Mapping evapotranspiration in the Indus Basin using ASTER data

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Online Publication Date: 01 January 2007


To link to this article: DOI: 10.1080/01431160600954654

URL: http://dx.doi.org/10.1080/01431160600954654
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(Received 22 June 2005; in final form 5 August 2005)

Conventional methods that use point measurements to estimate evapotranspiration are representative only of local areas and cannot be extended to large areas because of heterogeneity of landscape. To overcome this difficulty, remote sensing has proven to be the most suitable approach for large area estimation of evapotranspiration because remote sensing data can provide representative parameters such as radiometric surface temperature, albedo and vegetation index. The heterogeneity is more prominent in the Indus Basin as more than 80% of farmers have land holdings less than 4 ha, and within these holdings, two or three different crops are usually grown. The limitation of most remote sensing based procedures to estimate evapotranspiration is the measurements of large number of crop-specific and climatic parameters, which are not only difficult to obtain but also require considerable field work, equipment and therefore involve much expenditure. The purpose of this study was to present a simple methodology that requires minimum ground observations for estimation of evapotranspiration to test the reliability of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data for estimation of evapotranspiration in the Indus Basin. The methodology is based on surface energy balance to estimate sensible and latent heat fluxes by combining remotely sensed data from ASTER with common meteorological data. The various components of surface energy balance were computed during satellite overpass and 24-h integrated fluxes were derived for the full ASTER scene acquired over the lower Rechna doab region of the Indus Basin. The surface brightness temperatures were derived from thermal band 13 and NDVI from two VNIR bands of the ASTER. Evapotranspiration values from the maize field in the Indus Basin, as estimated using ASTER data at Shahkot, Jaranwala and Satiana locations, were estimated as 2.05, 2.77 and 2.32 mm day\(^{-1}\), respectively. The estimated evapotranspiration was compared with evapotranspiration computed at three different locations using CROPWAT software and was found to be in close agreement.

1. Introduction

Evapotranspiration and its spatial variation at the regional level is the most important parameter to assess the demand for irrigation. Reliable estimation of evapotranspiration can help to improve the performance of irrigation system operation. Conventional methods of estimating evapotranspiration provide accurate measurements over the homogeneous areas and are representative of local areas and cannot be extended to large areas due to regional variation of climatic parameters and heterogeneity of landscape.

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In recent years, remote sensing has proven to be the best tool to estimate evapotranspiration at regional level. The remote sensing data provide representative parameters such as radiometric surface temperature, surface albedo and vegetation indices. Multi-band sensors that measure reflected solar and emitted thermal radiation within discrete wavelength intervals could obtain detailed data over an extended area. The advantage of remote sensing based procedures is that the water consumed by the soil-water–vegetation system can be derived directly without quantifying complex hydrological process.

A variety of remote-sensing algorithms to estimate heat and evaporation fluxes is under investigation. A review of the most common ones is presented in Kustas and Norman (1996). Jackson (1985) proposed that on a local scale, the surface-dependent component of the energy balance could be evaluated remotely to estimate energy balance over agricultural areas. Bastiaanssen et al. (1998) developed a Surface Energy Balance Algorithm for Land (SEBAL) to calculate energy partitioning at the regional scale with an attempt to use minimum ground data. Norman et al. (1995) used Two-Source Energy Balance (TSEB) controlled by the vegetation density and surface temperature for estimating soil and vegetation energy fluxes. French et al. (2002) applied the Norman’s approach to estimate evapotranspiration over the grazing land using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery. All these approaches require a number of ground-based data and plant parameters, which are difficult to obtain for each land use class and over a large area.

Efforts are still underway to improve methodologies for estimation of land surface fluxes using remote sensing data. Out of various variables to estimate energy balance, the remote estimation of aerodynamic resistance to sensible heat transfer ($r_a$) is the most difficult one, which is expressed in terms of wind speed ($u$), surface roughness ($z_o$) and displacement height ($d$) and can not be determined analytically. The complications in the estimation of $z_o$ and $d$ led to the efforts to relate these parameters to crop biomass and vegetation height. Hatfield (1988) and Moran (1990) reported that $z_o$ and $d$ could be estimated from spectral vegetation indices such as normalized difference vegetation index (NDVI) and NIR/Red ratio. The objective of this paper is to present how ASTER data were used to estimate land surface fluxes and subsequently evapotranspiration over an irrigated area in the Indus Basin, Pakistan using a methodology requiring minimum ground data.

2. Materials and methods

The ASTER level-1B data ‘radiance at the sensor’ acquired on 4 October 2000 was applied to a scene with centre coordinates of 31.35° N, 73.49° E in the Indus Basin, Pakistan. There are a total of 14 spectral bands in ASTER in the visible and near-infrared (VNIR), the short-wave infrared (SWIR) and thermal infrared (TIR) spectrum for nadir observation. Ground resolutions are 15 m for the VNIR, 30 m for SWIR and 90 m for the TIR. Prior to radiometric correction, TIR bands originally coded in 16-bit was re-scaled to 8-bit for combination with VNIR and SWIR bands. Out of five TIR bands, only band 13 is used for generating a surface temperature map. The spectral range of band 13 is 10.25–10.95 μm. The reason behind this simple one-band approach is that a temperature/emissivity separation is available at a higher level in ASTER product (Gillespie et al. 1995). Richter (1996) based on a fast adoptive algorithm, developed a commercial software package ATCOR (atmospheric correction) for retrieval of ground temperature (Geosystems 2002).
2.1 Estimation of energy balance components

Remote sensing and ground-based data were used to calculate both the instantaneous and 24 h integrated surface heat fluxes. Net radiation was partitioned into latent heat flux, sensible heat flux and soil heat flux. The latent heat flux (LE) was computed as the residual of the energy balance as:

\[ LE = R_n - G - H \]  

where \( R_n \) is net radiation, \( G \) is soil heat flux and \( H \) is sensible heat flux.

2.1.1 Net radiation (\( R_n \)). The radiation balance at the Earth’s surface is composed of four spectral radiant fluxes: the incoming shortwave (0.14–4 \( \mu \)m) radiation that arrives from the sun (\( R_s \)), the amount of this energy that is reflected from the surface (\( R_s' \)), the incoming longwave (>4 \( \mu \)m) radiation from the atmosphere (\( R_L \)), and the amount of longwave radiation emitted from the surface (\( R_L' \)). Thus the net radiation was calculated as:

\[ R_n = R_s' - R_s + R_L' - R_L \]  

Due to absence of data from any ground-based instrument, \( R_s' \) was calculated from the product of instantaneous extraterrestrial radiation and two-way atmospheric transmittance (Parodi 2000). The absorption of solar radiation at the Earth’s surface is calculated using the following relation:

\[ R_{abs} = (1 - \alpha)R_s' \]  

where \( \alpha \) is the surface albedo. The broad-band surface albedo \( \alpha \) is determined from narrow band measurements by a weighted average technique (Liang 2000). The incoming longwave radiation (\( R_L' \)) was estimated from the ground-based measurement of air temperature and vapour pressure using the relation (4):

\[ R_L' = e_a \sigma T_a^4 \]  

where \( e_a \) is emissivity of atmosphere [\( e_a = 1.24(e_d/T_a)^{1/7} \)], \( \sigma \) is the Stefan–Boltzmann’s constant (5.67 \( \times \) 10^{-8} \( \text{Wm}^{-2}\text{K}^{-4} \)), \( T_a \) is the air temperature (\( ^{\circ}\text{C} \)), and \( e_d \) is vapour pressure deficit (mbar). The outgoing longwave radiation (\( R_L' \)) was obtained from the remotely measured surface temperature by ignoring the small contribution of reflected sky radiation using the following relation:

\[ R_L = e_s T_s^4 \]  

where \( e_s \) is surface emissivity and \( T_s \) is surface temperature (\( ^{\circ}\text{K} \)). According to Van de Griend and Owe (1993), an emissivity (\( e_s \)) for a spectral range of 8–14 \( \mu \)m could be predicted from NDVI with high correlation. The \( e_s \) is, therefore, calculated from NDVI using the following logarithmic relation:

\[ e_s = 1.0094 + 0.047 \times \ln(\text{NDVI}) \]  

The instantaneous net amount of radiation received by a surface is the sum of all incoming and outgoing radiant fluxes and was calculated as:

\[ R_n = (1 - \alpha)R_s' + e_a \sigma T_a^4 - e_s T_s^4 \]
2.1.2 Soil heat flux (G). Soil heat flux (G) could be as high as 0.3 $R_n$ for bare soil and decrease to 0.1 $R_n$ for full vegetation cover (Jackson et al. 1987). Several studies have shown that the daytime ratio of $G/R_n$ is related to, among other factors, the amount of vegetation present (Kustas and Daughtry 1990, Gao et al. 1998, Bastiaanssen 2002). Bastiaanssen (2000) presented the following relationship (8), which was adopted to estimate $G$ as follows:

$$G = R_n \left( \frac{T_s}{\alpha} \right) \times (0.0038\alpha + 0.0074\alpha^2) \times (1 - 0.98 \text{NDVI}^4) \quad (8)$$

2.1.3 Sensible heat flux (H). The estimation of reliable values of sensible heat flux is the most difficult aspect of this methodology because of its dependence on the aerodynamic resistance. $H$ is commonly expressed as the function of $T_s$ and $T_a$

$$H = \rho C_p (T_s - T_a) / r_a \quad (9)$$

where $\rho$ is the density of dry air (kg m$^{-3}$), $C_p$ is the specific heat capacity of air (J kg$^{-1}$C$^{-1}$) and $r_a$ is the aerodynamic resistance to heat transport (s m$^{-1}$). $r_a$ is often estimated by Monin–Obukhov similarity theory (Businger 1988). Many semi-empirical relations have also been proposed to estimate $r_a$ or $H$ (Thom and Oliver 1977, Viney 1991, Carlson et al. 1995). Of various semi-empirical relations Carlson et al. (1995) proposed the simplest one to estimate $H$ from a few easily obtainable measurements such as NDVI, $T_s$ and $T_a$. The problem with this approach is that it underestimates the $H$ over the urban areas (asphalt, concrete or building, etc.) where vegetation index is very low and consequently overestimates the LE (Richter 2002).

To avoid complication, a semi-empirical generalized expression for aerodynamic resistance proposed by Thom and Oliver (1977) as given below was adopted:

$$r_a = 4.72 \{ \ln(z/z_o) \}^2 / (1 + 0.54u) \quad (10)$$

where $z$ is the reference height of wind speed measurement (m), $z_o$ is the surface roughness length for momentum (m) and $u$ is the wind speed (m s$^{-1}$).

Hatfield (1988) and Moran (1990) reported that $z_o$ could be estimated from spectral vegetation index such as NDVI and the NIR/Red ratio. Gao et al. (1998) also related $z_o$ (cm) with NDVI to estimate the surface fluxes at regional level. Moran’s (1990) exponential relation (11) was used to estimate $z_o$ from the NIR and red reflectance.

$$z_o = \exp(0.1021 + 0.1484(\text{NIR}/\text{Red})) \quad (11)$$

2.2 Estimation of daily total LE from instantaneous values

There is sufficient evidence that evaporation fraction (EF), which is the ratio of latent heat flux to the sum of latent and sensible heat fluxes (LE/LE + $H$ = LE/$R_n$ - G), remains constant over the daytime period. Therefore the product of EF and daily net radiation ($R_n$) can provide the estimate of daily evapotranspiration. Heat flux measurements with eddy correlation devices confirmed that latent heat flux (LE) is approximately equal to ($R_n$ - G) when both terms are integrated over time (Wang et al. 1995). Thus (LE + $H$) is a good substitute for potential evapotranspiration and evaporative fraction (EF) is consequently similar to relative evapotranspiration. The
value of EF usually varies from 0 to 1. Several studies have shown that this technique is reasonable with differences in daily evapotranspiration less than 1 mm day$^{-1}$ (Kustas et al. 1994). Therefore, the daily actual evapotranspiration (ET) was estimated as:

$$\text{ET} = 0.0345 \times \text{EF} \times R_{n,d}$$

(12)

where EF is the evaporation fraction (–), $R_{n,d}$ is daily net radiation (W m$^{-2}$) and 0.0345 is a conversion factor. The daily net radiation was computed according to Holtslag et al. (1981) using standard meteorological data (13)

$$R_{n,d} = (1 - z)K^\parallel - 110K^\parallel / K_{exo}$$

(13)

where $z$ is surface albedo, $K^\parallel$ is global radiation at the surface level and $K^\parallel_{exo}$ is the theoretical extraterrestrial radiation.

3. Results and discussion

An examination of figure 1 shows that the agricultural fields closer to the river shows higher EF, indicated with the letter A as compared with the area far from the river on the top left corner of the image, indicated with letter B, which means that
significant energy is converted into sensible heat in the top left area. The white patches in the image shows the pixels where most of the energy is converted into sensible heat. Due to non-availability of detailed crop data, it was difficult to distinguish moisture levels among the fields. The whitish patches along the path of river, however, show extremely low EF because most of the area is bare sand with no vegetation.

The spatial variation in actual evapotranspiration within the scene is presented in figure 2. The values of evapotranspiration were found to vary from 0 to 4.25 mm day$^{-1}$. The bends of the river are clearly visible from the higher evapotranspiration due to higher evaporation rate from the water surface visible as almost black. The letters C in figure 2 clearly indicate less evaporation with the lowest near zero from sandy bare soil close to the river. Relatively higher evaporation is visible at other sites indicated with letter C when compared with bare soil near the river, which is ultimately an indicator of moisture stress in these areas. The rest of the scene shows higher evapotranspiration.

The evaporation from the surface of water bodies such as canals/rivers estimated using remote sensing data was compared with class A open pan evaporation and was found slightly underestimated than class A pan evaporation. This could be due to the fact that evaporation from a small area of a pan is usually more than from a river/canal surface because of the extra heat taken in through the pan’s sides.
(Linacre 1994). Furthermore, the 95th percentile of evaporation was calculated by selecting the pixels within the pure water body classes and was found to be 4.15 mm day\(^{-1}\). This value was compared with pan evaporation data at all three sites after multiplying by the respective pan coefficient (\(K_p\)) as presented in Table 1. The comparison indicates that the 95th percentile was in close agreement to the Jaranwala site (close to river) and higher when compared with the other two stations. This is because pan evaporation data near the river represent the actual condition comparable with remote sensing data.

### Table 1. Comparison of satellite evapotranspiration and CROPWAT model based evapotranspiration in the maize fields.

<table>
<thead>
<tr>
<th>Location (city)</th>
<th>Shahkot</th>
<th>Jaranwala</th>
<th>Satiana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>31(^\circ)33'52''</td>
<td>31(^\circ)19'00''</td>
<td>31(^\circ)12'11''</td>
</tr>
<tr>
<td>Longitude</td>
<td>73(^\circ)28'29''</td>
<td>73(^\circ)26'00''</td>
<td>73(^\circ)10'11''</td>
</tr>
</tbody>
</table>

**Remote sensing estimate of different components**

- Instantaneous net radiation (\(R_n\), W m\(^{-2}\))
- Instantaneous sensible heat flux (\(H\), W m\(^{-2}\))
- Instantaneous soil heat flux (\(G\), W m\(^{-2}\))
- Instantaneous latent heat flux (LE, W m\(^{-2}\))
- Daily net radiation (\(R_{n,d}\), W m\(^{-2}\))
- Remote sensing estimate of evapotranspiration (mm day\(^{-1}\))

**CROPWAT estimate of evapotranspiration (mm day\(^{-1}\))**

- Deviation (mm day\(^{-1}\))
- Pan evaporation (mm day\(^{-1}\))
- Pan evaporation after multiplying by pan coefficient (mm day\(^{-1}\))
- 95th percentile of evaporation

### Table 2. Instantaneous parameters over different agricultural crops during ASTER overpass.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Cotton</th>
<th>Sugarcane</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>73 12 48.07 E</td>
<td>73 26 42.43 E</td>
<td>73 12 59.60 E</td>
</tr>
<tr>
<td>Surface albedo</td>
<td></td>
<td>31 22 49.59 N</td>
<td>31 08 06.10 N</td>
<td>31 22 59.80 N</td>
</tr>
<tr>
<td>Surface emissivity</td>
<td></td>
<td>0.176</td>
<td>0.174</td>
<td>0.153</td>
</tr>
<tr>
<td>Roughness momentum</td>
<td>m</td>
<td>0.016</td>
<td>0.014</td>
<td>0.017</td>
</tr>
<tr>
<td>NDVI</td>
<td></td>
<td>0.392</td>
<td>0.194</td>
<td>0.298</td>
</tr>
<tr>
<td>Instantaneous (R_n)</td>
<td>W m(^{-2})</td>
<td>410</td>
<td>405</td>
<td>390</td>
</tr>
<tr>
<td>Instantaneous (H)</td>
<td>W m(^{-2})</td>
<td>121</td>
<td>150</td>
<td>105</td>
</tr>
<tr>
<td>Instantaneous (G)</td>
<td>W m(^{-2})</td>
<td>83</td>
<td>83</td>
<td>79</td>
</tr>
<tr>
<td>Instantaneous LH</td>
<td>W m(^{-2})</td>
<td>206</td>
<td>172</td>
<td>206</td>
</tr>
<tr>
<td>Instantaneous EF</td>
<td></td>
<td>0.629</td>
<td>0.534</td>
<td>0.662</td>
</tr>
<tr>
<td>24 h (R_n)</td>
<td>W m(^{-2})</td>
<td>101</td>
<td>96</td>
<td>106</td>
</tr>
<tr>
<td>24 h (H)</td>
<td>W m(^{-2})</td>
<td>36</td>
<td>54</td>
<td>25</td>
</tr>
<tr>
<td>24 h LE</td>
<td>W m(^{-2})</td>
<td>65</td>
<td>42</td>
<td>88</td>
</tr>
<tr>
<td>24 h evapotranspiration</td>
<td>mm day(^{-1})</td>
<td>2.20</td>
<td>1.77</td>
<td>2.42</td>
</tr>
</tbody>
</table>
The estimation of evapotranspiration calculated from climatic data using CROPWAT (Smith et al. 1990) and satellite estimation based on surface energy balance approach show that generally evapotranspiration values from satellite information are higher than computed using the CROPWAT model (table 1). The evapotranspiration computed by CROPWAT software was obtained after multiplying by the local crop coefficient ($K_c$) value of the maize.

To estimate evapotranspiration, instantaneous parameters and other fluxes (table 2) from the surface of different agricultural crops, fields that had cotton, maize and sugarcane were selected and coordinates were recorded using handheld GPS. The evapotranspiration of maize, cotton and sugarcane vary within the scene due to different levels of crop water requirements. Less evapotranspiration was found over sugarcane crop due to its early stage of growth, and high evapotranspiration was found over cotton and maize because of the maturity of both crops. Various instantaneous parameters, especially $z_o$, were found to vary from 0.014 to 0.017, which is close to the value reported by Kustas et al. (1989) and Moran and Jackson (1991).

4. Summary and conclusions

The evapotranspiration using simplified methodology found good matching with those estimated using meteorological data. Results were encouraging and ASTER may be considered for such an application in the Indus Basin. The methodology presented here is simple and used remotely sensed surface temperature in combination with air temperature to calculate the sensible, latent and soil heat fluxes. A simple semi-empirical approach was adopted to estimate the aerodynamic resistance to avoid the complexity involved in using Monin–Obukhov similarity theory. The developed methodology was applied to estimate the sensible and latent heat fluxes using ASTER satellite sensor data acquired over a region in the Indus Basin. Evapotranspiration values from the maize field in the Indus Basin using ASTER data at Shahkot, Jaranwala and Satiana locations were estimated as 2.05, 2.77 and 2.32 mm day$^{-1}$, respectively whereas evapotranspiration over cotton, sugarcane, and maize in selected fields was found to be 2.22, 1.77 and 2.2, respectively, showing variation in root-zone moisture. The methodology presented here can be successfully applied to assess moisture stress at a regional level for the better and timely management of water resources. However, to attain further accuracy, it is suggested that each component of surface energy balance should be measured in situ to validate different relations used in this paper.

References


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measurement site with ground measurements and satellite observations. Journal of
Applied Meteorology, 37, pp. 5–22.

GEOSYSTEMS., 2002, ATCOR for ERDAS Imagine (Germering, Germany: Geosystems).


Hatfield, J.L., 1988, Large scale evapotranspiration from remotely sensed surface


Jackson, R.D., Moran, M.S., Gay, W.L. and Raymond, L.H., 1987, Evaluating
evaporation from field crops using airborne radiometry and ground-based meteorological data. Irrigation Science, 8, pp. 81–90.


Moran, M.S., 1990, A satellite based approach for evaluation of the spatial distribution of


Version 1.0 (Wageningen, The Netherlands: International Institute for Aerospace and Earth Science (ITC)).


Richter, R., 2002, ATCOR for ERDAS Imagine (ver. 2.0), User Manual (Germering, Germany: Geosystems GmbH).

Smith, M., Clark, D. and El-Askari, K., 1990, CROPWAT 4 Windows (Rome, Italy: Land
and Water Development Division, Food and Agriculture Organization (FAO)).

Thom, A.S. and Oliver, H.R., 1977, On Penman’s equation for estimating regional
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