APPLICATION OF METRIC TO DETERMINE EVAPOTRANSPIRATION FOR SOUTHEASTERN AND SOUTHCENTRAL PORTIONS OF IDAHO INCLUDING THE EASTERN SNAKE RIVER PLAIN FOR 2006

Dr. Magali Garcia, Dr. Richard G. Allen and Clarence Robison
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1. Introduction

This report describes the procedures and products from processing of satellite, weather and land-use data for the Southeastern area of Idaho for year 2006, for the production of spatial and temporal maps of monthly and seasonal evapotranspiration (ET) for the region. The final product includes Actual Evapotranspiration (ET) as well as the fraction of Evapotranspiration in relation to a Reference Alfalfa crop. The latter product provides means to identify any water stress that crops might have been subjected to. The processed region was generally comprised of two paths (39 and 40) from Landsat and two rows (29 and 30) as shown later in figure 2.

The analyzed area has a semiarid climate with mean annual precipitation of approximately 280 mm. The irrigated agriculture relies on irrigation from the Snake River and regional groundwater systems. Center pivot, wheel line, and furrow irrigation are the predominant irrigation systems of the area. The major crops grown are alfalfa, dry beans, corn, pasture, potatoes, sugar beets, winter and spring small grains (wheat and barley), and peas. The average frost-free growing period (minimum air temperature >0 °C) extends from mid-May to early October at Twin Falls.

2. The METRIC Model

METRIC™ (Mapping Evapotranspiration with high Resolution and Internalized Calibration) is an ERDAS coded image processing model based on the evaluation of the energy balance at the earth's surface. METRIC™ processes instantaneous remotely-sensed digital and weather data and estimates the partitioning of energy into net incoming radiation, heat flux into the ground, sensible heat flux to the air, and latent heat flux. The latent heat flux, which is computed as a residual in the energy balance, represents the energy consumed by ET.

$$LE = Rn - G - H$$

where LE=latent energy consumed by ET; Rn=net radiation; G=sensible heat flux conducted into the ground; and H=sensible heat flux convected to the air. One utility of using energy balance is that actual ET rather than potential ET based on amount of vegetation is computed so that reductions in ET caused by a shortage of soil moisture are captured. A primary disadvantage of the energy balance approach is that the computation of LE is only as accurate as the summed estimates for Rn, G, and H. METRIC attempts to overcome this disadvantage by focusing the internal calibration not on LE but on H to absorb all intermediate estimation errors and biases (Allen et al., 2005; 2006).

METRIC™ utilizes spectral raster images from the visible, near infrared, and thermal infrared energy spectrum to compute the energy balance on a pixel-by-pixel basis.

In METRIC, Rn is computed from the satellite-measured narrow-band reflectance and surface temperature; G is estimated from Rn, surface temperature, and vegetation indices; and H is estimated from surface temperature ranges, surface roughness, and wind speed using buoyancy corrections.

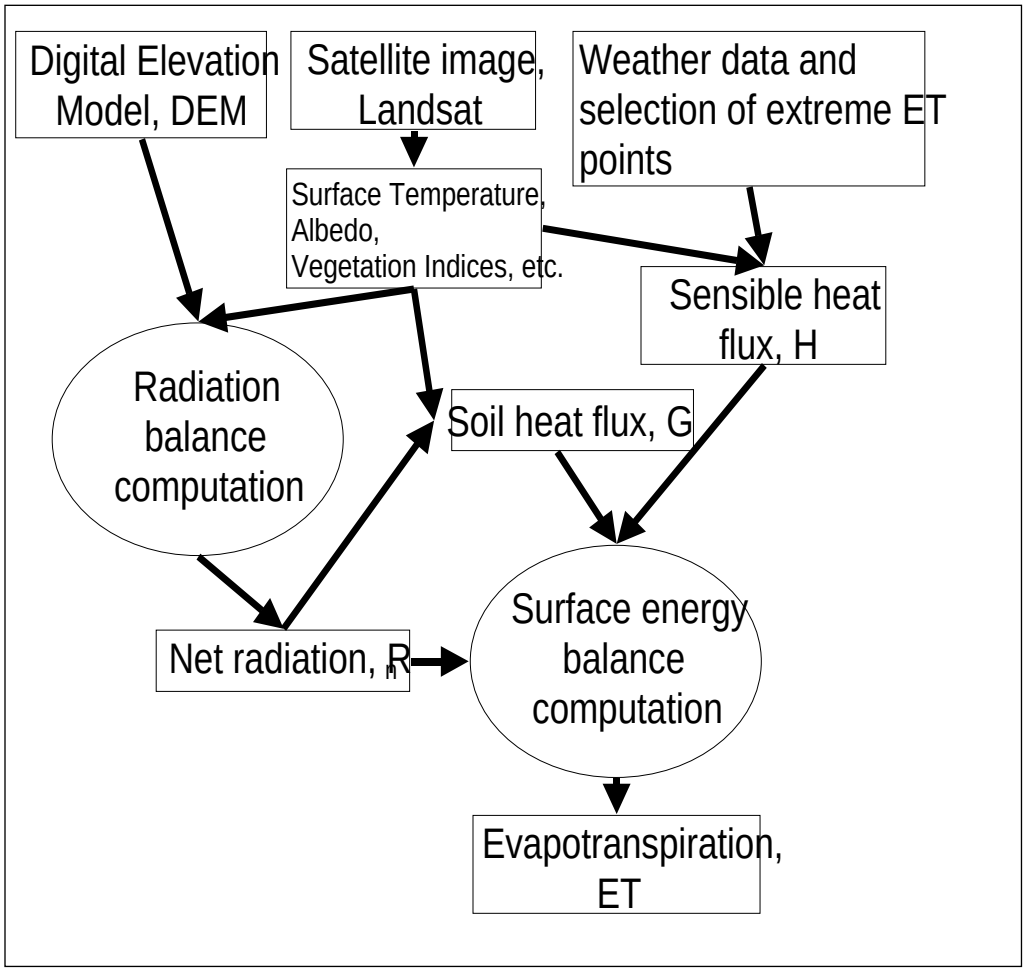


Figure 1. Scheme of the general computational process for determining evapotranspiration using METRIC.

The processing of ET using energy balance requires both an understanding of energy balance mechanisms and their interactions with physical conditions of the region under study. Each individual satellite image is uniquely calibrated, which requires skilled, learned expertise (Allen et al., 2007a,b).

METHODOLOGY

The evaluation and production of ETrF and ET images requires several intermediate steps and high quality weather data. ETrF is the fraction of reference ETr and is synonymous with the crop coefficient, Kc. Reference ET, ETr, is calculated from quality controlled hourly weather

data using the ASCE-EWRI (2005) standardized Penman-Monteith equation for the alfalfa reference.

Weather Data

High quality weather data are necessary for the application of METRIC. For year 2006, hourly data collected by nine weather stations were evaluated for path 39 and 40. Six of the stations were operated by the USBR Pacific Northwest Cooperative Agricultural Network (AGRIMET) and the other three were RAWS stations (Remote Automated Weather Stations) operated by the Program for Climate, Ecosystem and Fire Applications (CEFA), in cooperation with the Bureau of Land Management and the Desert Research Institute (DRI). Both weather station systems maintain an up to date website with weather data. The coordinates and characteristics of the meteorological stations are presented in Table below.

Table 1. Coordinates and characteristics of weather stations used for processing of year 2006.

Station	Latitude	Longitude	Elevation (m)	Institution in charge	Path
Aberdeen	42° 57’ 12”	112° 49’ 36”	1341	AGRIMET	39
Ashton	44° 01’ 30”	111° 28’ 00”	1615	AGRIMET	39
Rexburg	43° 51’ 00”	111° 46’ 00”	1486	AGRIMET	39
Picabo	43° 18’ 42”	114° 09’ 57”	1494	AGRIMET	40
Rupert	42° 35’ 42”	113° 50’ 17”	1267	AGRIMET	40
Twin Falls-Kimberly	42° 32’ 46”	114° 20’ 43”	1195	AGRIMET	40
Arco	43° 37' 23"	113° 23' 14"	1640	CEFA	40
Leadore	44° 42’ 00”	113° 21’ 00”	1812	CEFA	40
Salmon	45° 09' 00"	113° 56' 00"	1512	CEFA	40

Sources: http://www.raws.dri.edu/wraws/sidF.html and http://www.usbr.gov/pn/agrimet/location.html

A detailed report on Quality Control of weather data is presented in Appendix A. Most of the analyzed weather data were of good quality. In cases of obvious measurement error, measurement bias or missing data, standardized procedures for data correction and filling were applied. In the case of Agrimet stations, all 365 days of year 2006 were QA-QC’d and hourly ETr was calculated. The hourly ETr was summed each day to 24-hour values. In the case of the CEFA data, only hourly data for the satellite image dates was QA-QC’d and hourly ETr calculated, due to large periods having some missing hourly data. For all other days, 24-hour average weather data plus daily extremes for air temperature were QA-QC’d and ETr was calculated on a 24-hour timestep.

Satellite Images, DEM, Slope and Land Use Maps

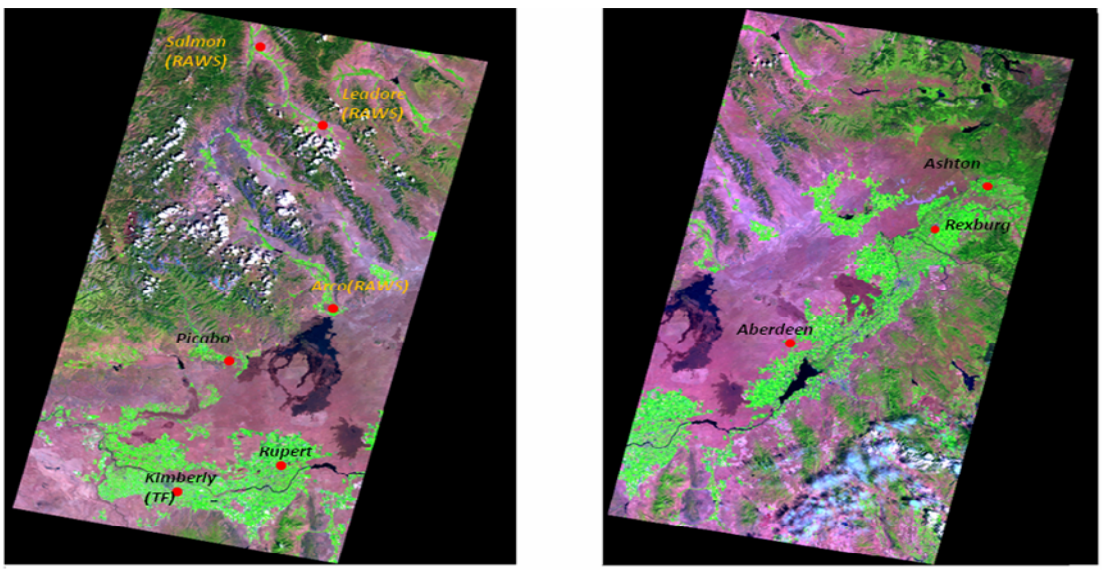
Spectral data from 19 Landsat images were processed for year 2006. The dates of the images are listed in Table 2 below. The images were mostly from Landsat 5, paths 39 and 40 and rows 29-30, with four images from Landsat 7 (same path/row). As illustrated in Figure 2, both paths 39 and 40 were comprised of a 2 row scene so that the vertical (north-south) extent of the images was about 300 km. Path width is about 150 km. The scenes for both paths were shifted, when

ordered from the USGS EROS data center, in a north-south direction to maximize the coverage of Idaho territory, especially irrigated areas. Path 39 was shifted __% to the south and path 40 was shifted 20%? to the south.

Table 2. Landsat image dates processed for year 2006 (L5 = Landsat 5 and L7 = Landsat 7).

Path 39	Path 40
2006-04-02 (L7)	2006-04-25 (L7)
2006-04-26 (L5)	2006-05-03 (L5)
2006-05-12 (L5)	2006-05-19 (L5)
2006-06-13 (L5)	2006-06-20 (L5)
2006-07-15 (L5)	2006-07-22 (L5)
2006-08-16 (L5)	2006-08-07 (L5)
2006-09-01 (L5)	2006-08-31 (L7)
2006-10-03 (L5)	2006-09-08 (L5)
2006-10-11 (L7)	2006-09-24 (L5)
	2006-10-10 (L5)

Path 39 was processed as a single image, due to the homogeneity of the weather and terrain over irrigated areas covered by it. On the other hand, the heterogeneity of both terrain and weather systems in path 40, caused by the northern mountains, required the splitting of the images area into two parts, North and South. The split generally followed the outline of mountain ranges along the eastern Snake River Plain (ESPA) as shown in Figure 3. Each image region was processed separately using different weather data sets and energy balance calibrations. Figure 2 shows the coverage areas and the included weather stations for each path:



Path 40 Path 39

Figure 2. Double-row Landsat scenese processed for path 40 and 39 for year 2006.

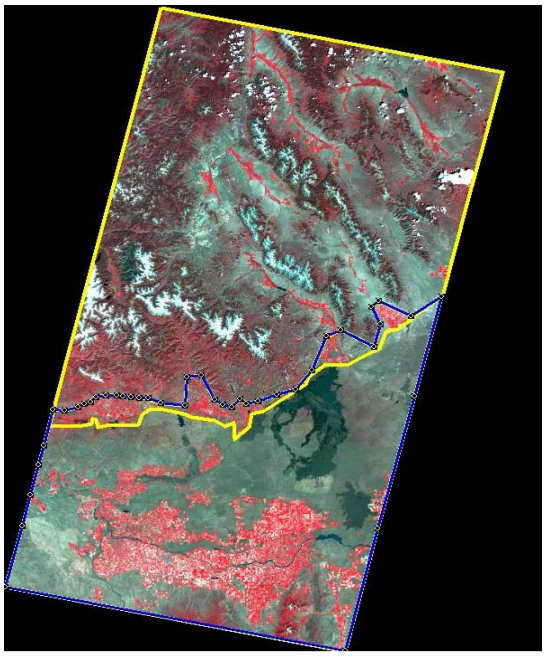


Figure 3. Areas of division for the two 'areas of interest' (AOI) for path 40. The blue line shows the area included for the analysis of the Southern part and the yellow line is the boundary corresponding to the Northern AOI. Each area was processed separately. The overlapped area was processed twice and provided for comparison of impacts of separate calibration of the two AOI's on the ET products.

Quality Control on images

Images were ordered from the USGS EROS data center using nearest neighbor (NN) resampling during the L1T terrain-correction process. The thermal band (6) was resampled to 30 m during this same process. The images were projected during the EROS processing as Idaho Transverse Mercator projection.

Once received, the images were assessed for their quality and integrity in all seven bands. It was found that the images processed by EROS as L1T terrain corrected contained registration differences between the six short wave bands and the thermal band, with band 6 being shifted to the south in relation to the short wave bands. The shifted distance was not constant and had to be evaluated for each image although a frequent value encountered was 60 m in a southward direction. A statistical technique was used to relate the spatial variability of NDVI with the spatial variation in the thermal band. Both should follow similar trends. The difference in the trend of variation gave an indication of the approximate shifted distance and necessary correction. Table 3 displays the amount of detected and corrected shifting for each image.

Table 3. Northern shift to band 6 required to align band 6 with bands 1-5 and 7 for L1T Landsat 5 images processed for 2006 by EROS in late 2007.

Path 39		Path 40	
Date	Shifted distance (m)	Date	Shifted distance
2006-04-26	90	2006-05-03	60

2006-05-12	60	2006-05-19	60
2006-06-13	30	2006-06-20	60
2006-07-15	60	2006-07-22	60
2006-08-16	60	2006-08-07	30
2006-09-01	60	2006-09-08	90
2006-10-03	90	2006-09-24	60
		2006-10-10	60

Addtionally, due to extreme cloudiness the image corresponding to April 2nd 2006 for path 39 and the Northern part of the image corresponding to September 8th 2006 for path 40 were excluded from the input images.

A Landuse Map is used in METRIC™ to support the estimation of aerodynamic roughness properties, emissivity, and the estimation of soil heat flux. The model also requires maps of DEM (digital elevation map), slope and aspect for the complete evaluation of ET. Those were provided by the University of Idaho (METRIC group) and by the Idaho Department of Water Resources. The local cover map used was that derived by Tasumi (2003) and Trezza (2002). The DEM was a 30 m map obtained from the USGS web site.

PRODUCTS FROM METRIC

Aplication of the METRIC energy balance to an image produces a rasterized 30x30 m map of ETrF (Fraction of Reference Evapotranspiration) and actual ET. The process uses an especial combination of both short and long-wave bands and several intermediate files to produce the final ETrF and ET maps. Each image was manually calibrated as described in the METRIC Manual version 2.0.4. Results were iteratively revised by the UI Remote Sensing team at Kimberly and reprocessed as needed. The full 'mountain model' was applied to account for effects of slope and aspect on solaration and net radiation as described in appendices of the manual.

Intermediate Products

During the METRIC™ process, dimensionless vegetation indices (NDVI, LAI and NDWI), surface reflectance (albedo), and surface and DEM temperature maps are created. NDVI (normalized difference vegetation index) and LAI (leaf area index) maps are used in METRIC™ as indicators of biomass and aerodynamic roughness, and as predictors of ratios of soil heat flux to net radiation. The LAI is defined as the total one-sided green leaf surface area per unit ground surface area. The typical range for LAI is zero to six, where zero represents bare soil and greater than four represents dense vegetation. LAI values above three represent "full cover" conditions, and generally imply maximum ET in well irrigated areas.

NDVI is calculated as the relative difference reflectance between the shortest near infrared band (band 4) and the red band (band 3), respectively:

$$\mathrm{NDVI} = \frac{\rho_4 - \rho_3}{\rho_4 + \rho_3}$$

where ρ3 and ρ4 are the at-satellite reflectances in bands 3 and 4 respectively. NDVI is somewhat sensitive to the color of the soil, spectral bandwidth, and atmospheric attenuation.

Typically, NDVI varies between 0.1 and 0.8, with the higher value indicating dense vegetation and values less than about 0.2 associated with soil/rocks. Negative NDVI values typically indicate water bodies and snow, which reflect more energy in the red spectrum than in the near infrared.

NDWI (normalized difference water index) is calculated as the relative difference in at-satellite reflectance between bands 5 and 2

$$\mathrm{NDWI} = \frac{\rho_5 - \rho_2}{\rho_5 + \rho_2}$$

where ρ5 and ρ2 are the at-satellite reflectances in bands 5 and 2 respectively. This is an index designed for the identification of water bodies. A value lower than zero indicates the presence of water bodies. In combination with NDVI, NDWI can be used to produce a good map of watery areas.

Lapse rate

DEM corrected temperatures are used in METRIC in the estimation of mean surface temperature gradients as a function of surface temperature. The production of DEM corrected temperatures requires the definition of an atmospheric lapse rate to remove artifacts from Ts caused by elevation alone. For the area of study a generic environmental value of 7C was used. However for some dates, the atmospheric instability, heterogeneity in air masses and the weather conditions over the image area required a reduction in the lapse rate used in path 40. That was the case for May 10th, when the applied lapse rate was 4C, June 20th when the applied lapse rate was 3C in the South and 4 C in the North and for July 22nd when the applied lapse rate was 5C for both areas. These customized lapse rates were determined by noting change in Ts with distance for well-watered vegetation and by noting maximum values calculated for ETrF for fields having full vegetation in different regions of the image.

Final Products

The final products of the METRIC™ process are rasterized Fraction of Reference Evapotranspiration (ETrF) maps having 30m by 30 m spatial resolution. Further processing of the ETrF maps produces a rasterized ET expressed as depth of water evaporated per period of time (daily, monthly, and seasonal).

ETrF is equivalent to the crop coefficient when the reference base is full-cover alfalfa. ET in units of depth per time (e.g. mm/month) can be converted into a volume per time (e.g. m3/month) for any integrated area larger than an individual 30 m by 30 m pixel.

Processing of Landsat 7 images

Starting in 2003, the Landsat 7 ETM satellite experienced problems with the scan line corrector and produced images having stiped gaps of missing information. Although for some purposes these images are unusable, a large quantity of information can be collected from the non-striped areas. Ordinarily, Landsat 5 images were processed since they constitute complete images.

However, for several time periods, Landsat 5 images were not available due to clouds and Landsat 7 images had to be used. A methodology for filling the striped parts of the final ETrF images was developed based on the Natural Neighbor Interpolation Tool included in the ArcGIS software. This tool 'grows' pixel information from gap edges into the gap. It was applied to processed ETrF images to fill in ETrF data. The results shown in Figure 4 indicate smoothed, filled areas providing what is considered to be relatively representative ETrF. Often, field shapes are reconstructed within the gaps relatively accurately.

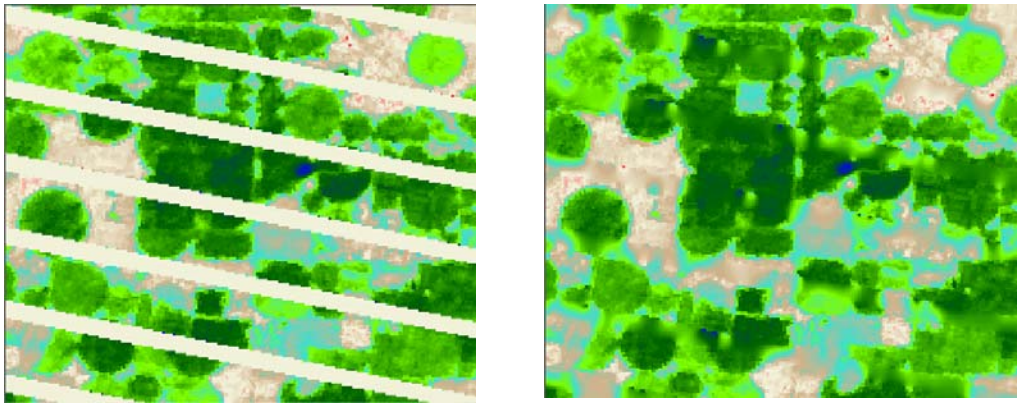


Figure 4. Left: Striped ETrF image for path 40 South derived from a Landsat 7 ETM image having data gaps. Right: The same image after the application of the ArcGIS Natural Neighbor interpolation technique to fill in the gaps. Note the consistent behavior of the filled interpolated values.

Sharpening of the final products obtained from the use of Landsat 5 TM images

Although the final products of METRIC are of high quality, a finer resolution for the images is highly desirable, considering the important use of the products. Unfortunately, spatial resolution of the longwave (thermal) band of Landsat 5 images have coarser than coincident shortwave bands, where the thermal band has 120 m pixel size and the short wave bands have 30 m pixel size. Because thermal information tends to dominate the ET process, the resulting ETrF and ET images tend to have a coarseness on the order of 120 m as shown in the left side of Figure 7. This coarseness in band 6 reduces fidelity of ET calculations.

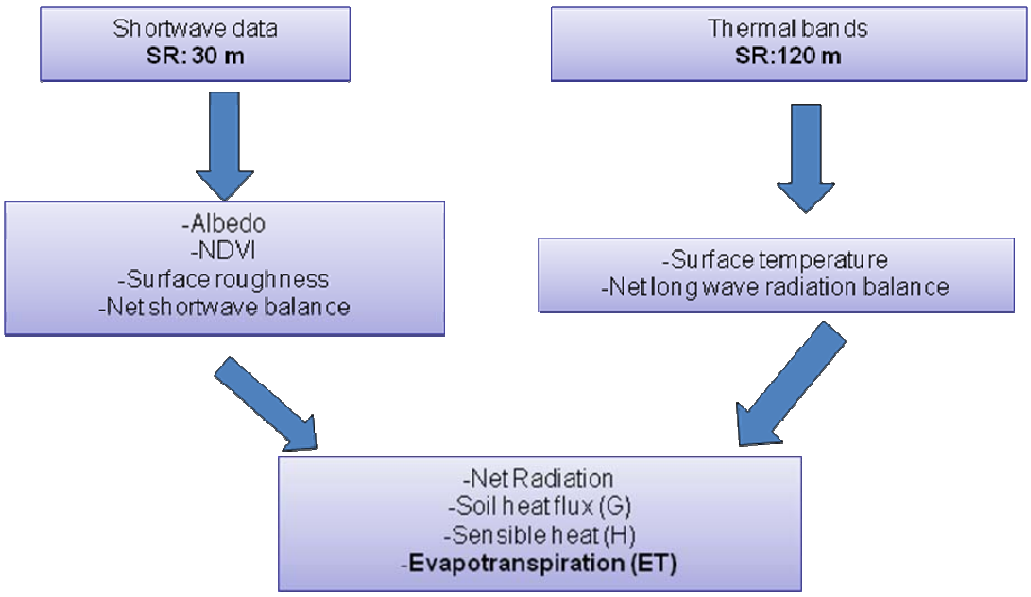


Figure 5. Flow chart of data flow in METRIC.

To improve the spatial quality of the results, a procedure known as *thermal sharpening* was applied to the thermal band of the Landsat 5 images. The sharpening procedure makes use of the close correlation between Surface temperatures (Ts) and vegetation indices (VI) as can be observed in figure 6. This physical relationship was exploited to sharpen Ts using NDVI. The technique was developed, using the concept of hot and cold thermal conditions associated with dry and wet surfaces and low and high NDVI during calibration to distribute Ts at a subpixel (30 m) scale within each original 120 m thermal pixel using 30 m NDVI.

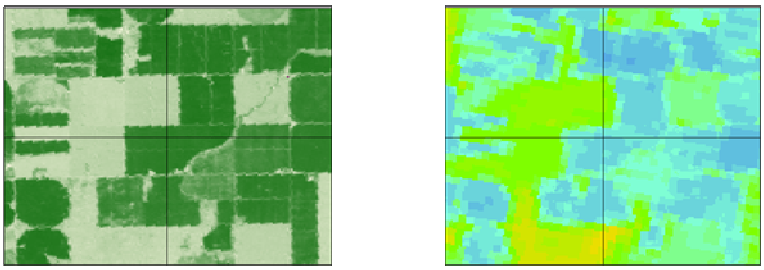


Figure 6. Left: NDVI image from path 40 derived from Landsat 5 TM at 30 m spatial resolution. Right: Ts values corresponding to the NDVI image where high NDVI denotes low temperature. The image in the right is clearly less sharp due to the 120 m resolution of the thermal infrared band.

The sharpening resulted in a Ts image having the spatial resolution of the short wave images. Following thermal sharpening, ETrF was reprocessed using the original calibrations, but with the 30-m sharpened thermal layer. Therefore, the resulting ET created from the reprocessed METRIC runs had equally high resolution.

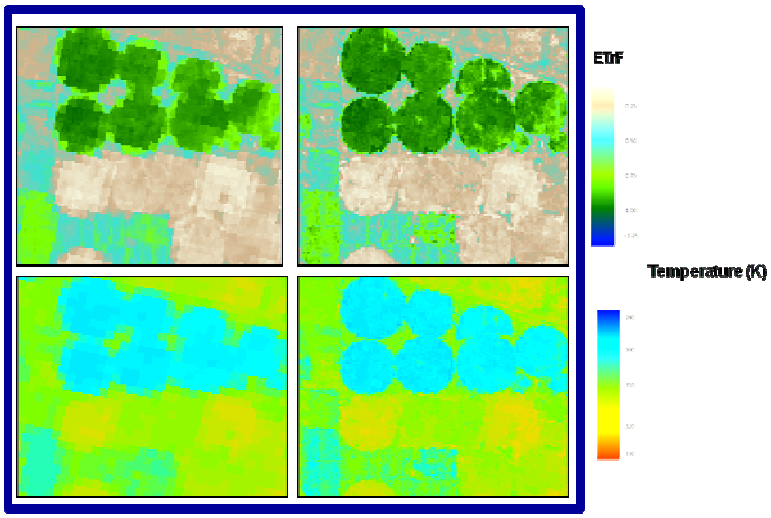


Figure 7. Unsharpened (left) and sharpened (right) Surface Temperature (below) and resulting ETrF (above) for May 19th 2006 path 40 South.

The sharpening process was conducted inside ArcGIS. The sharpening process in ArcGIS requires the input of band 6 as a digital number, the DEM-corrected Temperature image to be sharpened, the NDVI image and a water discriminating image (normally developed by a combination of NDVI and NDWI images). Complete detail of the procedures for the application of the sharpening process can be found in Allen et al., (2008).

Dealing with clouded parts of images

Satellite images often have clouds in portions of the images. ET_rF cannot be directly estimated for these areas using surface energy balance because cloud temperature masks surface temperature and cloud albedo masks surface albedo. ET_rF for clouded areas must be filled in before application of further integration processes so that those processes can be uniformly applied to an entire image. A linear interpolation is used to fill in ET_rF for clouded portions of images. The linear interpolation is used rather than curvilinear interpolation, such as the spline introduced later to interpolate between cloud-corrected images because some periods between cloud-free pixel locations can be as long as several months. Often, the change in crop vegetation amount and thus ETrF is uncertain during that period. Thus the use of curvilinear interpolation can become speculative.

An ERDAS Imagine Modelmaker code is available from the University of Idaho METRIC group to conduct the 'filling' of cloud masked portions of images using linear interpolation. The code accommodates up to eight image dates and corresponding ET_rF, with conditionals used to select the appropriate set of images to interpolate between, depending on the number of consecutive images that happen to be cloud masked for any specific location. Missing (clouded) ET_rF for end-member images (those at the start or end of the growing season) must be estimated by extrapolation of the nearest (in time) image having valid ET_rF, or alternatively, for end-member images, a 'synthetic' image can be created, based on daily soil water balance or other methods, to be used to substitute for cloud-masked areas. That was the case for the first image in both path 39 and 40, when the availability of images for early April was limited due to clouds. Although

for path 39, the first available image was the April, 2nd, 2006, the homogeneous surface profile (occurring after a snowy period), the strong cloudiness and the presence of stripes (being a Landsat 7 image) required the creation and use of a synthetic ET_rF image. In this case, the ETrF values in the synthetic image were based on soil-water balance –weather data model for the April 1 – 30 period to provide an improved estimate of ETrF over the early season for both paths. In both paths, the synthetic images were strategically placed, date-wise, so that the cloud-filling process and the cubic spline process had early enough end-points to provide ET_rF for all days of interest during the April-October growing period. In the case of path 39, the synthetic image had ETrF = 0.65 throughout the image and was placed at April 2. In the case of path 40s, ETrF = 0.6 was used and for 40N, ETrF = 0.7 was used to represent April 2.

Preparation of the monthly ETrF and ET images

Generation of daily ETrF images

Individual satellite images processed using METRIC yield images of ET_rF, where ET_rF is the fraction of reference ET. However, the available satellite images for path 39 and 40 were obtained relatively infrequently, having periods between ETrF images of up to 35 days. ET_rF is likely to change with time between images as vegetation develops or matures or as surface water availability varies. A common and useful objective of METRIC applications is to interpolate among individual satellite image dates to produce monthly and seasonal ET based on the information provided by the individual images. A common interpolation procedure is to use linear interpolation between images; however this does not reflect the generally smooth and curvilinear evolution in ET_rF occurring during growth and development of crops during a growing season. A cubic spline interpolation is able to better describe the curvilinear course of ET_rF for annual crops.

The term "spline" is used to refer to a wide class of functions that are used in applications requiring data interpolation and/or smoothing. Mathematically, spline interpolation is often preferred over polynomial interpolation because it yields similar results, while avoiding errors found for higher degree polynomials.

Figure 8 shows an example of point values of ET_rF sampled from a single location from multiple images processed for path 40 (South). The values on each image date are connected using linear interpolation between image dates.

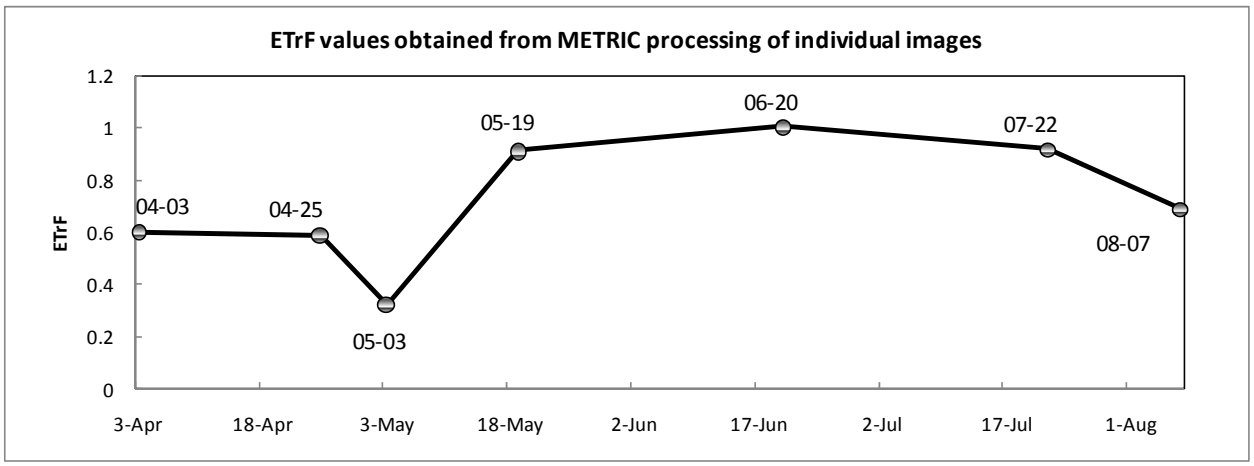


Figure 8. ET_rF for seven image dates in path 40 South with linear interpolation between images dates.

The relatively abrupt changes in slope between dates in Figure 8, when linear interpolation is applied, is evident. Figure 9 shows the result of application of a cubic spline interpolation method applied to the same images. This smoother interpolation is in most cases a better representation the development of ET_rF for vegetation compared to the linear interpolation.

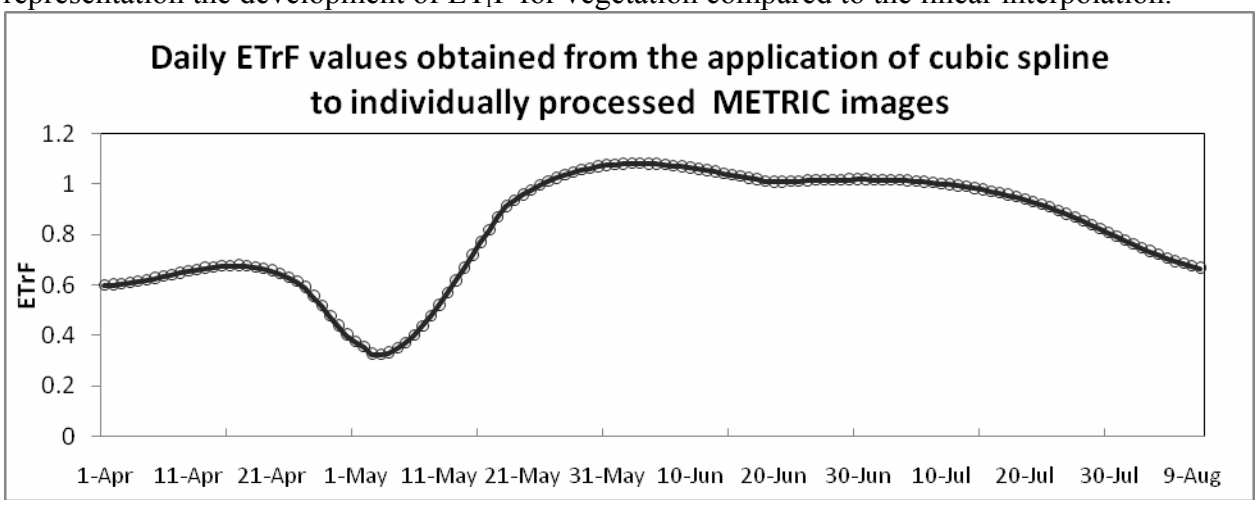


Figure 9. ET_rF interpolated applying a cubic spline between seven images dates during 2006.

The cubic spline procedure was applied to generate daily maps of ETrF for both paths. The detailed description of the algorithm used for the application of the spline procedure can be found in Allen et al. (2008).

ET monthly and seasonal maps

The application of the cubic spline procedure to derive monthly and seasonal ET_rF and ET is applied one month at a time to reduce complexity of the model and to reduce the likelihood of operator error. Once the daily images for ET_rF for each day of the month were created, the ET_rF for each day and for every pixel in an image was multiplied by the reference ET (ET_r), computed for that specific day according to weather data, as follows:

$$ET_{daily} = ET_rF_{daily} \times ET_{r\ daily}$$

Following the computation of daily ET for each day of the month, the ET_{daily} was summed to produce ET_{month}. The average monthly ET_rF_{month} was then determined by dividing the ET_{month} by the summed $ET_{r\ month}$:

$$ET_rF_{month} = ET_{month} / ET_{r\ month}$$

Because weather and reference ET_r can change spatially within an image domain, an ETr interpolation approach was applied by generating daily kriged ET_r images based on the 10 weather stations to create daily ETr surfaces. The resolution of the daily ET_r images was made coarser (1 km pixel size) than that for ET_rF, since ET_r changes only gradually in space.

Once ET and ETrF images for all considered months (April through October) were produced, the same concept as above was applied for the generation of the seasonal images, summing up the monthly ET and ETr images and ratioing them to generate a seasonal ETrF.

The final generated products were monthly ET and ETrF images from April through October and the seasonal total ET and ETrF images for paths 39 and 40. All ETrF images were generated as a Float Single Data Type and the ET images were generated as 16-Signed data type previously rounded to avoid data truncation.

RESULTS

Path 39

As previously described, path 39 had 9 images available, two of them being Landsat 7 and the others Landsat 5. However the large presence of clouds and the very homogeneous wet and cold soil surface of the first image (April 2nd, 2006), made it unusable. The decision was made to generate a synthetic image based on the soil water balance. The value assigned to the image was 0.65 (ETrF) to simulate the mean actual state of the soil surface over the first part of April. The image was assigned to April 2nd, 2006. Additionally the image corresponding to October 11th 2006 was from Landsat 7 ETM, and had to be gap filled as previously described. No other images for path 39 were discarded or presented anomalies considered to be important. Table 4 presents the utilized images and the corresponding satellite they come from.

Table 4. Final image dates and source for path 39, 2006

Path 39
2006-04-02 (synthetic)
2006-04-26 (L5)
2006-05-12 (L5)
2006-06-13 (L5)
2006-07-15 (L5)
2006-08-16 (L5)
2006-09-01 (L5)

2006-10-03 (L5)
2006-10-11 (L7)

Individual image results

Figure 10 presents two examples of the product of the ETrF product from the application of the METRIC model to individual images of May 12 and June 13 for path 39. The complete archive of the images has been provided to the IDWR and can be found in the archives of the University of Idaho METRIC group.

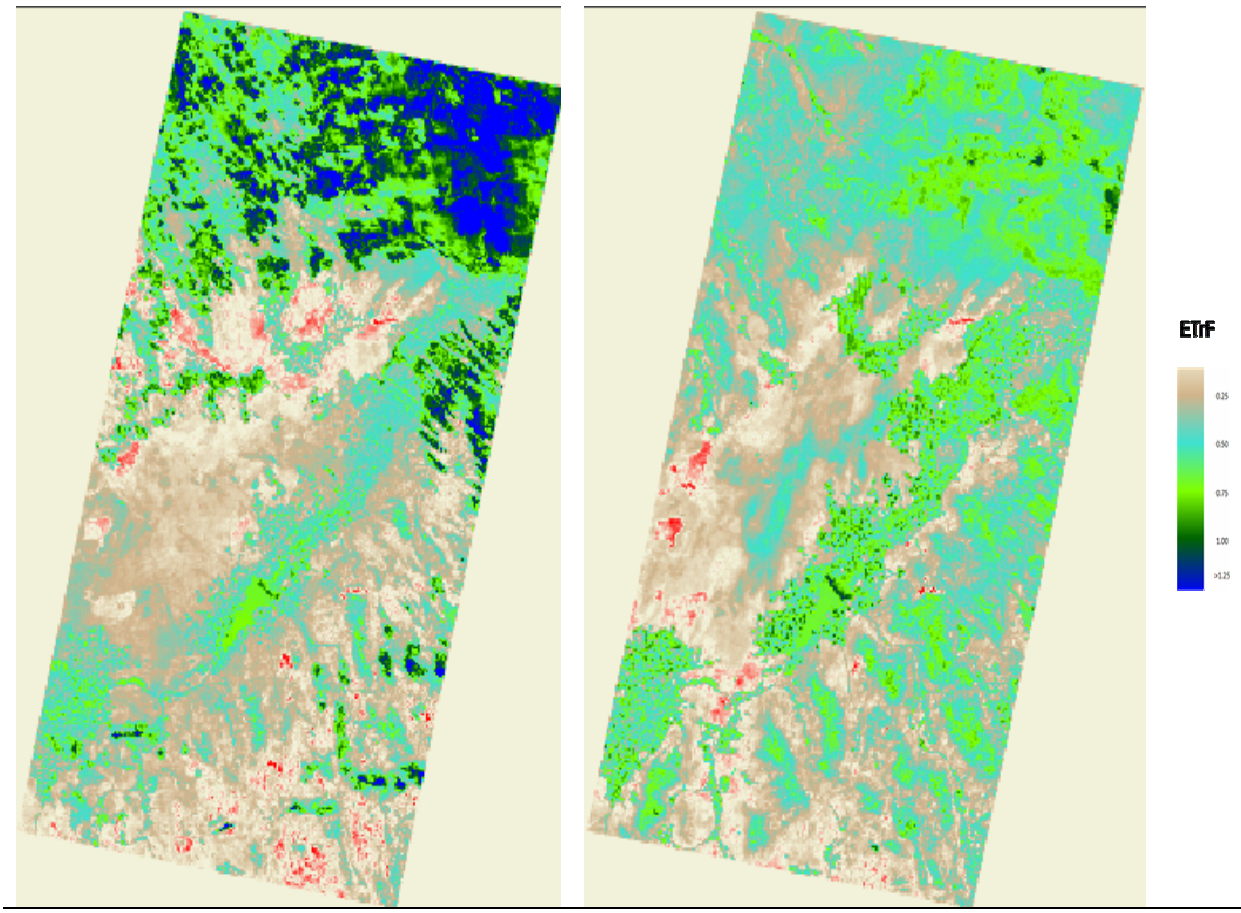


Figure 10. Left: ETrF image from path 39 derived from Landsat 5 TM at 30 m spatial resolution corresponding to May 12th 2006. Right: The same for June 13th 2006. Note the influence of cloudy areas on the calculation of ETrF (blue spots). Cloudy areas were later cloud masked as described above.

Monthly and seasonal images

After the application of the splining process, monthly images for ETrF and ET were generated as well as seasonal ETrF and ET. Figure 11 shows the May images for ETrF and ET for path 39. Figure 12 shows seasonal ETrF and ET.

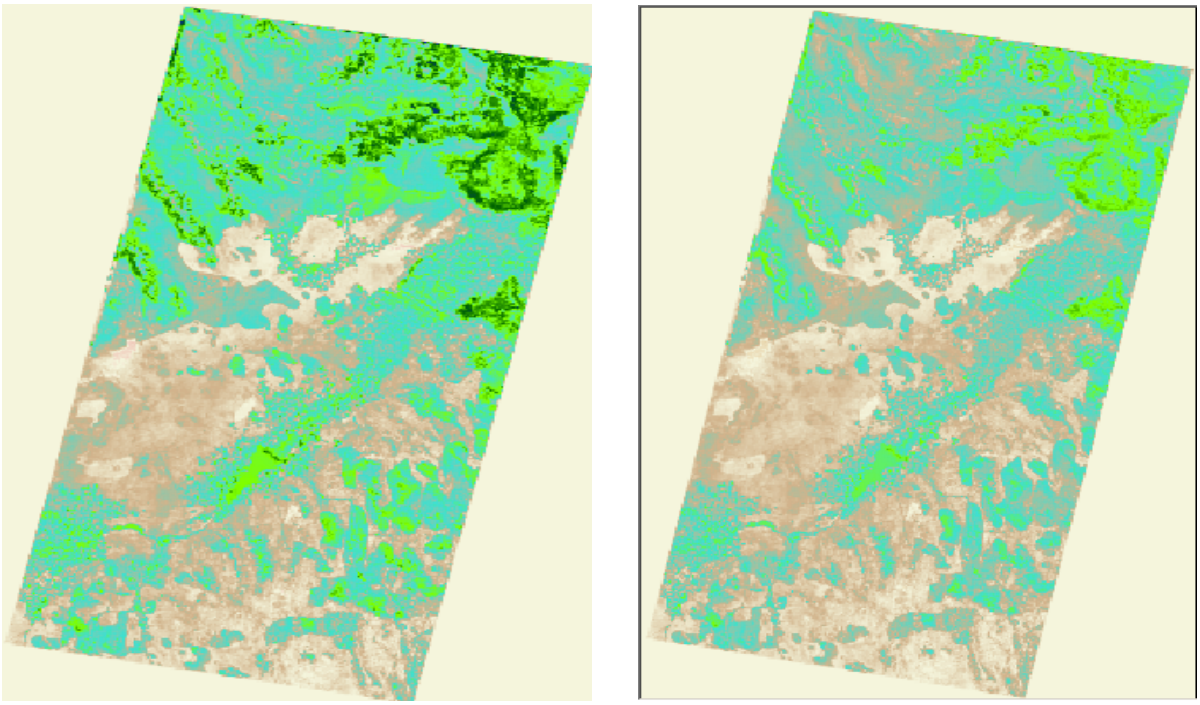


Figure 11. Left: ETrF image from path 39 corresponding to the month of May. The image was produced after the processing of individual images, cloud masking and splining procedures. Right: The same for ET during May 2006. Note that artifacts from masking clouded areas in individual images can be seen.

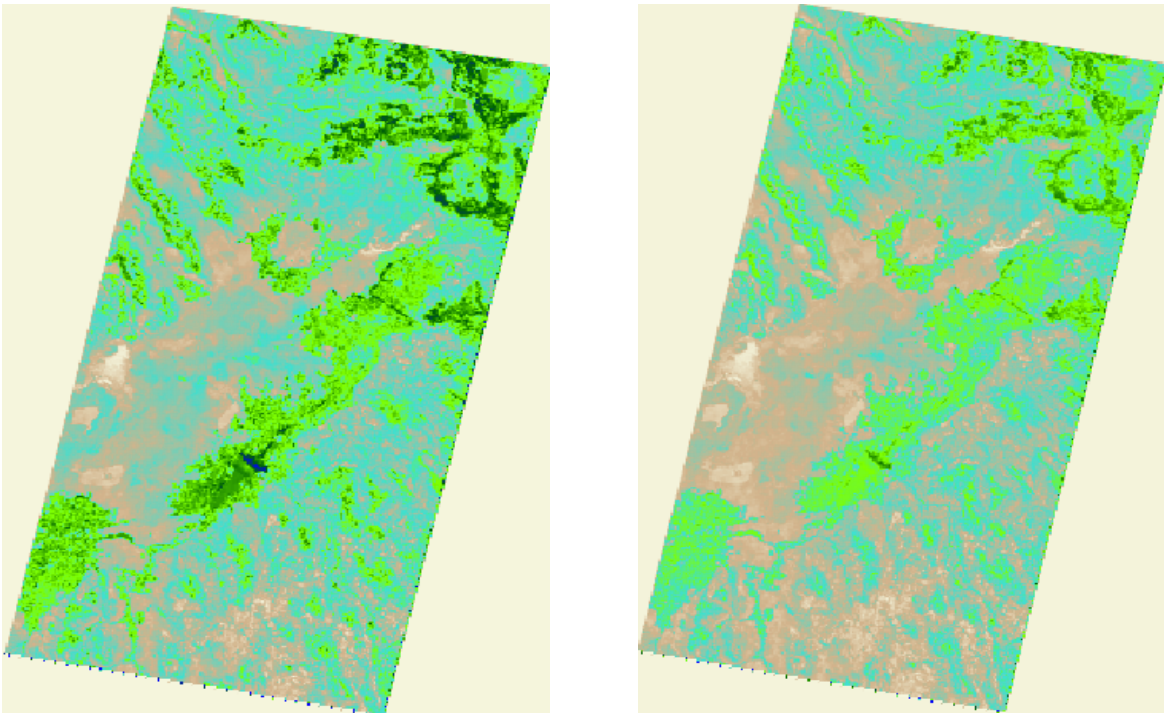


Figure 12. Left: Seasonal ETrF image for path 39 from April through October. The image was produced after the processing of individual images, cloud masking and spline procedures. Right: Seasonal ET for 2006 for path 39.

Path 40

Due to the heterogeneity in weather patterns in path 40 between northern mounains and the Eastern Snake River Plain (ESPA), path 40 was divided into two parts (North and South) as previously described. Path 40 had a total availability of 10 images during April-October, two of them being Landsat 7 and the others Landsat 5.

In the case of the Southern part of path 40, all images were of good quality with few cloudy areas, and therefore all the ten images were processed. The Northern area of interest (AOI), being mountainous, often had large areas with clouds and required extensive correction and cloud masking. In the case of the image corresponding to September 8th, 2006, the Northern area was almost completely covered by clouds and therefore, this image was not considered useful for processing.

Additionally for both AOI's of the path 40 image, a synthetic image was generated to simulate the ETrF during early days of April. The images were generated based on a daily soil water balance and the general weather behavior. In the South the soil water balance suggested a value of ETrF of 0.65 for early April and in the North 0.7 was the selected value assigned to a synthetic April 2 image.

Table 5 presents the distribution of images used for the processing of path 40.

Table 5. Distribution of images used for the processing of path 40 for AOI's north and south

North	South
2006-04-02 (Synthetic)	2006-04-02 (Synthetic)
2006-04-25 (L7)	2006-04-25 (L7)
2006-05-03 (L5)	2006-05-03 (L5)
2006-05-19 (L5)	2006-05-19 (L5)
2006-06-20 (L5)	2006-06-20 (L5)
2006-07-22 (L5)	2006-07-22 (L5)
2006-08-07 (L5)	2006-08-07 (L5)
2006-08-31 (L7)	2006-08-31 (L7)
2006-09-08 (L5)	2006-09-24 (L5)
2006-09-24 (L5)	2006-10-10 (L5)
2006-10-10 (L5)	

Individual results

Path 40 South

Given the few cloudy areas in the images, the individual results of the application of METRIC in path 40 South successfully produced high quality maps for ETrF. This is of extreme importance given the large agricultural use of water in this region and the requirement for high quality maps of water use.

Figure 13 presents two examples of the ETrF and ET products from the METRIC model to individual images. The complete archive of the processed images has been provided to the IDWR and can be found in the archives of the University of Idaho METRIC group.

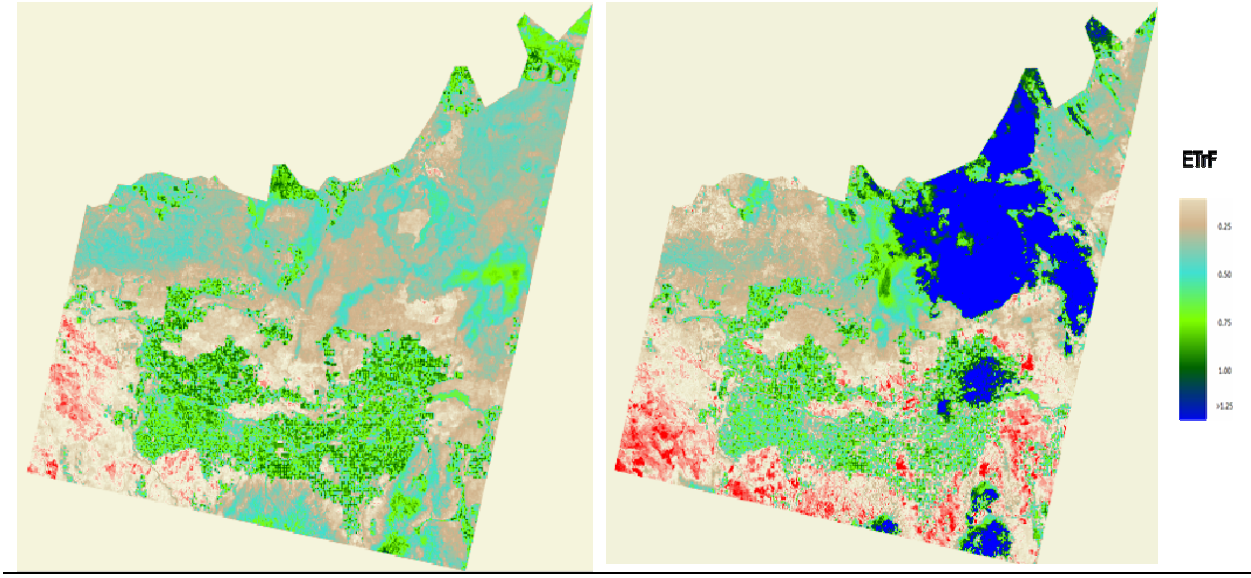


Figure 13. Left: ETrF image from path 40 South derived from Landsat 5 TM at 30 m spatial resolution from to July 22th 2006. The image does not include cloudy areas, but does show some evidence of evaporation from wet soil following a recent precipitation event. Right: The same for September 8th 2006. Note the influence of clouded areas on the calculation of ETrF (blue spots). The clouded areas occurred mostly towards the North and did not substantially affect the agricultural area. The red areas in the desert region to the south of the image represent negative ETrF caused by residual error in the METRIC process. ET during September from these areas was likely nearly 0, and the process can randomly estimate less than 0 for some areas.

Monthly and seasonal images

After the application of the cubic splining, monthly images for ETrF and ET were generated as well as seasonal for both parameters. Figure 14 illustrates the May images for ETrF and ET for path 40 South.

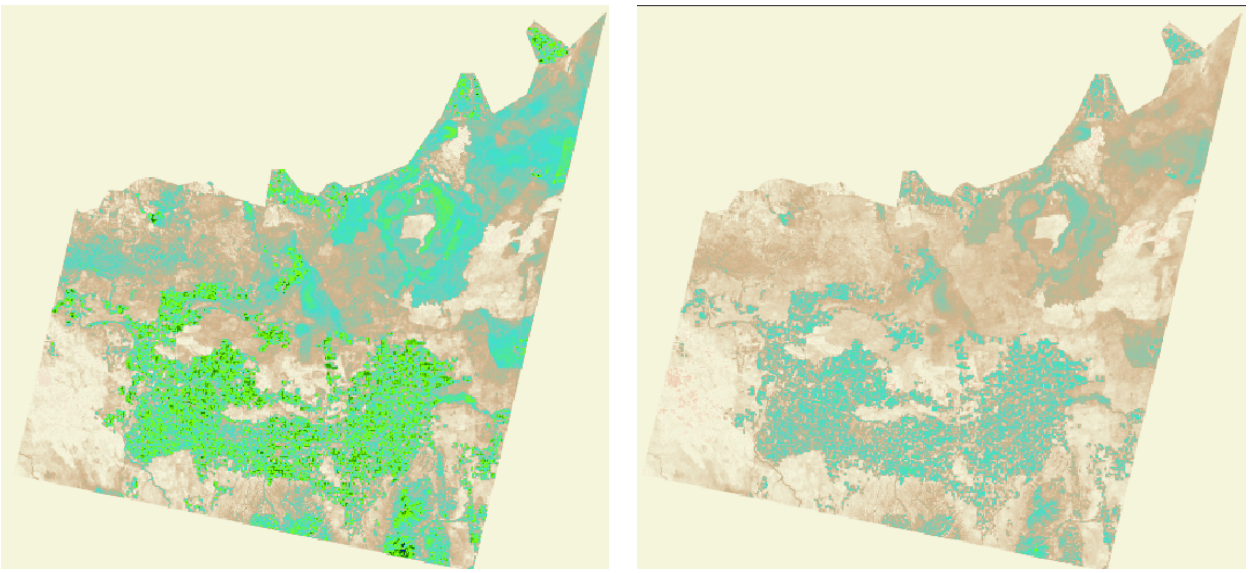


Figure 14. Left: ETrF image from path 40 South corresponding to the month of September. The image was produced after the processing of individual images, cloud masking and splining procedures. Right: The same for ET September 2006. Note that artifacts from masking clouded areas in individual images can be seen.

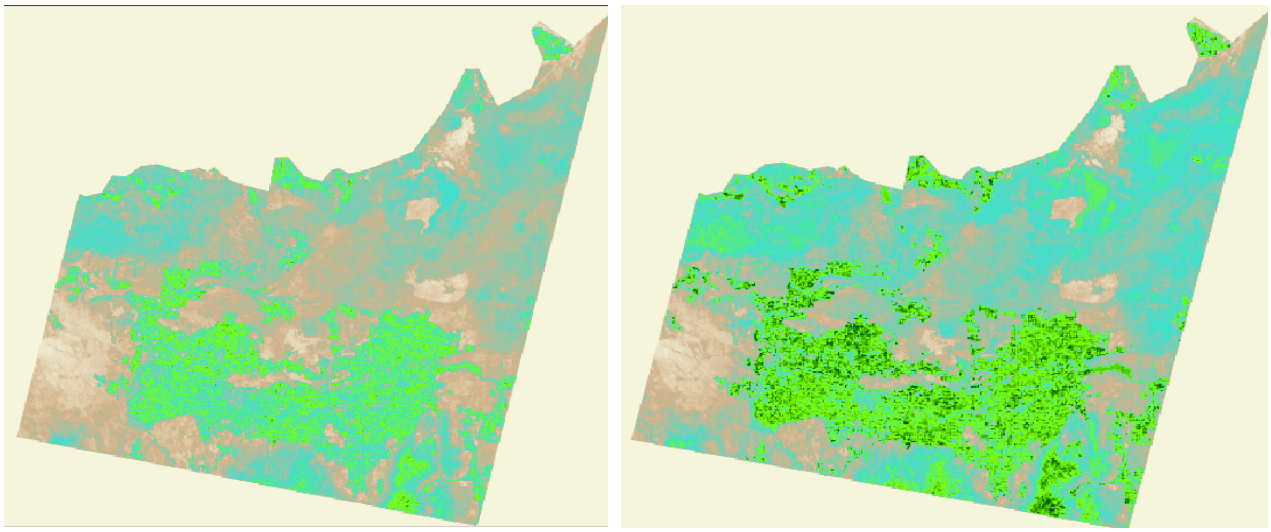


Figure 15. Left: Seasonal ETrF image from path 40 South from April through October. The image was produced after the processing of individual images, cloud masking and splining procedures. Right: The same for seasonal ET, April-October of 2006.

Path 40 North

Due to the mountainous geographic characteristics of the area enclosed by the path 40 north AOI, the images frequently contained large clouded areas. However, the agricultural valleys were often cloud free and therefore the processing of the images was completed following the standard procedures, with clouded area over mountains later masked out. The results were relatively successful in reflecting the crop water use for agricultural areas. In 40 north AOI, large wet land areas are sometimes intermixed with surface irrigated agriculture. Other areas utilize

pivot and wheel lined irrigation. The full METRIC mountain model was applied that includes correction of solar and net radiation on slopes.

Figure 16 presents two examples of the product of the application of the model to individual images. The complete archives of the images has been provided to the IDWR and can be found in the archives of the University of Idaho METRIC group.

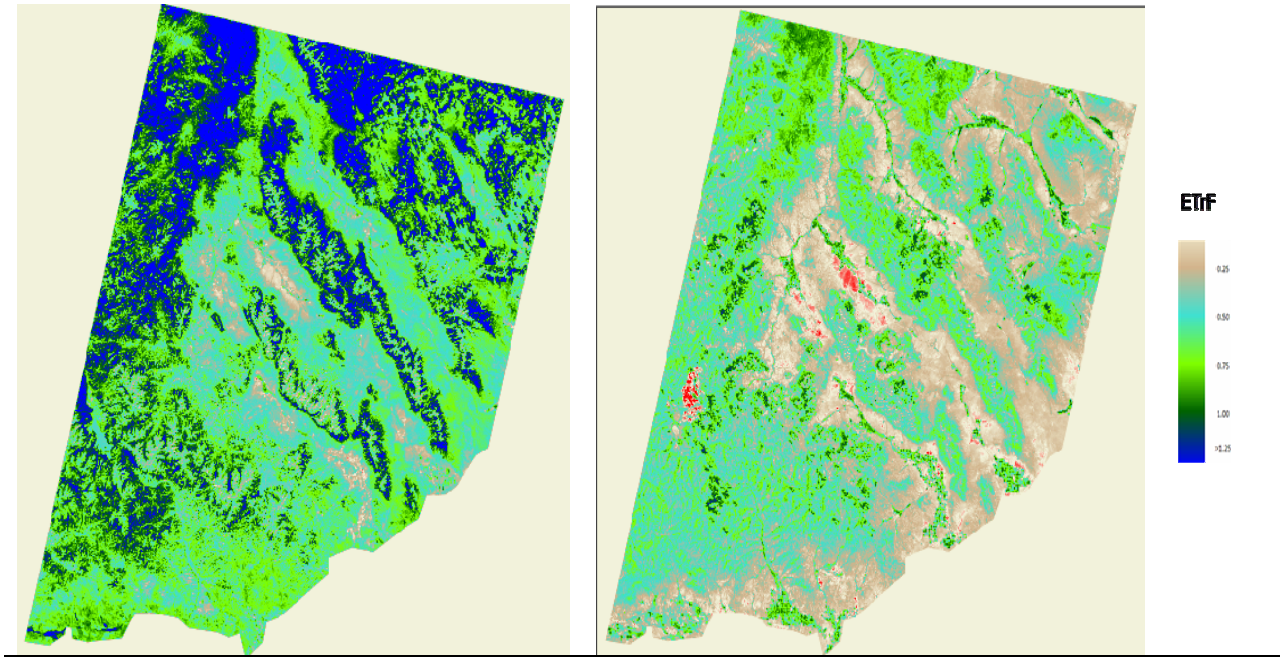


Figure 16. Left: ETrF image from path 40 North derived from Landsat 5 TM at 30 m spatial resolution corresponding to May 3rd 2006. Note the influence of cloudy areas and cold slopes on the calculation of ETrF (blue areas). Right: The same for September 24th 2006. Note that artifacts from masking clouded areas in individual images can be seen.

Monthly and seasonal images

After the application of cubic splining, monthly images for ETrF and ET were generated as well as seasonal for both parameters. Figure 17 presents the May images for ETrF and ET for path 40 North.

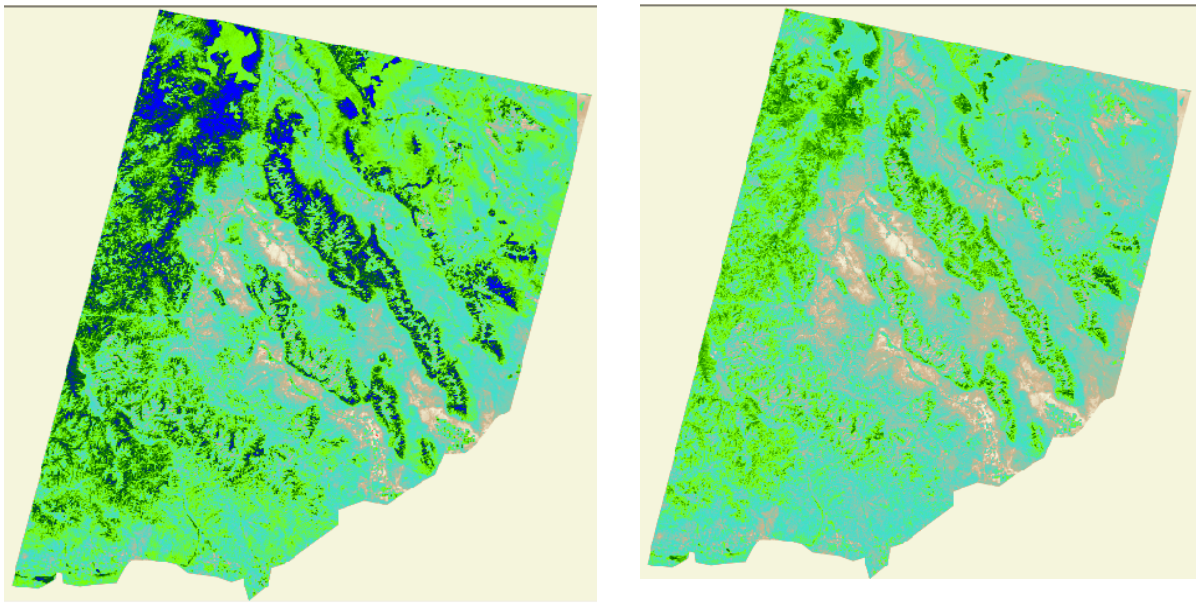


Figure 17. Left: ETrF image from path 40 North corresponding to the month of May. The image was produced after the processing of individual images, cloud masking and splining procedures. Right: The same for ET May 2006. Artifacts from masking clouded areas in individual images can be seen

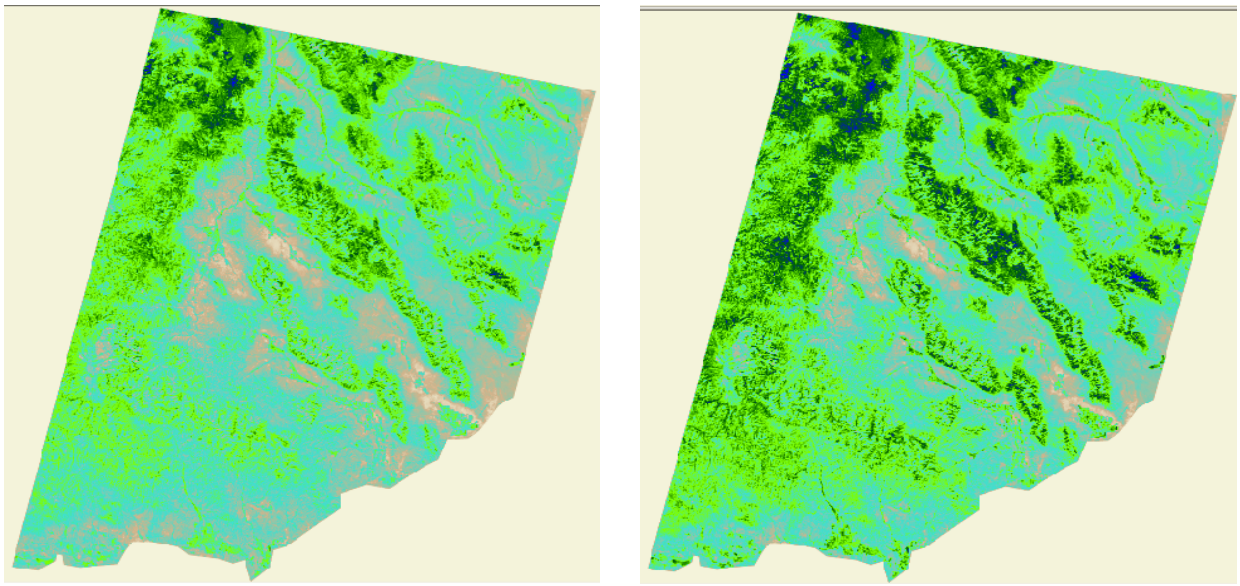


Figure 18. Left: Seasonal ETrF image from path 40 North from April through October. The image was produced after the processing of individual images, cloud masking and spline procedures. Right: The same for ET seasonal 2006.

CONCLUSIONS

The application of the METRIC model to Landsat satellite imagery for the Southeastern part of Idaho appears to have yielded good estimates of actual values of water consumption. Because the processing is based on actual weather data and surface energy balance, the ET represents actual ET, which may be lower than potential ET. New tools were applied to 2006 images including the sharpening of the thermal band and a required gap filling technique for the Landsat 7 images.

REFERENCES

Allen, R.G., M. Tasumi, and R. Trezza. 2005. Benefits from Tying Satellite-based Energy Balance to Reference Evapotranspiration. International Conference on Earth Observation for vegetation monitoring and water management, Naples, Italy, 10-11 Nov. 2005, published in *Earth Observation for Vegetation Monitoring and Water Management*. (D'Urso, G., A. Jochum, and J.Moreno (ed.)). American Institute of Physics; ISBN-10: 0735403465. p. 127-137.

Allen, R.G., M. Tasumi, and R. Trezza. 2006.Why Use Reference Evapotranspiration to Calibrate Satellite-based Energy Balances? Paper presented at the 2006 World and Environmental Resources Congress of the American Society of Civil Engineers and Environmental and Water Resources Institute, Omaha, NE, May 22-25, 2006. Published on CD-ROM, ASCE. 12 p.

Allen, R.G., M.Tasumi and R. Trezza. 2007a. Satellite-based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) -- Model. *J. Irrig. and Drain. Engrg,* ASCE 133(4), 380-394.

Allen, R.G., M.Tasumi, A. Morse, R. Trezza, W. Kramber, I. Lorite-Torres, C.W. Robison. 2007b. Satellite-based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) -- Applications. *J. Irrig. and Drain. Engrg,* ASCE 133(4): 395-406.

Allen, R.G., M.Tasumi, R. Trezza, and J. Kjaersgaard. 2008. METRIC - Mapping Evapotranspiration at High Resolution. Applications Manual for Landsat Satellite Imagery, Version 2.0.4, June 2008. University of Idaho Research and Extension Center, Kimberly, Idaho. 197 pages.

Allen et al., (2008). Description of the process used to sharpen the thermal band of Landsat 5. University of Idaho, Kimberly Research Center.

ASCE-EWRI, 2005. The ASCE Standardized Reference Evapotranspiration Equation. Report of the ASCE-EWRI Task Committee on Standardization of Reference Evapotranspiration. 147 p.

Tasumi M. 2003. Progress in operational estimation of regional evapotranspiration using satellite imagery. Ph.D. Dissertation, University of Idaho, Moscow, ID.

Trezza R. 2002. Evapotranspiration using a satellite-based surface energy balance with standardized ground control. Ph.D. Dissertation, Utah State University, Logan, UT.