
Chuck Dalby, Hydrologist, Water Resources Division, DNRC
Troy Blandford, Water Information System Manager, Montana State Library
Bill Greiman, Agricultural Engineer, Reserved Water Rights Compact Commission, DNRC
Kyle Blasch, Hydrologist and Assistant Director, U.S. Geological Survey (USGS), Montana Water Science Center
Roy Sando, GIS analyst, USGS, Montana Water Science Center (Helena, Montana)
Jared Oyler, Software Engineer, Numerical Terradynamic Simulation Group, Montana Climate Office College of Forestry and Conservation, University of Montana (Missoula Montana)
Topics

1. **What is ET? Why do we care and how is it measured?**

2. **Surface Energy-Balance Methods**
   - SEBAL (Wim Bastiassen, TU Delft)
   - METRIC (Richard Allen, UI-Kimberley Id.)

3. **Montana Applications**
   - **METRIC**
     - Flathead Basin (CSKT Compact--Bill Greiman)
     - Smith River (Water Budget, GW modeling--Roy Sando, Kyle Blasch
     - Dillon, S. Central MT, GW modeling --John Wheaton, Julie Butler
     - Wyoming (MT v. WY U.S. Supreme Court Litigation)
   - **MODIS**
     - Statewide--Temp. and ET model (Jared Oyler)
   - MWSI-ETCU -- Statewide ET and Consumptive Use (Greiman, Dalby, Blandford)
1. What is ET?

Evaporation = water vaporized and removed from the evaporating surface.

Transpiration = vaporization of liquid water contained in plant tissues and vapor removal to the atmosphere.

Evaporation and Transpiration (ET) occur simultaneously and are a function of:
- energy, vapor pressure gradient and wind.
- crop and growth stage
- soil
- water management
Why do we care about ET?

ET is typically 10 to 50 (or >) % of annual water budget

\[ \text{ET} = \text{P} - \text{R} - \Delta S \]

where

- \( ET \) = evapotranspiration
- \( P \) = precipitation,
- \( R \) = outflow,
- \( S \) = change in water storage (lakes, reservoirs, groundwater)
1. What is ET? Why do we care and how is it measured?

WHY IS EVAPOTRANSPIRATION from IRRIGATED LAND IMPORTANT?

~2.5 million acres 500,000 acres of irrigated agriculture in Montana
>90% of total water diverted for use, is diverted for irrigation;
of the total water consumed >90% is consumed by irrigation.

Accurate information on ET is essential for good water management,
(hydrologic modeling, water planning, water rights administration).

NRCS Photo
How is ET measured?

1. What is ET? Why do we care and how is it measured?

2. ET measurement

3.1. ET using change in soil water

3.2. Evapotranspiration from mass balance over large areas

3.3. Lysimetry

3.4. Bowen Ratio Energy Balance (BREB)

3.5. Eddy covariance

3.6. Fetch requirements for boundary layer measurements

3.7. Scintillometers

3.8. Sap flow methods

3.9. Remote sensing energy balance

3.10. Satellite-based ET using vegetation indices
ET from mass balance over large area: (residual of watershed water budget)

ET = P - R - ΔS

where

ET = evapotranspiration
P = precipitation,
R = outflow,
ΔS = change in water storage (lakes, reservoirs, groundwater)

Key problem: errors in inputs and outputs accumulate in ET
(problem for all methods that calculate ET as residual)
1. What is ET? Why do we care and how is it measured?

**Lysimetry: weigh soil cube to measure ET**

Considered most accurate, but essentially a "point" measurement.
1. What is ET? Why do we care and how is it measured?

Scintillometry: measure small changes in refractive index of air caused by changes in temp, humidity

ET is calculated as a residual of the energy balance:

- \( ET = R_n - G - H \)
- Net radiation, \( R_n \), and soil heat flux, \( G \), must be measured
- All error in \( R_n \), \( G \) and \( H \) transfer into \( ET \)
Surface-Energy Balance Methods rely on Conservation of Energy to calculate energy balance in boundary layer, and ET as residual of energy balance.

\[ R_n - G = H + LE \]

≈ boundary layer over field (~3m for alfalfa)
Why Energy balance?

ET is calculated as a “residual” of the energy balance

\[ \text{ET} = R_n - G - H \]

**Latent heat flux = energy consumed by ET**

- \( R_n \): radiation from sun and sky
- \( H \): heat to air
- \( G \): sensible heat flux to ground

**Basic Truth:** Evaporation consumes Energy

**Source:** Rick Allen, University of Idaho
Convert latent heat flux into mass flux of water

\[ L = \rho_w \lambda_v ET \]

\[ \text{Wm}^{-2} (\text{Jm}^{-2}\text{s}^{-1}) = \frac{\text{kg} \cdot \text{J}}{\text{m}^3 \cdot \text{kg} \cdot \text{s}} \]

or \[ ET = \frac{L}{\rho_w \lambda_v} \]

- \( L \) = latent heat flux
- \( ET \) = evapotranspiration rate (m s\(^{-1}\))
- \( \rho_w \) = density of water (1000 kg m\(^{-3}\))
- \( \lambda_v \) = latent heat of vaporization (2.5\( \times \)10\(^6\) J kg\(^{-1}\))
- Latent heat exchange per unit area converts a volume of water (per unit area) to vapor
  
  The energy required for this conversion is
  - the volume of water per unit area (\( E \))
  - multiplied by the latent heat of vaporization
    - energy required to convert a kg of water to vapor
  - and by the density of water
  - which converts the mass per unit area to a volume per unit area

1. What is ET? Why do we care and how is it measured?
2. SURFACE-ENERGY BALANCE METHODS

Operational ET “mapping” using energy balance – two common models

**METRIC analysis provides:**
- daily, weekly, *monthly* ET
- 30 m pixel resolution

**SEBAL analysis provides:**
- daily, weekly, *monthly* ET
- 30 m pixel resolution

**Mapping EvapoTranspiration with high Resolution and Internalized Calibration**

Allen and associates and partners
University of Idaho, Kimberly
- development began in 2000
- rooted in SEBAL

**Surface Energy Balance Algorithm for Land**

Dr. Wim Bastiaanssen,
WaterWatch, The Netherlands
- beginning in 1990
- SEBAL is commercially applied in the U.S.A. by SEBAL-North America

2011 ET Workshop – Boise, Idaho
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
ET = R_n - G - H

- **Net Radiation** \( (R_n) \) = function of:
  - date and time
  - *reflectance* (brightness) of surface
  - *surface temperature*
  - humidity (minor effect)

- **Heat to Air** \( (H) \) = function of:
  - *surface temperature*
  - wind speed
  - *vegetation* type and "roughness"
  - surface to air temperature difference:
    - H at the "cold" pixel = \( R_n - G - ET_{\text{reference}} \)
    - H at the "hot" pixel = \( R_n - G - 0 \)

- **Heat to Ground** \( (G) \) = function of:
  - *amount of vegetation*
  - *Net radiation*
  - *surface temperature, reflectance*

---

Solution: Use Inverse Modeling

- Calibrate against known ET at extreme conditions (end points)
- Incorporate biases of all inputs into the internal calibration
- Biases then fallout during the final estimation process

\( \text{CIMEC} = \text{calibration using inverse modeling at extreme conditions} \)
It is rocket science: requires team with remote sensing/ag engineering/atmospheric physics background to apply
2. SURFACE-ENERGY BALANCE METHODS

Weather Station (flux tower) installation (May/June 2008):
MT v. WY Yellowstone River Compact Orig. 139 U.S. Supreme Court

Rick Allen
Jeppe Kjaersgaard
2. SURFACE-ENERGY BALANCE METHODS

Accuracy of Remote Sensing/SEB Methods Compared with other ET Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Typical error, %</th>
<th>Error for an experienced expert, trained and steeped in the physics of the process, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter</td>
<td>5–15</td>
<td>5</td>
</tr>
<tr>
<td>Soil water balance</td>
<td>10–30</td>
<td>10</td>
</tr>
<tr>
<td>Bowen ratio</td>
<td>10–20</td>
<td>10</td>
</tr>
<tr>
<td>Eddy covariance</td>
<td>15–30</td>
<td>10–15</td>
</tr>
<tr>
<td>Remote sensing energy balance</td>
<td>10–20</td>
<td>5–15</td>
</tr>
<tr>
<td>Remote sensing using vegetation indices</td>
<td>15–40</td>
<td>10–30</td>
</tr>
<tr>
<td>Sap flow</td>
<td>15–50</td>
<td>10–40</td>
</tr>
<tr>
<td>Scintillometers(^3)</td>
<td>10–35</td>
<td>10–15</td>
</tr>
</tbody>
</table>

\(^3\) Scintillometers measure sensible heat flux, only, and require estimating ET as a residual of the energy balance.
METRIC Automated Calibrated Algorithm

- Mimic user calibration process
- Blind comparison to measured data
Future direction?

- Run METRIC for entire states / years in one shot
- Provide ET as a downloadable product

DRI is collaborating with NASA Ames/Cal State Monterey Bay (Forrest Melton)

Implement METRIC on the NASA Earth Exchange (NEX) high performance computer
2. SURFACE-ENERGY BALANCE METHODS

Idaho ET Applications

Water Planning
Aquifer Depletion
Hydrologic Modeling
Endangered Species
Legal Finding-of-Fact
Agricultural Water Use
Water Rights Buy-Back
Water Rights Compliance
Water Rights Administration
Water-Use Curtailment Orders
Tribal Water Rights Negotiations

WATER ADMINISTRATION
Monitoring Water Rights Compliance
Irrigation Without a Water Right
3. Montana Applications

METRIC

Flathead Indian Reservation
irrigation water consumption for
managing streamflows
(UI for MDNRC)

Ground water recharge estimation
in four basins: Helena, White Sulpher
Springs, Dillon, and Bozeman.
(UI for USGS, MBMG)

Green River/Upper Colorado River
(UWYO, S1A, RTI, ET for WY-OSE)

Upper North Platte --
water decree compliance
(UI, ET+)

DRI: Desert Research Institute
Montana
(Bill Greiman, Stan Jones, Seth Makepeace)

Flathead Indian Reservation, W. Montana

Improving streamflows for endangered species
(by managing irrigation impacts)

July 10, 2002
3. Montana Applications

Montana

Ground water recharge and water balance in four basins (for USGS / Montana Bureau Mines and Geology) (Kyle Blasch, Roy Sando, John Wheaton, Julie Butler)
3. Montana Applications

April – October 2007 ET
Southcentral Montana

Close up – Upper Smith River

Close up – Dillon area
MODIS (Moderate Resolution Imaging Spectroradiometer)

Remote Sensing of ET: MODIS ET

- Penman-Monteith approach
- ET = sum of:
  - Soil surface E
  - Canopy intercepted water E
  - Vegetation T
- 8-day, monthly, annual products
- 1-km resolution
- **Main advantages**
  - Generalized model that can be run globally
  - 8-day temporal resolution
  - Relatively straightforward to operationalize
- **Main disadvantages**
  - Generalized model
  - Spatial resolution

MODIS (Moderate Resolution Imaging Spectroradiometer)

MODIS ET and Landscape-Scale Climate Data for Montana

Jared W. Oyler
PhD Student, Software Engineer
Numerical Terradynamic Simulation Group (NTSG), Montana Climate Office
College of Forestry and Conservation, University of Montana
3. Montana Applications

**MODIS** (Moderate Resolution Imaging Spectroradiometer)

**Stepwise MODIS ET Improvements for Montana**

1. Improved landscape-scale weather data
2. Regionally and/or crop optimized land cover model parameters
3. Improved MODIS ET model
4. Finer resolution (500m)
Estimates of statewide consumptive use at 4th code HUC scale: focus on irrigated agriculture

A: Apply DNRC Consumptive Use Rules statewide

B: Remote Sensing/Modified Vegetation Index Method
   --Use Landsat for 2007 (medium dry year) for analysis;
3. Montana Applications

Each method applied to statewide irrigated land parcel geodatabase developed from multiple sources (see Ruby River poster)

lwr_irrigation.shp

- Flood
- Sprinkler
- Pivot/Sprinkler
Vegetation Index methods may underestimate ET

METRIC shows irrigation
Vegetation Index: no irrigation

Evaluate MWSI methods uncertainty by comparison with METRIC at MT locations
Thank You! Questions?
Errors in Outflow and Precip accumulate in residual -- ET

Assume Known Values: Outflow = 800 ac-ft ±5%
                        Precip = 1000 ac-ft ±10%
                        ΔS = 0

\[
ET = (1000 - 800 - 0) = 200 \text{ ac-ft}
\]

if Outflow is underestimated by 5% (800 - 40) = 760 ac-ft
and,
Precipitation is overestimated by 10% (1000 + 100) = 1,100 ac-ft

THEN,
\[
ET = (1,100 - 760) = 340 \text{ ac-ft}
\]

True ET overestimated by 1.7 times
Variables

$T_{\text{air}}$ = temperature of the air

$T_L$ = temperature of the leaf

$e_a$ = actual vapor pressure of the air

$e_{\text{sat}}(T_{\text{air}})$ = saturation vapor pressure of the air

$e_{\text{sat}}(T_L)$ = saturation vapor pressure of the boundary layer

$e_{\text{sat}}(T_L) \cdot e_a$ is called the vapor pressure deficit

Diffusion or Vapor Transfer (evaporation)

If $e_a < e_{\text{sat}}(T_L)$ then molecules will diffuse from the boundary layer to the air

conceptual model of a stomata
Please keep in mind..

- Satellite image ≠ Photo
- Image color ≠ real color

http://asterweb.jpl.nasa.gov/images/spectrum.jpg
~11.7 million acre-feet

~2.7 million acre-feet

~20% of total diverted is consumed

of total consumption, ~94% is consumed by irrigation
<table>
<thead>
<tr>
<th>SATELLITE</th>
<th>COUNTRY</th>
<th>LAUNCH</th>
<th>PAN RES. M</th>
<th>MS RES. M</th>
<th>SWATH KM</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeEye-1</td>
<td>US</td>
<td>03/16/07</td>
<td>0.41</td>
<td>1.64</td>
<td>15</td>
</tr>
<tr>
<td>WorldView-1</td>
<td>US</td>
<td>07/01/07</td>
<td>0.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>WorldView-2</td>
<td>US</td>
<td>07/01/08</td>
<td>0.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>QuickBird-2</td>
<td>US</td>
<td>10/18/05</td>
<td>0.6</td>
<td>2.5</td>
<td>18</td>
</tr>
<tr>
<td>EROS B1</td>
<td>Israel</td>
<td>04/25/06</td>
<td>0.7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>EROS C</td>
<td>Israel</td>
<td>03/21/06</td>
<td>0.7</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>Pleiades-1</td>
<td>France</td>
<td>07/01/08</td>
<td>0.7</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Pleiades-2</td>
<td>France</td>
<td>07/01/09</td>
<td>0.7</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>IKONOS-2</td>
<td>US</td>
<td>09/24/99</td>
<td>1.0</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>OcoView 3</td>
<td>US</td>
<td>06/26/03</td>
<td>1.0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Reussat DK-1 (RI-N0)</td>
<td>Russia</td>
<td>06/10/06</td>
<td>1.0</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>KOMPSAT-2</td>
<td>Korea</td>
<td>07/03/05</td>
<td>1.9</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>IRS Cartosat 2</td>
<td>India</td>
<td>06/18/06</td>
<td>1.0</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**HIGH RESOLUTION (1.8 TO 2.5 METERS)**

- EROS A1: 1999, China: 1.8, 10, 12
- FormSat-1 (RotSat2): Taiwan: 2004, 2.0, 8, 24
- THIES: Thailand: 2007, 2.9, 15, 22, 60
- SPOT-5: France: 2002, 2.5, 10, 120
- IRS Cartosat 1: India: 2004, 2.5, 30
- TopSat (BSSL): UK: 2004, 2.5, 30, 10, 10
- ALOS: Japan: 2006, 2.5, 10, 35, 70
- RapidEye A,B,C,D,E: Germany: 2007, 6.3, 70
- KOMPSAT-1: Korea: 2009, 6.6, 17
- Röth: South Africa: 2009, 6.6, 7.5
- Proba: ESA: 2001, 6.6, 30, 30, 10
- MONITOR E1: Russia: 2005, 6.6, 50, 50, 10

**HIGH MEDIUM RESOLUTION (4 TO 8 METERS)**

- Beijing-1 (SSTL): China: 2002, 4.0, 32, 600
- WinSat-1 (SSTL): Vietnam: 2003, 4.0, 32, 600
- CBERS-3: China/Brazil: 2005, 6.0, 30, 95, 120
- CBERS-4: China/Brazil: 2008, 6.0, 30, 95, 120
- IRS 1C: India: 2005, 6.0, 23, 50, 130
- IRS 1D: India: 2007, 6.0, 23, 85, 140
- IRS ResourceSat-1: India: 2009, 6.0, 23, 50, 24, 140, 740
- RapidEye A,B,C,D,E: Germany: 2012, 6.3, 70
- KOMPSAT-1: Korea: 2012, 6.6, 17
- Röth: South Africa: 2013, 6.6, 7.5
- Proba: ESA: 2012, 6.6, 30, 30, 10
- MONITOR E1: Russia: 2015, 6.6, 50, 50, 10

**MEDIUM RESOLUTION (10 TO 20 METERS)**

- SPOT-2: France: 01/02/90, 10.0, 30, 120
- SPOT-4: France: 02/28/98, 10.0, 30, 120
- EO-1: US: 11/21/00, 10.0, 30, 37
- X-Sat: Singapore: 04/18/08, 10.0, 50
- LDCM: US: 07/01/11, 10.0, 30, 177
- DMC BlastSat (SSTL): Turkey: 09/27/03, 12.0, 30, 24, 52
- Landsat 7: US: 04/19/99, 10.0, 30, 100
- TERRA (ASTER): Japan/US: 12/15/04, 10.0, 30, 30, 90, 60
- CBERS-2: China/Brazil: 16/21/03, 20.0, 20, 115
- CBERS-2B: China/Brazil: 2007, 20.0, 20, 115

**LOW MEDIUM RESOLUTION (30 TO 56 METERS)**

- Landsat-5: US: 02/01/94, 30, 185
- DMC AllSat-1 (SSTL): Algeria: 11/23/02, 30, 600
- Thaicom-5 (SSTL): Thailand: 12/01/04, 30, 600
- DMC-3 (SSTL): Nigeria: 06/27/03, 30, 600
- DMC UK (SSTL): UK: 09/27/03, 30, 600
- IRS ResourceSat-1 AMFS: India: 16/11/03, 56, 740
- IRS ResourceSat-2 AMFS: India: 12/15/06, 56, 740

* Near Equatorial Orbit * Revised 7/20/06