USING A SURFACE ENERGY BALANCE MODEL TO CALCULATE SPATIALLY DISTRIBUTED ACTUAL ET

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ABSTRACT

Remote sensing algorithms are currently being used to estimate regional surface energy fluxes [e.g., latent heat flux (LE) or evapotranspiration (ET)]. Many of these surface energy balance models use information derived from satellite imagery such as Landsat, AVHRR, ASTER, and MODIS to estimate ET. The remote sensing approach to estimating ET provides advantages over traditional methods. One of the most important advantages is that it can provide regional estimates of actual ET at low cost. Most conventional methods are based on point measurements (i.e., soil water sensors, lysimeters, weather station data, etc.), limiting their ability to capture the spatial variability of ET. Another advantage of remote sensing/surface energy balance ET models is that they are able to estimate the actual crop ET as a residual of the energy balance without the need of using reference crop ET and tabulated crop coefficients. This study focuses on the use of the energy balance-based model "Remote Sensing of ET" (ReSET) that uses an enhanced procedure to deal with the spatial and temporal variability of ET. ET was estimated for several years of data for the Arkansas River Basin, South Platte, and Palo Verde Irrigation District along with one day ET estimates for the Southern High Plains. Comparisons between the Remote Sensing ET values and ET values from more conventional ET methods [e.g., 2005 ASCE-EWRI Standardized Reference Evapotranspiration (Penman-Monteith) Equation] also are presented.

INTRODUCTION

Water resources management is especially important in regions of the world that are experiencing water scarcity. Evapotranspiration (ET) is the main consumptive use of irrigation in agriculture, and in most places the largest water use, therefore accuracy in ET estimation is needed for better irrigation management which can contribute to improving agricultural production and water conservation.

Solving Surface energy balance equations using satellite image based models has proven to provide good results in estimating ET. This approach captures the spatial variability between and within agricultural fields over traditional methods that use reference crop ET and a tabulated crop coefficient to calculate crop ET with the assumption that all fields have similar conditions of water availability and quality, pest issues, nutrient

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management, etc. Models based on a surface energy balance equation estimate the actual ET with a high level of spatial resolution. ET grids produced by these models can be used in other applications such as identifying unauthorized irrigations or detecting areas of a field that are not uniformly irrigated.

In this study, the objectives were: a) apply the ReSET model to several areas (Arkansas River Basin, South Platte, and Palo Verde Irrigation District along with one day ET estimates for the Southern High Plains) and b) compare between the Remote Sensing ET values and ET values from more conventional ET methods [e.g., 2005 ASCE-EWRI Standardized Reference Evapotranspiration (Penman-Monteith) Equation].

METHODOLOGY

Remote Sensing of ET (ReSET) Model

ReSET is a surface energy balance model built on the same theoretical bases of its two predecessors METRIC (Allen et al., 2007 a,b) and SEBAL (Bastiaanssen, 1998 a,b) with the addition of the ability to handle data from multi weather stations, which enhances the ET estimates by taking into consideration the spatial variability of weather data acquired from different weather stations. ReSET can be used in both the calibrated and the un-calibrated modes. The calibrated mode is similar to METRIC. Reference ET from weather stations is used to set the maximum ET value in the processed area, while in the un-calibrated mode it follows a similar procedure as SEBAL where no ET value is imposed on the model.

Models that use remote sensing images to model surface energy interpret radiation reflected on the satellites image bands into ground surface characteristics, such as albedo, vegetation indices (e.g., NDVI), surface temperature, and surface thermal emissivity. By adding the geographic information and the digital elevation map of an area the surface energy balance equation can be solved.

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

in which R_n is the net radiation calculated from the incoming and outgoing radiation (shortwave and long wave), G is the soil heat flux (rate of heat conducted and stored in soil and vegetation) calculated using an empirical equation by Bastiaanssen (2000), H is the sensible heat flux to the atmosphere or towards the surface. All units in Equation 1 are in energy units of W m^{-2}. Then, when all the previous terms have been calculated LE, which is the latent heat flux, is estimated as a residual of the energy balance (Equation 1) and the result is converted to an equivalent amount of water depth that was evapotranspirated in units of millimeters per hour or day.

Since R_n is calculated as well as G then what is left to estimate is H. The basic assumption to obtain the value of H for each pixel is that the air temperature gradient between near the ground surface and/or within the canopy and the adjacent screen level air layer changes linearly (i.e., is proportional) with the ground surface temperature (T_s, K). This is defined by a linear model represented by a "dT" function (i.e., dT = a T_s + b), Allen et al. (2007a). Based on this assumption a set of two points are selected to represent a maximum ET location and a minimum ET location. The point selected to represent zero ET is selected at a hot area (e.g., fallow/dry field) while the second point representing the maximum ET is selected at a well irrigated cropped field.

The assumption is that there is no ET at the hot pixel which can be translated using the energy balance equation as LE = 0, thus the equation just becomes R_n = G + H, which is solved for H at that hot pixel. This last case applies when using a model such as SEBAL; however if there has been a significant rainfall event a few days to a week before the remote sensing over-pass, then H should be calculated at that hot point by means of a soil water balance as proposed in METRIC. In terms of the cold pixel, it is assumed to be the point of maximum ET; therefore H is set to zero in the case of the un-calibrated model where no reference ET from weather stations is used for internal calibration such as SEBAL. In contrast, in the case that the model uses a reference ET for internal calibration such as in METRIC, any possible value of H will be calculated at the cold pixel as H = (R_n – G) – 1.05 λ_v ET_r, in which ET_r is the hourly alfalfa reference ET (mm hr^{-1}) at the time of the satellite overpass and λ_v is the latent heat of vaporization (J kg^{-1}, Equation 4). Further, the Monin–Obhukov similarity theory is used for correcting the calculations of sensible heat flux for atmospheric stability conditions. This is achieved through an iterative process where the aerodynamic resistance of heat transport (r_{ah}, s m^{-1}) at the cold and hot points are updated after each iteration until numerical stability is reached for the aerodynamic resistance (typically less than 5% difference between consecutive iterations of r_{ah}). Once numerical stability is reached, then H is calculated for the entire image using the dT function "a" and "b" coefficients and "r_{ah}" updated values. In the next step, the spatially distributed latent heat flux is calculated using the energy balance equation (Equation 1). Using the estimated distributed LE image the instantaneous "actual" evapotranspiration (ET_{inst}, mm h^{-1}) and the evaporative fraction is calculated. The entire day evapotranspiration can be calculated by assuming that the instantaneous evaporative fraction, calculated at the time of the satellite overpass, is constant over a whole day (24 hours), as follows:

$$EF(inst) = LE/(Rn - G) \tag{2}$$

in which R_n, G, and LE are all instantaneous values in W m^{-2}. ET 24-hour is calculated as shown in Equation 3, below:

$$ET24 = 86{,}400 * EF(inst) * (Rn24 - G24)/\lambda_V \tag{3}$$

Twenty four hour evapotranspiration is represented by ET_{24}, 86,400 is a time conversion from seconds to days, R_{n24} represents the 24-hour net radiation, 24-hour soil heat flux is G_{24}, L is the latent heat of vaporization that is used to convert energy to millimeters of evaporation calculated based on surface temperature. λ_v represents the energy needed to evaporate a unit mass of water, which is calculated using Equation 4 and was developed by Harrison (1963) and modified by Allen et al. (2007a), who instead of using air temperature used surface temperature un-calibrated for atmospheric interference (basically at sensor of brightness temperature).

$$\lambda_v = (2.501 - 0.00236(Ts - 273.16)) * 10^6) \qquad (4)$$

in which, *Ts* is the un-calibrated surface temperature in Kelvin.

MODEL APPLICATIONS

South Platte Basin

Seasonal ET Estimates for Corn

The South Platte Basin (Colorado) is covered by two Landsat 5 scenes (33/32 and 32/32) (Figure 1). In this paper, eleven 2006 Landsat images were used to calculate the seasonal ET. The images used corresponded to six images from path 32/32 for 2006: May 11 (DOY 131), May 27 (DOY 147), June 28 (DOY 179), July 14 (DOY 195), July 30 (DOY 211), Sept. 16 (DOY 259) and five images from path 33/32 for 2006: April 16 (DOY 106), May 18 (DOY 138), June 19 (DOY 170), July 21 (DOY 202), Aug. 22 (DOY 234).

By selecting images from two different satellite paths (same row) the potential number of images per month, covering the study area, doubled. Instead of having one image every 16 days, for the particular study area, it was possible to have the potential for one image every 8 days. This advantage provides additional flexibility in selecting the cloud free images while still having images fairly frequently. Normally an image per month is recommended for seasonal estimates for crops that grow over a period of 4 or 5 months such as corn. For crops that have a shorter growing season the error increases if additional images are not used given the rapid change in the crop phenology and the fact that one image per month would represent a significant portion of the growing season for that crop (e.g. some vegetables).

The concept of seasonal ET calculations is based on calculating ET grids for the individual dates when the images are available for an area, then an interpolation is carried out between scenes to calculate an ET grid for every day. The sum of those daily grids is the seasonal ET for the area, for details about the interpolation technique you are referred to Elhaddad and Garcia (2008).

To evaluate the accuracy of the remote sensing-based ET estimation and the seasonal interpolation technique used in this study, a comparison between the seasonal estimates developed by the ReSET model and the seasonal ET calculated using the 2005 standardized ASCE reference ET (ASCE-EWRI, 2005) equation for alfalfa fields was conducted. An excellent agreement is not expected since the ASCE method assumes ideal crop growing/agronomic conditions, which are rarely encountered in the “real” world.

Seasonal Comparisons

Seasonal estimates of ET were calculated for corn fields (identified by using a crop classification map generated by Northern Colorado Water Conservancy District) in the South Plate basin using two approaches, the ReSET approach and the ASCE-EWRI (2005) ET approach using the Integrated Decision Support Group Consumptive Use model (IDSCU) (http://www.ids.colostate.edu/index.html?/projects/idscu/) with average corn crop coefficients.

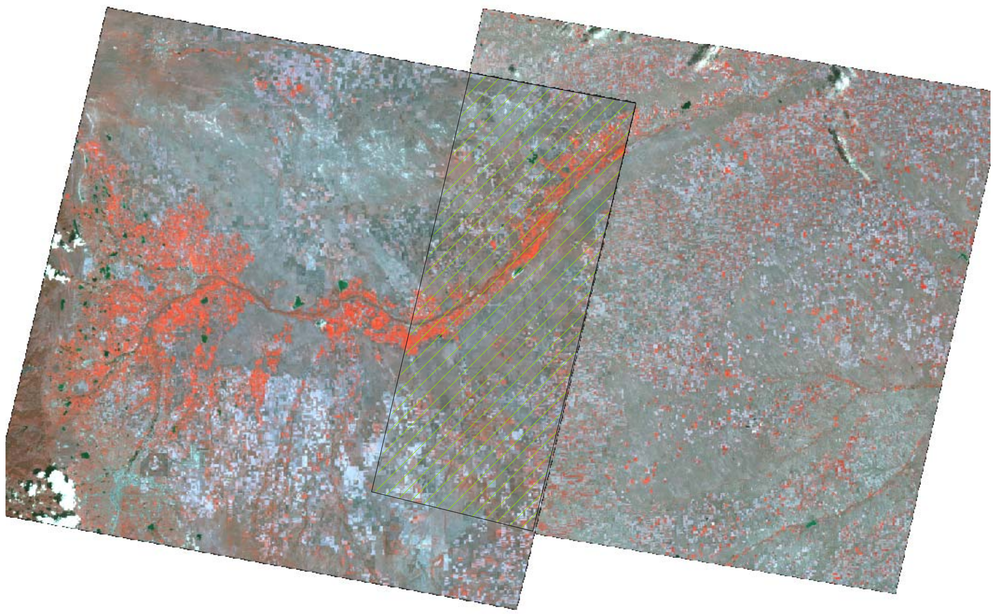


Figure 1. Overlap area for Landssat 5 scenes path/row 33/32 and 32/32 in the South Platte River Basin, CO.

To compare the seasonal ET calculated by ReSET against a traditional method such as ASCE a ratio was created by dividing the calculated ASCE-EWRI corn seasonal ET for each field by the estimated corn seasonal ET from the ReSET model for the same field. The seasonal ET of a field was calculated by taking the arithmetic mean value of all pixels in the field. However, to avoid edge effects (pixel contamination) a buffer of 60 meters (two pixels) around the edge of the field was implemented. For each field, since the ASCE method is calculating ideal seasonal ET values then it should be compared to the best part of the field meaning the maximum ET reported. Therefore, the maximum ET value for each of 418 corn fields was extracted. The ratio (ASCE/ReSET maximum pixel) ranged from 0.9 to 1.25 as shown in Figure (2), the average of the ratio was 1.07. Corn fields that had normal growing conditions (no crop damage, early harvest (silage) or water stressed) fall within 5 percent difference from the ASCE seasonal estimates (see Figure 3).

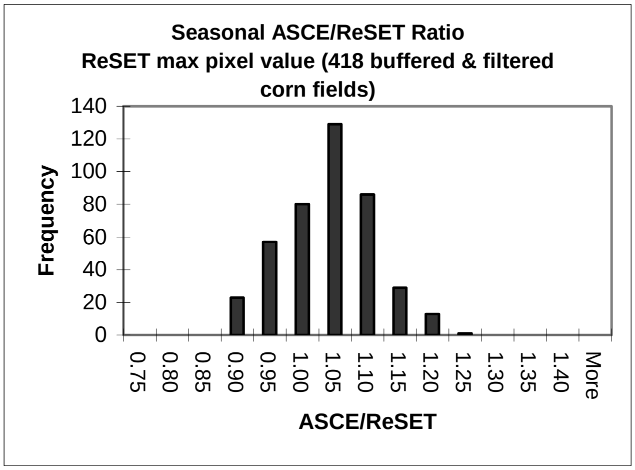


Figure 2. Ratio of ASCE/ReSET maximum pixel value for each field.

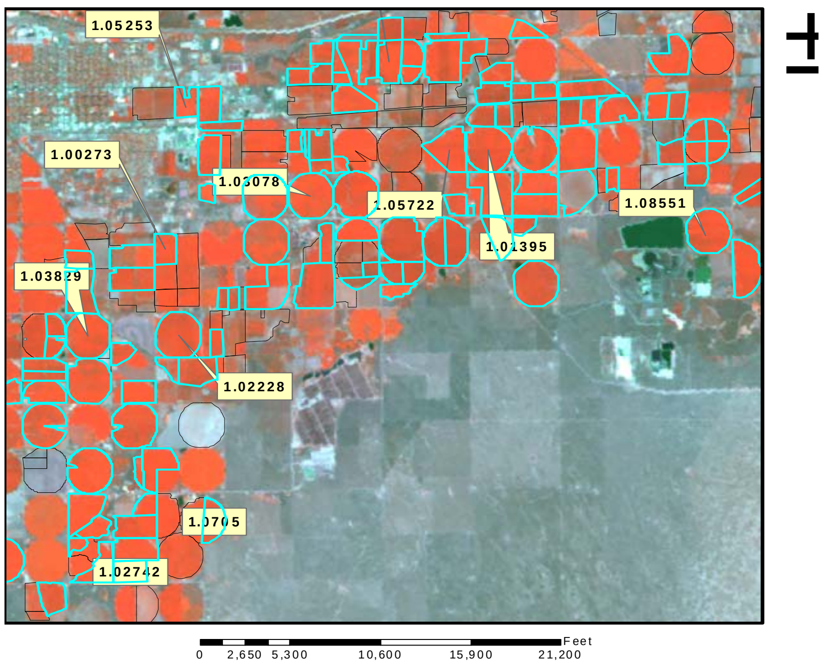


Figure 3. ASCE/ReSET corn seasonal ET ratio around 1 – (background image 7/14/2006)

Model application in the lower Arkansas River Basin region in Colorado.

The ReSET model can be used to calculate the total amount of water consumed by fields in a region, the model was applied to the lower Arkansas River Basin in Colorado. The study region contains a large agricultural area. This region grows a variety of crops, most commonly corn and alfalfa, with a variety of other crops including onions and melons. Seven Landsat 5 images were obtained for the area, using the ReSET model, ET grids were developed for the 2007 growing season starting in late April and ending in early October. Seasonal estimates of ET were developed using the ReSET seasonal tool (Elhaddad and Garcia 2008) which calculates ET for a specific period using individual ET grids processed from single Landsat scenes and interpolating between them. The ET grids for days between the scenes are created based on temporal and spatial interpolation between actual Landsat image dates using the daily reference ET from weather stations in the region as an interpolation index.

The seasonal ET results of ReSET were combined with a Geographic Information System (GIS) to determine the total water consumption per pixel (900 mts^2) which were aggregated to a field and then to a canal service area. The actual water consumption can be compared to the water requirements of the crops and this information can be used to identify areas of water stress. This information can also be used to help farmers or water managers improve their irrigation management.

<u>Single ET Grids Estimated by ReSET from 4/28/07 to 10/5/07</u>

Figure 4 below shows the individual ET scenes and the original Landsat 5 imagery. As can be seen from the processed images the ET is low at the beginning and end of the season (as expected) while it goes to the highest value during the middle of the season. Some of the images show an increase in ET in the non-irrigated areas and this is most likely due to rainfall prior to the image date or due to upward flux from a shallow water table or seepage during the middle of the season due to irrigation activities.

<u>Seasonal Evapotranspiration Grids</u>

When developing a seasonal Evapotranspiration grid, the main crop of interest determines the start and end date of the seasonal grid. Figure 5 shows two seasonal estimates of water consumed by different types of crops, on the left is the ET estimated from April 28, 2007 (DOY 118) and Oct. 5, 2007 (DOY 278) which targets crops such as alfalfa. The grid shows ET values up to 1,200 millimeters for the growing season. The grid on the right covers the ET for the period from May 30, 2007 (DOY 150) and October 5, 2007 (DOY 278) which targets crops such as corn. The grid shows ET values up to 900 millimeters for the growing season.

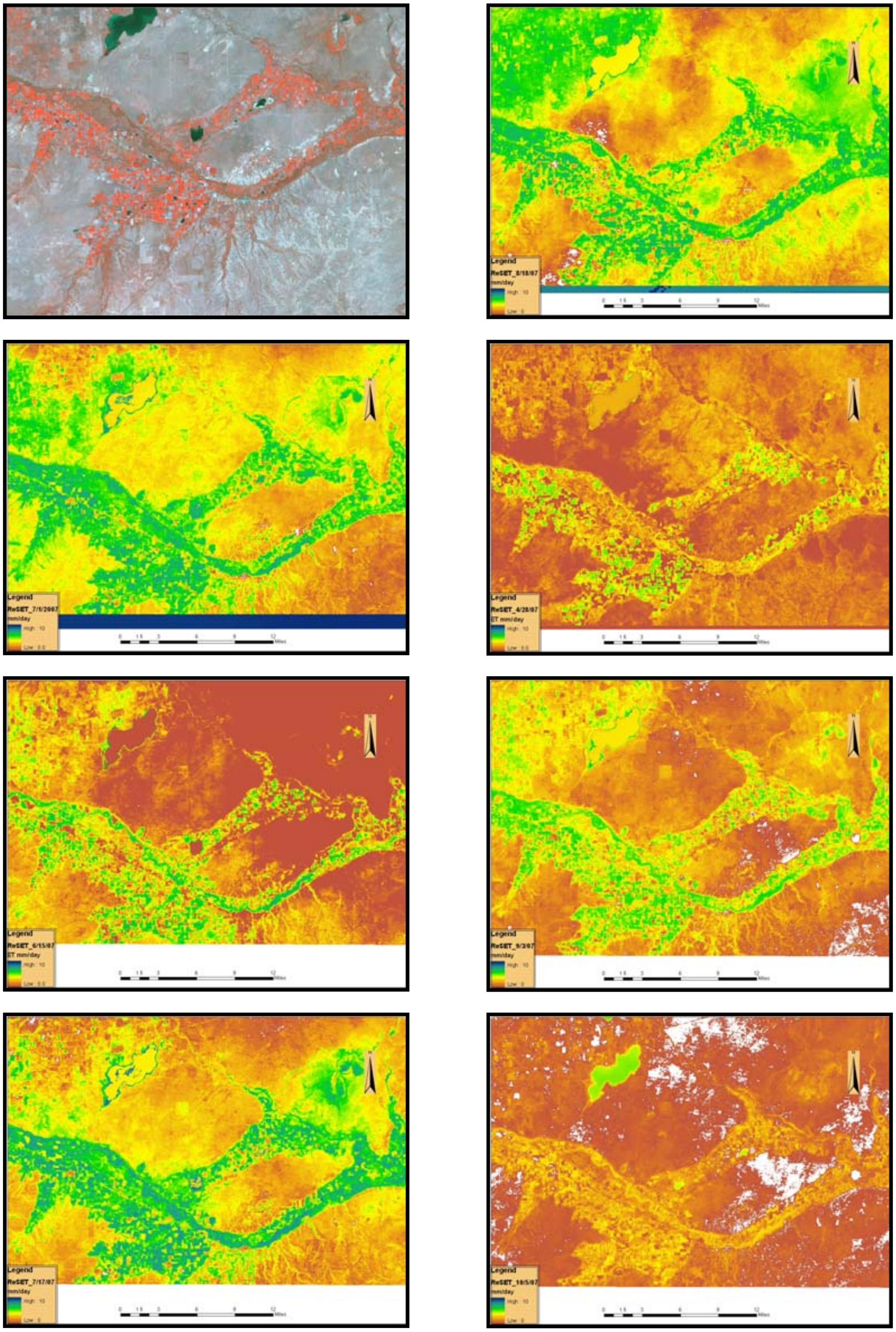


Figure 4. ReSET images for 2007

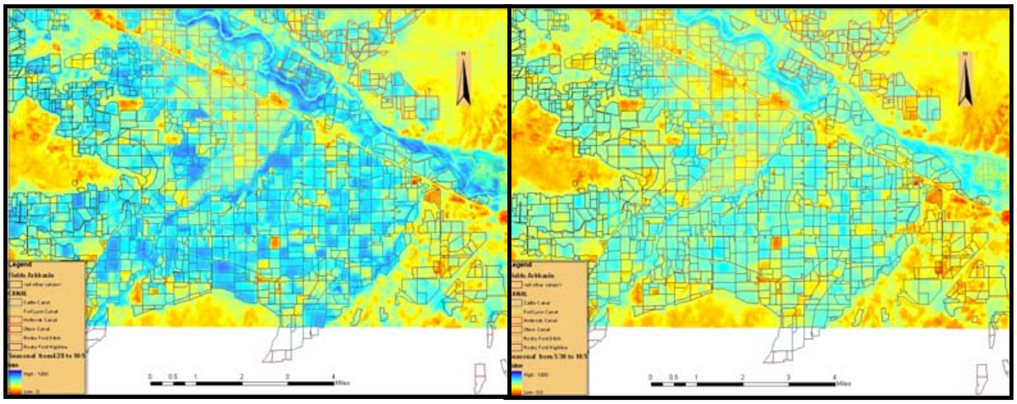


Figure 5. Seasonal Evapotranspiration grids for alfalfa (left) and corn (right).

Seasonal ET for Canal Service Areas

When evaluating the performance of a canal one important issue is the water conveyance efficiency of the canal. What are the losses? Are the fields at the lower end of the canal getting enough water, similar to the fields located at the head of the canal? What is the actual amount of water consumed by the crops in the canal service area? All these questions can be answered fairly accurately by the remote sensing-based approach. The Catlin canal in the Lower Arkasas River Basin in Colorado was selected using GIS and Figure 6 shows some spatial information for this canal; such as the sum of the water consumed by the fields in this canal service area. For the Catlin canal the model estimated the ET to be 57,525x10^3 m^3 (46,636 acre feet), this number represents the actual water used by the crops in all the fields in the Catlin canal service area during the period from April 28, 2007 (DOY 118) and October 5, 2007.

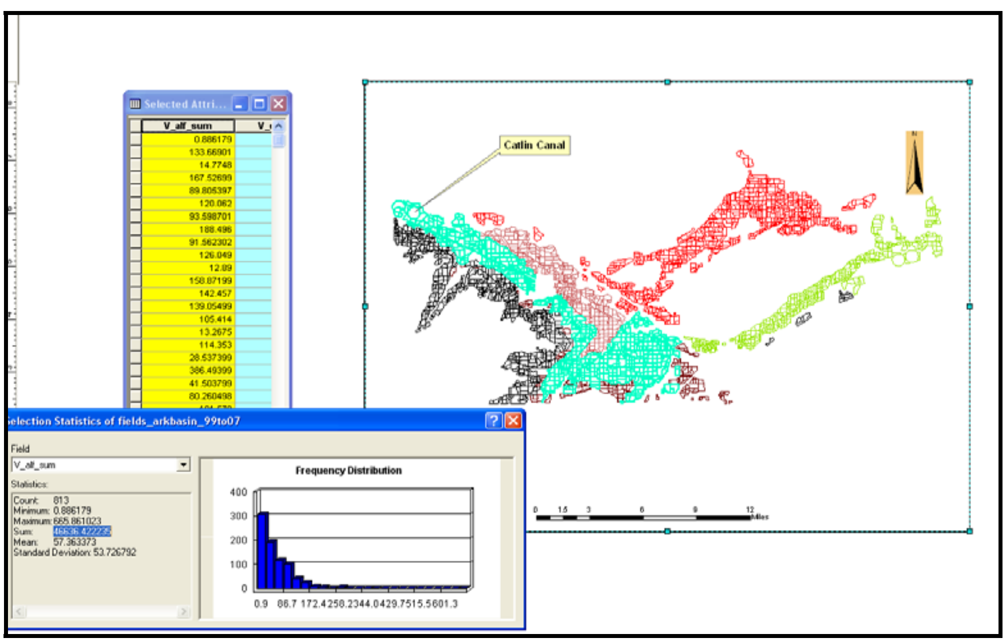


Figure 6. Seasonal evapotranspiration for the Catlin Canal service area

Model Application in Palo Verde Irrigation District (PVID)

The Palo Verde Irrigation District service area falls on the overlap between two Landsat scenes (39/37 and 38/37), which made it possible to collect over 30 usable images for the area in the year 2002 (a combination of Landsat 5 and 7 scenes). Seasonal estimates were calculated from single ET grids processed using both the un-calibrated for atmospheric effects and the calibrated for atmospheric effects ReSET models. The alfalfa fields in the area had a maximum ET value of 1,748 mm/yr when estimated using the calibrated process. The alfalfa ET for the Blythe weather station from the California Irrigation Management Information System (CIMIS) is 1,774 mm/yr which is 1.5% more than the annual ET estimated by the calibrated ReSET model. Figure (7) shows the seasonal ET using the un-calibrated ReSET ET grids where the seasonal alfalfa ET estimates resulted in a maximum annual ET of 1,612 mm/yr which is 9.1 percent lower than the CIMIS estimates.

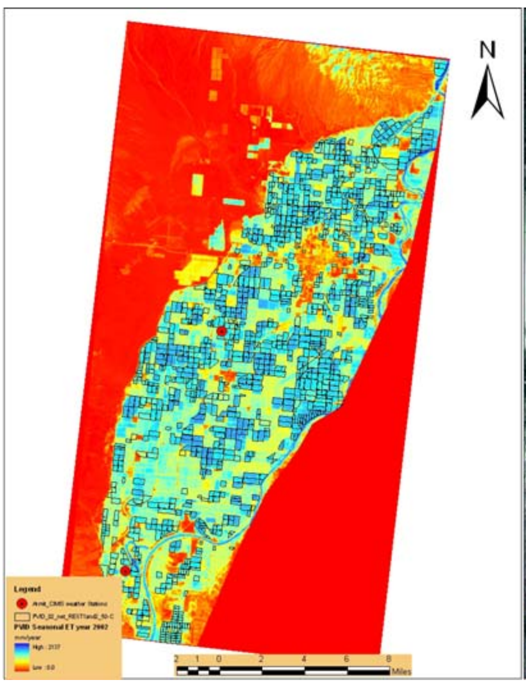
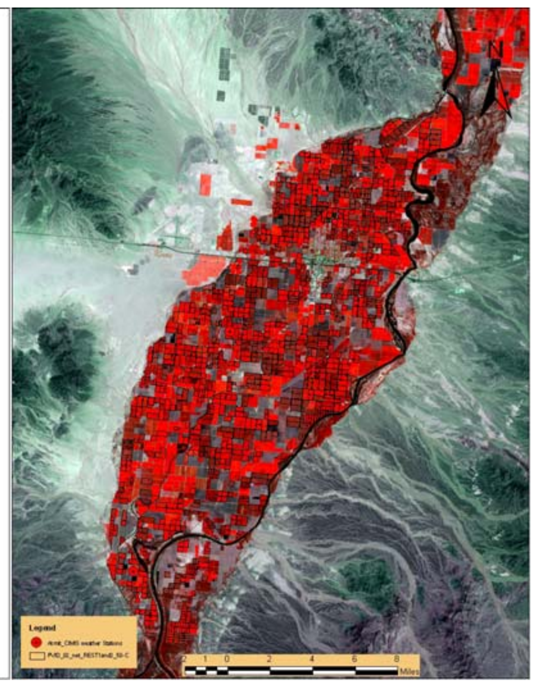


Figure 7. Seasonal ReSET ET



Landsat 7 image for the study area

ReSET Model ET Comparison to Lysimetric ET

Lysimeters provide accurate measurements of actual ET. The ReSET model ET estimates were compared with ET derived from the USDA-ARS Lysimeters at Bushland, Texas.

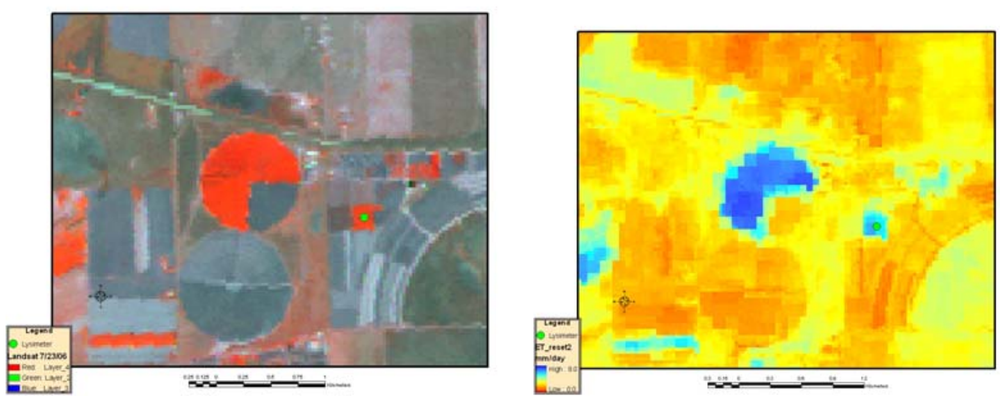
The Conservation and Production Research Laboratory (CPRL) of the USDA-ARS located in Bushland, Texas is located at 35° 11’ N, 102° 06’ W, and its elevation is 1,170 m above mean sea level.

Estimates of ET for a Landsat 5 Thematic Mapper ™ image acquired on 7/23/06 were evaluated. The scene path/row was 31/36 and was acquired at 17:20 GMT [11:20 am

Central Standard Time (CST) in the US], DOY 204. The TM band 6 image was captured at a coarser resolution of 120 m, and was re-sampled to 30 m by the image supplier.

There were four lysimeter fields, each planted to clumped grain sorghum (northwest dryland field), row grain sorghum (southwest field), silage corn (northeast irrigated field), and silage sorghum (southeast irrigated field) respectively. Each lysimeter was located in the middle of approximately 4.5 ha fields.

The satellite image was processed using the ReSET model in its two modes (un-calibrated and the weather station calibrated mode), the weather station used in the model calibration was the Bushland-ARS station. The daily ET from the sorghum planted in the southwest Lysimeter was (ground data) 7.79 mm/day for that day. The selected cold pixel had a UTM coordinates of (3,897,719 N, 763,374 W), the hot pixel UTM coordinates was (3,878,382 N, 799,004 W).
The daily ET value for the Lysimeter estimated by the un-calibrated model was 6.73 mm/day (Figure 8) with a difference of -13.6 percent from the daily estimate of the Lysimeter, with the reference ET calibrated run the difference goes to -11.16%. The Lysimeter had sorghum grown for forage. A center pivot next to the Lysimeter was selected as our well irrigated field in the modeling process, it had an ET of 7.29 mm/day and 8.02 mm/day in the un-calibrated and the calibrated modes respectively. In the calibrated mode the reference ET used was 7.62 mm for the 24 hour ET and 0.76 mm for the hourly ET from the ARS-Bushland weather station. The field selected as a well irrigated field in the un-calibrated mode was 96 percent of the weather station reference ET and 105 percent of the reference ET in the calibrated mode.



Landsat imagery 7/23/06, Lysimeter location   Calibrated ReSET ET (7/23/06)

Figure 8. Lysimeter Landsat 5 image and ReSET ET estimates.

CONCLUSION

The ReSET model was used to estimate daily and seasonal ET for several regions in the USA (South Platte river basin, CO; Arkansas river basin, CO; Palo Verde Irrigation District, CA; and Bushland, TX), for the daily estimates the model was compared with ET measured by lysimeters in Bushland, TX, showing only 5 percent difference from the daily ET recorded by the lysimeter. Seasonal estimates for the South Platte river basin were compared to the ASCE seasonal estimate for corn, the ratio of ASCE divided by the ReSET seasonal estimates for 418 corn fields had an average for ratios of 1.07, a similar application was done in the PVID to determine seasonal estimates of alfalfa ET in that area. The maximum yearly ET for reference alfalfa estimated by the calibrated ReSET model was 1,748 mm/yr while the estimated ET from the Blythe weather station was 1,774 mm/yr which represents a 1.5 percent difference. The results presented support the idea of using the ReSET model as a tool for water management, such as the example from the Arkansas river valley in Colorado where the model was used to estimate the ET for a group of fields based on the service area for a canals. This information can be used to calculate canal efficiency and irrigation system efficiency. The applications presented in this paper show that remote sensing of ET provides a valuable tool for water management.

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REFERENCES

Allen, Richard G.; Tasumi, Masahiro; Trezza, Ricardo 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) - Model. *Journal of Irrigation and Drainage Engineering*, 133(4):380-394, July/August 2007.

Allen, Richard G.; Tasumi, Masahiro; Morse, Anthony; Trezza, Ricardo; Wright, James L.; Bastiaanssen, Wim; Kramber, William; Lorite, Ignacio; Robison, Clarence W. 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. *Journal of Irrigation and Drainage Engineering*, 133(4):395-406, July/August 2007.

ASCE-EWRI. 2005. The ASCE standardized reference evapotranspiration equation. Report by the American Society of Civil Engineers (ASCE) Task Committee on Standardization of Reference Evapotranspiration. Allen, R.G., I.A. Walter, R.L. Elliot, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder (eds.), ASCE, 0-7844-0805-X, 204 pp., Reston, VA.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, A.A.M. Holtslag. 1998a. Remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology* 212-213(1-4): 198-212.

Bastiaanssen, W.G.M., H. Pelgrum, J. Wang, Y. Ma, J.F. Moreno, G.J. Roerink, and T. van der Wal. 1998b. Remote sensing surface energy balance algorithm for land (SEBAL): 2. Validation. *Journal of Hydrology* 212-213(1-4) 213-229.

Bastiaanssen, W.G.M. 2000. SEBAL based sensible and latent heat fluxes in the irrigated Gedez Basin, Turkey. *Journal of Hydrology* 229(1-2):87-100.

Elhaddad, Ayman; Garcia, Luis A. 2008.Surface energy balance-based model for estimating evapotranspiration taking into account spatial variability in weather**.** *Journal of Irrigation and Drainage Engineering*, 134(6):681-689, 2008

Harrison, L. P. 1963. Fundamental concepts and definitions relating to humidity. In: *Humidity and moisture. Vol. 3.*, Wexler, A., ed. New York, N.Y.: Reinhold Publishing Company.

U.S. Department of the Interior, 2004 "Lower Colorado River Accounting System Calendar Year 2002", Bureau of Reclamation, Lower Colorado Regional Office, Boulder City, Nevada.