Modeling Consumptive Water Use in the Green River Basin, Wyoming Using Remotely Sensed Data and the METRIC/SEBAL Model

Final Report to the Wyoming State Engineer

6/30/2008
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Executive Summary

This report describes a pilot study effort to improve estimation and mapping of consumptive water use in the Upper Green River basin of Wyoming for the Wyoming State Engineer's Office Interstate Streams Division. In collaboration with the Engineer's Colorado River Coordinator WyGISC investigated techniques to map a key water use estimation variable EvapoTranspiration or ET. A spatially explicit modeling approach was selected using in-situ weather station data and remotely sensed imagery as inputs.

We chose a model in use by colleagues in the western US and internationally, METRIC^{tm}: Mapping EvapoTranspiration at high Resolution using Internalized Calibration. This report describes the process of model development at the University of Wyoming's Wyoming Geographic Information Science Center, deployment of supporting in-situ weather stations by the State Engineer's Office, and use of this station data with remotely sensed inputs from the Landsat5 satellite Thematic Mapper imager.

Spatially explicit estimates of ET for the Upper Green River basin were generated as a grid of data locations representing 30 meter by 30 meter orthogonal areas on the ground. This data is loaded and delivered in a spatially co-registered Geographic Information System for further analysis. Results represent a pilot or preliminary study level effort and are discussed in detail within; further analysis is suggested in the final section.

Contents

1. Background

Estimation of consumptive water use for irrigation is increasingly important as demand for water resources increases and water supplies become scarcer and/or more variable in time and space as a result of both land use change and climate fluctuation (*e.g.* Thomas 2000). This is especially true in semi-arid and arid regions like Wyoming. Historically, water use has been estimated in irrigated lands by balancing surface water models – irrigation water input minus runoff output was assumed to be a reasonable estimate of water use by irrigators. But as battles for water rights become contentious, more accurate estimates that account for, among other things, evapotranspiration (ET), have become important.

ET can be measured directly, using various techniques (*e.g.*, CIMIS California Irrigation Management Information System, http://wwwcimis.water.ca.gov/cimis/welcome.jsp or US Bureau of Reclamation AgriMet http://www.usbr.gov/pn/agrimet/) at point locations or for small areas (*e.g.* FIFE, Sellers *et.al.* 1992), but measurements of actual ET over large heterogeneous regions is more difficult. Hydrologic modeling can be used for ET estimation, but the models are difficult to parameterize (Zhang and Wegehenkel 2006). Remote sensing methods are increasingly employed in combination with modeling for ET estimation because they can provide multi-temporal, spatially-distributed estimates of key variables based on spatially distributed measurement.

Two general strategies have been used for estimating ET with remotely sensed data. The first is to extrapolate on-the-ground point measurements to larger areas by assuming that similar land cover types and green leaf area (LAI) will result in similar ET. Remote sensing has been used with great success for many years to characterize both of these land surface attributes (*e.g.*, Driese *et al.* 1997, Carlson and Ripley 1997). The second approach couples thermal and optical remote sensing with energy balance models to estimate ET. This approach is process-based and less reliant on ground measurements which can be expensive and are difficult to collect densely enough to capture all of the important variations in vegetation and other relevant environmental conditions (Olioso *et al.* 1999, Carlson *et al.* 1995, Choudhury *et al.* 1986). Some projects have also tested the empirical determination of surface roughness and soil moisture availability using active microwave remote sensing, such as SAR synthetic aperture radar (Li *et al.* 2006, Neusch and Sties 1999).

In this report, we describe a project using remotely sensed data coupled with an energy balance model (METRIC^{tm} /SEBAL) to test our ability for estimating ET in the Upper Green River Basin of Wyoming. This project is a feasibility study for this approach which, if successful, may later be used over larger areas in Wyoming and the region. We feel that this approach holds promise for improving estimates of consumptive water use over large areas in near real time but there are challenges, particularly in the realm of satellite data acquisition.

The specific objective of this project was to test the METRIC^{tm} model (Allen, Tasumi, and Trezza, Version 2.0) (see section 2.2 below) coupled with Landsat 5 Thematic Mapper (TM5) satellite data for modeling consumptive water use in the Upper Green River Basin. This pilot project will be evaluated in this report to determine if the methods can be used operationally to produce sufficiently accurate ET estimates to assess the potential for extending these methods to larger areas.

METRIC^{tm}: Mapping Evapotranspiration at high Resolution using Internalized Calibration **is trademarked to Dr. Richard G Allen Professor of Water Resources Engineering, University of Idaho Research and Extension Center, 3793 North 3600 East Street Kimberly, Idaho 83341.**

2. Methods

2.1 Overview

The Mapping Evapotranspiration at High Resolution using Internalized Calibration (METRIC^{tm}) model (Allen *et al.* 2007b) uses an energy balance approach with remotely sensed inputs to calculate spatially distributed actual ET. The model operates at high resolution on a regional scale and does not require field-specific identification of crop types. Consequently, it is an ideal choice for the work described here. The model is based on the Surface Energy Balance Algorithm for Land (SEBAL) developed by Dr. Wim Bastiaanssen and colleagues (Bastiaanssen *et al.* 1998) modified to METRIC^{tm} by researchers at the University of Idaho (Allen, Tasumi, and Trezza 2007a). METRIC^{tm} estimates ET by calculating net surface radiation, soil heat flux and sensible heat flux and then assuming that latent heat flux closes the energy balance equation (Eq. 1).

Eq. 1. $Rn = G + H + LE$

Where

Rn is net surface radiation,
G is soil heat flux,
H is sensible heat flux,
and LE is latent heat flux.

More specifically, the energy budget is described by Eq. 2,

Eq. 2. $R_n = (1 - \alpha)R_s\downarrow + R_L\downarrow - R_L\uparrow - (1 - \varepsilon_0)R_L\downarrow$

where the variables shown below in underlined bold type are derived from direct or indirect satellite data inputs:

R_n = net radiation
α = surface albedo
$R_s\downarrow$ = incoming shortwave radiation
$R_L\downarrow$ = incoming longwave radiation
$R_L\uparrow$ = outgoing longwave radiation
ε_0 = broad band surface emissivity

Importantly, the model is robust in terms of satellite input. Though formulated in its current version using Landsat TM and ETM+ data, METRIC^{tm} is easily modified to ingest data from other satellites, a capability that will become important with the impending demise of the current Landsat generation (see section 2.4 below) and that may be important due to problems acquiring cloud free imagery on the 16-day return times of Landsat. This is discussed further in the Recommendations section below.

Inputs required and/or recommended for using METRIC^{tm} include the following:

1. Cloud-free short-wave (reflective) and long-wave (thermal) satellite imagery from multiple dates
2. High quality weather data (for hourly and daily reference ET (ET_r))
   (must include humidity [from hourly vapor pressure and dew point], hourly solar radiation, hourly air temperature, wind speed at time of satellite overpass, precipitation data in preceding 5 day period [not required], solar radiation data [not required]
   1. A land use map of the area of interest (for roughness length)
   (classes should include agriculture, urban, water, desert, forest, grassland, etc.)
   2. A digital elevation model (if the region includes steep terrain)

The model should be run for several time steps using multi-temporal satellite acquisitions to capture the change in ET over the growing season. METRIC^{tm} authors recommend one image per month with higher frequency during periods of rapid change (probably early June to mid-July in the Green River Basin).

2.2 Study Area

The study area for this project is the intersection of Landsat Path 37 imagery and the Upper Green River Basin as defined by the several 4th order watersheds (Figure 2.1). Coverage of this entire area with Landsat imagery requires the equivalent of 3 Landsat scenes for each acquisition date though two scenes from Landsat Path 37 cover virtually all of the area save a small sliver near the southern border from Landsat Path 36. As a result, the project used only the 2 primary scenes to reduce cost. In terms of land cover, the area is occupied by a wide range of cover types in addition to irrigated agriculture including: grassland, mixed conifers and shrublands in mountain foothill landforms, sagebrush steppe dominated mesa land forms, semi-desert shrubland and barren land in basin landforms, and a riparian zone of cottonwoods, willows, and exotic shrub complexes (Rodemaker and Driese 2006).

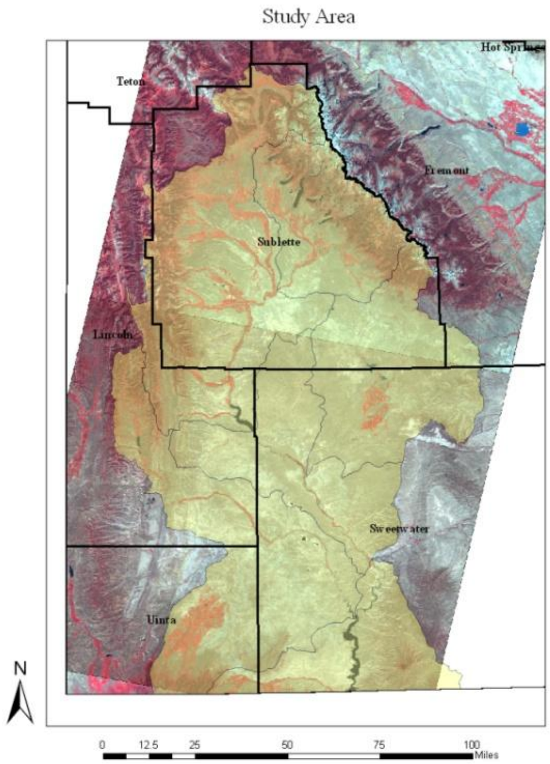


Figure 2.1. The study area (yellow) overlaid on Landsat imagery.

2.3 Hendrickx Collaboration

Estimation of ET using the METRIC^{tm}/SEBAL modeling approach is well documented by model developers (e.g. Bastiaanssen *et al.* 1998, Allen *et al.* 2007b, Allen *et al.* 2007c) but also benefits from hands-on experience, especially regarding the identification of erroneous results and the choice of some critical model inputs, such as particular hot and cold reference satellite image pixels. The complexities of operating METRIC^{tm} or SEBAL require intensive understanding of the Physics underlying each module of the model. For this reason we subcontracted with Consultant Dr. Jan Hendrickx whose company is Soil Hydrology Associates LLC, Los Lunas, New Mexico. As a collaborator of SEBAL/METRIC^{tm} developers Drs. Wim Bastiaanssen and Rick Allen, Dr. Hendrickx has primary experience modeling ET using the METRIC^{tm}/SEBAL approach in semi-arid and arid environments like the Upper Green River Basin. He implemented one of the earliest applications of SEBAL for an agricultural area in the southwestern US (Rio Grande) and has gone on to develop applications of the approach for the Imperial Valley, California as well as internationally such as the Volta Basin in Africa.

Dr. Hendrickx performed the following tasks: 1) developed a Level1 METRIC^{tm} application appropriate for the Upper Green River Basin, Wyoming, 2) modeled ET for 2007 Upper Green River Landsat images in parallel with WyGISC as a means of double-checking the WyGISC estimates, 3) helped develop a collaborative research team of Upper Green River ET researchers, 4) traveled the study area with the SEO collaborative research group to investigate in-situ sampling, 5) performed METRIC^{tm}/SEBAL training at the University of Wyoming for WyGISC and other SEO researchers, and 6) acted as a consultant for the duration of the project. Dr. Hendrickx has produced detailed progress reports which are included as Appendix A to this report.

2.4 Weather Data

Existing Stations

High quality weather data at the time of satellite overpass are critical for successful ET modeling using the METRIC^{tm} model. Specific required weather data inputs are listed in the description of METRIC^{tm} modeling below (Section 2.7).

At the initiation of the project, existing permanent stations in the Upper Green River Basin that collect suitable data for METRIC included two primary weather stations in the study area, one at Pinedale and one at Big Piney. There were numerous secondary weather stations scattered throughout the study area that collected some but not all required model inputs. WyGISC researchers worked with the State Engineer's Office (SEO) and the Wyoming State Climatologist, Steve Gray, to assess available stations and to develop means of acquiring necessary data for running METRIC^{tm}.

Available Weather Stations in Upper Green River Basin

We accessed the Mesowest website to search for available station data (http://www.met.utah.edu/mesowest/). Unfortunately at the time of initiating this project only one AgriMet station was available in the Bear River drainage. According to Mesowest, stations with downloadable data are shown in figure 2.1 and include:

Stations collecting all required inputs

- Anderson Ridge (South Pass)
  Hourly collection of all required fields
  About 70 km from Farson agriculture area.
- Half Moon (just east of Pinedale at Half Moon Lake)
  25-minute intervals of all required fields.
  20 km from Pinedale/Cora agricultural areas (good site)
- Hoback (Bondurant)
  Hourly collection of all required fields.
  Not in Upper Green area and about 70 km from Cora/Daniel agriculture
- Muddy Creek (East of Evanston)
  Hourly collection of all required fields
  About 20 km for big agriculture area around Ft. Bridger.

- Snider Basin (In Wyoming Range west of Big Piney)
  Hourly collection of all required fields.
  20 km from significant agriculture (but at different elevation)
- Snow Springs Creek (South of Rock Springs)
  Hourly collection of all required fields.
  Not close to any obvious large agricultural areas.

Stations collecting all but solar radiation

- Big Piney (Marbleton Airport)
  Hourly data except solar
  Directly adjacent to large agricultural areas
- Evanston
  Hourly data except solar
  Adjacent to agricultural area but out of Upper Green River Basin.
- Kemmerer
  Hourly data except solar
  Adjacent to agriculture
- Pinedale (Ralph Wenz Field Airport south of town)
  20 minute intervals all data except solar.
  Adjacent to agriculture
- Rock Springs (Sweetwater County airport)
  Hourly data except solar.
  Not close to obvious large agricultural area.

Figure 2.2. Figure from Mesowest website plotting the locations of weather stations in southwest Wyoming.

Another station was identified and investigated by Steve Wolff. This station is operated by the USDA-Natural Resources Conservation Service and is located in Farson. Field notes presented later in this report briefly describe this station; see Figures 2.3a and 2.3b for field photos of the NRCS Farson station.

Figure 2.3a. NRCS station at Farson.

Figure 2.3b. SEO research group investigating NRCS station at Farson. Kneeling is Steve Wolff, Colorado River Coordinator and from left to right are Steve Gray, Fred Ogden, and Jan Hendrickx. Photo taken by Eli Rodemaker, with Ken Driese not present.

SEO Installations

Steve Wolff was able to purchase and install two additional weather stations in the Upper Green River study area at the outset of this project. These stations were installed 1) at North Cottonwood Creek west of Daniel, Wyoming in the northern portion of the study area at (110°18’6”W, 42°50’17”N) and 2) at the Smith’s Fork near Robertson, Wyoming (in the Ft. Bridger area) in the southern part of the study area at (110°24’56” W, 41°12’4”N). These stations collect all meteorological data required for METRIC^{tm} modeling and were operational on May 2 and 3, 2007, respectively. Figures 2.4a and 2.4b show the SEO weather stations and sites.

	
Figure 2.4a. Ryegrass Ranch station on north Cottonwood Creek looking North at flood irrigated pasture/hay meadow and riparian shrub complex.	**Figure 2.4b**. Robertson station on the Smiths Fork looking NE at hay field. Station on edge of flood irrigated hay field about 15ft from riparian trees and shrubs as seen on right edge of photograph.

Sites for the weather stations were determined by the SEO in collaboration with WyGISC based on anticipated needs of the METRIC^{tm} protocol over a large high elevation basin. The METRIC^{tm} protocol has historically been restricted to the processing of one Landsat image at a time with at least one representative weather station. As the Upper Green River Basin in Wyoming covers more than one Landsat image from North to South, a Landsat image is approximately 185 km north to south; we chose to place one station in the northern portion of the basin and one in the south. Figures 2.5a and 2.5b show the SEO weather stations locations within the basin.

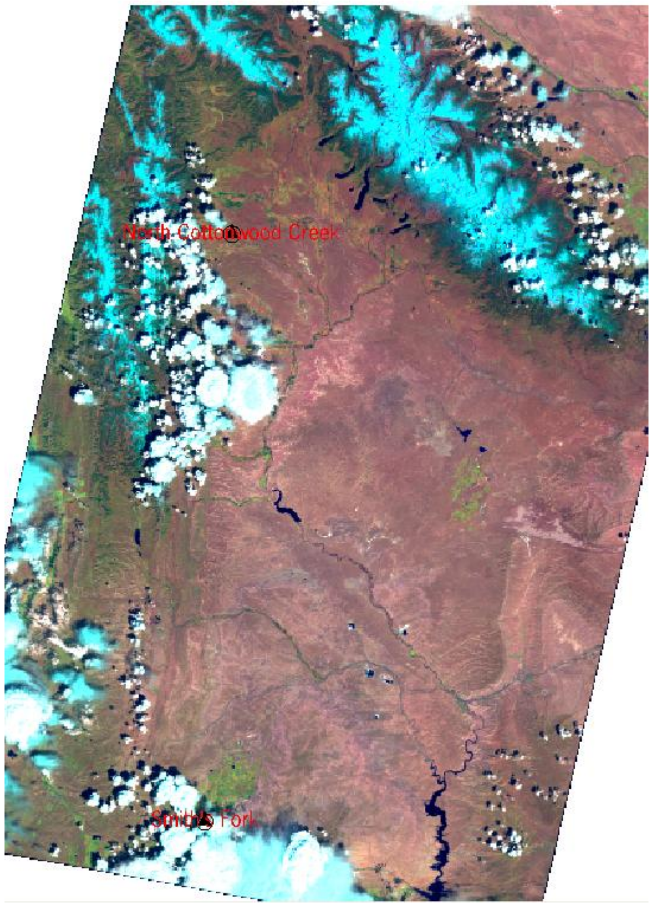


Figure 2.5a. 17 May 2007 Landsat5 imagery as RGB: 5, 4, 2 with the location of the two SEO stations.

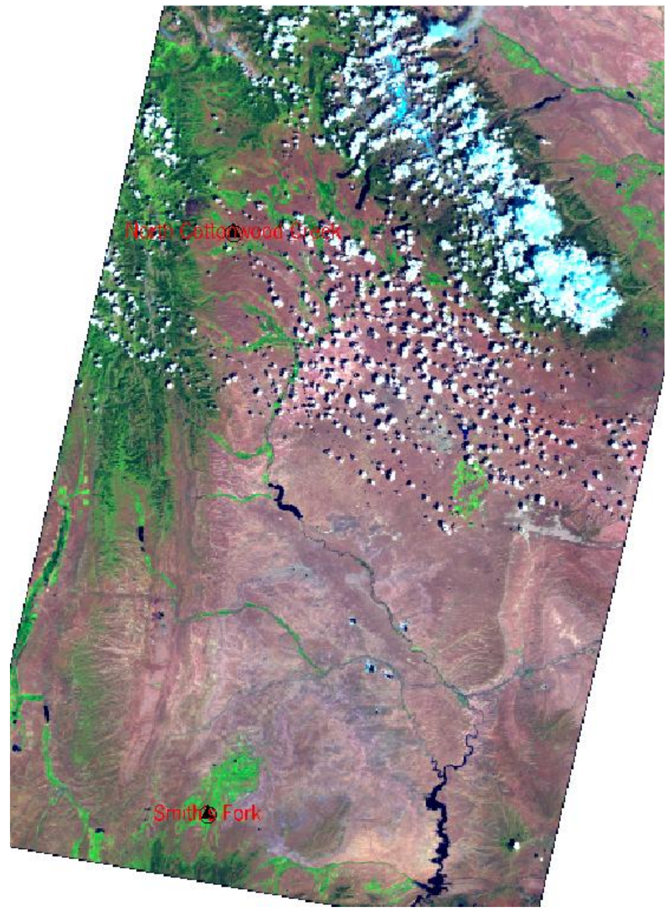


Figure 2.5b. 4 July 2007 Landsat5 imagery as RGB: 5, 4, 2 with the location of the two SEO stations.

2.5 Satellite Imagery

Energy balance modeling requires both optical and thermal inputs which can be derived from satellite (or airborne) data. Although many satellites are currently tasked with gathering information about the land surface, only a small subset of these are capable of capturing thermal data with the spatial resolution required for fine-scale assessment of consumptive water use in the study area. Specifically, the State Engineer's Office requested resolution of parcels as small as 10 acres (~4 ha) so that individual fields can be assessed. Isolation of these 10 acre parcels from surrounding parcels requires considerably finer spatial resolution than the dimensions of a single 10 acre parcel (~2000 m x 2000 m).

For this project we used Landsat5 Thematic Mapper (TM5) data that are currently being collected every 16 days for the entire U.S. land area and much of the globe. Landsat5 TM data has visible and infrared bands with 30 m spatial resolution and a thermal IR band with 120 m spatial resolution. The version of METRIC^{tm} (v. 2.0) described by Allen, Tasumi and Trezza that we modified for this project is calibrated for Landsat inputs and these data are readily available to researchers at WyGISC through existing archives developed with the WyomingView program and the Upper Midwest Aerospace Consortium, and through discounted purchase from the USGS Data Center in Sioux Falls, SD (a benefit of WyomingView). The State Engineer's Office (SEO) is a WyomingView consortium member and is eligible for discounted imagery. Landsat imagery will be free in the future.

We chose to assess use of the METRIC^{tm} protocol with 2007 satellite imagery. This allowed us to use the new weather stations installed by the SEO and to visit the field site during the same season or day as the image acquisitions. Since high quality weather data and determination of the internal calibration of surface energy properties via hot and cold pixels for each image date are critical factors in the use of METRIC^{tm}, we were able to prepare in late 2006 and early 2007 for the upcoming data acquisition of the following growing season.

For the Upper Green River Basin (Landsat Path 37), Landsat 5 collected imagery on the following dates spanning the 2007 growing season:

April 15, May 1 and 17, June 2 and 18, July 4 and 20, August 5 and 21 and September 6 and 22, October 8

At the outset of the project, we selected 10 ideal dates for modeling to allow interpolation of ET estimates across the entire growing season. These dates are:

April 15, May 17, June 2, June 18, July 4, July 20, August 21, September 6, September 22, October 8

Unfortunately, most of the Landsat overpasses during the 2007 growing season were contaminated by cloud cover. Only 2 overpass dates were useable: May 17 and July 4. As a result, accurate growing season interpolation from model results for 2007 was not possible. This limitation is discussed in the "Recommendations" section (Section 4) below.

Landsat 5 remains operational at this writing and imagery is being collected for North America. The Landsat 7 ETM+ sensor has suffered mechanical problems since 2003 causing data omissions which are unacceptable for ET modeling. Landsat 5 is near the end of its lifespan and is likely to fail by the middle of 2008 when its remaining power supplies are exhausted. A new Landsat-equivalent satellite is not scheduled to be operational "by some estimates," (from the Landsat website) until 2012. Failure of Landsat 5 could occur at any time since this platform is well beyond its design life. Such an event would force consideration of other satellite platforms. These limitations are discussed in Section 4 (Recommendations) below.

2.6 Field Survey

Field visits to the Upper Green River study area were made by WyGISC researchers twice during the course of the project. Dr. Driese visited weather stations throughout the area on June 18-19, 2007 to assess the ET environments in the immediate area around the stations and to attempt to identify potential hot and cold pixels. A Landsat5 satellite overpass occurred during 18 June, 2007 coincident with this field reconnaissance. In May 7-9, 2008 Rodemaker, Wolff, Hendrickx, Gray, and Ogden conducted a field trip through the basin. See Appendices C and D for photographs and notes on the field survey.

2.7 METRIC/SEBAL Modeling

SEBAL and METRIC*tm* are related models differentiated by the quantitative use of in-situ meteorological measurements. SEBAL employs no in-situ ground measurement for calculation of surface energy components; however both SEBAL and METRIC*tm* application can benefit from using meteorological data such as precipitation and air temperature to assess surface conditions at the time of overpass. In this qualitative case, many days worth of weather data prior to the date of overpass can be used to assess overall soil saturation (e.g. from recent rain events) and dramatic deviations in air temperature may point to times of atmospheric instability. Quantitative use of ground data in METRIC*tm* requires hourly in-situ measurement for calculation of reference ET.

In this project, we developed a 'Level One' application of METRIC*tm* as shown in the November, 2007 Version 2.0.3 METRIC*tm* Applications Manual (Allen *et al.*, 2007a). A Level One application employs algorithms calibrated via Dr. Allen and Dr. Bastiaanssen's previous research in Idaho and the Rio Grande valley for example (Allen *et al.,* 2008). While sensitivity to local conditions, in a Level One application, is provided by the quantitative use of in-situ weather data some application algorithms may need to be investigated for suitability to the Upper Green River Basin in Wyoming. As a feasibility study this project was scoped to test the basic applicability of the SEBAL or METRIC*tm* approach. Development of a Level Two METRIC*tm* application would employ in-situ empirical measures to calibrate some algorithms to local conditions. Tuning of these models to increase precision or accuracy of results was not the intent of the limited scope of the activity.

Weather Input Data for METRIC*tm*

In order to calculate reference ET values needed for quantitative calibration in METRIC*tm* four hourly measurements are needed during the satellite overpass. Required fields include, wind speed at time of satellite overpass and bracketed around the overpass; dew point or vapor pressure or humidity at satellite overpass used to calculate atmospheric transmissivity or, if necessary, dew point can be calculated from daily minimum air temperature; incoming solar radiation; and air temperature.

As noted previously it is also helpful to have an idea of the weather conditions at the time of the satellite overpass and in preceding days. Rain events for example could adversely affect the internal calibration processes of SEBAL or METRIC^{tm}. A normally dry piece of bare ground would have no ET for instance but once wetted by rain would. So, optional but recommended fields would include at least precipitation and temperature prior to the satellite overpass.

The spatial distribution of weather stations used to calibrate METRIC^{tm} is an issue with limited prior investigation largely due to the few example applications of the process and paucity of stations typically available. Generation of a Level One METRIC^{tm} application as performed in this project implies a process of control for unpredicted model results by duplicating the successful procedures of previous METRIC^{tm} application. Lessons learned from these previous applications have shown that weather stations should be located within the agricultural area used to pick hot and cold anchor pixels and at a distance of less than 50km from these pixels. In this way regional physical relationships are constrained allowing for the internal calibration technique of SEBAL/ METRIC^{tm} to fit. For example, it is preferable to pick a hot and cold pixel from two areas of similar soil types and land use practices experiencing the same weather. Past applications enjoying multiple weather stations per image have used averaged values for METRIC^{tm} modeling.

3. Results

3.1 Landsat Overpass Quality and Scene Selection

Twelve Landsat5 Thematic Mapper images were identified for the 2007 growing season. The dates for 2007 were: April 15, May 1 and 17, June 2 and 18, July 4 and 20, August 5 and 21 and September 6 and 22, and October 8. Computer screen duplications of the Landsat images as accessed from the United States Geological Survey's GloVIS website (http://glovis.usgs.gov) for the 2007 growing season can be seen in AppendixB. Various types of atmospheric cloud formations are evident in all images and unfortunately result in few areas of useable data for the Upper Green. Even thin clouds not visible at the resolution shown in AppendixB make the underlying interpretation of surface properties, especially temperature and albedo, difficult and biased. For example, one effect of most thin clouds on thermal images is to make surface temperatures apparent to the satellite lower than actual. Correction for even thin clouds is not recommended for METRIC^{tm} application.

As can be inferred from previous explanation, cloud free areas must also have an associated cloud free weather station (ideally within 50 km – personal communication from Tony Morse). It may be possible to focus on small areas such as the Smith's Fork to maximize cloud free scenes (dates), but for the entire basin we could only recommend two 2007 images dates as suitable to METRIC^{tm} /SEBAL 17 May and 4 July. The 2 June image at the resolution shown in Appendix B appeared to have the same relative quality as the best two; however, in the process of applying METRIC^{tm} it was apparent that thin atmospheric haze was detrimental to reliable surface property measurement.

Unfortunately we also have noticed issues with the Landsat5 Thematic imagery from 2007 see Figure 4.1 showing radiometric errors in the data. The total effect of this radiometric error is unknown, but apparently can be identified in certain rows of the image. Anomalous ET measures should be flagged and those pixels excluded. If excluded pixels are within agricultural areas, then a local neighborhood average can be used to replace the bad pixels.

Ultimately, we ordered the following image dates, for Landsat Path 37 rows 30 and 31: 17 May, 2 and 18 June, 4 July, and 21 August. We also ordered only path 31 for the date 22 September, due to apparent atmospheric clarity over Farson and Eden. These dates were identified with the USGS GloVis internet application that provides preview images of Landsat images at degraded resolution. Purchased images were chosen if significant areas of agricultural lands seemed to be atmospherically clear and all other dates could be rejected due to heavy cloud cover. Thin cloud cover and precise spatial measurements on image areas cannot usually be discerned with GloVis.

The imagery dataset was imported into the WyGISC image processing system and GIS from source GeoTiFF files of terrain corrected imagery. Imagery was ordered and followed the geometric and systematic processing system of the USGS AmericaView (AV) program (http://www.americaview.org/index.htm).   SEO membership in the WyomingView consortium of AmericaView (http://www.wygisc.uwyo.edu/wyview) provided eligibility to reduced cost imagery.

Once imported the reflective and thermal imagery for each date were used in conjunction to search for atmospheric cloudiness and haze over agricultural areas. From this screening we identified two potential dates to test METRIC^{tm}: 17 May and 4 July. For 17 May, clouds cover the Smith's Fork weather station and are within 2km of the North Cottonwood station. For 4 July, a cloud had recently pass over the North Cottonwood station and a cloud shadow was about 260 m south east of the station, but the Smith's Fork area was clear.

3.2 Model Coding and Duplication

Imagery for 17 May and 4 July was subset to a domain to include the entire Green River basin within the Landsat overpass Path 37, Row 30 and 31 imagery. The Landsat imagery was subset to the extent of the coordinates: Upper Left X 485880, Upper Left Y 4814220, Lower Right X 692520, and Lower Right Y 4530810 (project UTM Zone 12, Spheroid GRS1980, and Datum NAD83). The study domain is thus restricted to areas of imagery within this subset with 'white' areas outside of the image excluded from analysis; see Figure 3.1 showing the 4 July, 2007 image.

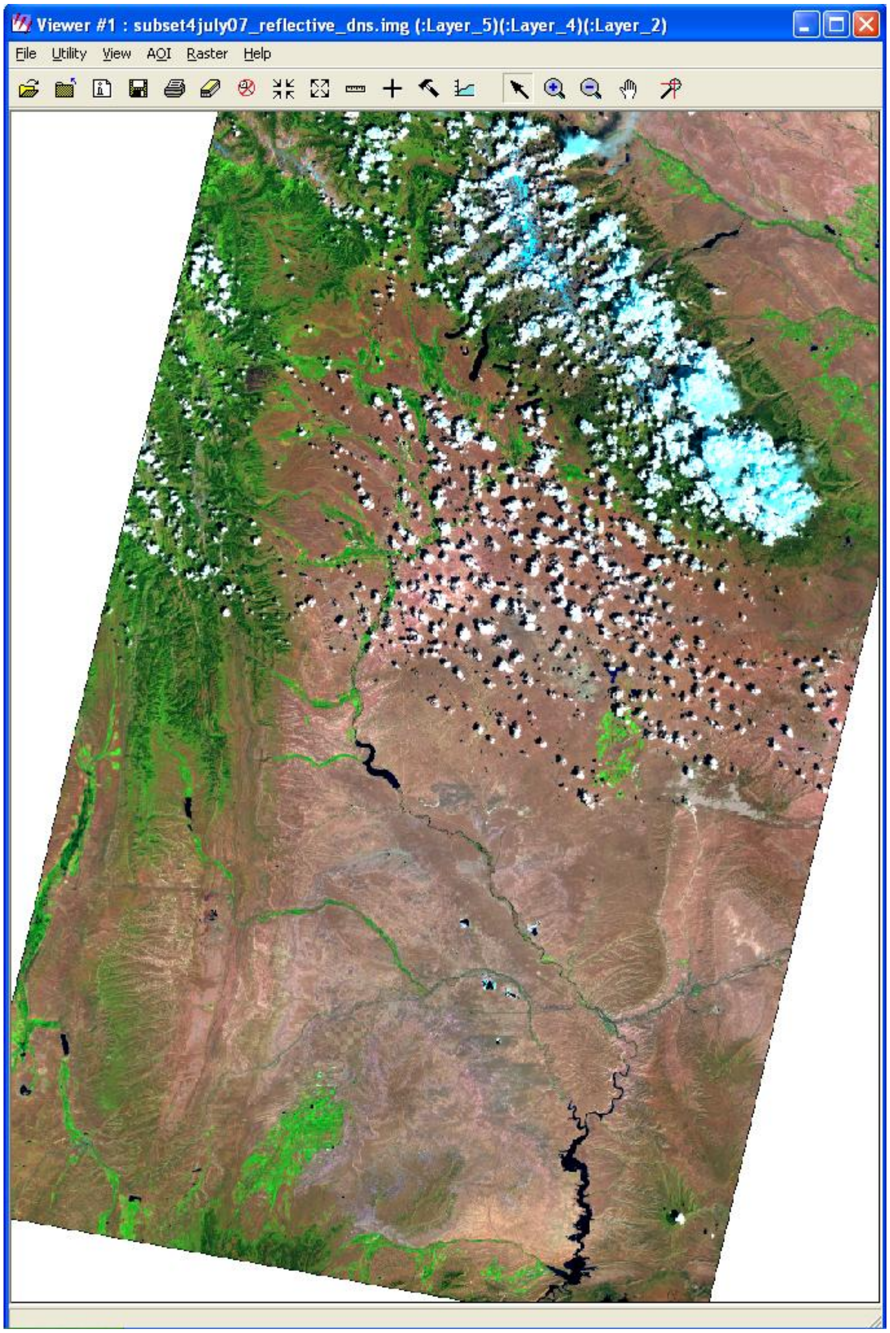


Figure 3.1. Showing Landsat imagery from 4 July, 2007 subset to the model domain. Imagery channels 5, 4, and 2 shown in a red, green, and blue color composite display.

Coding followed recent development of METRIC^{tm} by the University of Idaho, copyrighted as 'METRIC^{tm}: Mapping Evapotranspiration at High Resolution – Applications Manual' by Dr. Richard G. Allen, Dr. Masahiro Tasumi, and Dr. Ricardo Trezza (2007a). The applications manual used was for version 2.0.3 of METRIC^{tm} from November, 2007. The applications process involves using multiple software including spreadsheets, a statistical analysis and visualization tool, and graphical models generated in the image processing system. In our case the applications were performed on a Microsoft WindowsXP operating system computer using the software ERDAS Imagine version 9.2 (Leica Geosystems Geospatial Imaging, LLC, Norcross, GA), SAS version 9.1.0.0 (SAS Institute Inc., Cary, NC), and Microsoft Excel version 2007. Notes on processing of individual scenes are included as Appendix A. Some explanation of decisions in processing will follow.

We have described the application of METRIC^{tm} as thirteen steps in the processing notes of Appendix A. In Steps 1 through 4 the remotely sensed imagery is converted into physically meaningful surface variables. These variables are then used in Steps 5 through 13 to perform the METRIC/SEBAL process of human assisted and self calibration to produce measures of the surface energy balance and subsequently ET.

For the first step one, a spreadsheet is used to create model constants related to solar radiation, wind speed, and actual vapor pressure sensed at the weather stations. Input data for Step 1 into 'Spreadsheet 1' include the Landsat image scene center location and time of acquisition. Since we employ two Landsat images for coverage of the basin there is more than one scene center. However, the time of acquisition for two images can be ignored or averaged as imaging of the basin by one Landsat path occurs in under a minute. We investigated the location of scene centers relative within the basin and determined that the row 31 scene center occurs in an advantageous location. Scene center coordinates needed for Step 1 could thus be extracted directly from the path31 scene header (metadata) file for each date. Figure 3.2 shows the location of the scene center of row 31 for the 4 July 2007 Landsat overpass.

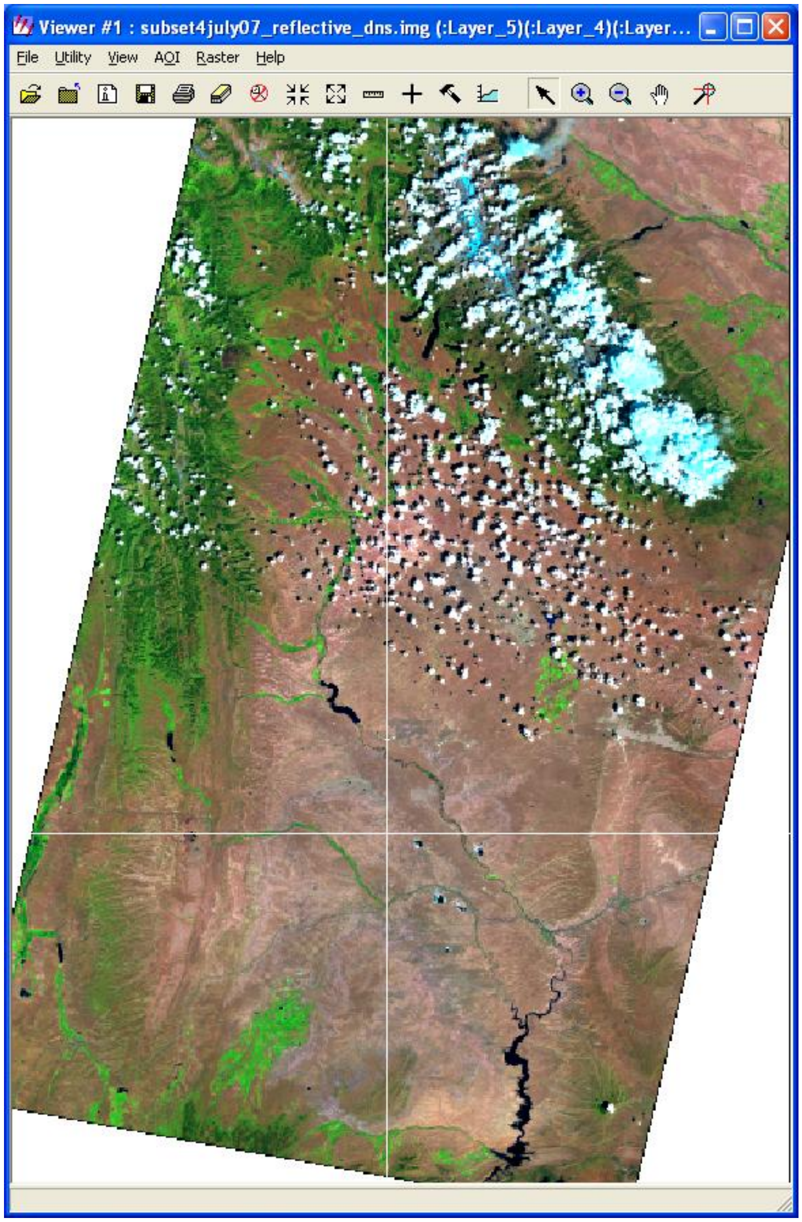


Figure 3.2. Showing the location of the row 31 scene center as a white cross-hair for the 4 July, 2007 Landsat overpass of Path 30.

Constants calculated in Step 1 can be used to normalize the satellite imagery for solar radiation angles in Step 2 and then atmospheric effects in Steps 3 and 4. We employed the 'Mountain Model' (Appendix 12 of the manual) to incorporate correction for local topography in the Step 1 normalization. With these processes we prepare imagery for ingestion into standardized algorithms that can ignore the effects of day of the year and the location on the earth.

3.3 Use of Weather Data

Quality assessment and quality control of weather data followed ASCE guidelines (ASCE, 2004). Weather fields used include actual vapor pressure, air temperature, incoming solar radiation, and wind speed at 2m at the station. When atmospherically clear the values of the two stations were averaged. Specific use of data within the model application algorithms is noted in Appendix A.

A spreadsheet was created by WyGISC in Microsoft Excel to perform the METRIC^{tm} process of correcting for buoyancy effects in the atmosphere (Allen *etal.* 2007a). The spreadsheet produces coefficients for calculating H, sensible heat flux, by iteratively fitting to conditions of the identified Hot and Cold pixels.

3.4 Calibration of the METRIC^{tm} Process (Hot/Cold Pixels)

Knowledge of local land cover including GIS data was crucial in discovering appropriate land surfaces on the images where calibration pixels could be sampled. As noted earlier field survey was used to investigate appropriate land types. Hot and Cold pixels selected are ideally from sites of similar soils and local meteorological condition such as recent rain events, but containing extremes of vegetative cover from full to no cover.

We looked for sites of significant size within agricultural areas and on flat terrain. We selected dry and bare ground in the case of the hot pixel or full cover and not water limited for the cold pixel. Use of the Landsat imagery and derived NDVI, aerial photographs, and other ancillary GIS layers helped guide the selection of hot and cold pixels. GIS layers included a digital elevation model and derived terrain slope. Appendix A contains the values and a brief description of the process used to sample pixels for each date.

3.5 Comparison to In-Situ ET Measurement

ET measurements from the two SEO weather stations were calculated using the Penmen-Monteith procedure for three unique cases of hypothetical crop types by the SEO system software and as a standardized ASCE-EWRI (ASCE 2004) reference from the 'REF-ET' software of Dr Richard Allen at the University of Idaho-Kimberly (http://www.kimberly.uidaho.edu/ref-et/ last entered Aril 20, 2008). Table 3.1 lists the ET station descriptions and ET calculation approach. Table 3.2 compares the three ET measures from hypothetical crop types, the REF-ET calculation, and the value of 24 hour ET generated for the Landsat pixel located at the ET station coordinates for the dates 17 May and 4 July, 2007.

CRCAP1A:	North Cottonwood Creek @ Ryegrass Ranch	
110° 18’ 6 “ W; 42° 50’ 17” N		
Elevation:	7,447 feet	
CRCAP2:	Smith’s Fork Near Robertson	
110° 24’ 56” W; 41° 12’ 4” N		
Elevation:	7,166 feet	
ET Calculation Methods:		
1. FAO56	Modified Penman-Monteith Method	Reference crop is a hypothetical crop with an assumed height of 0.12 meters, surface resistance of 70 s m^{-1} and an albedo of 0.23.
2. ASCE_Tall	Modified Penman-Monteith Method	Reference crop is full-cover alfalfa with an assumed height of 0.50 meters, surface resistance of 45 s m^{-1} and an albedo of 0.23.
3. ASCE_Short	Modified Penman-Monteith Method	Reference crop is a clipped, cool season grass with an assumed height of 0.12 meters, surface resistance of 70 s m^{-1} and an albedo of 0.23.

Table 3.1. Weather station ID, description, coordinates, and three methods used to calculate 24 hour ET from the station by the State Engineer’s Office.

CRCAP2 – Smiths Fork near Robertson (2 meter anemometer height)					
Date	**FAO56 Daily Eto (mm/day)**	**ASCE_Tall Daily Eto (mm/day)**	**ASCE_Short Daily Eto (mm/day)**	**REF-ET_Allen Daily Eto (mm/day)**	**METRIC^{tm}_GREEN _RIVER Daily Eto (mm/day)**
5/17/2007	3.58	4.70	3.64	Clouded	Clouded
7/4/2007	6.06	7.39	6.21	7.78	6.72

CRCAP1A – North Cottonwood Creek @ Ryegrass Ranch (2 meter anemometer height)					
Date	**FAO56 Daily Eto (mm/day)**	**ASCE_Tall Daily Eto (mm/day)**	**ASCE_Short Daily Eto (mm/day)**	**REF-ET_Allen Daily Eto (mm/day)**	**METRIC^{tm}_GREEN _RIVER Daily Eto (mm/day)**
5/17/2007	3.93	5.58	4.21	5.20	3.02
7/4/2007	5.94	7.65	6.15	7.50	4.52

Table 3.2. 24 hour ET estimates for the 17 May and 4 July, 2007 image dates from each station and METRIC^{tm}.

While the SEBAL/ METRIC^{tm} procedure is complex the basic strength of the model is a self calibrating technique that allows for close approximation of surface and atmospheric conditions at the time of data acquisition. Results of station calculated daily ET to METRIC^{tm} computed ET may seem poor at first in viewing table 3.2. Review of the source imagery shows that of the four estimates, 24 hour ET at the two stations for two dates, only one estimate occurs in a truly cloud free portion of imagery. The Smith's Fork station near Robertson on 4 July, 2007 was in an atmospherically clear portion of imagery many kilometers from any perceivable cloud cover; see Appendix B for examples of the Landsat imagery. Table 3.3 shows the difference in METRIC^{tm} derived estimation to the REF-ET value. Values from the Smith's fork on 4 July 2007 exhibit the smallest difference, estimating daily ET to be 6.72 mm/day from METRIC^{tm} and 7.78 mm/day from the reference ET or a -13.6% underreporting 'error'.

CRCAP2 – Smiths Fork near Robertson
(2 meter anemometer height)

	REF-ET_Allen	METRIC^{tm}_GRN_RIVER	
Date	**Daily Eto (mm/day)**	**Daily Eto (mm/day)**	**Error on Image Date**
5/17/2007	Clouded	Clouded	
7/4/2007	7.78	6.72	-13.6%

CRCAP1A – North Cottonwood Creek @ Ryegrass Ranch
(2 meter anemometer height)

	REF-ET_Allen	METRIC^{tm}_GRN_RIVER	
Date	**Daily Eto (mm/day)**	**Daily Eto (mm/day)**	**Error on Image Date**
5/17/2007	5.20	3.02	-41.92%
7/4/2007	7.50	4.52	-39.73%

Table 3.3. Relative error of METRIC^{tm} to 'REF-ET' calculated 24 hour ET expressed as percent difference.

Comparison to previous application of METRIC^{tm} shows our results to be similar. Allen *etal.* (2007c) found <u>absolute</u> error ranges of 39 to 2 percent difference between Lysimeter and METRIC^{tm} based calculation of multiple day ET for Kimberly, Idaho; their relative errors ranged from 139 to -26 (see Table2 of Allen *etal.* 2007c).

Direct comparison of the station ET value to the Landsat sensed measurement is difficult due to the inherent scale discrepancies. The area influencing the ET value from each measure, station or pixel, are not analogous. Sources of differences between station data and remote sensing based methods are numerous and are touched upon in the next section.

4. Recommendations

4.1 Feasibility of Operational METRIC Modeling in Wyoming

Modeling of evapotranspiration using the METRIC^{tm}/SEBAL approach appears to have been successful for areas of the individual Landsat acquisition dates that were not contaminated by clouds.

The most significant challenge for the 2007 growing season was cloud contamination of Landsat imagery which is discussed in more detail below. Cloud contamination of Landsat images in 2007 resulted in no completely clear image within the growing season. We chose two of the least clouded dates to prototype the modeling. Interpolation of ET across the entire growing season in 2007 from these two dates may produce consumptive water use estimates with a relatively wide variance of results from what actually was used. Allen *etal.* (2007c) have shown relatively wide ranges of error on the order similar to ours for individual image dates, but have also shown that with enough images (dates) random error is negated resulting in much tighter seasonal ET measurement.

Our experience in examining the Landsat image archive (1985 to present) for the Upper Green shows that it may be possible to calculate seasonal ET from a historic year, but it appears that cloudy conditions are frequent. If cloud contamination is typical for the Upper Green or other places in Wyoming during the agricultural growing season we suggest that annual METRIC^{tm}/SEBAL *ET modeling in the future is not a viable method for <u>the entire basin</u> when driven by Landsat imagery alone* with 16-day return times. However, other satellites with shorter return times (*e.g.*, MODIS) are available and would assure acquisition of more cloud-free dates which in turn would allow defensible basin-wide seasonal interpolation.

The modeling method itself is an efficient way to estimate ET over large areas in an operational framework if adequate satellite imagery is available. We believe that the SEO should consider driving the METRIC^{tm}/SEBAL approach with other satellite platforms (see below).

4.2 Challenges with Satellite Imagery for Modeling

The critical requirement for successful METRIC^{tm}/SEBAL modeling in agricultural areas is the availability of cloud-free satellite imagery of sufficient spatial resolution to resolve field units and sufficient temporal resolution to allow defensible interpolation of ET estimates for the entire growing season. Landsat imagery fits these general qualifications and has been used successfully in many ET modeling projects outside of Wyoming. However, there are problems with using Landsat imagery, the most profound being that the current Landsat sensor is beyond its design life and is not expected to be able to continue collecting imagery going forward. The most likely date for launch of a Landsat replacement is at least 2012.

In the current feasibility study, the 16-day return time of Landsat presented another serious problem: for most of the Upper Green River Basin Landsat acquisition dates during the 2007 growing season, significant cloud cover was present which made all but two Landsat scenes unusable for METRIC^{tm} modeling. At this writing, this problem appears to be repeating itself for the 2008 growing season. Investigation of the past decade (1997 to 2007) Landsat archive for the Upper Green River Basin and the Platte River Basin to the east has shown that on average only two atmospherically clear image dates per year occurred. This problem may be anomalous, but it suggests that Landsat may not have adequate return time to avoid cloudy acquisitions. Multiple Landsat satellites would result in a much quicker return time and would be more ideal, however the near term situation is one of basically no Landsat data until at least 2012 and then only one instrument is planned. See Appendix B for examples of 2007 Landsat5 overpasses during the growing season.

Finally, and unfortunately we have noticed serious issues with the Landsat5 Thematic imagery from 2007 see Figure 4.1 showing radiometric errors in the data.

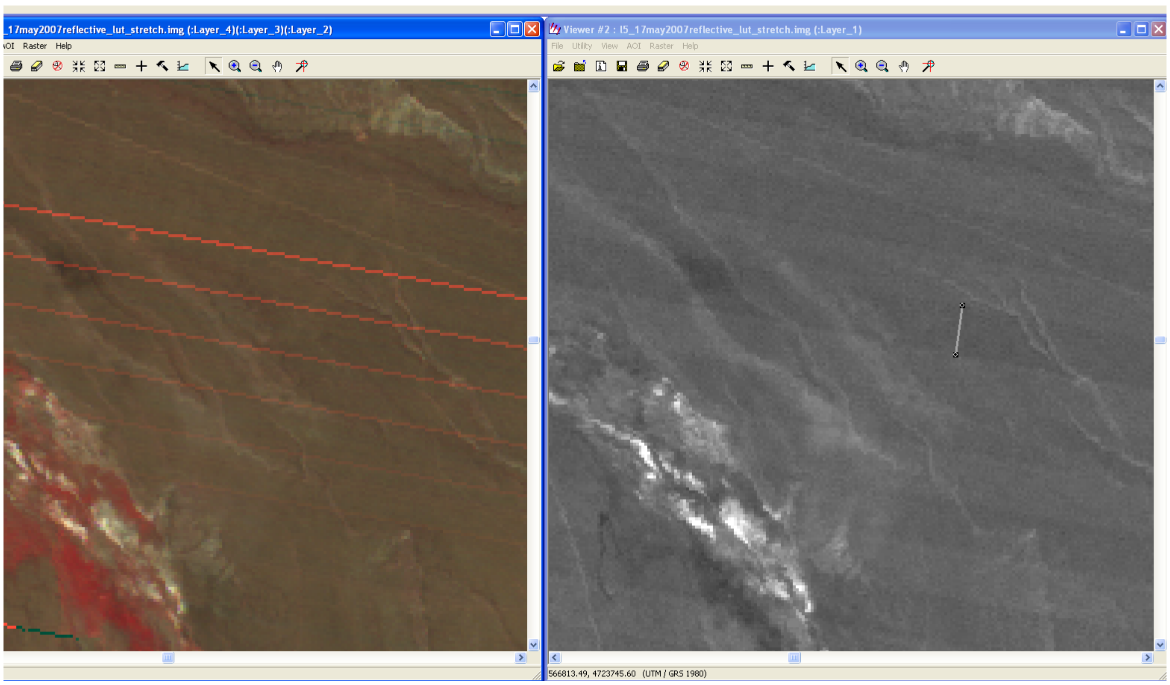


Figure 4.1. Landsat imagery from 17 May 2007 shown in Red, Green, and Blue for Channels 4, 3, 2 with scan lines artifacts shown apparent as red lines on the left and a systematic yet more subtle radiometric error in channel1 of the same image on the right.

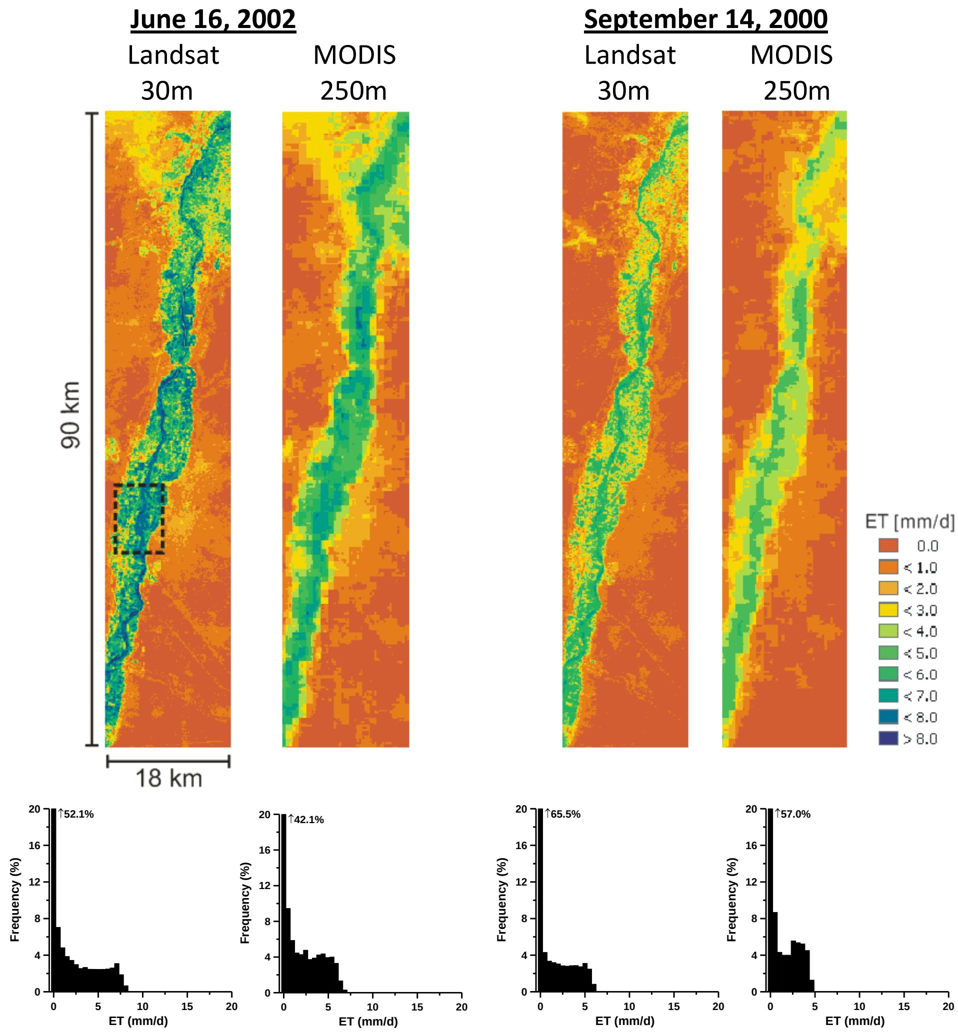
4.3 A Combined Imagery Alternative: Terra MODIS and Landsat Thematic Mapper

We envision a combined use of Landsat Thematic Mapper and Terra MODIS to calculate seasonal ET for the Upper Green River basin. The combined use would take advantage of the strength of each sensor, with Landsat providing needed spatial resolution and MODIS providing needed temporal resolution. Use of both imagers requires separate model applications of SEBAL/ METRIC^{tm} but both have been successfully employed by collaborators (Allen *et al.,* 2008, Hong *et al.,* 2008a).

Integration of both Landsat and MODIS derived ET estimates proposes issues of scale and precision that are currently being researched, but initial results show validity to the approach. Examples of daily ET maps over the Middle Rio Grande Basin aggregated from Landsat images were in good agreement with ET maps directly derived from MODIS images (Hong, 2008; Hong *et al.*, 2008) (see Figure 4.2).

Although the MODIS ET maps yield reliable ET estimates on the scale of MODIS pixels (250 to 1000 m), these maps do not allow to directly estimate the ET from irrigated lands only since many pixels will consist of a mixture of irrigated lands, riparian areas, and dry sage brush areas. However, a recent study by Hendrickx and his students has shown that it is possible to improve the spatial resolution of MODIS ET maps to Landsat scale in order to produce ET maps with an acceptable temporal as well as a fine spatial resolution (Hong, 2008; Hong *et al.*, 2008c). For example, Figure 4.3 presents three different methods to downscale the MODIS ET map to Landsat scale. Since method (a) produces the best results we will use this method in any proposed study.

Our novel method for downscaling MODIS ET maps makes it possible to separate water use from irrigated areas from that in riparian areas. Although a downscaled MODIS ET map cannot be as accurate as a Landsat ET map, it reveals much more information than can be obtained with any other method under the cloudy conditions so characteristic for the Upper Green River Basin.



Min	**0.00**	**0.00**	**0.00**	**0.00**
Max	15.19	7.37	7.51	5.16
Mean	1.81	1.86	1.10	0.90
Std	2.46	2.07	1.78	1.39

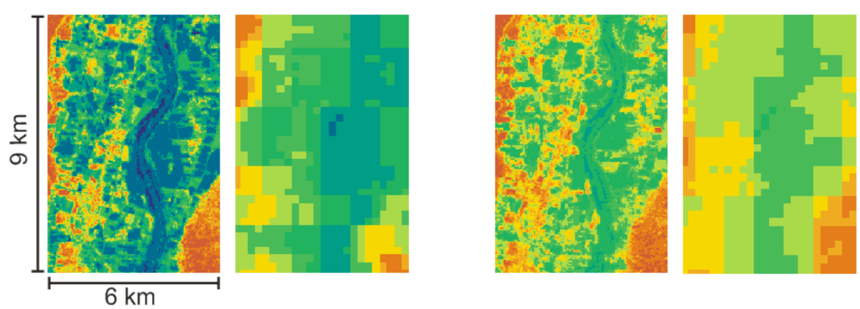
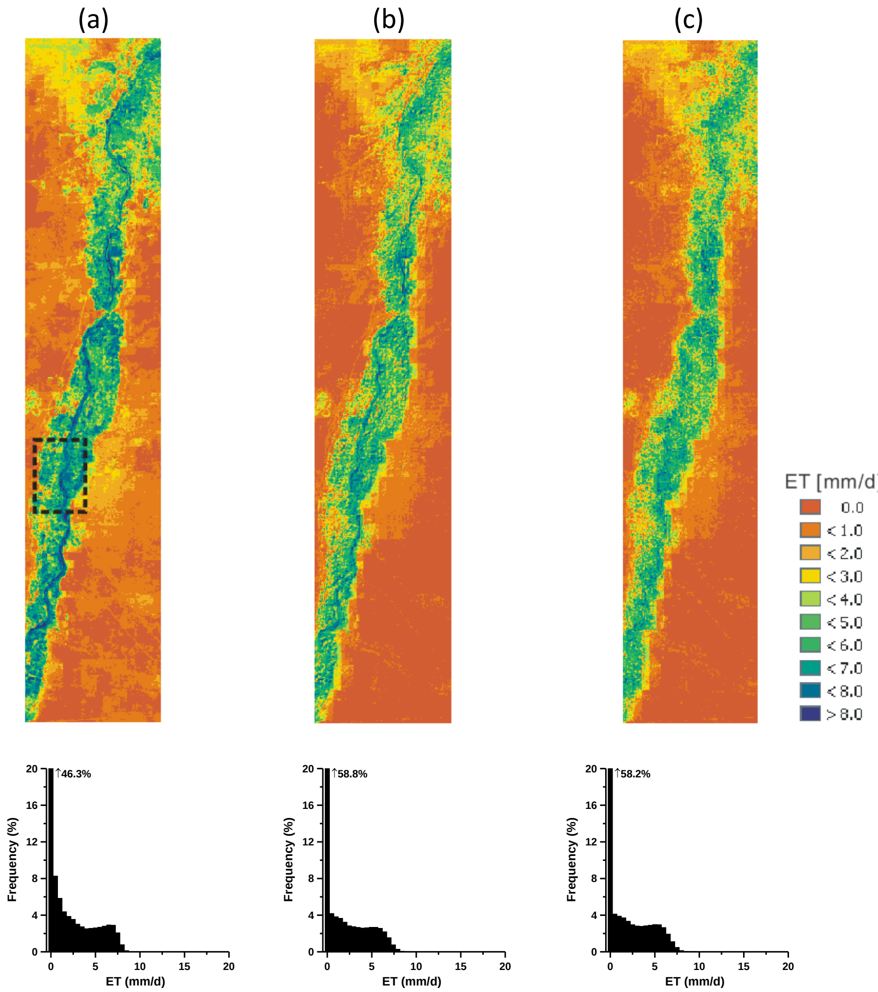


Figure 4.2. Landsat (30 m) and MODIS (250 m) derived ET by SEBAL of June and September. Bin size of the histogram is 0.5 mm/d and frequency occurrence exceeding 20% marked next to the arrow. The histograms and basic statistics are based on the entire maps (18 km x 90 km). Enlarged areas (9 by 6 km) shown at the bottom correspond to the dotted square of the upper images (Hong, 2008; Hong *et al.*, 2008b).



	(a)	(b)	(c)
Mean	1.97	1.52	1.53
Std	2.47	2.24	2.21

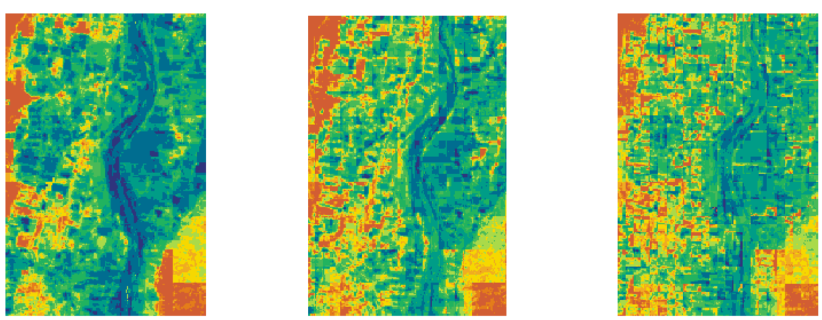


Figure 4.3. Down-scaled ET maps from MODIS image of June 16, 2002, using three different methods. For the North Platte study we will use method (a) that produces the best results. Compare the detailed downscaled MODIS ET map with the Landsat ET map for the same date in Figure 4.2 to appreciate the good agreement between the original Landsat ET map and the downscaled MODIS ET map.

4.4 Alternative Sources of Satellite Imagery for Modeling

Finally, we discuss the merits of alternative sources of satellite imagery appropriate to SEBAL/ METRIC^{tm}.

ASTER

The ASTER satellite, carried aboard the TERRA and AQUA platforms could potentially be used as a Landsat substitute in the future or in the event of TM5 failure. ASTER collects data in sufficient visible and IR bands (15 and 30 m spatial resolution) and in the thermal (90 m spatial resolution) to run METRIC^{tm}. A constraint on the use of ASTER is that it is an "on demand" satellite, meaning that it does not collect data continuously but instead must be tasked for specific acquisitions. This requires pre-planning and limits alternatives if there are clouds present during data acquisition. For these reasons ASTER is probably not a viable alternative for operational ET modeling on a regular basis.

MODIS

The MODIS sensor, also carried on TERRA and AQUA, collects data of the entire earth once a day (twice per day between the two platforms) in the visible, reflected IR and thermal regions of the spectrum. Although the spectral resolution is sufficient for running METRIC, the spatial resolution is coarse. MODIS thermal data are collected on a 1000 m grid and will not isolate 10 acre parcels as required by the current project. Data, however, are free, and in the absence of other options MODIS would be a suitable alternative for coarse analysis of ET. The daily return time of MODIS is an advantage for avoiding cloudy acquisitions that plagued the current project and it is possible that even with coarse spatial resolution the results may be precise enough for estimation of basin wide ET. Our collaboration with Dr. Hendrickx also benefits from his experience in using a combined Landsat and MODIS set of data to calculate ET with METRIC^{tm}.

Sino-Brazilian CBERS platform

A satellite called CBERS2B is currently being operated through a partnership between China and Brazil. This satellite collects data in optical and thermal (160 m spatial resolution) bands of sufficient spatial resolution to be a potential substitute for Landsat. Epiphanio (2008) reports that CBERS imagery can be downloaded at no charge (see http://www.dgi.inpe.br/CDSR). This imagery may be a viable Landsat alternative going forward and deserves consideration.

4.5 Need for Validation Data

We describe our application of METRIC^{tm} as a 'Level One' deployment. Further calibration of the model for the Upper Green River in Wyoming would constitute a 'Level Two' application. We propose to develop a Level Two application in a second phase of this pilot study. In phase 2, further development of Hot/Cold pixel calibration approaches and in-situ measurement of required weather data for primary variable and calibration values will be pursued. One consideration for operational use of an Upper Green model is therefore land access and ownership constraints. We have, through our SEO collaborators, gained necessary access to agricultural lands for the fixed locations of weather and ET stations and verification of Hot and Cold pixel land use and type. Sites of Hot and Cold pixel locations are variable by date and may not be accessible. Development of a GIS database including recent land use and land cover data as well as aerial photographs would support model application.

Existing weather stations installed by the SEO can calculate a reference ET that is basically a point measure at the station. Understanding of the upwind area or fetch contribution to these measures is crucial. Eddy covariance towers and scintillometer measurements can also provide ET verification measurements corresponding to different scales of fetch they are measuring. Team members have identified proper locations within the study domain and installed two ET stations in 2008. We are researching areas and applicable use of scintillometers to acquire validation data at larger scales than point station measures. Figures 4.4a and 4.4b show a potential scintillometer base location overlooking the newly installed ET station at Duck Creek.

Figure 4.4a. Photograph looking north at small knoll on the edge of The Pinedale Mesa.

Figure 4.4b. View looking north at Duck Creek station site from knoll on north edge of The Pinedale Mesa.

Empirical calibration of the model application may improve results. As Table 4.1 shows generation of the reference ET values may vary considerably. Use of more remotely sensed (e.g. for net radiation) or in-site (e.g. scintillometer based ET) measurement would help needed model development. Dr. Hendrickx has noted several places in the model application process where values or coefficients in algorithms may need to be tuned for Wyoming. See examples within Appendix A: Hendrickx Reports.

CRCAP2 – Smiths Fork near Robertson (2 meter anemometer height)					
Date	FAO56 Daily Eto (mm/day)	ASCE_Tall Daily Eto (mm/day)	ASCE_Short Daily Eto (mm/day)	REF-ET_Allen Daily Eto (mm/day)	METRIC^{tm}_GREEN _RIVER Daily Eto (mm/day)
5/17/2007	3.58	4.70	3.64	Clouded	Clouded
7/4/2007	6.06	7.39	6.21	7.78	6.72
CRCAP1A – North Cottonwood Creek @ Ryegrass Ranch (2 meter anemometer height)					
Date	FAO56 Daily Eto (mm/day)	ASCE_Tall Daily Eto (mm/day)	ASCE_Short Daily Eto (mm/day)	REF-ET_Allen Daily Eto (mm/day)	METRIC^{tm}_GREEN _RIVER Daily Eto (mm/day)
5/17/2007	3.93	5.58	4.21	5.20	3.02
7/4/2007	5.94	7.65	6.15	7.50	4.52

Table 4.1. 24 hour ET estimates for the 17 May and 4 July, 2007 image dates from each station and METRIC^{tm}.

In the long term, hydrologic monitoring of ET fraction and sources of water can be tested with weir and fractional measure of chlorides in order to improve estimates of consumptive use, but this will require a significant future effort to test.

We will consider these issues in further development of the model approach in Phase2 of our study of the Colorado River in Wyoming.

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Appendix A: Hendrickx Reports

SEBAL/METRIC TRAINING PROJECT – WyGISC

Progress Report I April 2008
Green River Basin Image of May 17, 2007

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Purpose
The purpose of this Progress Report is to present the results of the first SEBAL/METRIC application in the Green River Basin on the image of May 17, 2007. The outputs of SEBAL^{NM} will be used to check the code implemented by WyGISC.

In this phase of the project the focus is on implementing SEBAL/METRIC at WGISC. Therefore, the ET maps generated will be preliminary.

Approach
For this SEBAL/METRIC application we have implemented an improved version of SEBAL^{NM} using recent progress for the evaluation of the net radiation and other elements of the energy balance (Allen *et al.*, 2007b). As done by WyGISC we followed the steps described in the November, 2007 METRIC – Applications Manual (Allen *et al.*, 2007a). The main difference between SEBAL and METRIC is that SEBAL can be applied without any ground measurements while METRIC requires high quality hourly meteorological measurements for determination of the reference evapotranspiration.

Input Files and Meteorological Data provided by WGISC
WGISC provided a composite Landsat5 image for May 17, 2007, consisting of image Path37-Row31 and a small part of image Path37-Row30. Some striping is seen in this image but this will not affect the results except for the pixels on the stripes. WGISC also provided the 30 m DEM of the area and meteorological data from two weather stations: North Cottonwood Creek and Smith's Fork. Since Smith's Fork was covered by clouds on the May 17, 2007, so that only the data from North Cottonwood Creek could be used. The location of the North Cottonwood Creek weather station is just outside of the northern edge of the Landsat image. The meteorological measurements on May 17, 2007, and the cloud distribution on the image indicate that the weather station had clear sky conditions during the satellite overpass. This was confirmed by checking image Path37-Row30 for May 17, 2007.

The weather stations are: (1) Smith's Fork near Robertson (lat 41.195160 lon -110.417353; UTM 12, spheroid: GRS 1980, datum: NAD83, X=548857, Y=4560585; elevation about 2184 m) in southern part of basin and (2) North Cottonwood Creek (lat 42.838611, lon -110.299722; UTM 12, spheroid: GRS1980, datum: NAD83, X=557228, Y=4743131; elevation about 2270 m) in northern part of basin. Measurements are taken every 5 seconds. The 11:00 am timestamp is the mean for measurements taken from 10:01-11:00. Time-stamps are in Mountain Daylight Savings time.

At satellite overpass for this image we use an average windspeed of 1.97 m/s; the windspeed at 200 m height (the blending height) is 4.13 m/s. The actual vapor pressure is 0.506 kPa.

We used the weather data for North Cottonwood Creek and calculated an instantaneous reference ET_r of 0.71 mm/hour at satellite overpass. We calculated an ER_{r_24} of 5.2 mm/day.

Description of Input and Output of SEBAL^{NM} Models

Our implementation of SEBAL^{NM} consists of nine ERDAS IMAGINE models and several EXCEL spreadsheets. To assist WyGISC with the program structure of their code, we present all input and output information for each of these models and spreadsheet for the Landsat image of May 17, 2007, provided by WGISC.

Step One: Spreadsheet I

Purpose:
1. Calculate model constants that relate to solar radiation.
2. Gather and calculate other meteorological data needed such as wind speed and actual vapor pressure.
See METRIC Manual Appendix 12 and Allen *et al.* (2007b).

Input Data:
The input data for Spreadsheet I are found in the header file of the image (Appendix A).
Latitude at center of image: 41.78662
Longitude at center of image: -110.05486
Time of image: 17:56:05 GMT (average of start and end time)

Output Data:

Local Time 10:56:05
Solar Time 10:39:34

As a check the angles are also calculated in degrees.

δ (rad)	0.33699544	declination (degree)	19.30842	
φ (rad)	0.729314102	latitude (degree)	41.78662	
ω (rad)	0.350896263	hour angle (degree)	-20.1049	
ϕ (rad)	1.078279544	solar elev angle (degree)	61.78087	
θ (rad)	0.49251678	incident angle “flat surface”	28.21913	
Dr	0.97661532			
cosθ_horizontal	0.881145602		0.881146	sinϕ
sinδ sinφ	0.220333411		0.666358	sinφ
sinδcosφ	0.246545357		0.330653	sinδ
cosδcosφ	0.703691635		0.745632	cosφ
cosδsinφ	0.6288773		0.943752	cosδ

cosδ	0.943752391	0.949717	sin sunset angle
sunrise angle	-1.889263043	1176	Ra(inst) on Horizontal surface
sunset angle	1.889263043	461	Ra(24) on Horizontal surface

Windspeed (200m) 4.130195799 m/s

Step Two: ERDAS Imagine Model 1

Purpose: Calculate the “at satellite” or “top of atmosphere” reflectance for each band.

See Eq. [6] in METRIC Manual and Eq. [10] in Allen *et al.* (2007b).

Input Data:
DEM
green_river_p37r31_l5_17may2007_bands_1_2_3_4_5_7.img
green_river_p37r31_l5_17may2007_band_6.img
δ (rad)
φ (rad)
ω (rad)
dr
ESUN values for Landsat 5 are from Chander and Markham (2003).

Band of Landsat5	ESUN ($W/(m^2.\mu m)$
1	1957
2	1826
3	1554
4	1036
5	215.0
7	80.67

LMIN and LMAX values for Landsat5 are from Chander *et al.* (2007).

Band of Landsat5	LMIN	LMAX
1	-1.52	193.0
2	-2.84	365.0
3	-1.17	264.0
4	-1.51	221.0
5	-0.37	30.2
6	1.2378	15.303
7	-0.15	16.5

Output Data
cos_theta_solar_incidence_angle.img

(Eq. [12-1] in METRIC manual, note error on 4^{th} line: sin of latitude should be sin of aspect; Eq. [7] in Allen *et al.* (2007)).

Reflectance_toa_bands_1_2_3_4_5_7.img
thermal_radiance_band_6.img
aspect_rad.img
slope_rad.img
Images of slope and aspect are needed for the selection of hot and cold pixel.

Step Three: ERDAS Imagine Model 2

Purpose: Calculate the broad band albedo (α_s) (Eq. [15] in Allen *et al.* (2007b)) and the incoming broad-band short wave, i.e. solar, radiation ($R_{s\downarrow}$) (Eq. [3] in Allen *et al.* (2007b).

Input Data:
DEM
Constants C_1 to C_5 for Eqs. [12-13], C_b for Eq. [14], and W_b for Eq. [15] for use in Landsat images from Table 1 in Allen *et al.* (2007b).
$K_t = 1.0$
cosθ_horizontal
cos_theta_solar_incidence_angle.img
dr
e_a near-surface vapor pressure (kPa) = 0.506
reflectance_toa_bands_1_2_3_4_5_7.img

Output Data:
reflectance_surface_bands_1_2_3_4_5_7.img
surface_albedo.img
w_water_in_atmosphere.img
transmittance_sw.img
broad band atmospheric transmissivity (τ_{sw}) (Eq. [4] in Allen *et al.* (2007b))

Step Four: ERDAS Imagine Model 3

Purpose: Calculate the surface temperature (T_s) (Eq. [20] in Allen *et al.* (2007b) and the lapse rate adjusted surface temperature (T_{s_DEM}) (Eq. [12-9] in the METRIC manual).

Input Data:
L = 0.1 (constant L for SAVI calculation in Eq. [19] of Allen *et al.* (2007b)
DEM
$R_p = 0$
$R_{sky} = 0$
$\tau_{NB} = 1$
thermal_radiance_band_6.img
$K_1 = 607.8$ for Landsat5
$K_2 = 1261$ for Landsat5
Elevation of arbitrary datum (meters) = 1881 m (elevation of the cold pixel)
reflectance_surface_bands_1_2_3_4_5_7.img
surface_albedo.img
C_lapse = 0.0065 K/m (this is an average rate; in the Green River Basin we need to study this

rate)

Output Data:
ndvi.img (Eq. [23] of Allen *et al.* (2007b))
surface_emissivity.img (Eq. [17] of Allen *et al.* (2007b))
surface_temperature.img
surface_temperature_dem.img

Step Five: Select "Cold" and "Hot" Pixels

See Appendix 7 of the METRIC Manual for selection of the cold and hot pixels.

The cold pixel should be rather cool, have a NDVI>0.7 and an albedo typical for well-growing alfalfa or other vegetation (0.16-0.24).

The hot pixel should be rather warm –but not necessarily the hottest pixel in the image-, have a NDVI<0.20 which is typical of bare soil, and an elevated albedo>0.27.

We have selected the following hot and cold pixels:

T-hot	X	Y	slope	NDVI	albedo	**T-cold**	X	Y	slope	NDVI	albedo
312.01	613964	4612863	0	0.115	0.316	**297.99**	612262	4612461	0	0.82	0.217

I use also SAS models for the selection of hot and cold pixels. I can share those models with WGISC.

Step Six: ERDAS Imagine Model 4

Purpose: Calculate the net surface radiation (R_n) (Eq. [2] in Allen *et al.* (2007) and the soil heat flux (G) (Eq. [26] in Allen *et al.* (2007b).

Input Data:
C_lapse = 0.0065 K/m (this is an average rate; in the Green River Basin we need to study this rate)
DEM
Temperature of cold pixel
Elevation of cold pixel
transmittance_sw.img
ndvi.img
surface_temperature.img
surface_albedo.img
surface_emissivity.img
incoming_solar_radiation.img

Output Data:
net_surface_radiation.img
soil_heat_flux.img

longwave_in.img
longwave_out.img

Step Seven: Spreadsheet II

Purpose: Determine the coefficients a_1 and b_1 in Eq. [34b] of Allen *et al.* (2007b).

Input Data:
Select pixels with known vegetation of different heights, bare soil, water, etc. Make columns of NDVI, albedo, and estimated roughness length z_{om}. Then, after transforming the variables run a regression for determination of the coefficients a_1 and b_1.

Output Data:
A preliminary regression yielded:
a_1 = 0.75766
b_1 = -5.65024

In the future we need to determine these coefficients with a wider range of land covers and more reliable data. For the purpose of implementing SEBAL/METRIC these coefficients suffice.

Step Eight: ERDAS Imagine Model 5

Purpose: Calculate the initial estimates for the friction velocity, u_*, (Eq. [31] in Allen *et al.* (2007)) and aerodynamic resistance, r_{ah}, (Eq. [30] in Allen *et al.* (2007b)).

Input Data:
ndvi.img
surface_albedo.img
a_1 = 0.75766
b_1 = -5.65024
Wind speed at 200 m = 4.130 (Eq. [32] of Allen *et al.* (2007b))

Output Data:
I_u_star.img
initial_rah.img
zom.img (Eq. [34b] of Allen *et al.* (2007))

I am not so sure about the zom_adj and the wind_coeff, especially in a more or less flat but slanted basin. We need to explore this more in the future. For now let us just ignore them in the model. So use Eqs. [30], [31], [32], and [34b] but not Eqs. [35] and [36].

Step Nine: ERDAS Imagine Model 6

Purpose: Calculate the 24 hour incoming extraterrestrial solar radiation R_a for horizontal and sloped surfaces (Eq. [6] in Allen *et al.* (2006). The values of R_{a24} are needed to calculate the incoming 24 hour solar radiation at the earth surface on horizontal and sloped surfaces (see Eq. [3] and Eq. [57] in Allen *et al.* (2007b)).

Input Data:
dr
sinδ sinφ
sinδcosφ
cosδcosφ
cosδsinφ
cosδ
sunrise angle
sunset angle
cos_aspect.img
sin_aspect.img
sin_slope.img
cos_slope.img

Output Data:
ra_24hours.img

This is a rather complicated model. I will assist WGISC with the implementation of this model following Allen *et al.* (2006).

Step Ten: Put weather data into REF-ET for calculation of ET_r and ET_{r_24}

The software REF-ET has been developed by Dr. Richard Allen and can be downloaded from his webpage http://www.kimberly.uidaho.edu/ref-et/ (last entered April 20, 2008).
Purpose: Calculate ET_r and ET_{r_24} from high quality hourly weather data. ET_r (mm/hour) is the instantaneous reference ET when the satellite passes over while ET_{r_24} is the daily reference ET.

We used the weather data for North Cottonwood Creek and Smith's Fork to calculate an average instantaneous reference ET_r of 0.71 mm/hour at satellite overpass. We calculated an average ER_{r_24} of 5.2 mm/day.

Step Eleven: Spreadsheet III

Purpose: Calculation of the *a* and *b* parameters in Eq. [29] of Allen *et al.* (2007b) using an iteration process.

Input Data:
ET_r = 0.71 mm/hour
Height of the blending layer = 200 m
Windspeed at 200 m (from Eq. 32 in Allen *et al.* 2007b) = 4.1302 m/s
z_1 = 0.1 m
z_2 = 2.0 m
Elevation of cold pixel = 1881

Elevation of hot pixel = 1881
Temperature of cold pixel = 297.99
Temperature of hot pixel = 312.01
Net radiation at cold pixel = 624.80 W/m^2
Net radiation at hot pixel = 449.64 W/m^2
Soil heat flux at cold pixel = 47.38 W/m^2
Soil heat flux at hot pixel = 107.19 W/m^2
z_{om} at cold pixel = 0.03 m (for hay grass)
z_{om} at hot pixel = 0.005 m (for bare agricultural soil)
EtrF or "crop coefficient" at cold pixel = 1.05
EtrF or "crop coefficient" at hot pixel = 0
For this implementation the SEBAL approach is used dT = 0 at cold pixel.

Output Data:
The coefficients a and b for Eq. [29] for ten iterations.

Iteration #	a	b
1	1.167024604	-347.7616618
2	0.226075993	-67.36838526
3	0.543501469	-161.9580028
4	0.40374526	-120.31205
5	0.451669398	-134.592964
6	0.433820927	-129.2742981
7	0.440259503	-131.1929292
8	0.437910258	-130.4928779
9	0.438763856	-130.7472415
10	0.438453231	-130.6546784

Step Twelve: ERADS Imagine Model 7

Purpose: To conduct the iterations for a correct estimate of u* and r_{ah} using the a and b coefficients from iteration numbers 4-10 and to calculate the final sensible heat flux H for each pixel.

Input Data:

Iteration #	a	b
4	0.40374526	-120.31205
5	0.451669398	-134.592964
6	0.433820927	-129.2742981
7	0.440259503	-131.1929292
8	0.437910258	-130.4928779
9	0.438763856	-130.7472415
10	0.438453231	-130.6546784

surface_temperature.img
surface_temperature_dem.img

zom_img
wind speed at 200 m = 4.130195799

Output Data:
final_h.img

Step Thirteen: ERDAS Imagine Model 8

Purpose: To calculate the instantaneous ET (ET_{inst} as mm/hour), the reference ET fraction (ET_rF), and the 24-hour ET (ET_{24}). (See Eqs. [52-56] in Allen *et al.*, 2007b).

Input Data:
net_surface_radiation.img
soil_heat_flux.img
final_h.img
ET_{r_inst} = 0.71 mm/hour
ET_{r_24} = 5.2 mm/day
ra_24hours.img
R_{a_inst} on horizontal surface = 1176 W/m^2
R_{a_24} on horizontal surface = 461 W/m^2
cos_theta_solar_incidence_angle.img
d_r = 0.976615320000
surface_temperature.img
Output Data:
et_inst.img
et_24_hours.img

All input and output images for May 17, 2007, have been uploaded on an external hard drive and sent to WGISC.

Appendix A.1: Header file for image LT50370312007137EDC00

Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT50370312007137EDC00
Spacecraft Identifier	
Sensor Mode	
Station Identifier	EDC
Day Night	DAY
WRS Path	037
WRS Row	031
WRS Type	2
Date Acquired	2007/05/17
Start Time	2007:137:17:55:52.85244
Stop Time	2007:137:17:56:19.46544
Sensor Anomalies	N
Acquisition Quality	9
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9
Quality Band 7	9
Cloud Cover	0
Cloud Cover Quadrant Upper Left	20
Cloud Cover Quadrant Upper Right	0
Cloud Cover Quadrant Lower Left	30
Cloud Cover Quadrant Lower Right	10
Sun Elevation	61.868577
Sun Azimuth	136.689048
Scene Center Latitude	41.78662 (41°47’11.83”N)
Scene Center Longitude	-110.05486 (110°03’17.50”W)
Corner Upper Left Latitude	42.72880 (42°43’43.68”N)
Corner Upper Left Longitude	-110.90051 (110°54’01.84”W)
Corner Upper Right Latitude	42.40651 (42°24’23.44”N)
Corner Upper Right Longitude	-108.69009 (108°41’24.32”W)
Corner Lower Left Latitude	41.15205 (41°09’07.38”N)
Corner Lower Left Longitude	-111.39444 (111°23’39.98”W)
Corner Lower Right Latitude	40.83739 (40°50’14.60”N)
Corner Lower Right Longitude	-109.23521 (109°14’06.76”W)

SEBAL/METRIC TRAINING PROJECT – WGISC

Progress Report II, May 2008
Green River Basin Image of July 4, 2007

Prepared by Jan M.H. Hendrickx
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Purpose

The purpose of Progress Report II is to present the results of the SEBAL/METRIC application in the Green River Basin on the image of July 4, 2007. The outputs of SEBAL^{NM} will be used to check the code implemented by WyGISC.

In this phase of the project the focus is on implementing SEBAL/METRIC at WyGISC. Therefore, the ET maps generated will be preliminary.

Approach

For this SEBAL/METRIC application we have implemented an improved version of SEBAL^{NM} using recent progress for the evaluation of the net radiation and other elements of the energy balance (Allen *et al.*, 2007b). As done by WyGISC we followed the steps described in the November, 2007 METRIC – Applications Manual (Allen *et al.*, 2007a). The main difference between SEBAL and METRIC is that SEBAL can be applied without any ground measurements while METRIC requires high quality hourly meteorological measurements for determination of the reference evapotranspiration.

Input Files

WGISC provided a composite Landsat5 image for July 4, 2007, consisting of image Path37-Row31 and a small part of image Path37-Row30. WGISC also provided the 30 m DEM of the area and meteorological data from two weather stations: North Cottonwood Creek and Smith's Fork. We composed subsets of the original images provided by WGISC using the following coordinates: ULX = 486000, ULY = 4750000, LRX = 691300, LRY = 4531000 (UTM 12, spheroid: GRS 1980, datum: NAD83.

Meteorological Data provided by WGISC

The weather stations are: (1) Smith's Fork near Robertson (lat 41.195160 lon -110.417353; UTM 12, spheroid: GRS 1980, datum: NAD83, X=548857, Y=4560585; elevation about 2184 m) in southern part of basin and (2) North Cottonwood Creek (lat 42.838611, lon -110.299722; UTM 12, spheroid: GRS1980, datum: NAD83, X=557228, Y=4743131; elevation about 2270 m) in northern part of basin. Measurements are taken every 5 seconds. The 11:00 am timestamp is the mean for measurements taken from 10:01-11:00. Time-stamps are in Mountain Daylight Savings time.

Last precipitation at Smith's Fork on June 6: 0.254 mm. Last precipitation at North Cottonwood Creek on June 6: 4 mm. So, the surface temperature of the hot pixel will not be affected by previous rainfall.

At satellite overpass the wind speeds at Smith's Fork and North Cottonwood Creek are, respectively, 1.58 and 3.05 m/s. For this image we use an average windspeed of 2.54 m/s. Estimating the surface roughness length as 0.03 m at the weather stations and wind speed measurements at 2 m height, the windspeed at 200 m height (the blending height) is 5.33 m/s.

Both stations are without clouds at satellite overpass but North Cottonwood Creek appears to be about 300 m upwind of a cloud shadow. This might have influenced the surface temperature; it could be somewhat lower compared to the one expected without cloud effect. The radiation measurements indicate that at the end of the afternoon cloud cover is increasing. At North Cottonwood Creek 0.5 mm precipitation is measured around 9:30 pm.

The actual vapor pressures at Smith's Fork and North Cottonwood Creek during satellite overpass are, respectively, 0.88 and 1.19 kPa. For the analysis of this image we take the average value of 1.03 kPa.

The hourly reference ET_r at Smith's Fork and North Cottonwood Creek during satellite overpass are, respectively, 0.83 and 0.92 mm/h. For the analysis of this image we take the average value of 0.88 mm/h. The daily reference ET_r at Smith's Fork and North Cottonwood Creek during satellite overpass are, respectively, 7.78 and 7.5 mm/d. For the analysis of this image we take the average value of 7.6 mm/d.

Description of Input and Output of SEBAL^{NM} Models

Our implementation of SEBAL^{NM} consists of nine ERDAS IMAGINE models and several EXCEL spreadsheets. To assist WGISC with the program structure of their code, we present all input and output information for each of these models and spreadsheet for the Landsat image of July 4, 2007, provided by WyGISC.

Step One: Spreadsheet I

Purpose:

1. Calculate model constants that relate to solar radiation.
2. Gather and calculate other meteorological data needed such as wind speed and actual vapor pressure.

See METRIC Manual Appendix 12 and Allen *et al.* (2007b).

Input Data:

The input data for Spreadsheet I are found in the header file of the image (Appendix A).
Latitude at center of image: 41.762
Longitude at center of image: -109.969
Time of image: 17:55:22 GMT (average of start and end time)

Output Data:

Local Time	10:55:22
Solar Time	10:31:25

As a check the angles are also calculated in degrees.

δ (rad)	0.398797113	declination (degree)	22.84939	δ (sin)	0.388310128
φ (rad)	0.728884402	latitude (degree)	41.762	φ (cos)	0.745917897
ω (rad)	-0.386496945	hour angle (degree)	-22.1446	φ (sin)	0.666037905
ϕ (rad)	1.109124979	solar elev angle (degree)	63.54818	δ (cos)	0.921528754
θ (rad)	0.46167135	incident angle "flat surface"	26.45182		
dr	0.967030554				
cosθ_horizontal	0.895309255		0.895309	sinϕ	
sinδ sinφ	0.258629264		0.666038	sinφ	
sinδcosφ	0.289647474		0.38831	sinδ	
cosδcosφ	0.68738479		0.745918	cosφ	
cosδsinφ	0.613773081		0.921529	cosδ	
cosδ	0.921528754		0.926518	sin sunset angle	
sunrise angle	-1.956543027		1184	Ra(inst) on Horizontal surface	
sunset angle	1.956543027		481	Ra(24) on Horizontal surface	
Windspeed (200m)	5.325227071	m/s			

Step Two: ERDAS Imagine Model 1

Purpose: Calculate the "at satellite" or "top of atmosphere" reflectance for each band.

See Eq. [6] in METRIC Manual and Eq. [10] in Allen *et al.* (2007b).

Input Data:
DEM
green_river_p37r31_l5_4july2007_bands_1_2_3_4_5_7.img
green_river_p37r31_l5_4july2007_band_6.img
δ (rad)
φ (rad)
ω (rad)
dr
ESUN values for Landsat 5 are from Chander and Markham (2003).

Band of Landsat5	ESUN (W/(m^2.µm)
1	1957
2	1826
3	1554

4	1036
5	215.0
7	80.67

LMIN and LMAX values for Landsat5 are from Chander *et al.* (2007).

Band of Landsat5	LMIN	LMAX
1	-1.52	193.0
2	-2.84	365.0
3	-1.17	264.0
4	-1.51	221.0
5	-0.37	30.2
6	1.2378	15.303
7	-0.15	16.5

Output Data
cos_theta_solar_incidence_angle.img
(Eq. [12-1] in METRIC manual, note error on 4th line: sin of latitude should be sin of aspect; Eq. [7] in Allen *et al.* (2007b)).
Reflectance_toa_bands_1_2_3_4_5_7.img
thermal_radiance_band_6.img
aspect_rad.img
slope_rad.img
Images of slope and aspect are needed for the selection of hot and cold pixel.

Step Three: ERDAS Imagine Model 2

Purpose: Calculate the broad band albedo (α_s) (Eq. [15] in Allen *et al.* (2007b)) and the incoming broad-band short wave, i.e. solar, radiation ($R_{s\downarrow}$) (Eq. [3] in Allen *et al.* (2007b).

Input Data:
DEM
Constants C_1 to C_5 for Eqs. [12-13], C_b for Eq. [14], and W_b for Eq. [15] for use in Landsat images from Table 1 in Allen *et al.* (2007b).
K_t = 1.0
cosθ_horizontal
cos_theta_solar_incidence_angle.img
dr
e_a near-surface vapor pressure (kPa) = 1.03
reflectance_toa_bands_1_2_3_4_5_7.img

Output Data:
reflectance_surface_bands_1_2_3_4_5_7.img
surface_albedo.img
w_water_in_atmosphere.img
transmittance_sw.img

broad band atmospheric transmissivity (τ_{sw}) (Eq. [4] in Allen *et al.* (2007b))

Step Four: ERDAS Imagine Model 3

Purpose: Calculate the surface temperature (T_s) (Eq. [20] in Allen *et al.* (2007b) and the lapse rate adjusted surface temperature (T_{s_DEM}) (Eq. [12-9] in the METRIC manual).

Input Data:
L = 0.1 (constant L for SAVI calculation in Eq. [19] of Allen *et al.* (2007b)
DEM
$R_p = 0$
$R_{sky} = 0$
$\tau_{NB} = 1$
thermal_radiance_band_6.img
$K_1 = 607.8$ for Landsat5
$K_2 = 1261$ for Landsat5
Elevation of arbitrary datum (meters) = 2250 m which equals the mean elevation between the two weather stations.
Reflectance_surface_bands_1_2_3_4_5_7.img
surface_albedo.img
C_lapse = 0.0065 K/m (this is an average rate; in the Green River Basin we need to study this rate). For this image we found no evidence for a lapse rate of 0.0065, more about zero. However, we will run the model for now with the average lapse rate of 0.0065.

Output Data:
ndvi.img (Eq. [23] of Allen *et al.* (2007b))
surface_emissivity.img (Eq. [17] of Allen *et al.* (2007b))
surface_temperature.img
surface_temperature_dem.img

Step Five: Select "Cold" and "Hot" Pixels

See Appendix 7 of the METRIC Manual for selection of the cold and hot pixels.

The cold pixel should be rather cool, have a NDVI>0.7 and an albedo typical for well-growing alfalfa or other vegetation (0.16-0.24).

The hot pixel should be rather warm –but not necessarily the hottest pixel in the image-, have a NDVI<0.20 which is typical of bare soil, and an elevated albedo>0.27 if possible.

We have selected the following hot and cold pixels:

T-hot	X	Y	slope	NDVI	albedo	**T-cold**	X	Y	slope	NDVI	albedo
317.05	547185	4568178	0.006	0.18	0.21	**296.68**	547504	4557802	0.00 rd	0.83	0.18

Elevation of cold pixel is 2258 m. Elevation of hot pixel is 2119 m.

I use also SAS models for the selection of hot and cold pixels. I can share those models with WyGISC.

We need to use a soil and vegetation map to improve the selection of the hot pixel.

Step Six: ERDAS Imagine Model 4

Purpose: Calculate the net surface radiation (R_n) (Eq. [2] in Allen *et al.* (2007b) and the soil heat flux (G) (Eq. [26] in Allen *et al.* (2007b).

Input Data:
C_lapse = 0.0065 K/m (this is an average rate; in the Green River Basin we need to study this rate)
DEM
Temperature of cold pixel
Elevation of cold pixel
transmittance_sw.img
ndvi.img
surface_temperature.img
surface_albedo.img
surface_emissivity.img
incoming_solar_radiation.img

Output Data:
net_surface_radiation.img
soil_heat_flux.img
longwave_in.img
longwave_out.img

Step Seven: Spreadsheet II

Purpose: Determine the coefficients a_1 and b_1 in Eq. [34b] of Allen *et al.* (2007b).

Input Data:
Select pixels with known vegetation of different heights, bare soil, water, etc. Make columns of NDVI, albedo, and estimated roughness length z_{om}. Then, after transforming the variables run a regression for determination of the coefficients a_1 and b_1.

Output Data:
A preliminary regression yielded:
a_1 = 0.75766
b_1 = -5.65024

These coefficients need to be determined or checked for each image.
In the future we need to determine these coefficients with a wider range of land covers and more reliable data. For the purpose of implementing SEBAL/METRIC these coefficients suffice.

Zom at cold pixel is 0.115
zom at hot pixel is 0.007

Step Eight: ERDAS Imagine Model 5

Purpose: Calculate the initial estimates for the friction velocity, u_*, (Eq. [31] in Allen *et al.* (2007)) and aerodynamic resistance, r_{ah}, (Eq. [30] in Allen *et al.* (2007b)).

Input Data:
ndvi.img
surface_albedo.img
a_1 = 0.75766
b_1 = -5.65024
Wind speed at 200 m = 4.130 (Eq. [32] of Allen *et al.* (2007b))

Output Data:
I_u_star.img
initial_rah.img
zom.img (Eq. [34b] of Allen *et al.* (2007b))

I am not so sure about the zom_adj and the wind_coeff, especially in a more or less flat but slanted basin. We need to explore this more in the future. For now let us just ignore them in the model. So use Eqs. [30], [31], [32], and [34b] but not Eqs. [35] and [36].

Step Nine: ERDAS Imagine Model 6

Purpose: Calculate the 24 hour incoming extraterrestrial solar radiation R_a for horizontal and sloped surfaces (Eq. [6] in Allen *et al.* (2006). The values of R_{a24} are needed to calculate the incoming 24 hour solar radiation at the earth surface on horizontal and sloped surfaces (see Eq. [3] and Eq. [57] in Allen *et al.* (2007b)).

Input Data:
dr
$\sin\delta \sin\varphi$
$\sin\delta\cos\varphi$
$\cos\delta\cos\varphi$
$\cos\delta\sin\varphi$
$\cos\delta$
sunrise angle
sunset angle
cos_aspect.img
sin_aspect.img
sin_slope.img
cos_slope.img

Output Data:

ra_24hours.img

This is a rather complicated model. I will assist WGISC with the implementation of this model following Allen *et al.* (2006).

Step Ten: Put weather data into REF-ET for calculation of ET_r and ET_{r_24}

The software REF-ET has been developed by Dr. Richard Allen and can be downloaded from his webpage http://www.kimberly.uidaho.edu/ref-et/ (last entered April 20, 2008).
Purpose: Calculate ET_r and ET_{r_24} from high quality hourly weather data. ET_r (mm/hour) is the instantaneous reference ET when the satellite passes over while ET_{r_24} is the daily reference ET.

We used the weather data for North Cottonwood Creek and calculated an instantaneous reference ET_r of 0.88 mm/hour at satellite overpass. We calculated an ER_{r_24} of 7.6 mm/day.

Step Eleven: Spreadsheet III

Purpose: Calculation of the *a* and *b* parameters in Eq. [29] of Allen *et al.* (2007b) using an iteration process.

Input Data:
ET_r = 0.88 mm/hour
Height of the blending layer = 200 m
Windspeed at 200 m (from Eq. 32 in Allen *et al.* 2007b) = 5.33 m/s
z_1 = 0.1 m
z_2 = 2.0 m
Elevation of cold pixel = 2258
Elevation of hot pixel = 2119
Temperature of cold pixel = 296.68
Temperature of hot pixel = 317.05
Net radiation at cold pixel = 648.6 W/m^2
Net radiation at hot pixel = 499.3 W/m^2
Soil heat flux at cold pixel = 41.07 W/m^2
Soil heat flux at hot pixel = 117.07 W/m^2
z_{om} at cold pixel = 0.115 m (for tall hay grass)
z_{om} at hot pixel = 0.007 m (for bare agricultural soil)
EtrF or “crop coefficient” at cold pixel = 1.05
EtrF or “crop coefficient” at hot pixel = 0

Output Data:
The coefficients a and b for Eq. [29] for ten iterations.

Iteration #	a	b
1	0.893884825	-265.2004314
2	0.167591859	-49.72165559
3	0.423941262	-125.7761653

4	0.304875079	-90.45125304
5	0.347460623	-103.0856601
6	0.330774842	-98.13527232
7	0.337075073	-100.0044438
8	0.334663054	-99.28883885
9	0.335581583	-99.56135087
10	0.335231086	-99.45736434

Step Twelve: ERADS Imagine Model 7

Purpose: To conduct the iterations for a correct estimate of u* and r_{ah} using the a and b coefficients from iteration numbers 4-10 and to calculate the final sensible heat flux H for each pixel.

Input Data:

Iteration #	a	b
4	0.304875079	-90.45125304
5	0.347460623	-103.0856601
6	0.330774842	-98.13527232
7	0.337075073	-100.0044438
8	0.334663054	-99.28883885
9	0.335581583	-99.56135087
10	0.335231086	-99.45736434

DEM
surface_temperature.img
surface_temperature_dem.img
zom_img
wind speed at 200 m = 5.33

Output Data:
final_h.img

Step Thirteen: ERDAS Imagine Model 8

Purpose: To calculate the instantaneous ET (ET_{inst} as mm/hour), the reference ET fraction (ET_rF), and the 24-hour ET (ET_{24}). (See Eqs. [52-56] in Allen *et al.*, 2007b).

Input Data:
net_surface_radiation.img
soil_heat_flux.img
final_h.img
ET_{r_inst} = 0.88 mm/hour
ET_{r_24} = 7.6 mm/day
ra_24hours.img
R_{a_inst} on horizontal surface = 1184 W/m^2

R_{a_24} on horizontal surface = 481 W/m^2
cos_theta_solar_incidence_angle.img
d_r = 0.967
surface_temperature.img
Output Data:
et_inst.img
et_24_hours.img

The negative ET values in the desert should be replaced by zero.
The high ET values in the shade of clouds and on the top of clouds are not correct. These are caused by the lower temperatures in cloud shades and on the top of clouds.

Appendix A.2: Header file for image LT50370312007185EDC00

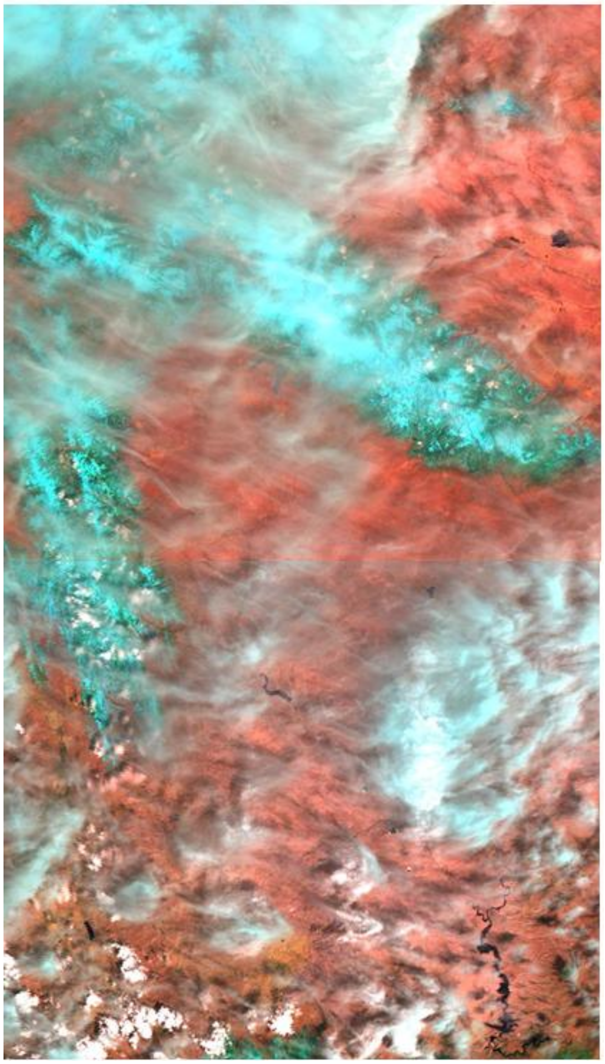
We took latitude and longitude from "NLAPS CORRECTION PROCESSING REPORT" which caused a few minor differences with the numbers in this header file.

Dataset Attribute	Attribute Value
Landsat Scene Identifier	LT50370312007185EDC00
Spacecraft Identifier	5
Sensor Mode	
Station Identifier	EDC
Day Night	DAY
WRS Path	037
WRS Row	031
WRS Type	2
Date Acquired	2007/07/04
Start Time	2007:185:17:55:09.64406
Stop Time	2007:185:17:55:36.25706
Sensor Anomalies	N
Acquisition Quality	
Quality Band 1	9
Quality Band 2	9
Quality Band 3	9
Quality Band 4	9
Quality Band 5	9
Quality Band 6	9

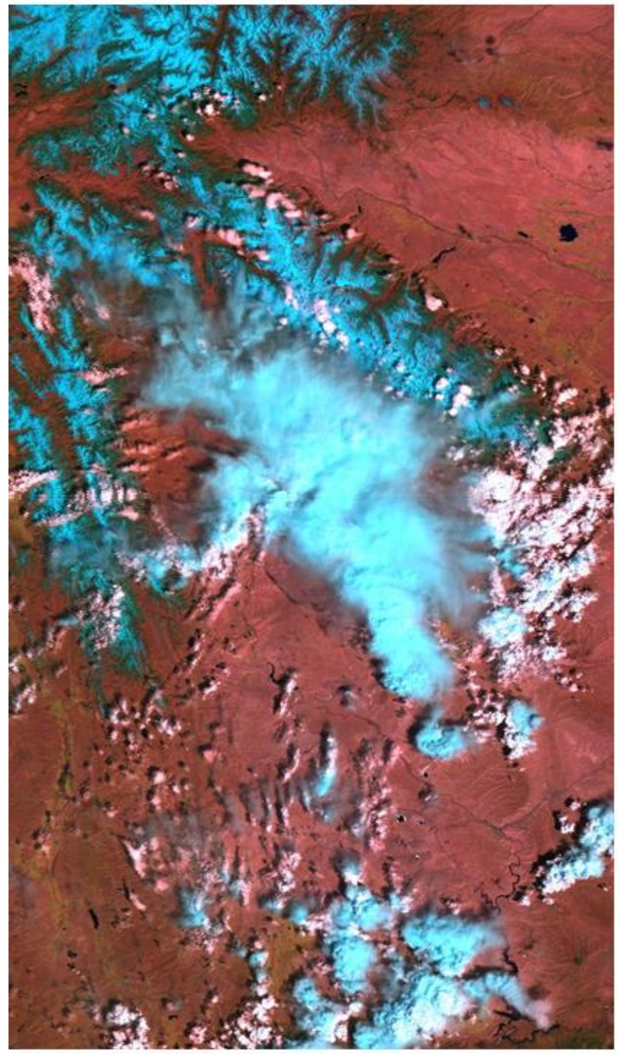
Quality Band 7	9
Cloud Cover	0%
Cloud Cover Quadrant Upper Left	0%
Cloud Cover Quadrant Upper Right	0%
Cloud Cover Quadrant Lower Left	0%
Cloud Cover Quadrant Lower Right	0%
Sun Elevation	63.50471
Sun Azimuth	128.608768
Scene Center Latitude	41.76642 (41°45’59”N)
Scene Center Longitude	-109.95930 (109°57’33”W)
Corner Upper Left Latitude	42.70857 (42°42’30”N)
Corner Upper Left Longitude	-110.80474 (110°48’17”W)
Corner Upper Right Latitude	42.38638 (42°23’10”N)
Corner Upper Right Longitude	-108.59500 (108°35’41”W)
Corner Lower Left Latitude	41.13179 (41°07’54”N)
Corner Lower Left Longitude	-111.29843 (111°17’54”W)
Corner Lower Right Latitude	40.81723 (40°49’02”N)
Corner Lower Right Longitude	-109.13984 (109°08’23”W)
Browse Exists	Y
Scene Source	LAM
CCT Source Available	N
DCT Source Available	N

Film Source Available	N

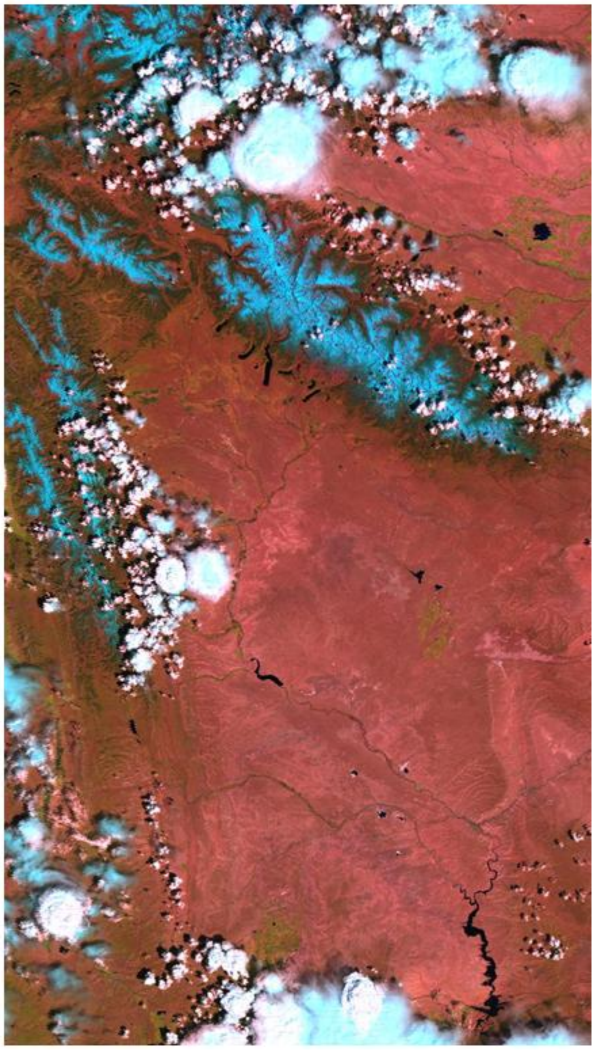
Appendix B: 2007 Landsat Image Examples



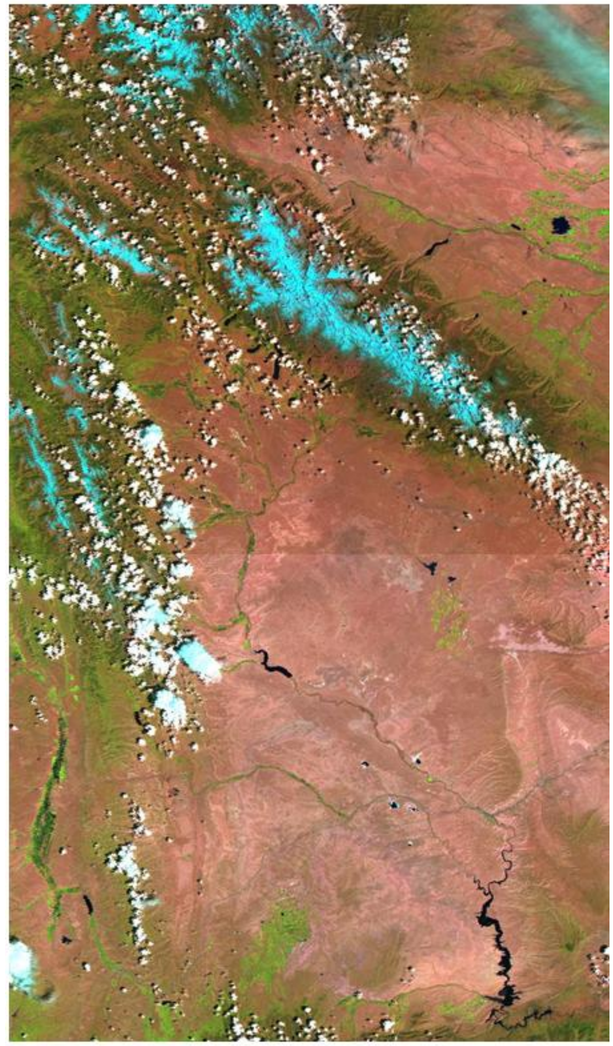
15 April



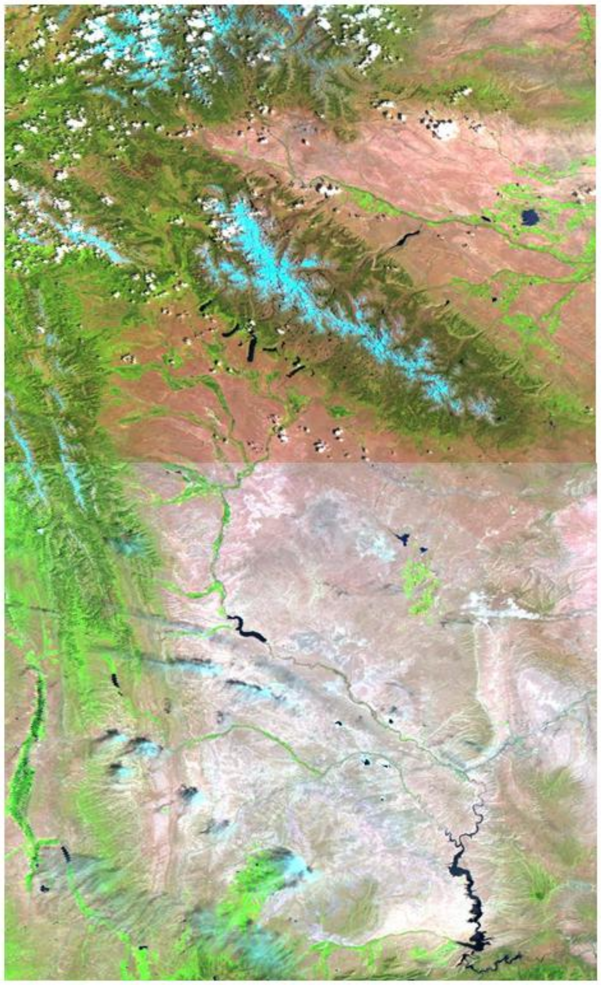
1 May



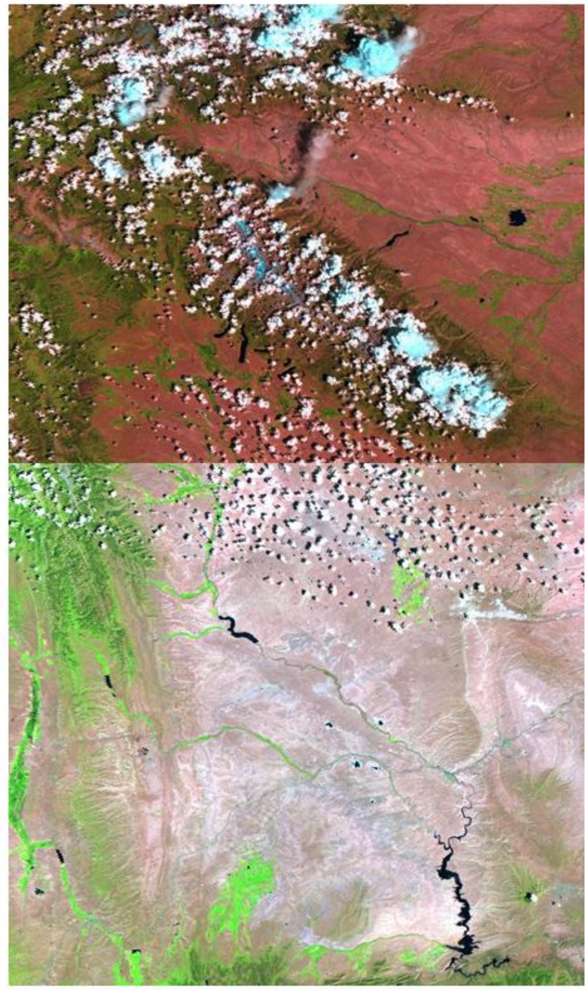
17 May



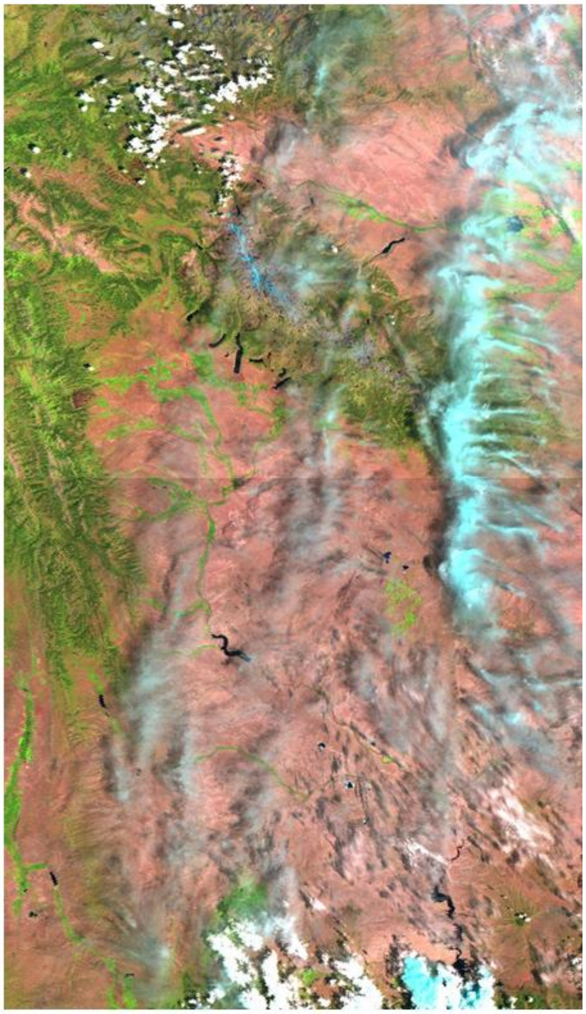
2 June



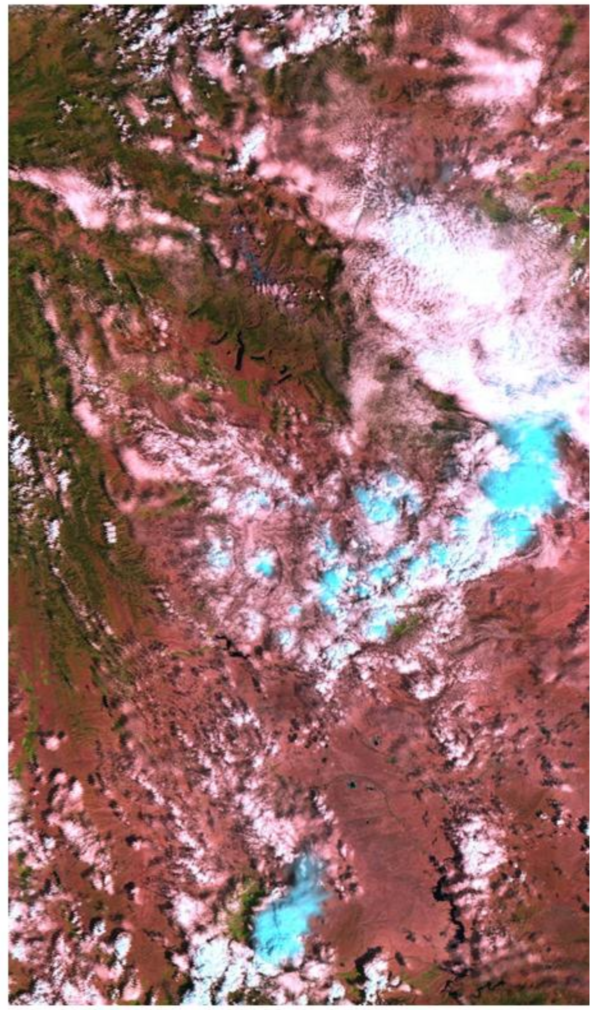
18 June



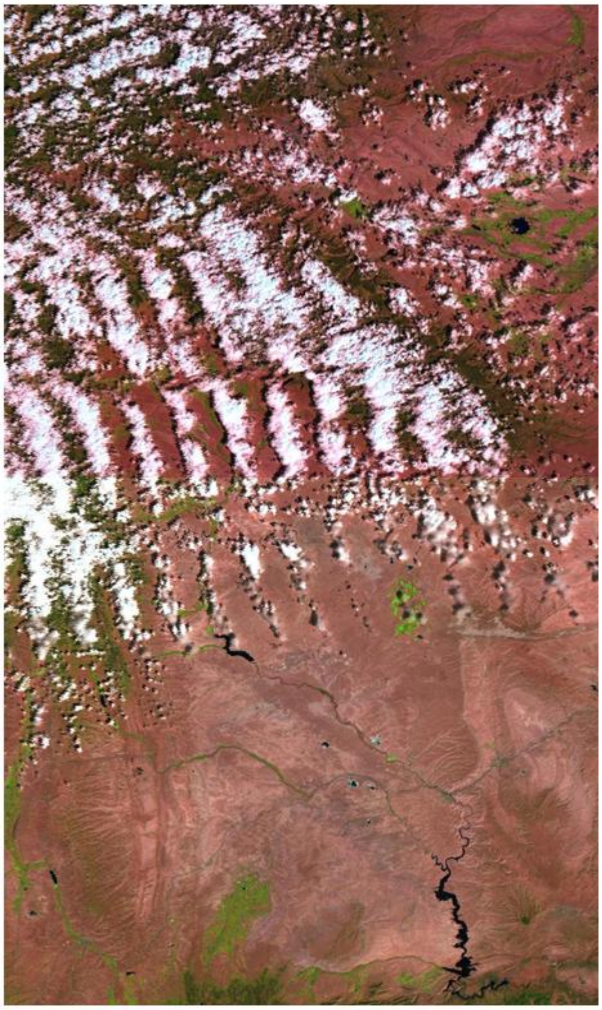
4 July



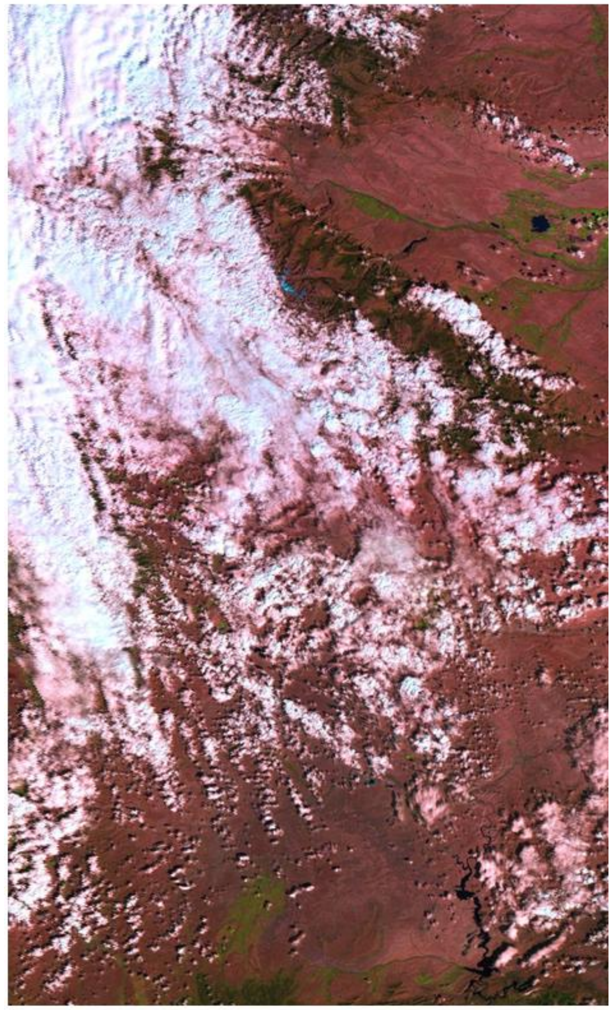
20 July



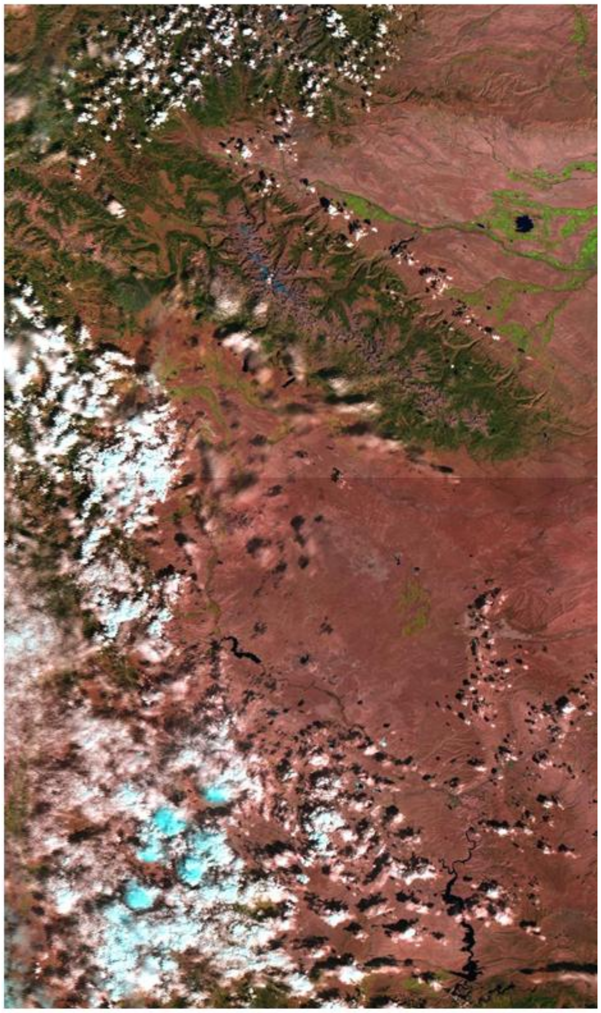
5 August



21 August



6 September



22 September

Appendix C: Field Survey Notes

2007 Field Trip, Notes: 18 – 20 June Field Trip to Upper Green

Rock Springs/Sweetwater County Airport Met Station (18 June 2007)

Station is beside runway on top of a butte that is much higher than surrounding country. Gentle rise up butte from direction of prevailing wind (west). Vegetation on butte is all sagebrush with no agriculture. No hot or cold pixels near weather station that I was able to find.

Snow Creek Met Station (18 June 2007)

Did not drive all the way to station (far out in a basin with little or no agriculture). Drove to coordinates 41 24 16 N, 108 58 56 W. From hear could survey area towards weather station which is in Wyoming sagebrush dominated rolling hills with no agriculture in area. No obvious hot or cold pixels near this station.

Killpecker Dunes north and a little east of Rock Springs (18 June 2007)

Could the Killpecker dunes, which are bare sand, serve as a hot pixel??? Lots of bare, unvegetated sand here (between Boar's Tusk and Steamboat Mt.). Top 6 – 12" of sand is dry but deeper than that there is moist sand

Eden area (19 June 2007)

Looked around Eden area. Lots of fields are under irrigation—mostly center pivot from what I could see. All irrigated areas looked like hayfields.

10:20 a.m. North of Eden found a fallow field without stubble. Possible "hot pixel" though there was some moist looking soil around the margins of some of the fields. Stopped at coordinates 41 03 41.494 N, 109 26 17.369 W on highway 191 and took photos looking west into these fallow fields. Photos are DSC_0409 and DSC_0410.

Farson area (19 June 2007)

10:35 a.m. Just west of Farson intersection (191 & 28) found a very lush green field (grass) being irrigated. Possible cold pixel though not ideal because not, e.g., alfalfa. Stopped at cords 42 06 18.463, 109 27 34.412 which are just south of the field along the road. Took photos DSC_0412 and DSC_0413 looking north from road (rt. 28) into the field.

Field east of the above green field is not green but is covered with dead vegetation. NOT a good hot pixel.

10:45 a.m. Just north of Farson and east of hwy 191 found another very green field being irrigated. Coordinates on road west of the field are 42 07 32.089 N, 109 27 18.327 W. Took photo DSC_0414 looking east into the field. Possible cold pixel.

Pinedale Airport Met station (19 June 2007)

Stopped to check out the weather station at the Pinedale airport. The area west of the airport (upwind) is sagebrush dominated for about 1 km. Then there is a cottonwood riparian zone running north south and west of the riparian is a bluff that looks like sparse sage. East of the airport (upwind) is a mixture of sagebrush and housing developments.

Half Moon Lake Met station (19 June 2007)

Investigated the Half Moon Lake Met station west of Pinedale in foothills of Wind Rivers. Station sits on top of an east-west oriented ridge that is dominated by sagebrush with a few pines (limber??) scattered around. No agriculture near the station. Photos DSC_0416 and DSC_0417 are looking south at the station on the ridge.

SEO North Cottonwood Creek at Ryegrass Ranch station west of Daniel (19 June 2007)

Visited the station that Steve Wolff installed west of Daniel and NW of Pinedale. Photos DSC_0418 and DSC_0419 are overview of area looking south into the stream bottom where station is located. Photo DSC_0420 and DSC_0421 in station area. Station is near Cottonwood Creek beside a house on a bluff that sits just south of Cottonwood Creek. Willows in stream bottom (Photo DSC_0422) but on bench where house is located is Wyoming sagebrush (Photo DSC_0423). No good hot or cold pixels near the station (some grass/sedge meadows north of Cottonwood Creek but not lush). There are some barren bluffs/badlands about 1 mile east of station and north of Cottonwood Creek (photos DSC_0424 and DSC_0425) but these are only bare on their steep faces and are vegetated on top.

South of t-intersection due south of above station is a large sedge/grass meadow (photo DSC_0426) that is not too lush.

All riparian in this area is willow dominated—no cottonwoods.

Fields were just starting to green-up a bit. Although folks were just starting to put some water in their ditches, very little field irrigation going. There is a stream gage on North Cottonwood Creek about 150 yards from the ET Station. The whole Wyoming Range area is water short, so we will probably see folks work hard to use water as judiciously as possible in this area.

Muddy Creek Met station (19 June 2007)

Drove out to check the Muddy Creek station but it required crossing private land to access. Met the rancher who told me that there is no agriculture anywhere in vicinity of station. Vegetation is sage/grass with patchy juniper. Rancher was willing to let me drive out there but suggested clearance of van might be a problem and he was nervous about his sheep in area which were lambing. So I took his word on the veg.

SEO station Smith's Fork north of Robertson (Ft. Bridger area) (20 June 2007)

Visited site of Steve Wolff's station near Robertson. Station is in scattered willows on private land in riparian zone (I couldn't see actual station but was very close). Scattered cottonwoods around station. Area east and west of station outside of riparian is grass pasture that gets irrigated. Not perfect cold pixels but as green as anything around. Photo DSC_0509 from road looking north into the area where I think the station is.

Green field near Robertson south of hwy 410 where it runs east-west. Field is grass that is being irrigated partially and it is green but not totally lush. Coordinates 41 11 07.925 N, 110 22 45.626 W are on road just north of the field. Photos DSC_0505 and DSC_0506 looking south into this site.

More lush fields (grass) being irrigated both north and south of hwy just east of Robertson. Coordinates 41 11 07.223 N, 110 24 20.196 W on hwy just north of site. Grass is about 1 foot tall. Possible cold pixel but not totally lush like alfalfa would be. Photos DSC_0907 and DSC_0908 looking south from hwy into the field.

Active small quarry north of Robertson station to west of hwy. Coordinates 41 14 16.967 N,
110 21 53.735 W are on hwy looking west into the quarry. Photos DSC_0503 and DSC_0504 are taken looking west into quarry area from hwy. Possible hot pixel BUT the area is not huge and is pretty heterogeneous—piles of quarry material, a little stray vegetation here and there, etc. This is the closest place I could find to bare ground in vicinity of met station—no fallow fields where I went.

Folks have been irrigating on the benches for a week or two. Fields along the creek bottoms (where this station is) haven't received much irrigation yet because soil moisture is still high. This sight is in an area with very senior water rights and owned by an individual who works hard to be a good water manager.

Due to a software problem on Campbell Scientific's end, the stations weren't operational until May 2 and 3, respectively.

Additional Farson NRCS ET Station

The NRCS station at Farson was not visited during this 2007 trip.

2008 Field Trip, Notes: 7 – 9 May Field Trip to Upper Green

Farson NRCS station (7 May 2009)

Extensive irrigated hay being produced in area including Eden irrigation district. No bare fields noted, but intense searching was not performed. NRCS station is located in an area (20m x 20m) of relatively tall big sagebrush (Artemisia tridentata) with an understory of bunchgrasses and rhizomatous grasses (see photos in Figures 2.3a and 2.3b). Steve Wolff was able to successfully access the station data logger and download data to his portal computer. The station is not in a very ideal location to calibrate METRIC^{tm}, but may serve as a comparative measure of local ET.

Pinedale (7 May 2008)

Travel from Farson to Pinedale was under heavily disturbed weather with rain, snow, and hail.

The group in conjunction with local staff from State Engineer's Office traveled to possible locations of good ET sampling and station location. Looking for areas of access including state land parcels the group traveled to two state parcels used as natural/semi-natural irrigated pasture. The first site contained a heavy component of woody vegetation and was less ideal. The second site, upon investigation, showed a fairly large extent dominated by short statured graminoid and forb plants comparable to local agricultural condition. Site is located within Duck Creek Drainage a State section of land about 4 miles west of Pinedale on highway 191.

SEO North Cottonwood Creek at Ryegrass Ranch station west of Daniel (7 May 2008)

From North Pine Creek the group traveled across relatively (for Upper Green River agricultural areas) high elevation pasture, hay field, and rangelands to the Ryegrass Ranch. Cool aspect slopes traversed in the area still contained significant amounts of moisture heavy snow pack.

Irrigation ditches in the area were filled. Sod forming grasses (such as bluegrass) dominate the area around the station. Depending on scale and prevailing winds, the station could be influenced by willow complex to north or sagebrush dominated hillside and road to south.

The group traveled through Big Piney to Evanston looking at land cover and possible areas for Hot and Cold pixels needed to calibrate the Landsat in METRIC.

SEO station Smith's Fork north of Robertson (Ft. Bridger area) (8 May 2008)

The group met up with local staff from the State Engineer's office in Ft. Bridger. We reviewed the irrigation methods whether the more common historic flood or more recently employed sprinkler systems.

Some steeply sloped irrigated fields as well as new conversions of rangelands to pivot irrigation hay fields were noted. Soils usually are thin with mollic characteristics over alluvial outwash that, for example, is coarse at the station.

The Smith's Fork station is about 20 m from the river and experiences a heavy influence from trees up to 25 ft tall near the station. The station could not be easily situated with the hay field itself so is along the edge of the field and the Smith's Fork riparian zone.

Pinedale (18 August 2008)

Rodemaker traversed the edge of the mesa to the south of our Duck Creek station installed by Dr. Ogden in July.   A site was identified that may provide a suitable location to collect scintillometer data across the Duck Creek station area. The top of the knoll was recorded to be at coordinate 587281 meters east, 4745285 meters north in the 12th zone of the Universal Transverse Mercator projection system using datum *NAD83* and spheroid *GRS1980*. A stake was located at the coordinate when visited and is accessible via public road (2 track) across BLM and State lands.

	
Figure Xa. Photograph looking north at small knoll on the edge of The Pinedale Mesa.	**Figure Xb**. View looking north at Duck Creek station site from knoll on north edge of The Pinedale Mesa.

At the time, smoke from forest fire had dominated the Pinedale area for a number of days but had cleared by the 17/18th. Much of the hay had been cut in the Duck Creek fields recently. Disturbance associated with the PAPA, Pinedale Anticline Project Area, oil and gas development was occurring within 5 miles of the station including extensive road building generating dust.

Appendix D: Site Photographs


DSC_0409


DSC_0410


DSC_0412


DSC_0410


DSC_0414

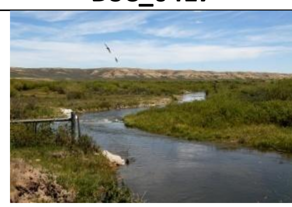

DSC_0416

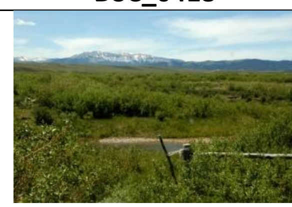

DSC_0417


DSC_0418


DSC_0419


DSC_0420

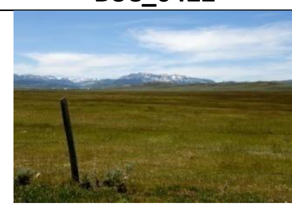

DSC_0421


DSC_0422


DSC_0423


DSC_0424


DSC_0425


DSC_0426


DSC_0449


DSC_0450


DSC_0503


DSC_0504


DSC_0505


DSC_0506


DSC_0507


DSC_0508


DSC_0509

Prepared for the Wyoming State Engineer

by

UNIVERSITY OF WYOMING