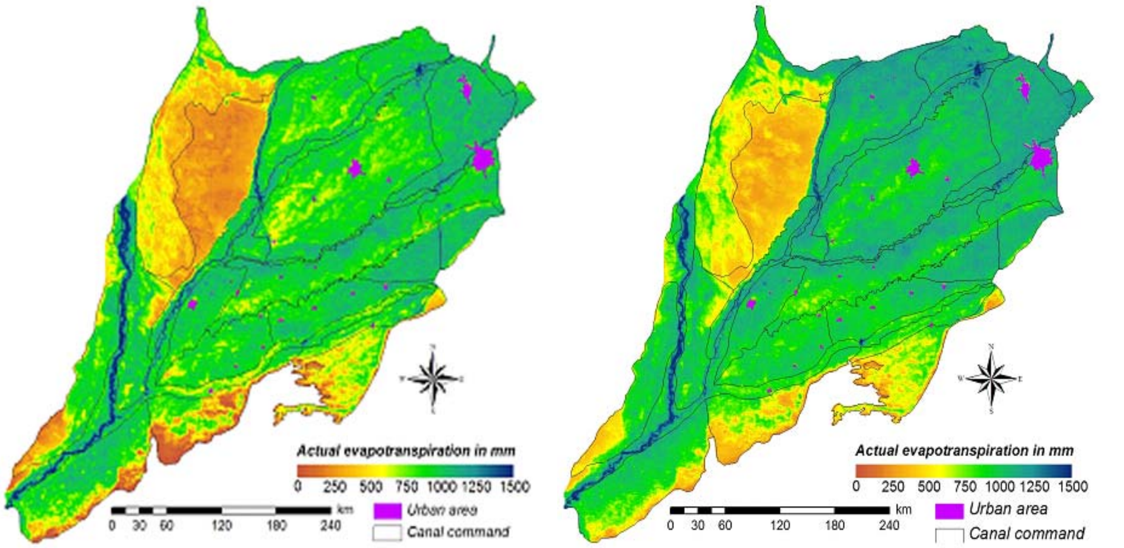

Figure 2. Annual ET_a of Punjab canal commands representing both cropping years. Cropping year 2004/05 (left) and cropping year 2006/07 (right).

3.2 Spatio-temporal variation in seasonal ET_a

The maps in Figure 3a and 3b show seasonal variation in ET_a of the Punjab Canal command areas. Generally, both *Rabi* seasons exhibit a similar ET_a distribution but higher values were shown in the cropping year 2006/07. Table 1 shows the magnitude of increase of seasonal ET_a in all canal commands. The results indicate that recent *Rabi* season exhibits

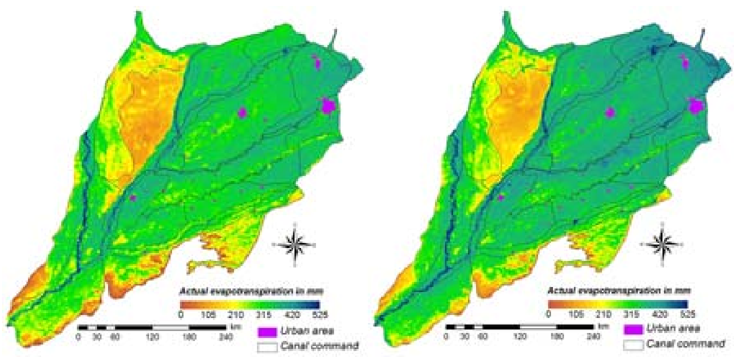

Figure 3a. Seasonal ET_a of Punjab canal command areas, left to right: *Rabi* 2004/05, *Rabi* 2006/07,

higher ET_a values with less spatial variation which could be result of better management practices and higher water availability. However, the spatial variation of ET_a values during the *Kharif* season is more pronounced than during Rabi season. Poor distribution and lower values of ET_a in the 2005 *Kharif* season is more significant than the ET_a in the 2007 *Kharif* season. The percentage of increase in water consumption is shown in Table 1. This reveals evapotranspiration has increased in the 2007 *Kharif* and 2006/07 *Rabi* seasons when compared to both seasons in 2004/05 (Table 1).

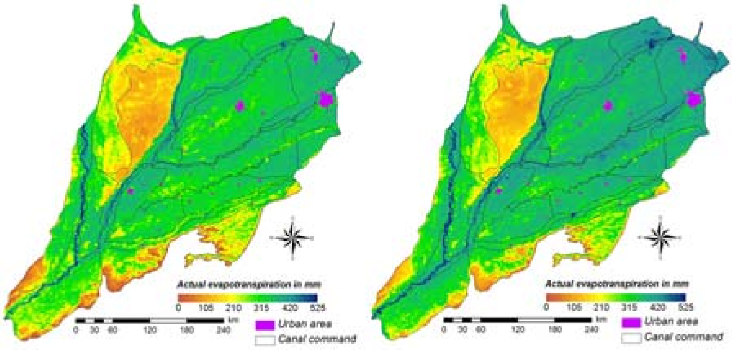

Figure 3b. Seasonal ET_a of Punjab canal command areas, left to right: *Kharif* 2005 and *Kharif* 2007

3.3 Water consumption at canal command level

Table 1 shows difference of ET_a values in each canal command and its percentage of increase or decrease with relevant to cropping seasons of cropping year 2004/05. About 8533 MCM (Million Cubic Meters) more water was consumed during 2006/07 than 2004/05, a total increase of 9.4%. In seasonal scenario the water consumption of 2006/07 *Rabi* and 2007 *Kharif* seasons has increased 10.5 and 9%, respectively than that of in the seasons of 2004/05 *Rabi* and 2005 *Kharif*. These increased consumptions could be result of the increase of cultivation area and better water availability to tail ends. This may facilitated with the better land management practices which were introduce after 2004/05. Further Table 1 reveals the increase of the consumption is highly varying among the canal commands. These variations agree with the spatial variation of the ET_a in Figure 3a and 3b as a result of water availability, management practices with existing soil and climatic conditions.

Table 1. Mean annual, seasonal and gross volume of ET_a for main canal commands in Punjab and seasonal changes in gross

	Difference in Kharif 2005 and 2007		Difference in Rabi 2004/05 and 2006/07	
Canal Name	Vol. (10^6 m^3)	Vol. % change	Vol. (10^6 m^3)	Vol. % Change
Upper Jehlum	235	14.61	175	19.93
Lower Jehlum	1,075	28.87	161	6.8
Marala Ravi Link	48	8.94	47	14.42
Upper Chenab	181	4.36	208	9.07
Lower Chenab	1,289	16.81	486	10.37
Central Bari Doab	110	8.33	79	10.37
Upper Depalpur	30	2.6	50	8.25
Lower Bhari Doab	87	2.02	222	9.31
Lower Depalpur	21	1.39	48	5.96
Pakpattan	-114	-4.5	137	10.47
Fordwah	-44	-4.23	47	9.06
Sadiqia	17	0.99	145	15.07
Haveli	50	9.09	20	6.69
Sidhnai	93	4.92	57	5.21
Mailsi	47	1.97	117	8.85
Bahawal	340	23.22	140	15.1
Thal	1,321	44.28	342	14.49
Chasma Right Bank	4	3.13	9	12.33
Rangpur	78	8.6	27	5.14
Muzaffar Grag	193	9.26	38	3.23
Dera Ghazi Khan	368	15.33	119	9.32
Panjnad	25	0.62	405	22.35

3.4 Equity

As shown in Figure 4, mean seasonal coefficient of variation (CV) for irrigated area is less in 2006/07 as compared to 2004/05 in all canal commands with higher amounts of improvement in Lower Jehlum, Lower Chenab and Thal. During the *Rabi* season, equity of water consumption is higher compared to the *Kharif* season as a result of winter-driven less demand on water. In contrast, lesser CV from irrigated areas in 2006/07 indicated improvement in the equity of water consumption. Canal command level variability in consumptive water use shows that Central Bari Doab, Bahawal, Thal, Chasma Right Bank, Muzaffar Grag and Panjnad improved by 2, 12, 11, 7, 8 and 8%, respectively, in the 2007

Kharif season than in the 2005 *Kharif* season. This could be result of better availability of the water to southern part with higher rainfall in *Kharif* 2007.

3.5 Adequacy

According to Figure 5, both Rabi seasons do not reveal much of a difference in the level of adequacy but a gradual decrease is shown to Southern Punjab. All canal commands except for Sadiqia, Fordwah, Bahawal and Panjnad show better and improved value of means evaporative fraction (adequacy) in the 2007 *Kharif* season signaling the better adequacy level of the water. This overall improvement in the adequacy of the *Kharif* 2007 season could trigger with higher precipitation in the particular season and changes that have taken place in the irrigation management process.

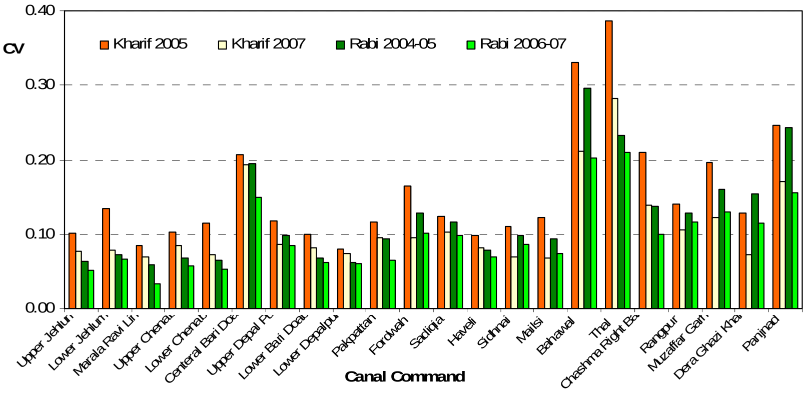

Figure 4. Spatial coefficient of variation (equity) of ET_a in canal commands of Punjab, Pakistan.

Anyhow, head to tail water discrimination was observed in all canal commands with a gradual reduction in the level of adequacy from the northern to the southern part of the Punjab. But the area adjacent to the head of other major canal commands or rivers show a great level of adequacy with existing groundwater irrigation. Groundwater irrigation is triggered in the head of canals with better recharge the water table with high flux of canal flows. This conjunctive water use benefit to reduce water logging and washed off the prevailing salinity conditions of the field, ultimately paved way to better crop. Additionally, a reduction in the value of the adequacy in the southern area could be result of sandy soil where more water infiltrates to the layers below.

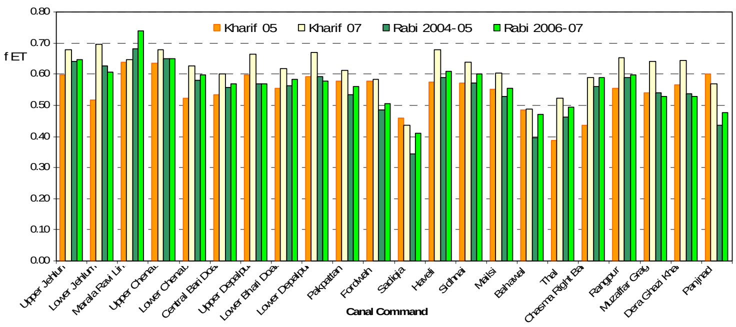

Figure 5. Average seasonal evaporative fraction in the *Rabi* and *Kharif* seasons indicating adequacy of water availability.

4.0 CONCLUSIONS

Overall, the results show the usage of the medium level resolution remote sensing data to monitor and evaluate the irrigation system. Accordingly, policymakers and managers can use this information to evaluate and investigate the system for further developments which could lead to a secure future.

The annual mean ET_a has increased to 971 mm in 2006/07 compared to 896 mm in 2004/05. The seasonal analysis shows that the 2007 *Kharif* season consumed 9.12% and the 2006/07 *Rabi* season consumed 10.54% more water than their corresponding seasons in the previous year. Results revealed equity in water consumption has improved considerably in many canals, especially Central Bari Doab, Bahawal, Thal, Chashma Right Bank, Muzaffargarh and Panjnad in recent cropping seasons albeit head to tail discrimination still exists. Similarly, the overall level of adequacy has improved in the cropping year 2006/07 but not to its optimum level. This shows that there is a high potential for improving adequacy and thereby improvements in the yield per unit area. Improving poor adequacy levels in the southern part could increase the yield and, thus, water productivity with existing higher market value cropping patterns.

References

Ahmad, M.D. and Gamage, N. (2008), Monitoring agricultural water consumption and irrigation performance using freely available MODIS images and routine secondary data for a large irrigation system in Pakistan. CPWF Annual Forum 2008.

Ahmad, M.D., Biggs, T., Turral, H. and Scott C.A. (2006), Application of SEBAL approach and MODIS time-series to map vegetation water use patterns in the data scarce Krishna river basin of India, IWA Journal of Water Science and Technology 53 (10), pp. 83–90.

Alexandridis, T., Asif, S. and Ali, S. (1999), Water performance indicators using satellite imagery for the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project. Pakistan Research Report 87, International Water Management Institute. Lahore, Pakistan. pp,16.

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., Thoreson, B.P. and Allen, R.G. (2005), SEBAL model with remotely sensed data to improve water-resources management under actual field conditions, *ASCE Journal of Irrigation and Drainage Engineering* 131 (1), pp. 85–93.

Bastiaanssen, W.G.M., and Bos, M.G. (1999), Irrigation performance indicators based on remotely sensed data: a review of literature. *Irrigation and drainage systems* 13, 291-311.

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A. and Holtslag, A.A.M. (1998), A remote sensing surface energy balance algorithm for land (SEBAL), 1. Formulation, *Journal of Hydrology* 212-213, 198-212.

Bos, M.G., Burton, M.A. and Molden, D.J. (2005), Irrigation and Drainage Performance Assessment: Practical Guidelines, CABI Publishing, UK, pp. 158.

Brutsaert, W. and Sugita, M. (1992), Application of self-preservation in the diurnal evolution of the surface energy budget to determine daily evaporation, *Journal of Geophysical Research* 97 (D17), pp. 18,322–18,377.

Crago, R.D. (1996), Conservation and variability of the evaporative fraction during the day time, *Journal of Hydrology* 180, pp. 173–194.

Farah, H.O. (2001), Estimation of regional evaporation under different weather conditions from satellite and meteorological data. PhD Thesis. Department of Water Resources, Wageningen University, pp.170.

Gamage, M.S.D.N., Ahmad, M.D. and Turral, H. (2007), Semi-supervised technique to retrieve irrigated crops from Landsat ETM+ imagery for small fields and mixed cropping systems of South Asia, *International Journal of Geoinformatics* 3 (1) , pp. 45–53.

Liang, S., Shuey, C.J., Russ, A.L., Fang, H., Chen, M., Walthall, C.L., Daughtry C.S.T. and Raymond H. Jr (2002), Narrowband to broadband conversions of land surface albedo. II. Validation, *Remote Sensing of Environment* 84, pp. 25–41.

Liang, S. (2000), Narrowband to broadband conversions of land surface albedo. I. Algorithms, *Remote Sensing of Environment* 76, pp. 213–238.

Tasumi, M., Trezza, R., Allen, R.G. and Wright, J.L. (2003), U.S. Validation tests on the SEBAL model for evapotranspiration via satellite. ICID Workshop on Remote Sensing of ET for Large Regions Montpellier, France 17 Sept. 2003.

Tasumi, M. R. (2003), Progress in Operational Estimation of Regional Evapotranspiration Using Satellite Imagery, Dissertation University of Idaho, pp. 357.

van de Griend, A.A. and Owe, M. (1993), On the relationship between thermal emissivity and the normalized difference vegetation index for natural surfaces, *International Journal of Remote Sensing* 14 (6), pp. 1119–1131.