METRIC: High Resolution Satellite Quantification of Evapotranspiration

University of Idaho, Kimberly, Idaho

Part Three - applications

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Requirements of the Satellite
Any satellite with thermal band

- ASTER
  - 15 m short wave
  - 90 m thermal
  - 8 to 16 day overpass (potential)
  - Usually not “on” due to communication saturation (shares Terra with MODIS)
  - Need to be on science team to request
  - Usually two to three images per season
Any satellite with thermal band

- **Landsat**
  - 28.5 m short wave
  - 60 m thermal (LS7), 120 m (LS5)
  - 16 day overpass
  - LS5 has a few years of fuel (1984 launch)
  - LS7 has broken scan line corrector (1998 launch)
    - Some use if in middle 1/3 of image
  - The Very Best Satellite for METRIC and High Resolution ET Mapping (30 m is optimum size)
  - USGS / NOAA / NASA need encouragement to launch new Landsat. NPOESS (future MODIS) ‘may’ contain Landsat equivalent shortwave bands, but probably not thermal (at 60 to 120 m resolution).
Any satellite with thermal band

- **MODIS**
  - 500 m short wave (250 m for NDVI)
  - 1000 m thermal (WHEN near NADIR !!!!!)
  - Usable overpass each four days or so
  - Terra (10 – 11:30 am) and Aqua (1 to 2:30 pm)
  - Problems with:
    - Bow tie effect at large scan angle expands thermal pixels to 2000 m x 3000 m and short wave to 1000 m x 1500 m and displaces (creates smearing of resolution)
    - Thermal (LST) fallout near hot/cold boundaries
    - Streaks in some short wave bands
    - 8 day thermal (LST) is average of all clear days including smeared pixels on high scan angle days
    - 8 day reflectance and albedo are for single day, usually near nadir, but can be a mix of days.
    - Therefore, energy balance, which ‘would like to know’ the time of overpass for total image for computing solar radiation and for defining the \( \Delta T \) vs. \( T_s \) function, is not the same for all pixels.
Any satellite with thermal band

- AVHRR of NOAA
  - ~1000 m short wave
  - 1000 m thermal (WHEN near NADIR !!!!!)
  - Usable overpass each four days or so
  - Has been used extensively in past studies by WaterWatch with SEBAL
Impacts of Satellite on Resolution: MODIS
MODIS is a ‘daily’ Satellite but does not provide useable images every day.
Landsat and MODIS

705 km

Earth

6400 km
MODIS (Terra and Aqua)

Earth

705 km
6400 km
1400 km
2400 km

60°
705 km
1400 km
Landsat

705 km

7° max

160 km

6400 km

Earth
MODIS-AM

range of solar zenith angles

Δ θ°

Backscatter view zenith angle

θ°

Forward scatter view zenith angle

Nadir

BRDF

Increasing pixel size with view angle

2330 km swath
descending orbit MODIS-AM
Panoramic bowtie effect -- MODIS

Scan Angle

Track

Scan

Satellite

Cross Track

Along Track

Scan Lines

Scan 1

Scan 2

Scan 3

2340 km

20 km

10 km

from MCM-ATBD-01-U-DNCN
MODIS pixel dimensions, cross-track and along-track, change with scan angles: 
0° - 250 x 250 m; 15° - 270 x 260 m; 30° - 350 x 285 m; 45° - 610 x 380 m
Over Pass Time, Twin Falls, Idaho

August 1-16, 2004 ---MODIS

Day of Year

Over Pass Time, hrs, Local Time

Aqua
Terra
Scan Angle (from Zenith), Twin Falls, Idaho

August 1-16, 2004 ---MODIS

Sensor Scan Angle, Deg from Zenith

Day of Year

Aqua
Terra
Scan Angle Effect on Reflectance, S. Idaho
Scan Angle Effect on Reflectance, S. Idaho

MODIS Surface Reflectance -- Desert

Aqua

Terra
Scan Angle Effect on Reflectance, S. Idaho

MODIS Surface Reflectance -- Crop Uniform

Aqua

Terra
Scan Angle Effect on Reflectance, S. Idaho

MODIS Surface Reflectance -- Lava

Aqua

Terra
Scan Angle (from Zenith), Twin Falls, Idaho

August 1-16, 2004 ---MODIS

Sensor Scan Angle, Deg from Zenith

Aqua
Terra

Day of Year
Landsat5: 8/31/2003

\[ \overline{ET_rF} = 0.40 \]
\[ \text{std. dev.} = 0.36 \]

MODIS: 8/31/2003 (57°)

\[ \overline{ET_rF} = 0.46 \]
\[ \text{std. dev.} = 0.20 \]

MODIS: 8/9/2004 (2°)

\[ \overline{ET_rF} = 0.37 \]
\[ \text{std. dev.} = 0.25 \]

\[ ET_rF \text{ by METRIC} \]
Ts (K)

290
303
316
330 +

Landsat5: 8/31/2003
MODIS: 8/31/2003 (57°)
MODIS: 8/9/2004 (2°)
Landsat5: 8/31/2003
Conclusion: 8-day LST is strongly correlated with LST for each day, even though not 1:1. Therefore, $dT$ vs. $T_s$ from 8-day LST will probably work with any day.
Level 1 calibrated radiance, imported using nearest neighbor resampling, has “holes” for all evaluated shortwave and longwave bands (i.e. bands 1~7 and 31&32).

When imported using Bilinear resampling, holes disappeared due to averaging from surrounding pixels. However, smearing increases and information is lost.
MODIS: 8/31/2003, Level2 5min LST

Level 2 5min LST represents a daily instantaneous LST image. White locations are ‘missing’ LST due to missing thermal emissivity due to mis-categorization of pixel as a cloud near irrigated/desert boundaries.

Daily LST products have these fall-outs also, but the number of the holes is less, primarily because of the smearing effect of resampling.

Currently, METRIC uses Level 1 radiance (using calibration of LST vs. radiance by aggregation of ‘good’ pixels in LST image). Level 3 8-day LST may also be useable
Another problem with MODIS Sensors:
Band 5 (2\textsuperscript{nd} NIR) has been having striped output.
Stripes are present in all Level 1 – 3 products.
This problem has been reported for many bands as “known issues”.
http://modland.nascom.nasa.gov/cgi-bin/QA_WWW/getSummary.cgi?esdt=MOD09

These two images false color using Bands 5-1-4.
Solution: Omit band 5 from albedo computations.
Problem in 8-day reflectance product:

One image (date) is selected to represent reflectance for each pixel, based on a ‘minimum Blue-Band (MinB) method.’ This method generally selects near-Nadir image pixels and generally works well. However:

a) The method tends to select shadows by clouds (low in blue band)
b) Each pixel can potentially come from a different date (therefore, confusion in Energy balance as to which \( \cos(\theta) \) to use.

Other Satellite-based Energy Balance
SEBI/SEBS

- Surface Energy Balance Index
- Surface Energy Balance System
- Menenti and Su of Wageningen, NL
- Considered by MODIS Team for global ET coverage
SEBI/SEBS

Advantages:

- Derives hot/dry and cold/wet “anchor” points from and for each pixel independent of all others
  - Penman equation (~saturated surface is inverted to solve for $T_s$ for wet condition)
  - Penman-Monteith equation (high resistance) is inverted to solve for $T_s$ for dry condition
- Does not require a thinking human at the controls (as much)
Disadvantages/Challenges:

- To invert Penman equation, a vapor pressure of air estimate is needed for large areas
  - Vapor pressure can vary widely in western U.S. from desert to irrigated
  - Air temperature at some blending height (~200 m) must be specified and assumed constant over large area
- Problem of flux divergence and heat/vapor absorption between surface and blending height (resistance equations and “k” theory assume instantaneous arrival of heat/vapor at blending height and no storage (problem in arid climates)
SEBI/SEBS

$T_{\text{air}}$ at blending ht

$T_s$ from satellite, $T_s$ from Penman wet, $T_s$ from P-M dry
Disadvantages/Concerns:

- Bias in $T_s$ from satellite is not removed
  - Therefore, $T_s$ from satellite is not congruent with back-calculated $T_s$ endpoints from PM eqn.

- Aerodynamic Temperature vs. Radiometric temperature (even with accurate $T_s$ from satellite)

- Need for vapor pressure for PM equation
TSEB

- Two-source energy balance
- Each pixel split into vegetated vs. bare soil according to NDVI or other VI
- Assumes clustered vegetation rather than distributed
- (energy balance process is relatively linear. Partitioning may not buy much)
Comparison to $K_c$ Curves
Use to Refine Local $K_c$ Curves

Potato

Average “curve”

717 fields in the Twin Falls area

Vegetation Index

Seasonal Evaporation during 2000 Eastern Snake River Plain, Idaho
$K_c$ near 1.0 indicating high production agriculture
Comparison with Local $K_c$ Curves
-- south-central Idaho

Agrimet $K_c$’s are based on Wright (1981) (ASCE Manual 70)

AgriMet is a USBR weather-based irrigation advisory service in the Pacific Northwest
Comparison with Local $K_c$ Curves
-- south-central Idaho

Agrimet $K_c$'s are based on Wright (1981) (ASCE Manual 70)

**Corn**

**Potato**

**Sugar Beet**

**Peas**

Little need to adjust $K_c$
Use to Refine Local $K_c$ Curves

Sugar Beet

(Original $K_c$ curve is in ASCE Manual 70)
Use to Refine Local $K_c$ Curves

Sugar Beet

(emergence, cover or harvest dates from Agrimet are modified to match METRIC)

(Original $K_c$ curve is in ASCE Manual 70)
Use to Refine Local $K_c$ Curves

(W. Grain)

(Original $K_c$ curve is in ASCE Manual 70)
Use to Refine Local $K_c$ Curves

W. Grain

(emergence, cover or harvest dates from Agrimet are modified to match METRIC)

(Original $K_c$ curve is in ASCE Manual 70)
Refine Local $K_c$ Curves: Wheat in Imperial Valley

WST = Water Study Team (1998) – estimated ET using the CIMIS-style linearized $K_c$ method
Crop Coefficient (ETrF) vs. NDVI

717 Potato Fields, 2000

3 June
Crop Coefficient (ETrF) vs. NDVI for 717 Potato Fields, 2000

Data points for 3 June and 19 June are shown.

717 Potato Fields, 2000
717 Potato Fields, 2000

Crop Coefficient (ETrF) vs. NDVI

Dates:
- 3 June
- 19 June
- 21 July
717 Potato Fields, 2000

Crop Coefficient (ETrF) vs. NDVI

“basal” Kc

3 June, 19 June, 21 July
717 Potato Fields, 2000

Crop Coefficient (ETrF)

NDVI

“mean” $K_c$

“basal” $K_c$

3 June

19 June

21 July
“mean” $K_c$ vs. NDVI

May to September 2000
Magic Valley, Idaho
Averages of 100's of fields each satellite date

Well-watered fields

$K_c (ETrF)$ vs. NDVI (toa)

Alfalfa
Sugar Beet
Corn
Potato
S.Grain
W.Grain

$ETrF = 1.25 \text{ NDVI}$
Hysteresis on increasing and decreasing NDVI

Magic Valley, 2000, METRIC

Averaged over 100’s of fields
"mean" $K_c$

Potato

$K_c$

NDVI

- 6/3
- 6/19
- 7/5
- multi-field average (for 12 images Mar-Oct)
“Population” of ET from fields of the same Crop
(i.e., not all alfalfa fields are the same)

Alfalfa ET in Sample - Ab / Am Falls 2000

Seasonal ET by METRIC

Bryce Contour, Univ. Idaho
Application of ET "maps"
Applications of METRIC™

Bear River:
- Three-state commission for managing allowable depletion by state

Eastern Snake Plain Aquifer
- ET for water rights management
- Estimation of ground-water pumpage (to replace the use of power consumption factors)
- ET for ground-water model calibration and operation for impact / injury of ground-water pumping on spring discharge and aquiculture
- Derivation / correction of crop coefficient curves
Applications of METRIC™

- All of Southern Idaho
  - Total consumption by irrigated agriculture by county and state
  - Water balances of stream basins

- Salmon River and Lemhi River (Idaho)
  - Management of irrigation diversions to leave water instream for endangered species
  - ET input into the MIKE-Basins hydrologic model

- Boise River
  - ET by land use type
  - Change in ET with conversion of agriculture to residential
Applications of METRIC™

Imperial Valley in S. California
- District-wide ET
- ET variation within fields
- Ease administrative burdens for assessment or verification of impacts from water transfer
- Provide an independent look at the quantity of water freed up from fallow and other programs

Middle Rio Grande in New Mexico
- Actual consumptive use by irrigated agriculture
- Consumptive use by riparian vegetation (cottonwood and salt cedar)
- Evaporation from shallow water tables
Snake River Plain and Aquifer
Yellow “dots” are ground-water wells

“Senior” Irrigators from River ~1900

“Junior” Irrigators from Aquifer ~1960

Senior Aquiculture from Springs ~1950

Junior consumption from Aquifer “Injures” Senior River and Spring Rights

“Senior” Irrigators from River ~1900
AVERAGE ANNUAL SPRING DISCHARGE TO SNAKE RIVER
BETWEEN MILNER AND KING HILL
1902-2002  (Thousand Springs area)
Trend Line: Decline 430 cfs to 338 cfs in 52 years - 21.4%

\[ y = -0.0048x + 518.12 \]
Ground Water Pumping Impact to Springs
(Appearing after 3 Years)

Courtesy Brockway Engineering, Twin Falls, Idaho
Boise River Valley, Idaho

ET BY LAND USE CLASS

• Benefit: New Information
• Cost: ±$70,000

<table>
<thead>
<tr>
<th>Class Name</th>
<th>ET in mm</th>
</tr>
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<tbody>
<tr>
<td>Petroleum Tank Yards</td>
<td>237</td>
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<tr>
<td>Rangeland</td>
<td>242</td>
</tr>
<tr>
<td>Unclassified</td>
<td>298</td>
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<tr>
<td>Barren</td>
<td>335</td>
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<tr>
<td>Commercial / Industrial</td>
<td>380</td>
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<td>Transportation</td>
<td>420</td>
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<td>Idle Agriculture</td>
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<td>Abandoned Agriculture</td>
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<td>Junk Yard</td>
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<td>Recreation</td>
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<td>Water</td>
<td>924</td>
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<tr>
<td>Wetland</td>
<td>1,025</td>
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</tbody>
</table>

Class Name: ET in mm
Actual ET from wetlands and riparian systems

Boise Valley Seasonal ET 2000
ET maps on the web: Southern Idaho – ET by year
http://maps.idwr.state.id.us/et
Middle Rio Grande Region of New Mexico

- Interest in consumptive use of irrigated agriculture
  - Small holdings
  - Less than full water supply in areas
  - Some areas of water logging
- Interest in nonbeneficial consumptive use
- Interest in ET by riparian systems
Area just south of Albuquerque along Middle Rio Grande
False color, Daily, Monthly and Annual ET_{rF} for an area along the MRG south of Albuquerque.

Daily
8/26/2002

Monthly
August 2002

Annual
2002

ET (mm/yr)
0
500
1000
1500
2000
2500

ET_{rF}
0.00
0.25
0.50
0.75
1.00
1.25
False color, Daily, Monthly and Annual ET$_{rF}$ path 34, San Acacia, New Mexico to Colorado

- Daily: 8/26/2002
- Monthly: August 2002
- Annual: 2002
Middle Rio Grande Region of New Mexico

Alfalfa* - MRG, 2002

Open Water - MRG, 2002

Cottonwood - MRG, 2002

Salt Cedar - MRG, 2002

* Sample fields were alfalfa in 2004, but might be other crops in 2002.
Middle Rio Grande Region of New Mexico

Area is between Cochiti and San Acacia
Other Uses:
Variation in ET between Tops and Bottoms of Fields

Do bottoms of Surface-Irrigated Fields suffer lower ET due to poor irrigation or salinity?
Close up showing field outlines (green) and high elevation quarter (red) and low elevation quarter (blue) for fields
ET Variation within Fields

Quartered and buffered field polygons
ET Variation within 4200 Fields: 2002

$ET_\text{F}$ is the “fraction” of reference $ET = K_c$

Blue lines are regression lines. Red lines are regression through origin.
ET Variation within 4200 Fields: 2003

$\text{ET}_f F$ is the “fraction” of reference ET $= K_c$

*blue lines are regression lines*  *red lines are regression through origin*
ET Variation by crop type: 2003

ET<sub>rF</sub> is the “fraction” of reference ET = K<sub>c</sub>
Aggregation of ET in Space
Aggregation of ET for pumping entities

Blue dots are wells

IDWR Arcview field and ownership boundaries

American Falls Reservoir

T. Morse, IDWR
Aggregation of ET for pumping entities

Seasonal ET

IDWR Arcview field and ownership boundaries

American Falls Reservoir

T. Morse, IDWR
WIMS Pumpage vs. SEBAL ET, 2000

1:1 w/ 200 mm Precip shift

Depleted Soil Moisture?

Questionable Pumping Records

T.Morse, IDWR
24-hour Evapotranspiration - July 10, 1999

Tampa Bay, Florida:
Impact of Ground-water pumping by City on Natural Vegetation

The brighter the pixel, the greater the Evapotranspiration

Water (Gulf of Mexico)

Agriculture

Forests + Wetlands

Tampa Bay City
Aggregation of ET for Hydrologic units

SEBAL: Tampa Bay area, Florida
July, 1999

ET, inches/week

Use ArcView, etc., to aggregate the ET for an area of interest
Imperial Valley

ET during January - March, 2003
Aggregation of ET maps with GIS

- Geographical Information System (GIS) of IID (by USBR) structured for analysis of ET
  - individual field polygons by BOR using satellite
GIS allows for statistical analyses

- Distribution of Field Lengths in southern Imperial Valley
Aggregation of ET in Time
Calculation of the Energy Balance

Seasonal Evapotranspiration during 2000
Eastern Snake River Plain, Idaho

4 million acres with 30 m resolution
Conclusions

- ET maps are valuable for:
  - Determining *Actual* ET
  - Refining Crop Coefficient Curves (f.e. for a new ET reference)
  - Water Rights Conflicts
  - Ground-water Management
  - Consumption by Riparian Vegetation

- ET maps by METRIC™ have good accuracy and consistency with the Reference ET approach
Requirements for SEBAL or METRIC™

- Satellite images with **Thermal Band**
  - Higher resolution (Landsat) is needed for field scale maps

- Good quality weather data if local calibration is desirable

- Experienced, thinking human at the controls
More information at:

- www.kimberly.uidaho.edu/water/ (METRIC™)
- www.waterwatch.nl
- www.sebal.us (SEBAL™)
- http://maps.idwr.state.id.us/et