COMPUTATION OF EVAPOTRANSPIRATION IN PARTS OF THE SOUTH PLATTE AND NORTH PLATTE RIVER BASINS USING LANDSAT IMAGERY

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ABSTRACT

It is important to quantify the consumptive water use by the vegetation when managing regional water resources in irrigated areas. Suitable models and algorithms applied to high resolution (30 m) satellite imagery provide a cost effective and time efficient method to obtain evapotranspiration estimations from bare soil and vegetation. The METRIC image processing model calculates net radiation, soil heat flux and sensible heat flux through a number of steps before estimating evapotranspiration as the residual from the energy balance. Sensible heat flux algorithms are calibrated using an operator selected wet and dry pixel. The complete energy balance obtained from the satellite images is calibrated using ground based reference evapotranspiration estimations.

The paper describes an application of the METRIC model on parts of the South Platte and North Platte river basins in Colorado and Nebraska for individual days in 1997, 2001 and 2002. Landsat 5 and Landsat 7 shortwave and longwave bands were used. Weather data from selected meteorological stations within the study area was screened and used to estimate reference evapotranspiration. A water balance model was used to estimate evaporation from the soil. During the image processing it was necessary to iterate the selection of the wet and dry pixels after reviewing evapotranspiration behavior for natural vegetation and wet fields at full cover. Uneven distribution of recent precipitation events and operator dependency needed to be addressed. The resulting evapotranspiration maps appear to be congruent with ET from previous studies and will be used by local water management entities.

INTRODUCTION

It is important to quantify the consumptive water use (CWU) by vegetation when managing regional water resources in irrigated areas. In most of the western parts of the High Plains and Inter-Mountain West the CWU demands exceed the natural precipitation. Supplementation of water through irrigation is necessary to meet the CWU requirements via ground and surface water supplies. Nearly 30 % of the ground water used for irrigation in the United States is extracted from the Ogallala or High Plains aquifer which extends from South Dakota to Texas (Weeks et al., 1988). Together with water drained from the North and South Platte River systems the aquifer has supported irrigated agriculture in NE Colorado and Nebraska for decades. Increases in irrigated acreage, drought, advances in pump technologies, introduction of center pivot irrigation systems and increased urban water requirements have lead to an overexploitation of the available water resource. In many basins within the North and South Platte River systems the water demands meet or exceed supply limits.

Such fully appropriated or over-appropriated areas pose a challenge for local and regional water management entities. They must balance maintaining profitable agricultural operations dependent on irrigation while complying with water compacts or basin-wide or regional management goals. The key to successful implementation of the management plans is to understand and quantify how groundwater and surface water supplies interact with the actual CWU. Accurate quantification of CWU is required as input in hydrological modeling and aids prediction of the timing and spatial extent of depletions or gains in surface and ground water, all of which is necessary in both short term and long term management of water resources.

Considerable uncertainty exists regarding the spatial and temporal variability and distribution of CWU, not only for agricultural crops but also for rangeland, riparian zones and other areas with natural vegetation. The variability is caused by local and regional differences in weather, precipitation distribution and quantity, soil, land form and land use, vegetation type, cultivar and cropping system, irrigation application method and land management. Normally the majority of CWU is made up by evapotranspiration, ET. A recommended method to estimate actual ET (ET_a) from the ground and vegetation include multiplying a weather based reference evapotranspiration (ET_r) with a crop coefficient (K_c) (Allen et al., 1998; ASCE-EWRI, 2005). Allen et al. (2005) estimated this procedure is relatively accurate with an error of up to ± 20 %. Errors may arise from actual vegetation and growing conditions deviating from the idealized K_c values or results from undocumented water shortage in the vegetation. In addition, it is difficult to predict the correct crop growth stages for a large population of crops and fields.

Application of remote sensing algorithms solving the energy balance using high resolution satellite imagery has proven useful for establishing estimates of ET_a and K_c for large populations of fields and water users (Bastiaanssen et al., 1998; Tasumi et al., 2005, Allen et al. 2007a).

ET is generally estimated in energy balance processes as a residual of the energy balance as:

$$LE = R_n - G - H \tag{1}$$

where LE is the latent energy consumed by ET, R_n is net radiation flux density at the surface, G is heat flux density into the ground and H is sensible heat flux density into the air.

Models that solve the energy balance to estimate ET include Surface Energy Balance for Land (SEBAL) (Bastiaanssen, 1995; Bastiaanssen et al., 1998) and Mapping EvapoTranspiration with High Resolution and Internalized Calibration (METRIC) (Allen et al., 2007b). METRIC utilizes the innovative SEBAL method for estimating sensible heat flux by using the near surface temperature gradient dT for each image pixel based on a regression relationship between the dT and radiometric surface temperature of two “anchor” pixels. The advantage of the SEBAL approach to developing a dT vs. T_S relationship by inverting the energy balance at the two calibration points is that many biases in energy balance components are factored out, including those in T_S itself. In addition, the use of a dT that ‘floats’ above the surface may eliminate some of the issues with single source models as reported by Allen et al., 2007b. The anchor pixels ideally represent the conditions of an agricultural field with full and actively transpiring vegetation cover and a bare agricultural field with no vegetation cover. The anchor pixel representing full vegetation cover has the characteristics of green vegetation and its dT is low due to evaporative cooling. This condition is often referred to as the “cold” condition. The anchor pixel representing a bare field has the characteristics of bare soil and its dT is high due to radiometric heating of the surface and is generally referred to as the “hot” condition.

The METRIC procedure depart from SEBAL in using the alfalfa based ET_r to establish the energy balance at the cold pixel, thus establishing a ground reference for the satellite image based ET_a estimate. ET_r is calculated outside of METRIC using hourly (or shorter) weather data from a weather station preferably located toward the center of the study area. The use of ET_r is generally effective in tying down the energy balance calibration, especially in arid and semiarid climates having advection. The use of ET_r for calibration and extrapolation of ET to longer time periods makes the METRIC process congruent with traditional ET_r based estimation methods. One of the outputs from METRIC is a map of the ET from each pixel stated as a fraction of ET_r, ET_rF. ET_rF is synonymous with the well known K_c (for an alfalfa reference basis). Daily ET_a maps are calculated by multiplying the instantaneous ET_rF calculated for each pixel with the 24-h summed ET_r. The resulting high resolution maps of ET cover regions typically up to 150 km in scale. When used properly, METRIC provides a rapid and cost effective method to determine ET for focused regions.

The paper describes the application of METRIC in a study area within the South and North Platte River drainages and summarizes some of the experiences different users have gained while applying METRIC.

METHODS

Satellite images covering Northeast Colorado and the Nebraskan Panhandle and data from local weather stations were used to produce the ET maps. Landsat 5 and Landsat 7 images from four dates in 1997, four dates in 2001 and three in 2002 were processed. Sensor type, satellite overpass date, path and row are shown in Table 1. Bands 1 through 7 were used in the processing with the thermal band (band 6) being resampled to 30 m using nearest neighbor. The 1997 and 2002 images were georectified and terrain corrected by EROS as their L1T product. The 2001 images were georectified by EROS and terrain corrected by a private vendor. The METRIC model was coded and executed using the ERDAS Imagine Modelmaker tool. Reference ET was calculated using the RefET software (Allen, 2003) using meteorological data as input. Supporting input information, including a water balance to estimate residual evaporation from bare soil (for the hot pixel calibration) and the iterative numerical solution of the dT function equation based on the cold and hot anchor pixels, were carried out using a spreadsheet.

Table 1. Sensor type, satellite path, row and overpass date

Satellite	Path	Row	Date
Landsat 5	33	31	May 9 1997
Landsat 5	33	31	July 12 1997
Landsat 5	32	31	August 22 1997
Landsat 5	33	31	September 30 1997
Landsat 5	32	32	April 27 2001
Landsat 5	32	32	June 30 2001
Landsat 5	32	32	July 16 2001
Landsat 7	32	32	November 4 2001
Landsat 5	33	31	March 28 2002
Landsat 5	33	31	June 8 2002
Landsat 5	31	31	July 3 2002

Weather Data

Hourly weather data from the Sterling, CO weather station operated by Northern Colorado Water Conservancy District and the Scottsbluff and Sidney, NE Automatic Weather Data Network operated by the High Plains Regional Climate Center were used. The quality of all meteorological data used in the METRIC processing were checked following the recommendations by Allen (1996), Allen et al. (1998) and ASCE-EWRI (2005). As ET_r was also used to establish a soil water balance several months before each image date, the integrity of the meteorological data for the entire year for all three years where evaluated.

Hourly and daily values for solar radiation R_s were compared to computed clear sky solar radiation (R_{so}). R_{so} is the theoretical amount of solar radiation that reaches the ground on a clear sky day with low atmospheric aerosol content (e.g. no haze, dust, smoke from e.g. fires etc) and was calculated based on atmospheric pressure, sun angle and precipitable water in the atmosphere. Generally a good agreement was found between observed R_s on days with clear sky conditions and the theoretical R_{so} values, as exemplified in Figure 1 where daily R_s from the Sidney, Nebr. Station is compared to R_{so}.

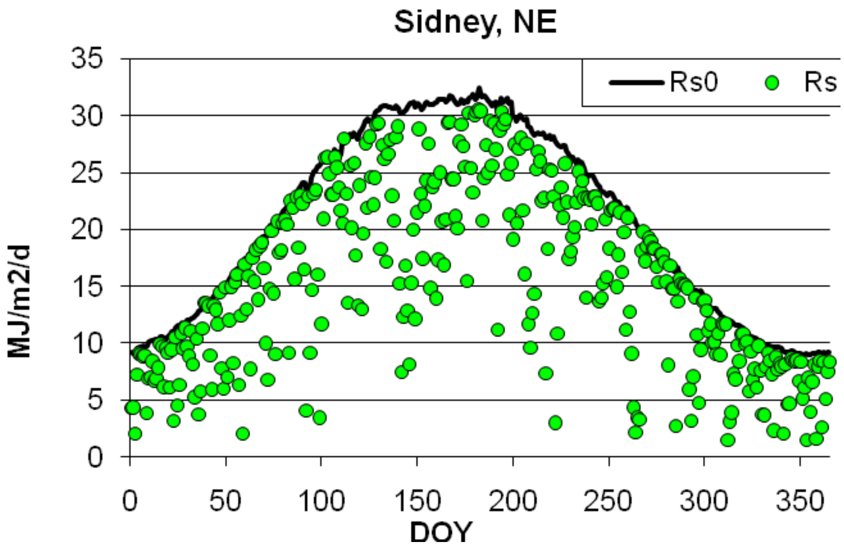

Figure 1. Daily solar radiation (R_s) from the Sidney, NE HPRCC weather station 1997 compared to a theoretical clear sky solar radiation (R_{so}) curve.

A range test was used to check daily minimum and maximum relative humidity. In addition, daily mean computed dewpoint temperature was compared to daily minimum air temperature following ASCE-EWRI (2005). The air temperature (T_a) was compared to nearby weather stations, and hourly T_a

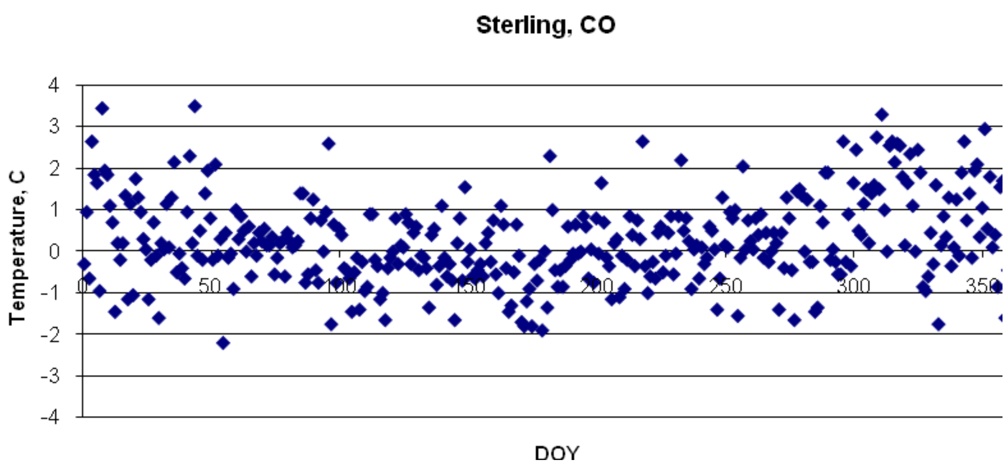

Figure 2. Average 24-h air temperature (T_a) subtracted from the difference between daily temperature extremes (minimum and maximum T_a) generally running below 3 °C at the Sterling, CO weather station 2001.

measurements were checked visually for sudden spikes and the expected diurnal occurrence of minimum and maximum values. Additionally, air temperature is analyzed by subtracting the average 24-h T_a from the difference between daily temperature extremes (minimum and maximum T_a) as shown in Figure 2. Systematic differences greater than 2-3 °C may indicate erroneous extremes in air temperature or impacts of missing data. Wind speed was checked by calculating the gust factor (ASCE-EWRI, 2005) and comparing average daily wind speed to that of other nearby weather stations.

The Automated Weather Data Network does not record precipitation during the period November 1 – March 31. Precipitation for these missing periods was filled in using information from nearby gauges under the National Weather Service Cooperative program.

Soil Water Balance

A daily water balance model described by Allen et al. (1998) was employed to estimate residual evaporation from the hot pixel (Figure 3). The satellite overpass moment were obtained from the respective image header files and used to estimate the zenith angle of the sun and instantaneous values of wind speed at screen height and 200 m, air humidity and ET_r.

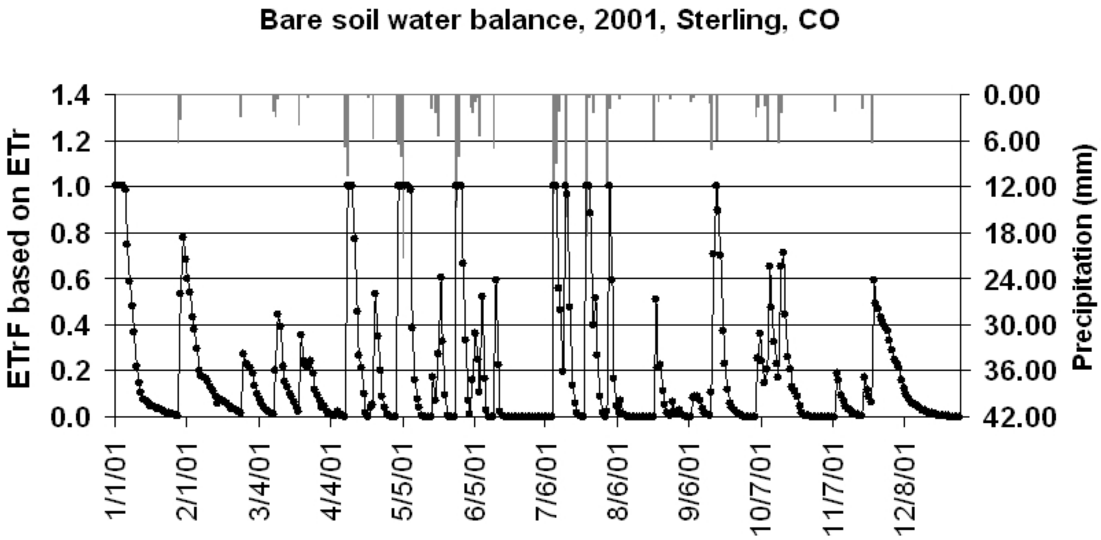

Figure 3. Soil water balance for bare soil calculated using meteorological data and precipitation from Sterling, CO 2001 and used to determine ET_rF for the hot pixel calibration.

Estimation of Momentum Roughness Length

The internalized calibration of sensible heat flux requires a measure of the momentum roughness length (z_{om}) as input to estimate the stability conditions of the atmosphere. A value for z_{om} was assigned for each land use class, other than irrigated agriculture, based on land use maps of the study areas. Initially the z_{om} values were assessed based on the metadata description for the land use maps. However, a field trip to the study areas proved invaluable in refining z_{om} values, as the generalized vegetation descriptions of the land use maps only poorly represented the study area. For some areas with natural range land vegetation this resulted in vales for z_{om} being more than halved. General values of z_{om} have been reported by e.g. Duffie and Beckman (2006). Roughness lengths for irrigated agriculture were estimated using leaf area index estimates that were based on reflectance bands from the Landsat images.

Reduction of Soil Heat Flux for Desert Areas

The functions used in METRIC estimate soil heat flux (G) for irrigated fields in Southern Idaho well (Tasumi, 2003). The upper soil layers in the cropped fields have usually been disturbed by tillage, emerging plants and plant roots and application of relatively large amounts of water. This has promoted a somewhat uniform vertical soil structure within the upper 20 – 30 cm. For undisturbed, dry desert soils, where vegetation is sparse and the upper soil layer are largely undisturbed, a thin crust often forms at the soil surface. This crust may be partially delaminated from the soil below by an air gap. Frost-thaw cycles, swelling clay minerals, compaction from snow pack and traffic (e.g. animals) may also cause a layering with differences in texture, structure and bulk density in the upper soil layers. The delamination will likely reduce G, as energy transfer by conduction from the crust to the immediate underlying soil layers is reduced. In addition, the dryness of the soil also reduces G, as water increases the thermal conductivity of the soil. As a result, the G function derived for irrigated conditions likely overestimates the energy flux in desert areas. During the processing this caused desert areas to have negative values of K_c. Reducing the G for pixels in the desert as a function of T_S using a now routine procedure in METRIC reduced negative values K_c for desert areas.

Selection of Anchor Pixels

Selection of representative anchor pixels is crucial for the accuracy of the ET estimations from METRIC. The cold anchor pixel should represent an agricultural field with full vegetation cover, having near minimum surface temperature and is assigned an ET equal to 1.05 times ET_r. The hot anchor pixel should represent a bare, dry agricultural field having a relatively high temperature. The field should have only very little vegetation residue cover and an albedo similar to other bare fields nearby. The location of the anchor pixels is preferably toward the center of a population of other pixels having similar properties (temperature, albedo, vegetation). The high resolution of Landsat 5 and 7 (30 m for shortwave reflectance, 120 and 60 m for surface temperature, respectively) allow sampling within individual fields.

The selection of the anchor pixels must be done manually by the user and is typically an iterative process. The selection may be aided by viewing the Landsat scene in specific band combinations, such as 4, 5 and 7 (C. Schneider, personal communication), colorize vegetation indices and temperature maps based on general criteria for selection of the anchor pixels, use ArcMap to aggregate data and use zonal statistics to output possible candidates (M. Hattendorf, personal communication) and identify fields with little or no residue cover based on other indices (van Deventer et al., 1997; Thoma et al., 2004).

At the hot anchor pixel it is assumed that little or no evaporation is taking place if there has been a long period since rainfall. Otherwise the surface soil water balance and evaporation estimation shown in Figure 2 is used to assign an ET_rF to the hot pixel. The dT function is calibrated for any possible residual evaporation.

RESULTS

METRIC produces of R_n, G and H which are used to calculate ET using Equation 1, as sketched in Figure 4. The estimation of H is an iterative process using the hot and cold anchor pixels is an iterative process. After running METRIC using initially selected anchor pixels to estimate H, a careful examination of the resulting ET_rF map may reveal whether the two pixels are representative. In general, the population of fields having no vegetation should have an ET_rF around the value predicted by the soil water balance, while the majority of fields at full cover and presumably evapotranspire at full rate have an ET_rF of 1.0. If an examination of a number of bare or fully vegetated fields shows a systematic bias above or below these thresholds in ET_rF, then new cold and/or hot anchor pixels must be selected or in special cases alternative ET_rF values are assigned. Applying a detailed color scheme greatly aids the assessment of the ET_rF map (Figure 5).

In some cases the selection of the hot and cold anchor pixels may pose to be challenging due to factors such as few fully vegetated fields (during winter periods), few bare fields (middle of growing season) or the ground or vegetation has not yet reached temperature equilibrium after being shaded by clouds. An example of the latter effect on ET_rF is shown in Figure 6. On this image date a strong SE wind was blowing a formation of low clouds towards the NW. A small part of the cloud system is visible in the upper left corner. Part of the image, which was cloud free, still suffered depressed surface temperatures from the prior cloud cover. This depression in T_S caused METRIC to infer higher ET_rF values extending in the wind direction.

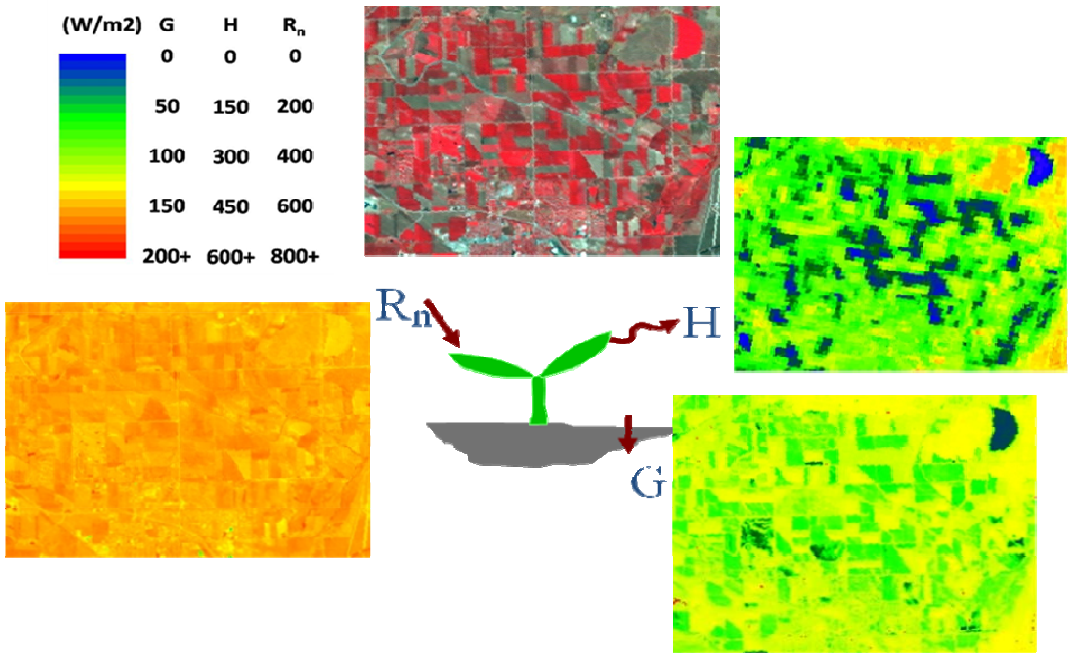

Figure 4. Intermediate products for net radiation (R_n), soil heat flux (G), sensible heat flux (H) produced by METRIC used to estimate evapotranspiration. A false color satellite image is shown at top center.

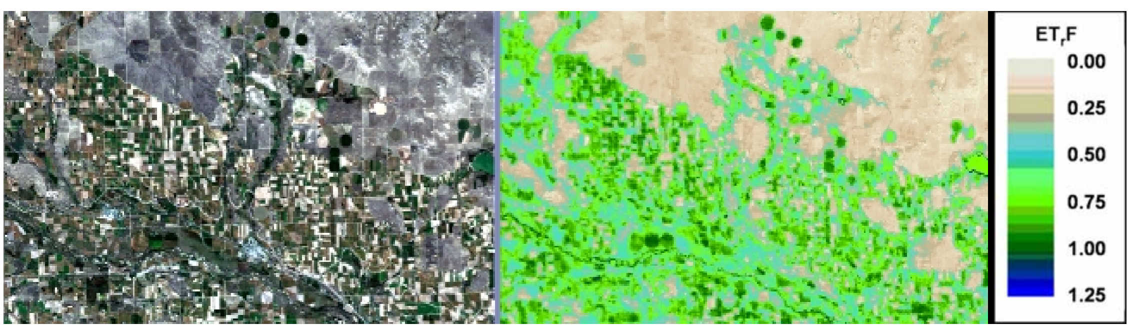

Figure 5. Satellite image in true color (left) and the corresponding ET_rF map (right) on September 30 1997, northwest of Scottsbluff, NE.

After the final iteration for selecting cold and hot anchor pixels, the instantaneous and daily ET was calculated based on the ET_rF and 24-h ET_r (Figure 7). A close-up of a resulting 24-hour ET map, where even the within field variation of ET is evident, is shown in Figure 8.

The resulting evapotranspiration maps appear to be congruent with ET from previous studies (Allen et al., 2007a; Tasumi et al 2005). Processing of another 35 images will further be used to validate the results and produce seasonal and annual ET maps. The final ET maps from the current study will be used by water resource management agencies in estimating CWU, in regional water balances and in specific studies as a basis for developing or revising water conservation policies and practices. As a consequence of the high resolution of the maps, they can be used to identify ET from individual fields and specific crops and cropping system types. ET maps produced using satellite images and algorithms that solve the energy balance accurately and with high resolution have the potential to become widely adopted by water resource managers and entities.

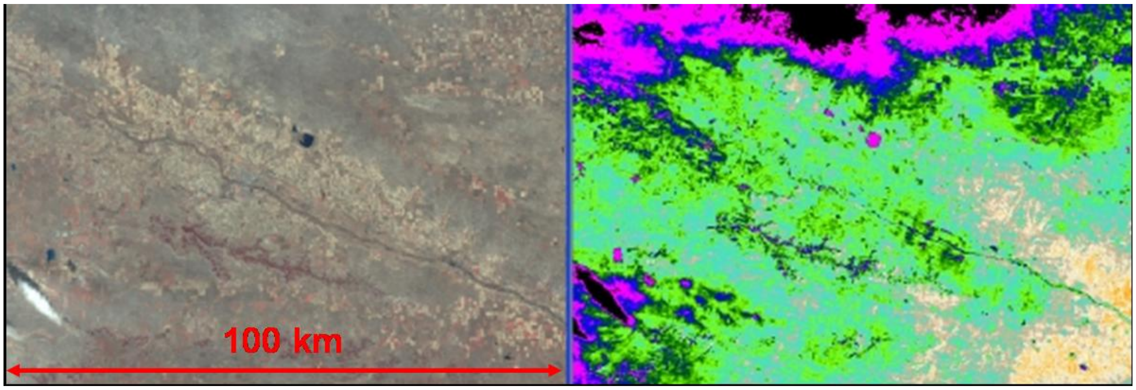

Figure 6. Clouds still visible on the false color image (left) created a gradient in ET_rF (right) across the image on this March 28 2002 date. Pink and black colors indicate clouds

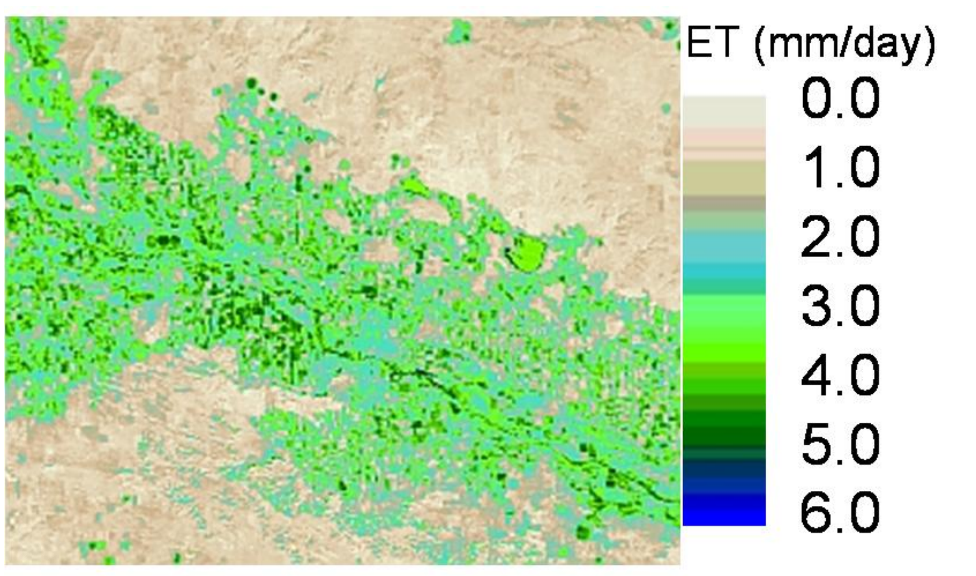

Figure 7. METRIC generated 24-h ET map on September 30 1997 along the North Platte River around Scottsbluff, NE.

Concluding Remarks

One of the major caveats in the current design of METRIC is that results are somewhat user dependent. Inter comparisons between ET maps produced using identical versions of METRIC by different users on the application teams illustrated that systematic differences of up to 10 % in the final ET maps are possible. It was also found, however, that at least half of this difference was caused by inexperience in running the model, insufficient weather quality control, incongruent application of the soil water balance model, lack of communication, missing updates of input parameters between model runs and lack of familiarity with the study area. The group studies have underlined the necessity of users to follow the same general guidelines and procedures for processing, and that the greatest care is used when setting up and running the model. It is also important that users review all intermediate results (such as maps of R_n, G, H, albedo, vegetation indices, temperature etc).

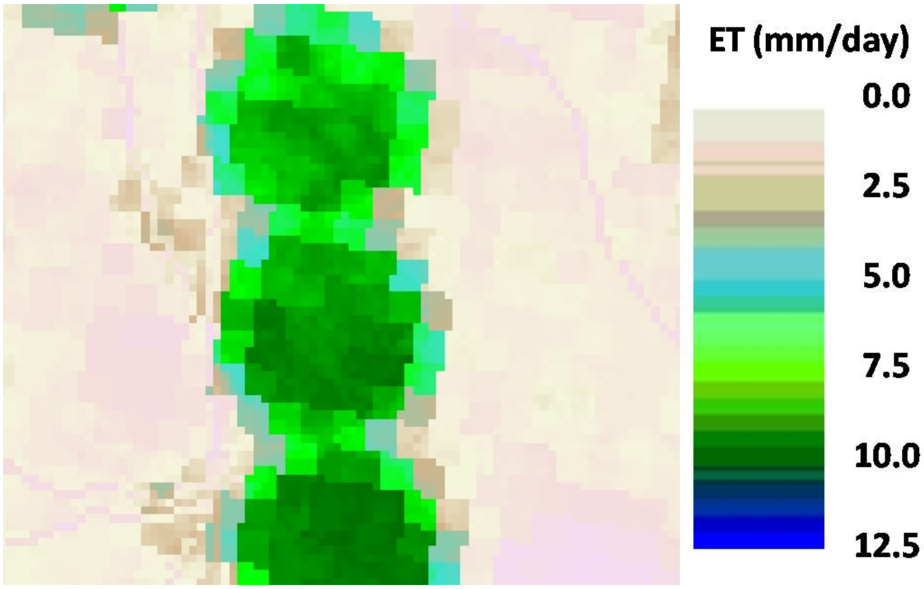

Figure 8. Close-up of METRIC generated 24-h ET map on July 16 2001 along the South Platte River south of Sterling, CO.

As part of the continuing efforts to improve the predictions of the METRIC model, work is currently being done to develop an automated selection of a population of anchor pixels. This may reduce the user dependency of the final ET maps further. Another issue that is being addressed is the interpolation from daily ET maps to seasonal or annual ET. With Landsat image capture dates being 8, 16, 32 days or more apart (depending on sensor availability and cloud cover) the interpolation method must be able to reproduce the trend between images dates as completely as possible. Unless there is a high frequency of image dates during growing season, a spline type interpolation method should be applied rather than e.g. linear interpolation. In addition, local precipitation events may have a temporal and spatial occurrence that are not registered by the soil water balance or are largely evaporated at the time of the next image capture causing an underestimation of predicted ET. To minimize this error, efforts are being made to expand the daily soil water balance to the entire study area.

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