Background on Methods for Estimating ET using Remote Sensing and Surface-Energy Budgets

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Helena, Montana

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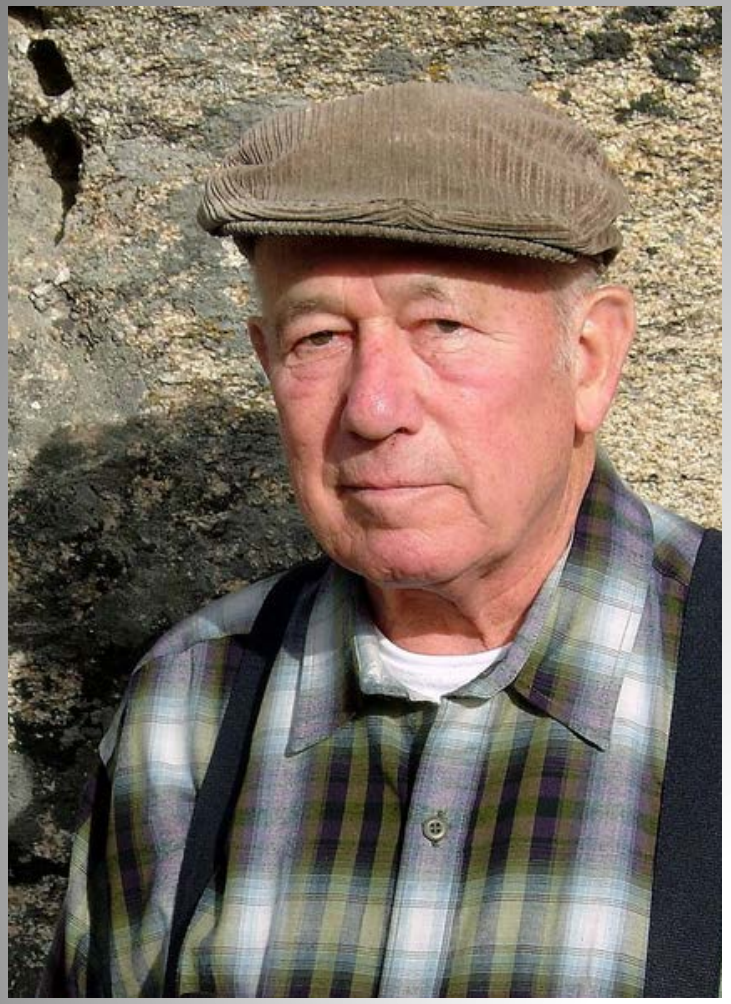
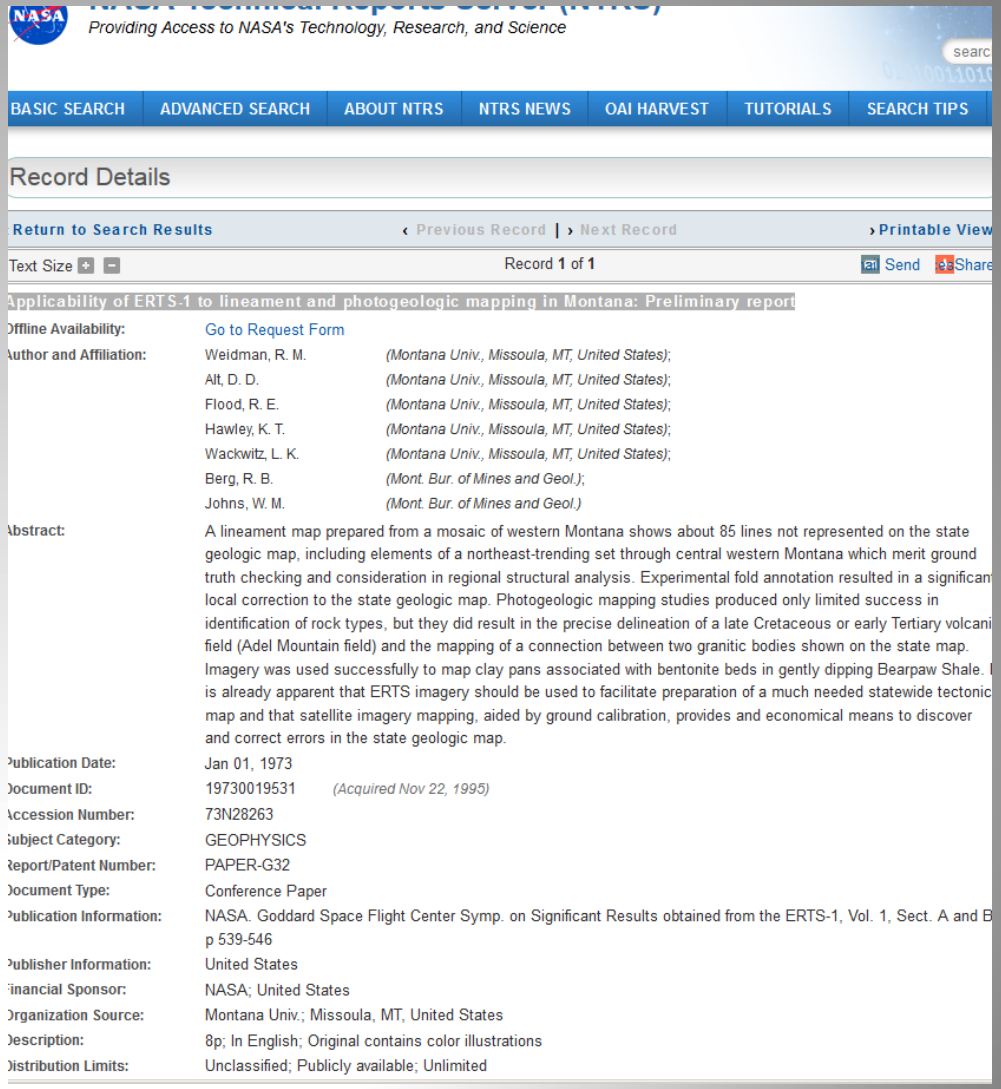
Topics

1. **Satellite Basics**
2. **What is ET ? Why do we care about it ?**
3. **How is ET measured/calculated ?**
4. **Intro to Surface-Energy Balance Methods**

1. Satellite Basics



David Alt 1933-2015
(Legendary UM Geology Professor)



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Applicability of ERTS-1 to lineament and photogeologic mapping in Montana: Preliminary report

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Abstract: A lineament map prepared from a mosaic of western Montana shows about 85 lines not represented on the state geologic map, including elements of a northeast-trending set through central western Montana which merit ground truth checking and consideration in regional structural analysis. Experimental fold annotation resulted in a significant local correction to the state geologic map. Photogeologic mapping studies produced only limited success in identification of rock types, but they did result in the precise delineation of a late Cretaceous or early Tertiary volcani field (Adel Mountain field) and the mapping of a connection between two granitic bodies shown on the state map. Imagery was used successfully to map clay pans associated with bentonite beds in gently dipping Bearpaw Shale. I is already apparent that ERTS imagery should be used to facilitate preparation of a much needed statewide tectonic map and that satellite imagery mapping, aided by ground calibration, provides and economical means to discover and correct errors in the state geologic map.

Publication Date: Jan 01, 1973
Document ID: 19730019531 (Acquired Nov 22, 1995)
Accession Number: 73N28263
Subject Category: GEOPHYSICS
Report/Patent Number: PAPER-G32
Document Type: Conference Paper
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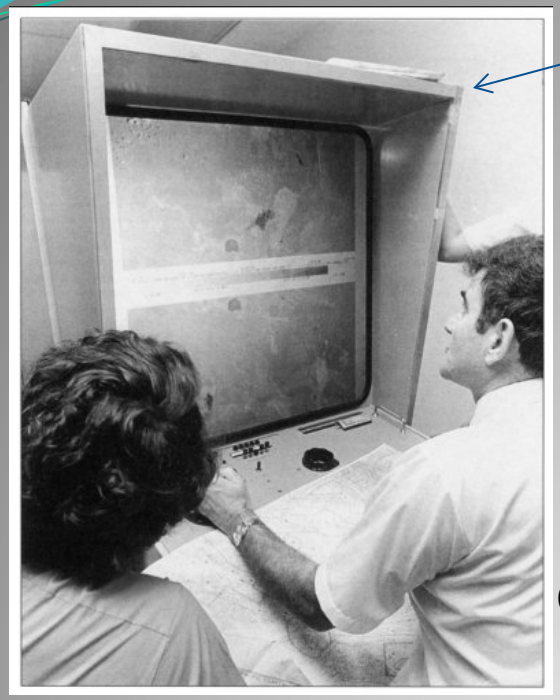
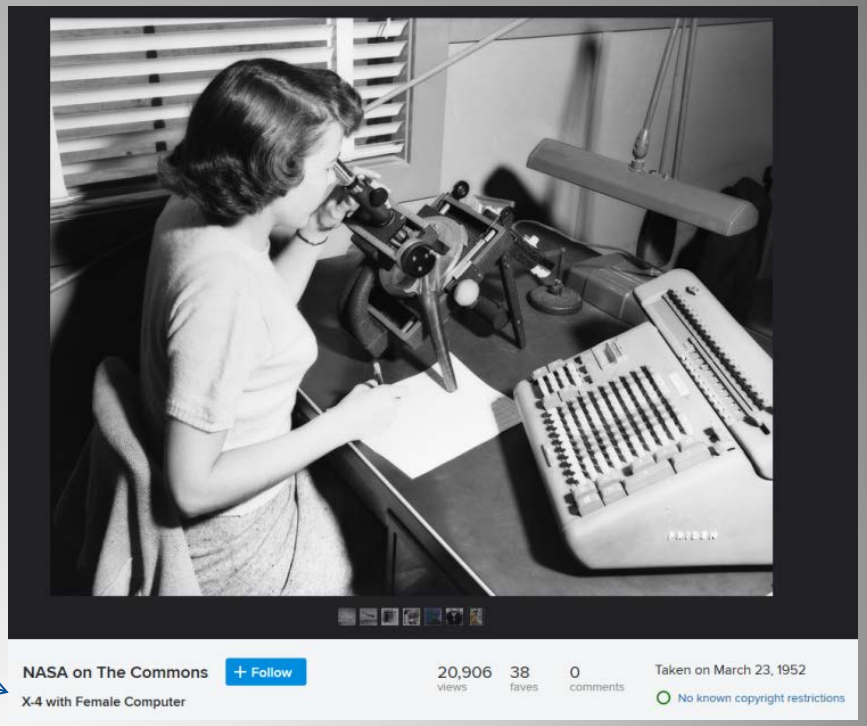
ERTS--Landsat 1-- in a high technology analog world (1973)



Special “viewer” for Landsat 1 imagery



Ground truthing with a female computer

NASA on The Commons + Follow
X-4 with Female Computer
20,906 views 38 faves 0 comments
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1. Satellite Basics

There are many !
(with different sensors
and resolution)

2 Primary Satellites for ET:

--Landsat series (5,7,8)

--MODIS
Terra(ASTER)
Aqua

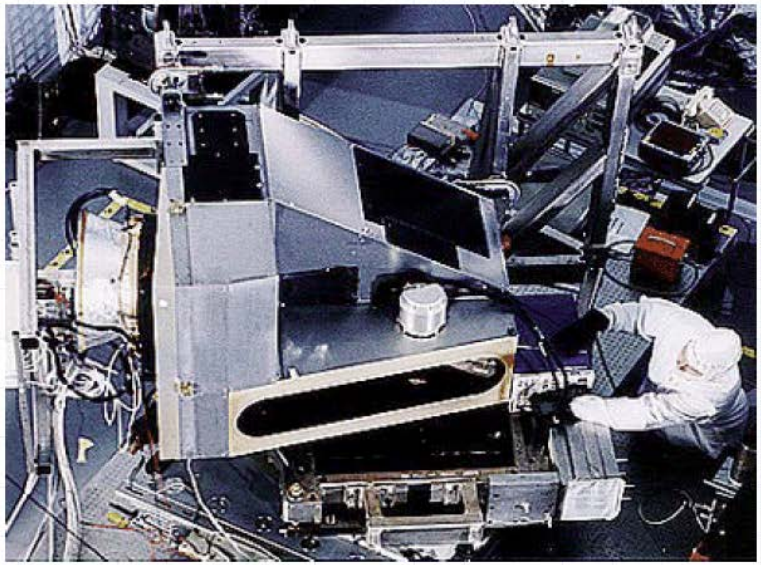
OPTICAL LAND IMAGING SATELLITES BY BEST RESOLUTION

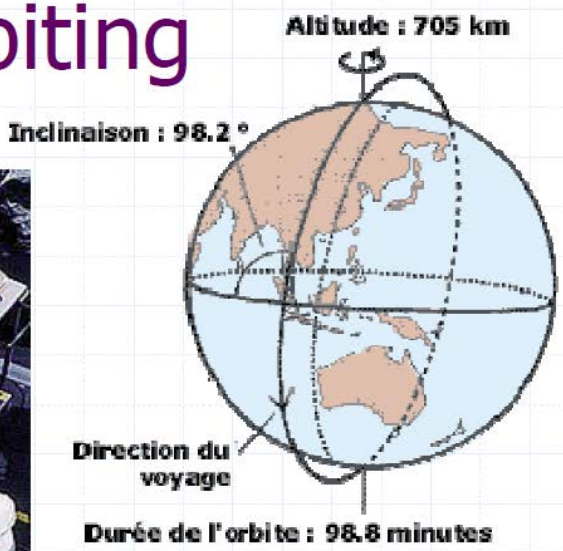
SATELLITE	COUNTRY	LAUNCH	PAN RES. M	MS RES. M	SWATH KM
VERY HIGH RESOLUTION (.41 TO 1 METERS)					
GeoEye-1	*US*	03/16/07	0.41	1.64	15
WorldView -1	*US*	07/01/07	0.5		16
WorldView -2	*US*	07/01/08	0.5	1.8	16
QuickBird-2	*US*	10/18/01	0.6	2.5	16
EROS B1	*Israel*	04/25/06	0.7		7
EROS C	*Israel*	03/21/08	0.7	2.5	16
Pleiades-1	France	07/01/08	0.7	2.8	20
Pleiades-2	France	07/01/09	0.7	2.8	20
IKONOS-2	*US*	09/24/99	1.0	4	11
OrbView 3	*US*	06/26/03	1.0	4	8
Resurs DK-1 (01-N5)	Russia	06/15/06	1.0	3	28
KOMPSAT-2	Korea	07/28/06	1.0	4	15
IRS Cartosat 2	India	08/15/06	1.0		10
HIGH RESOLUTION (1.8 TO 2.5 METERS)					
EROS A1	*Israel*	12/05/00	1.8		14
FormoSat (RocSat2)	Taiwan	04/20/04	2.0	8	24
THOES	Thailand	06/30/07	2.0	15	22, 90
SPOT-5	France	05/04/02	2.5	10	120
IRS Cartosat 1	India	05/04/05	2.5		30
TopSat (SSTL)	UK	10/27/05	2.5	5	10, 15
ALOS	Japan	01/24/06	2.5	10	35, 70
RazakSat*	Malyasia	11/01/06	2.5	5	?
Spain Sat	Spain	07/01/10	2.5		?
HIGH MEDIUM RESOLUTION (4 TO 8 METERS)					
Beijing-1 (SSTL)	China	10/27/05	4.0	32	600
VinSat-1 (SSTL)	Vietnam	11/01/06	4.0	32	600
MTI	US	03/12/00		5, 20	12
CBERS-3	China/Brazil	05/01/08	5.0	20	60, 120
CBERS-4	China/Brazil	07/01/10	5.0	20	60, 120
IRS 1C	India	12/28/95	6.0	23	70, 142
IRS 1D	India	09/29/97	6.0	23	70, 142
IRS ResourceSat-1	India	10/17/03	6.0	6, 23, 56	24, 140,740
IRS ResourceSat-2	India	12/15/06	6.0	6, 23, 56	24, 140, 740
RapidEye-A,B,C,D,E	*Germany*	06/01/07		6.5	78
KOMPSAT-1	Korea	12/20/99	6.6		17
R26m	South Africa	09/01/06		7.5	?
Proba	ESA	10/22/01	8.0	18, 36	14
MONITOR-E -1	Russia	08/26/05	8.0	20	94, 160
MEDIUM RESOLUTION (10 TO 20 METERS)					
SPOT-2	France	01/22/90	10.0	20	120
SPOT-4	France	03/24/98	10.0	20	120
EO-1	US	11/21/00	10.0	30	37
X-Sat	Singapore	04/16/08		10	50
LDCM	US	07/01/11	10.0	30	177
DMC BilSat (SSTL)	Turkey	09/27/03	12.0	26	24, 52
Landsat 7	US	04/15/99	15.0	30	185
TERRA (ASTER)	Japan/US	12/15/99		15, 30, 90	60
CBERS-2	China/Brazil	10/21/03	20.0	20	113
CBERS-2B	China/Brazil	06/15/07	20.0	20	113
LOW MEDIUM RESOLUTION (30 TO 56 METERS)					
Landsat 5	US	03/01/84		30	185
DMC AlSat-1 (SSTL)	Algeria	11/28/02		32	600
ThaiPhat (SSTL)	Thailand	12/01/04		36	600
DMC NigeriaSat-1 (SSTL)	Nigeria	09/27/03		32	600
DMC UK (SSTL)	UK	09/27/03		32	600
IRS ResourceSat-1 AWIFS	India	10/17/03		56	740
IRS ResourceSat-2 AWIFS	India	12/15/06		56	740

Commercial * Near Equatorial Orbit Revised 7/6/06

MODIS – Polar Orbiting

705 km, 10:30 a.m. (Terra) and 1:30 p.m. (Aqua)





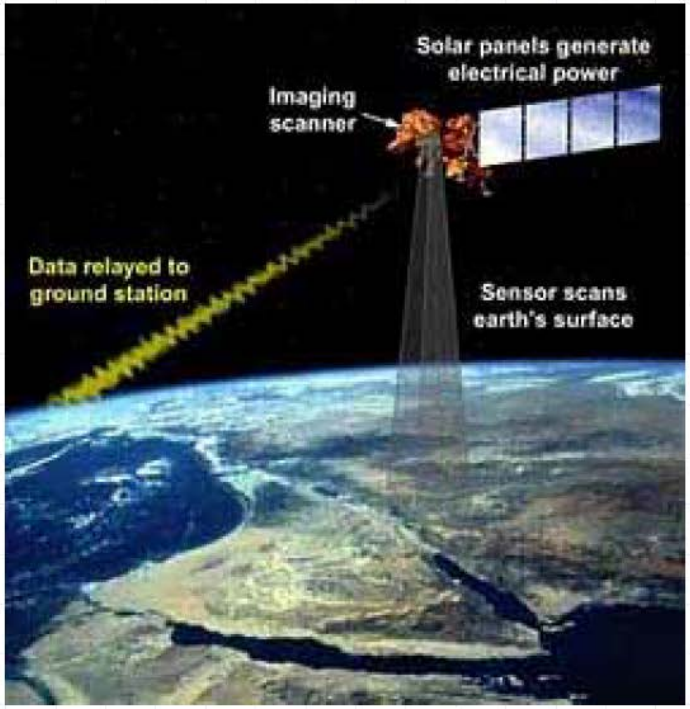
36 bands

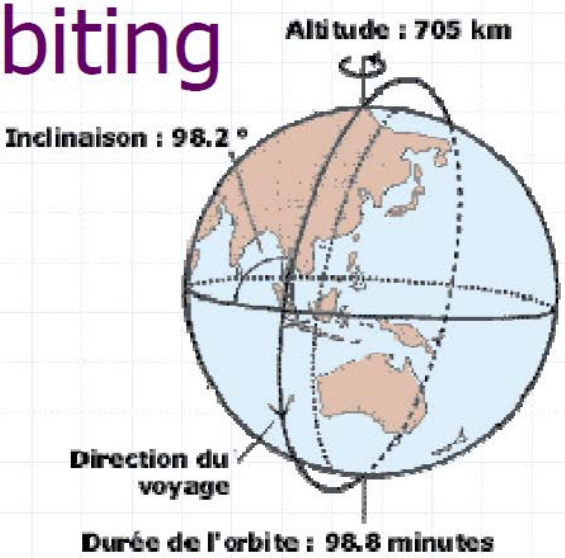
-- most at 1 km resolution

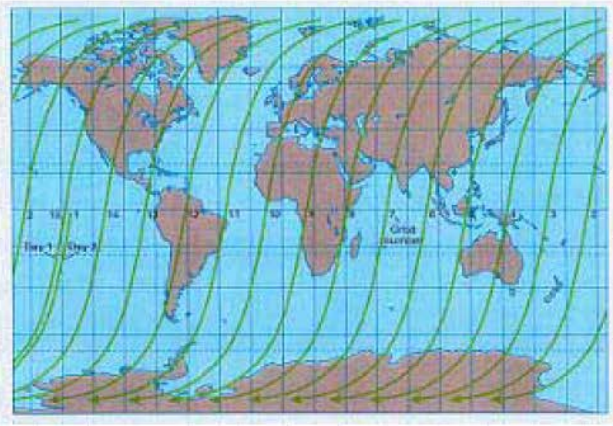
*A new image **each day** for a region*

University of Idaho *Source: Rick Allen, University of Idaho*

Landsat – Polar Orbiting



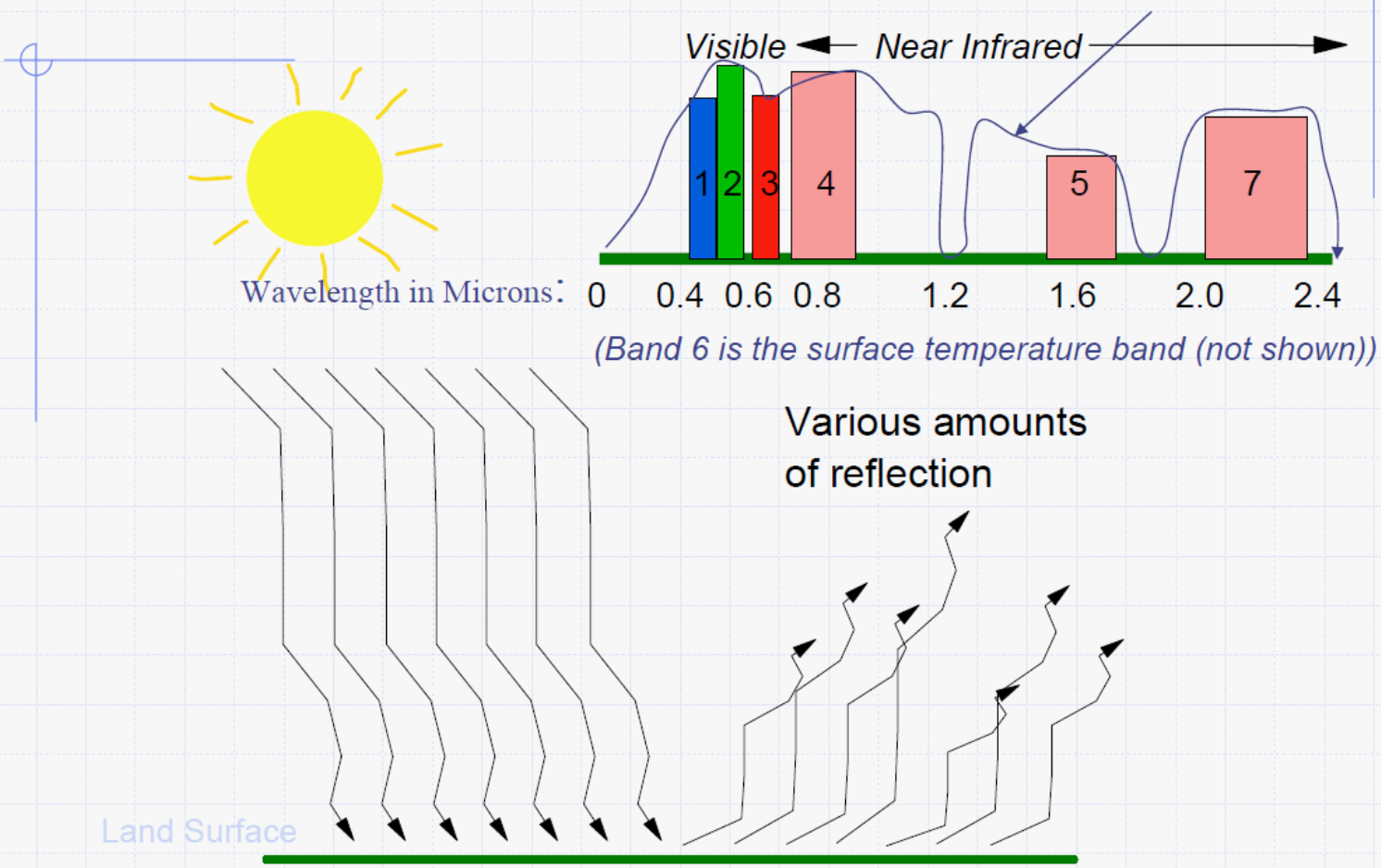




A new image each 16 days for a specific location

University of Idaho *Source: Rick Allen, University of Idaho*

What Landsat sees

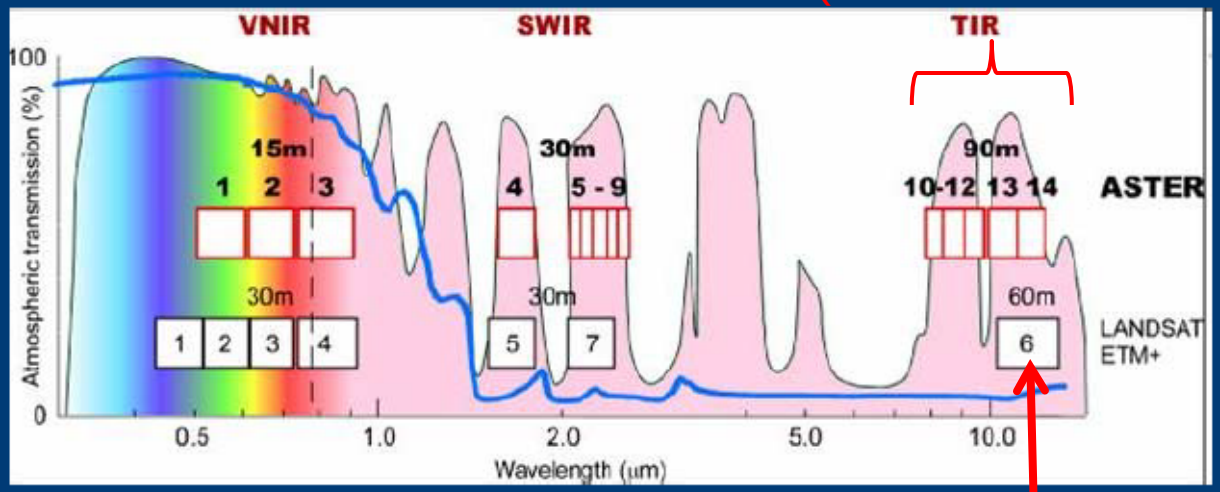


University of Idaho Source: Rick Allen, University of Idaho

Jet Propulsion Laboratory
California Institute of Technology

- Satellite image ≠ Photo
- Image color ≠ real color

Thermal Infrared
(5.6 microns to 1cm)



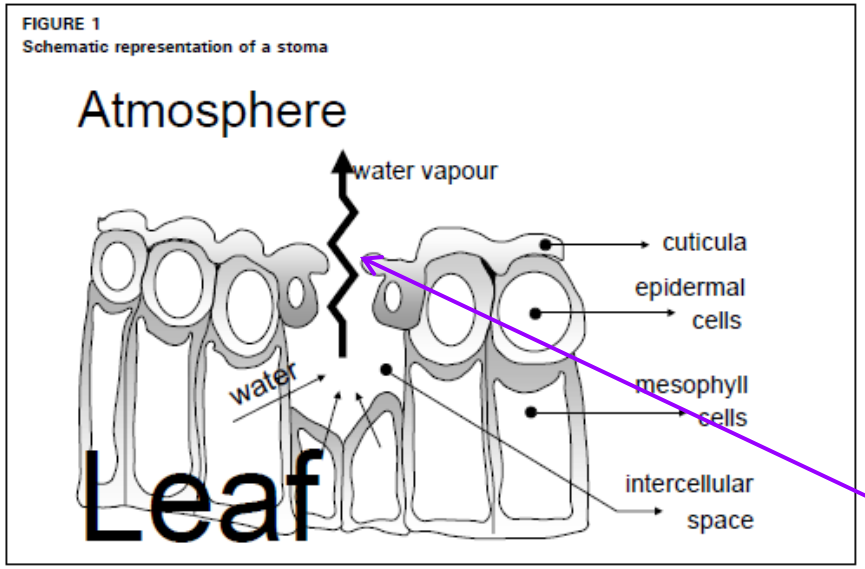
http://asterweb.jpl.nasa.gov/images/spectrum.jpg

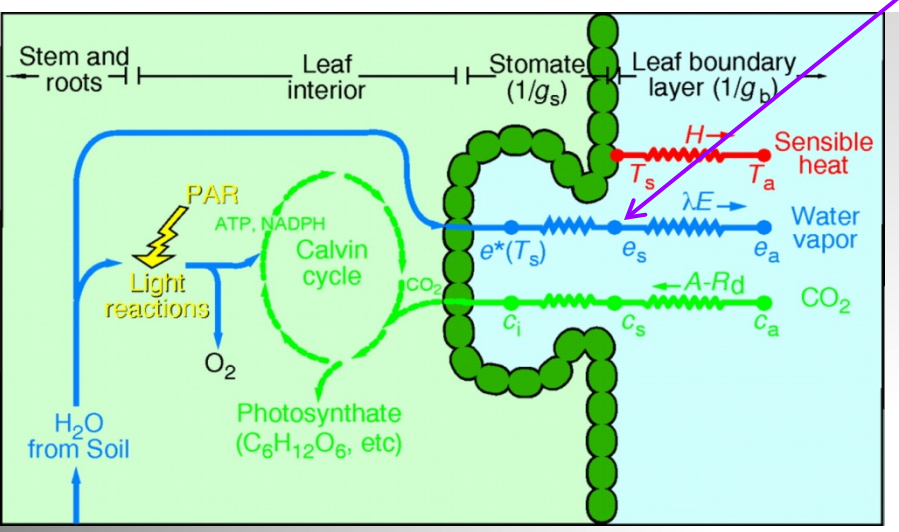
Color Infrared Photo
Infrared reflected energy to photo sensitive emulsion

Thermal IR Image:
Thermal scanner records photons

Landsat 7— Band 6 (10.6 to 11.19) microns
Landsat 8— Band 10 (10.6 to 11.19)
Band 11 (11.5 to 12.51)

2. 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:
f(energy, vapor pressure gradient and wind).
and: --crop and growth stage
--soil
--water management

Evaporation = Water Vapor Transfer:

Energy from sun main driver of ET—but water vapor pressure difference between ET surface and surrounding air controls vapor removal:

--*vapor pressure* is pressure of water vapor in the air above leaf surface or field

--*saturation vapor pressure* is pressure of water vapor in equilibrium with liquid phase—increases with air temperature

--if vapor pressure is < saturation vapor pressure then molecules evaporate

vapor pressure deficit--Latent Heat Flux is strongly influenced by difference between saturation and actual vapor pressure

Variables

T_{air} = temperature of the air

T_L = temperature of the LEAF

e_a = actual vapor pressure of the air

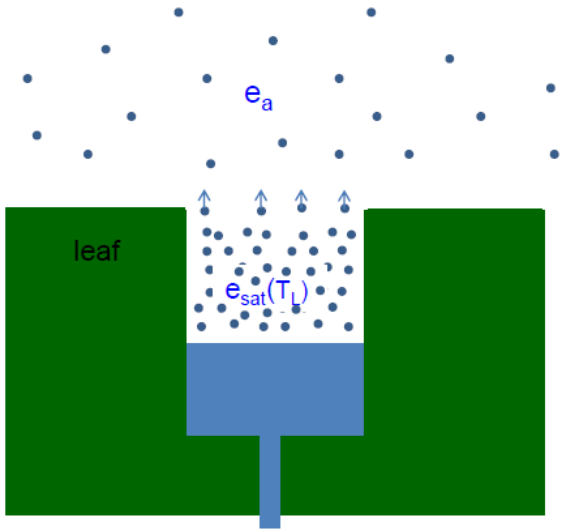
$e_{sat}(T_{air})$ = saturation vapor pressure of the air

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

$e_{sat}(T_L) - e_a$ is called the vapor pressure deficit

Diffusion or Vapor Transfer (evaporation)

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



conceptual model of a stomata

Why do we care about ET ?

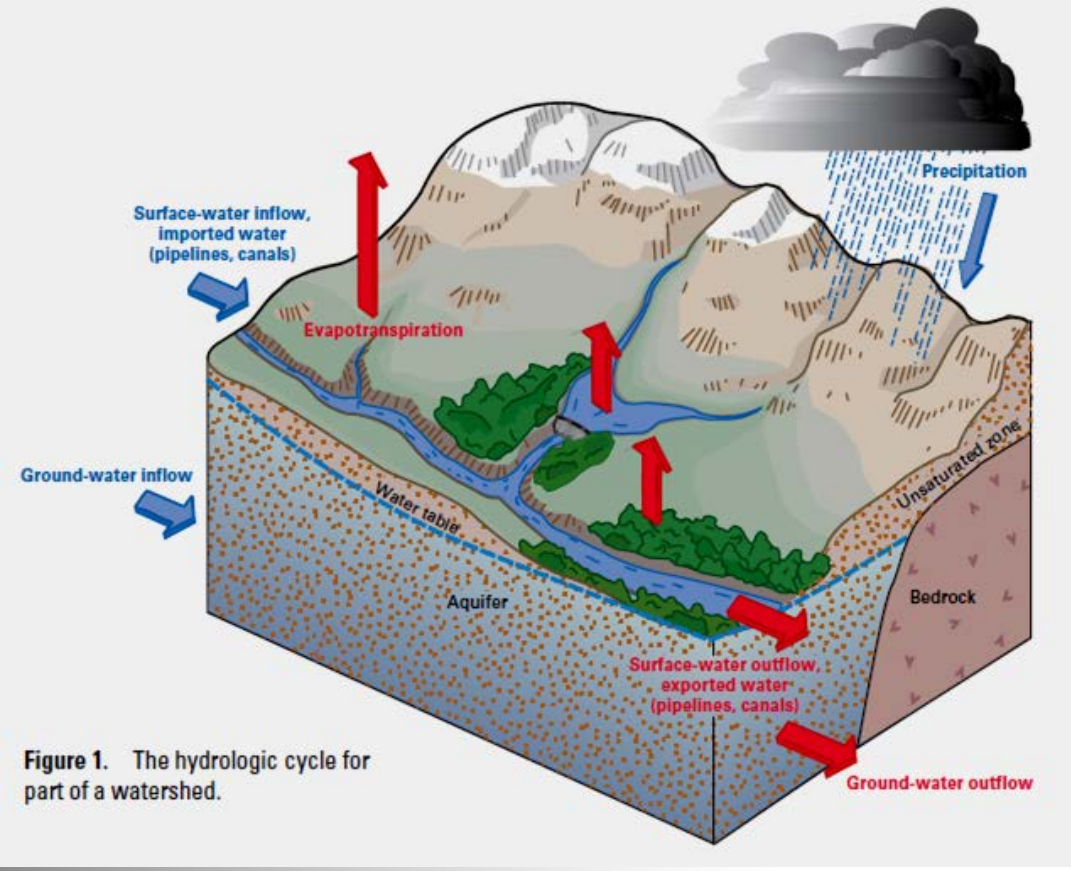


Figure 1. The hydrologic cycle for part of a watershed.

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

$$ET = P - R - \Delta S$$

where

ET = evapotranspiration

P = precipitation,

R = outflow,

S = change in water storage (lakes, reservoirs, groundwater)

WHY IS EVAPOTRANSPIRATION from IRRIGATED LAND IMPORTANT ?

~2.5 million acres ±500,00 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

3. How is ET measured/calculated?

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 .....

Agricultural Water Management 98 (2011) 899–920

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Review

Evapotranspiration information reporting: I. Factors governing measurement accuracy

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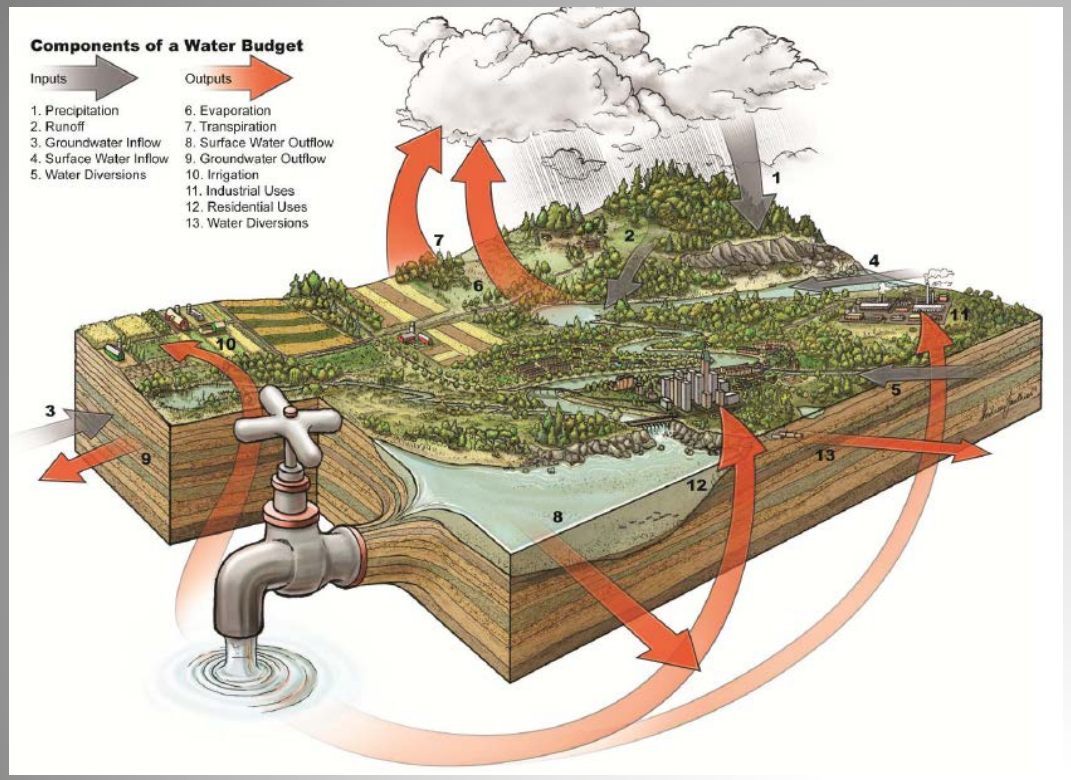
ET from mass balance over large area:
(residual of watershed water budget)



$$ET = P - O - \Delta S$$

where ET = evapotranspiration

P = precipitation,

O = 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)

Errors in Outflow and Precip accumulate in residual -- ET

Assume Known Values: Outflow= 800 ac-ft ±5%

Precip=1000 ac-ft ±10%

$\Delta S=0$

ET=(1000 - 800 - 0)

ET=200 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 ac-ft

True ET overestimated by 1.7 times

Lysimetry: weigh soil cube to measure ET

Considered most accurate, but essentially a "point" measurement

THE gold standard -- Kimberly, Idaho—Dr. James L. Wright, USDA-ARS (ret.) (See http://extension.uidaho.edu/kimberly/2014/04/lysimeters-inovagri-2014-workshop/)

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

(measuring rangeland ET—Rick Allen)

Scintillometers measure only Sensible Heat flux (H)

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

Bowen Ratio Energy Balance: measure gradients of air temperature and vapor pressure in near-surface layer to solve energy-balance equation

Eddy Covariance: uses statistical correlation (covariance) between vertical fluxes of vapor or sensible heat within upward and down ward "legs" of turbulent flux to solve energy-balance equation

Sap flow: measure flow of water in trunk or branch of plant by velocity of heat pulse

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

Table 2
Error, expressed as one standard deviation from the true mean value, expected for various types of ET

Method	Typical error, %	Error for an experienced expert, trained and steeped in the physics of the process, %
Lysimeter	5–15	5
Soil water balance	10–30	10
Bowen ratio	10–20	10
Eddy covariance	15–30	10–15
Remote sensing energy balance	10–20	5–15
Remote sensing using vegetation indices	15–40	10–30
Sap flow	15–50	10–40
Scintillometers[a]	10–35	10–15

[a] Scintillometers measure sensible heat flux, only, and require estimating ET as a residual of the en

SURFACE-ENERGY BALANCE METHODS

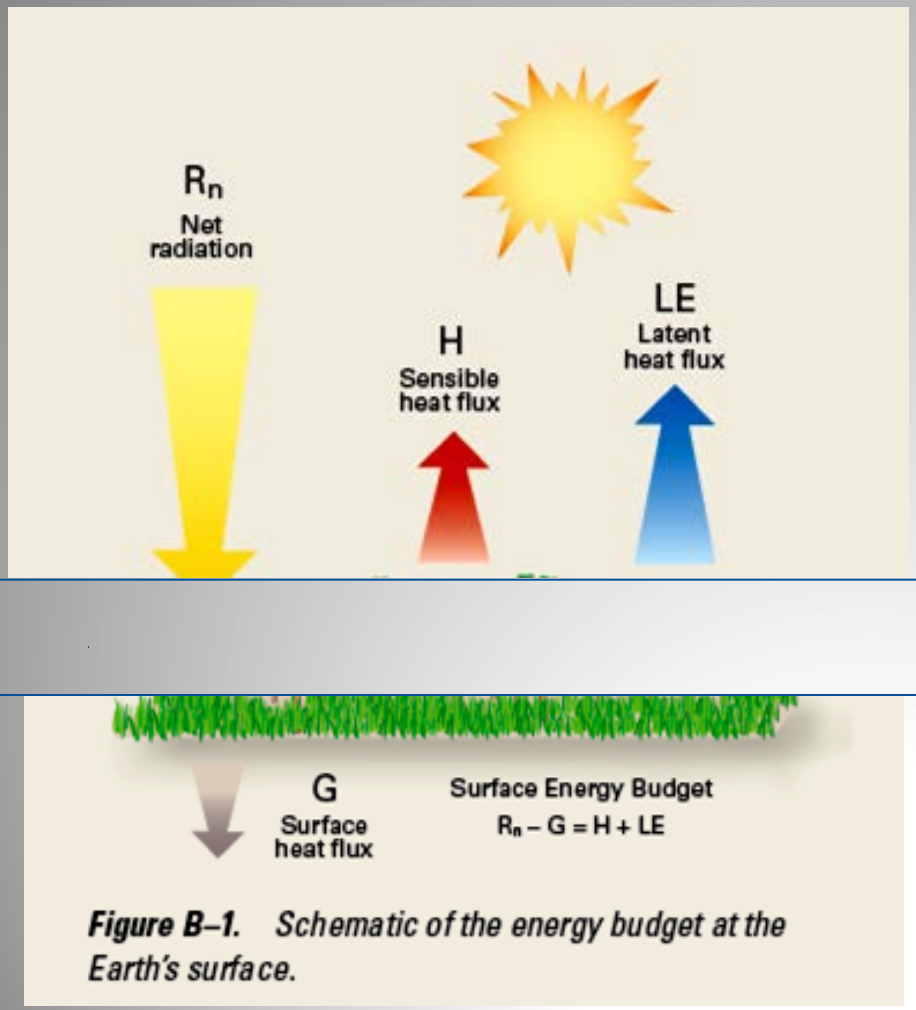
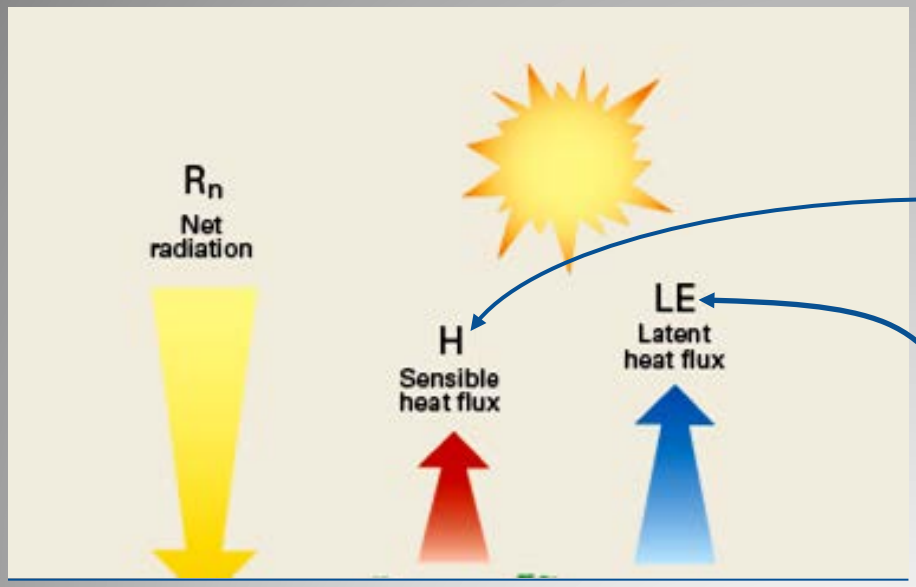


Figure B–1. Schematic of the energy budget at the Earth's surface.

Surface -Energy Balance Methods rely on Conservation of Energy to calculate energy balance in boundary layer, and ET as residual of energy balance

≈ boundary layer over field (~2 to 3m for alfalfa)

SURFACE-ENERGY BALANCE METHODS



≈ boundary layer over field
(~2 -3 m for alfalfa)

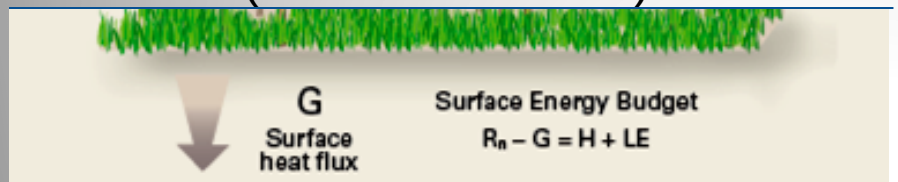
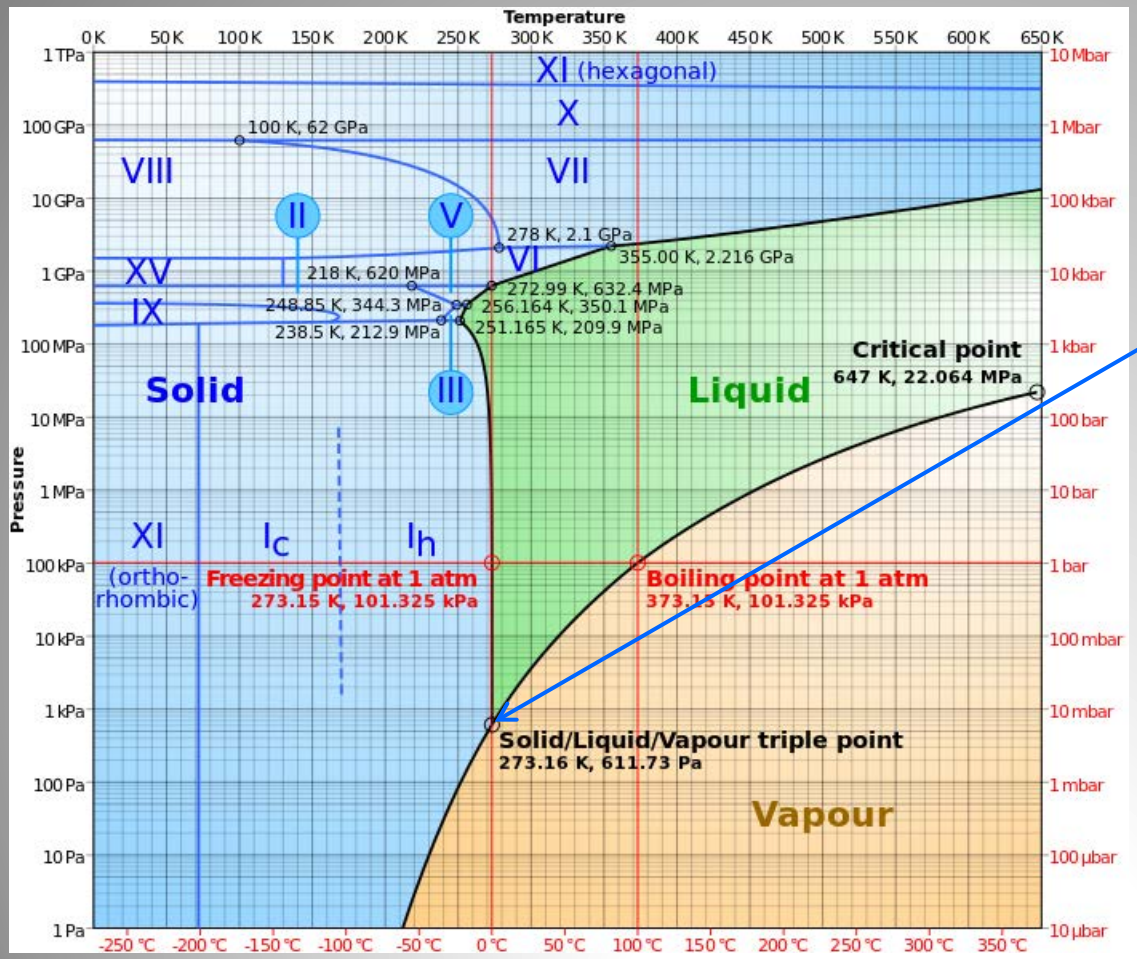


Figure B–1. *Schematic of the energy budget at the Earth's surface.*

Heat that causes a change in temperature of substance (can measure with thermometer)

Heat absorbed or released during phase change (liquid - gas)—heat causes change in state with no change in temperature

Phase Diagram for Water

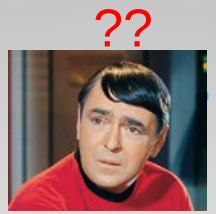


Triple Point of Water: Conversion from liquid to vapor (evaporation) consumes energy / conversion from vapor to liquid (condensation) releases energy

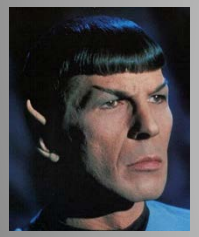
Convert latent heat flux into mass flux of water

$$L = \rho_w \lambda_v ET$$

$$\mathrm{Wm^{-2}(Jm^{-2}s^{-1})} = \frac{\mathrm{kg}}{\mathrm{m^3}} \frac{\mathrm{J}}{\mathrm{kg}} \frac{\mathrm{m}}{\mathrm{s}}$$



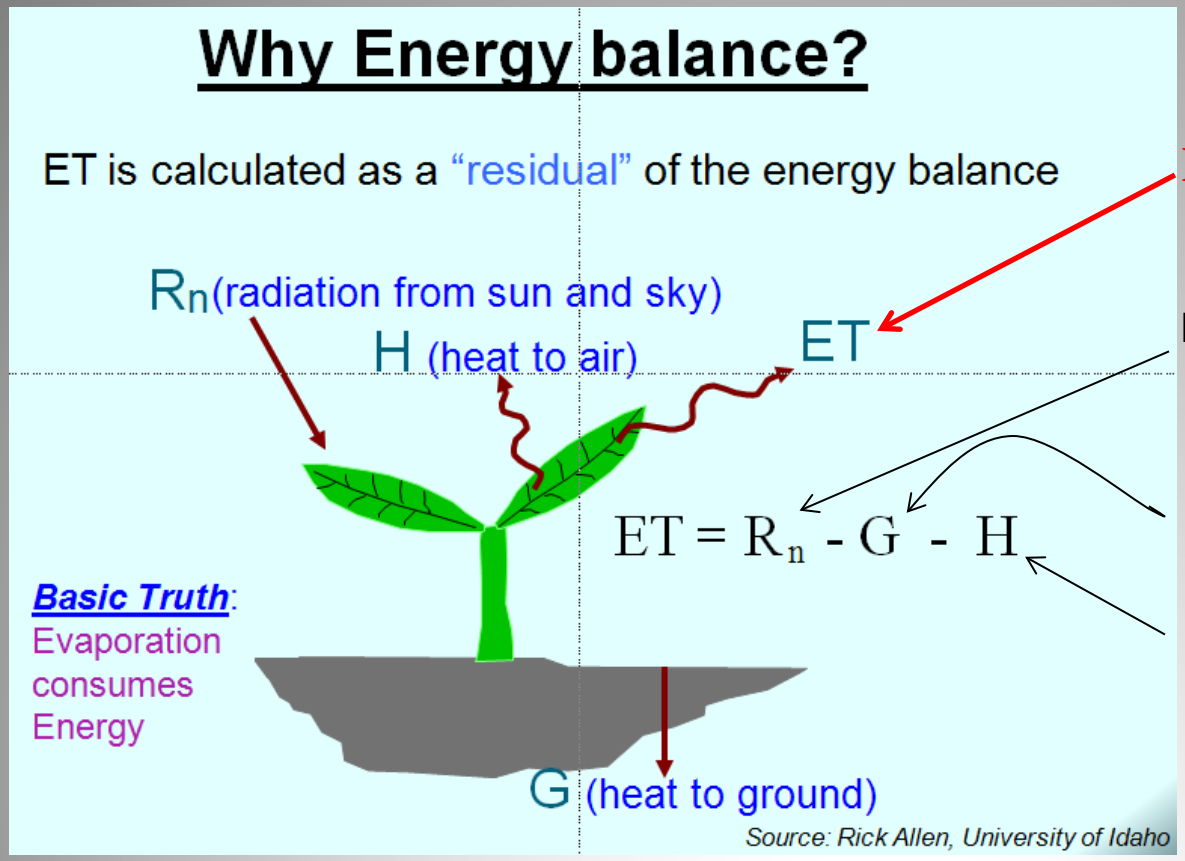
$$\text{or } ET = \frac{L}{\rho_w \lambda_v}$$



- L = latent heat flux
- ET = evapotranspiration rate (m s^{-1})
- ρ_w = density of water (1000 kg m^{-3})
- λ_v = latent heat of vaporization (2.5×10^6 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



Latent heat flux =energy consumed by ET

Rn = net radiation (sum of incoming and outgoing short and long wave radiation at surface)

G = sensible heat flux conducted to ground

H=sensible heat flux to air

H is the rate of convective/conductive heat loss from surface to air—driven by near-surface temperature gradient that can be measured

$$H = \rho_{\mathrm{air}} C_{\mathrm{p}} \frac{\mathrm{d}T}{r_{\mathrm{ah},1,2}}$$

Important ET Concepts

Potential vs. Reference ET

Potential ET

Penman (1940's and 50's):

"amount of water transpired in a given time by a short green crop completely shading the ground, of uniform height and with adequate water status in the soil profile".

(problem—not tied to any specific crop)

Reference ET_0

Originated by Jensen in 1970, developed and standardized by Allen and others (Allen et al.1994; 1996, FAO 56; ASCE 2005; Pereira et al. 2015)

ET_0 is the evapotranspiration rate from a reference surface not short on water. In the west, typically 0.5 m tall, well-watered alfalfa.

(Very specific operational definition not given here – see ASCE 2005)

Benefits of Reference ET and standard, physics-based method for calculation:

-- ET_o is "tied" to a reference surface that exists and can be identified in the field; e.g. well-watered alfalfa

-- ET_o represents the primary weather induced effects on water consumption; (can study effects of weather on evaporation independent of crop type)

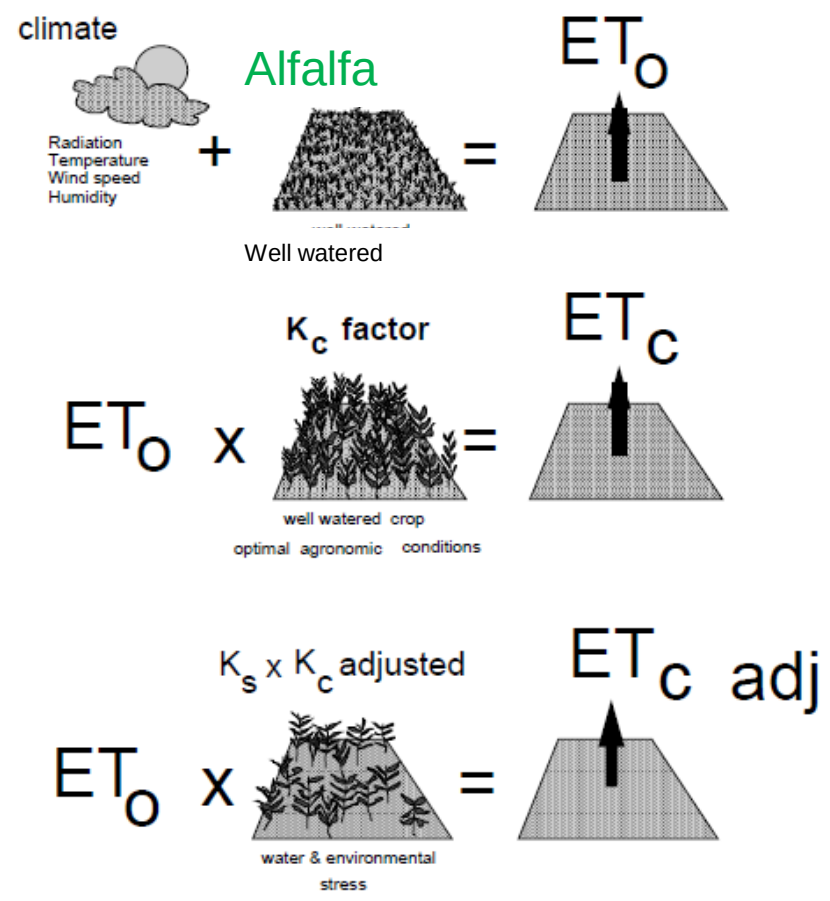
-- ET_o depends only on climatic/weather parameters and is independent of crop type. (don't need crop classification to apply reference ET)

Reference ET provides a means to "scale" and estimate ET for all other surfaces:

-- ET_o is calculated for alfalfa and then adjusted by crop coefficients (K_c) to give actual ET_c

--Satellite-based SEB methods calculate ET_rF (ET reference fraction ≈ K_c) for each pixel and then scale as fraction of ET_o to arrive at ET_c

FIGURE 4
Reference (ET_o), crop evapotranspiration under standard (ET_c) and non-standard conditions ($ET_{c\ adj}$)

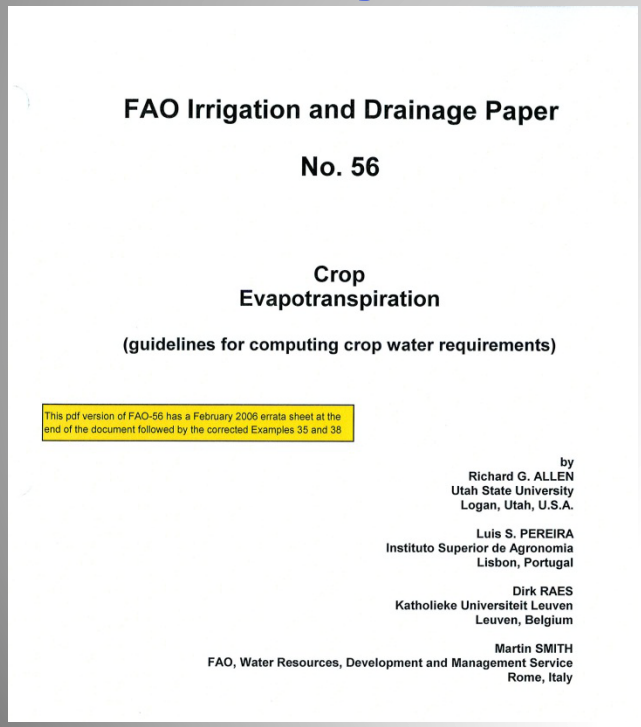


(modified from FAO56 2006)

Many, many, many ET equations to chose from !

ASCE Standardized Reference ET Equation:

FAO Penman-Monteith SEB most reliable if weather data available--requires representative measurements (or estimates) of air temperature, humidity, solar radiation, and wind speed.



FAO Irrigation and Drainage Paper

No. 56

Crop
Evapotranspiration

(guidelines for computing crop water requirements)

This pdf version of FAO-56 has a February 2006 errata sheet at the end of the document followed by the corrected Examples 35 and 38

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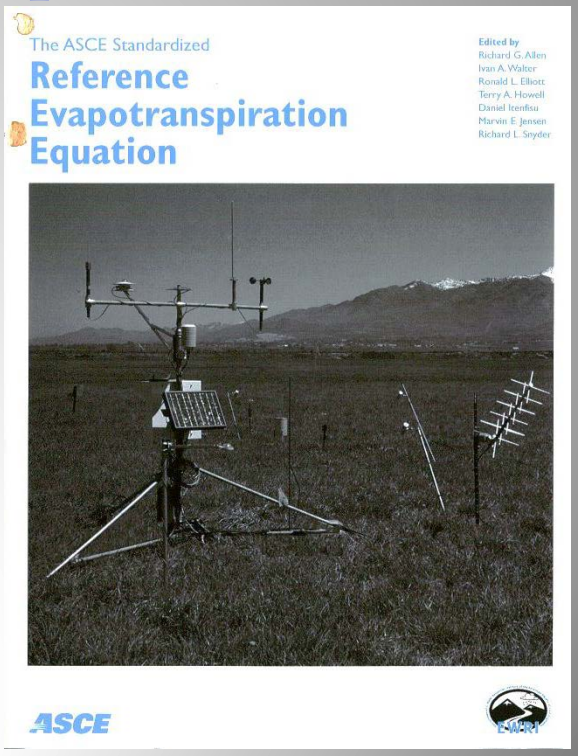

The ASCE Standardized
Reference
Evapotranspiration
Equation

Edited by
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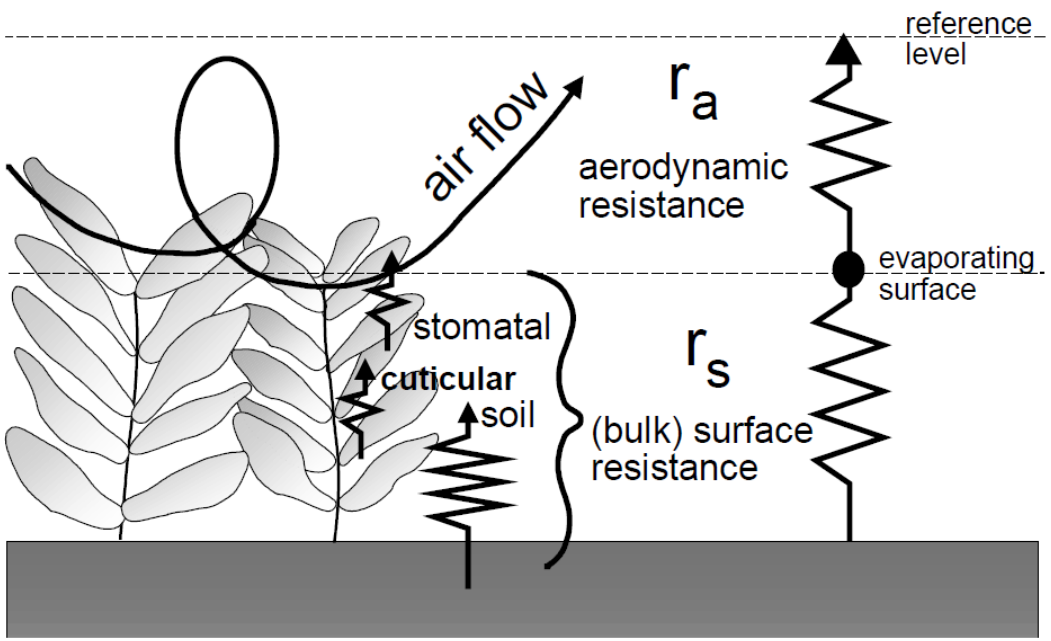
ASCE

Penman-Monteith combines energy balance and mass vapor transfer methods into a resistance-based equation that captures essential physics of energy and vapor transfer

FIGURE 7
Simplified representation of the (bulk) surface and aerodynamic resistances for water vapour flow



Transfer of heat and water vapor from surface into air above canopy determined by aerodynamic resistance

Resistance of vapor flow through stomata openings, leaf area and soil surface

(FAO56 2006)

ASCE Standardized Reference ET Equation: (meaning that computation procedures are "fixed" /not benchmarked)

$$ET_{sz} = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d\, u_2)}$$

where:

ET_{sz} = standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps),

R_n = calculated net radiation at the crop surface (MJ m^{-2} $d^{-1}$for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),

G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),

T = mean daily or hourly air temperature at 1.5 to 2.5-m height (°C),

u_2 = mean daily or hourly wind speed at 2-m height (m s^{-1}),

e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,

e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

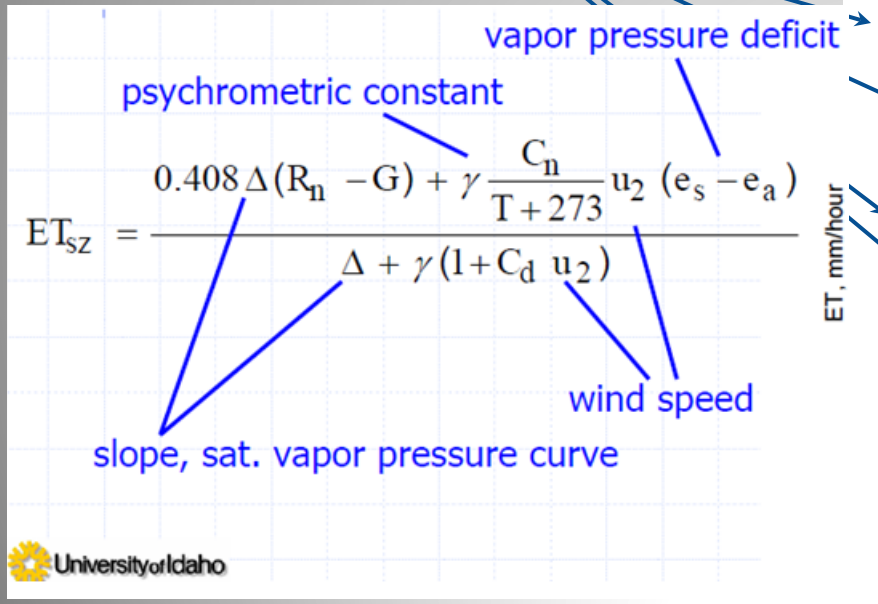
Δ = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}),

γ = psychrometric constant (kPa °C^{-1}),

C_n = numerator constant that changes with reference type and calculation time step (K mm s^3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1}) and

C_d = denominator constant that changes with reference type and calculation time step (s m^{-1}).

Key weather station inputs to calculate



(Allen et al. ASCE 2005)

4.Remote Sensing Based, Surface-Energy Balance Methods

Several "classes" of SEB methods and data products

Global Scale

Generally based on MODIS—weekly to monthly frequency at 1 km to 500 m (?) resolution.

MODIS-ET weekly to monthly at "low" spatial resolution for global climate and ecology applications.

Basin or Field (operational scale)

Generally based on Landsat—daily, weekly, monthly at 30 m scale.

METRIC- Landsat-ET at high (30 m) spatial resolution and daily to monthly resolution.

"Popular" operational satellite SEB methods include:

◆ Mapping EvapoTranspiration with high Resolution and Internalized Calibration

Allen and associates and partners
University of Idaho, *Kimberly*
– ***development began in 2000***
– ***rooted in SEBAL***[2000]

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

◆ 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*

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

Simplified Surface Energy Balance

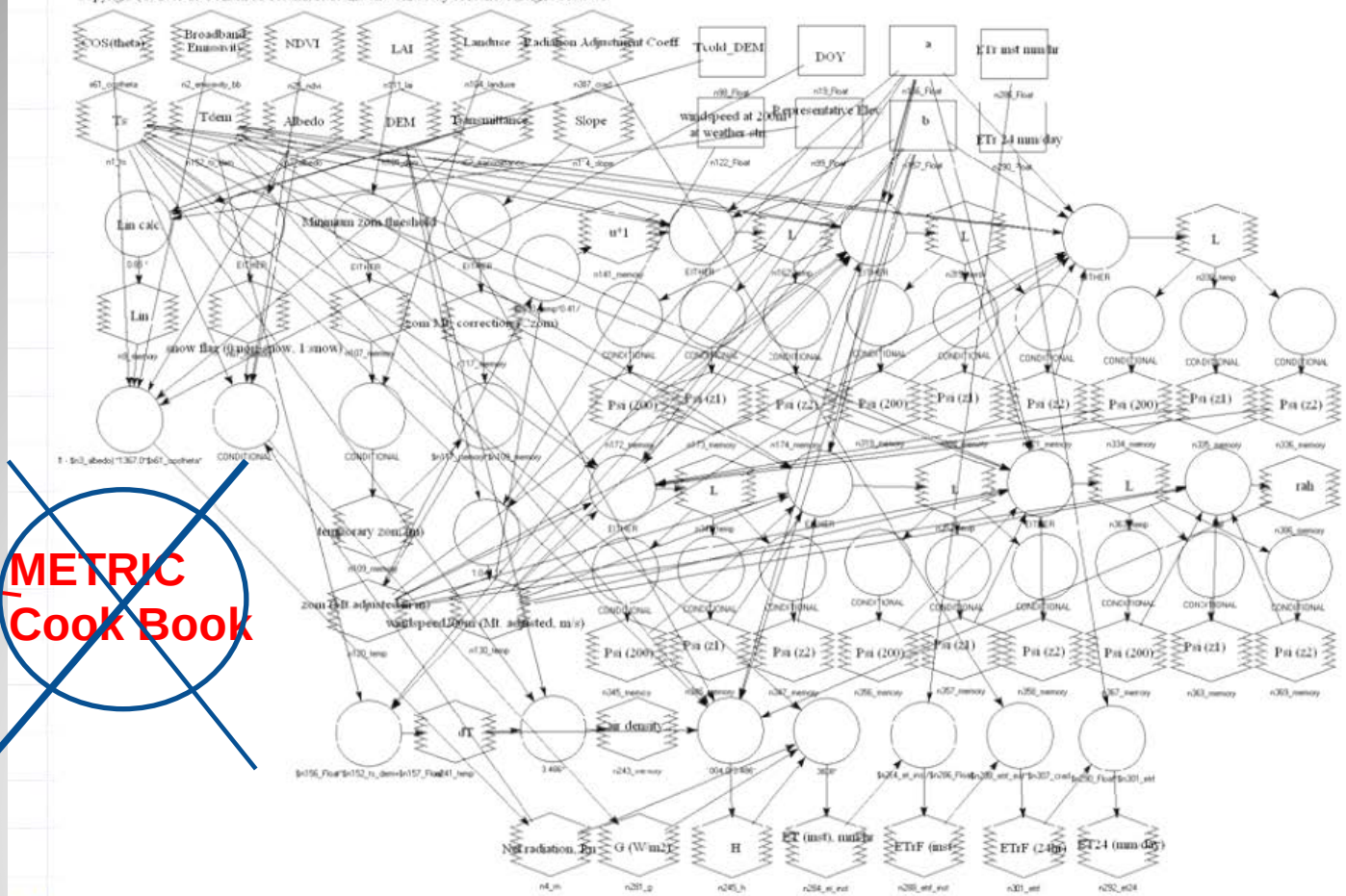
Gabriel Senay (USGS)

SSEB provides:
daily, weekly, monthly ET
-30 m pixel resolution

4. Surface-Energy Balance Methods

‘ all this science I don’t understand,
it’s just my job five days a week’

METRIC^{tm}-ERDAS submodel for sensible heat and ETrF

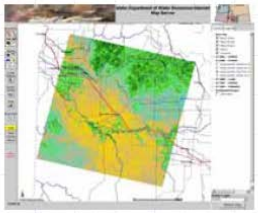


METRIC
Cook Book

University of Idaho

METRIC application requires good imagery, and weather station data, and inter-disciplinary knowledge and experience to operate METRIC with periodic, enlightened-user intervention, and assessment of results.

METRIC^{tm} Level One Requirements



- ***Background in:***
  - ***hydrologic science or engineering*** *(to know behavior of soil, vegetation and water systems)*
  - ***Environmental physics***
    - *Radiative*
    - *Aerodynamic*
    - *Heat transfer*
- ***Familiarity with***
  - ***Vegetation systems*** *(to know what one is looking at and growth and canopy characteristics)*
  - ***Specific human activities*** *(agriculture, irrigation, etc.)*
  - ***Remote Sensing*** *Science and Applications*
  - *Image Processing*

University of Idaho

METRIC in Progress

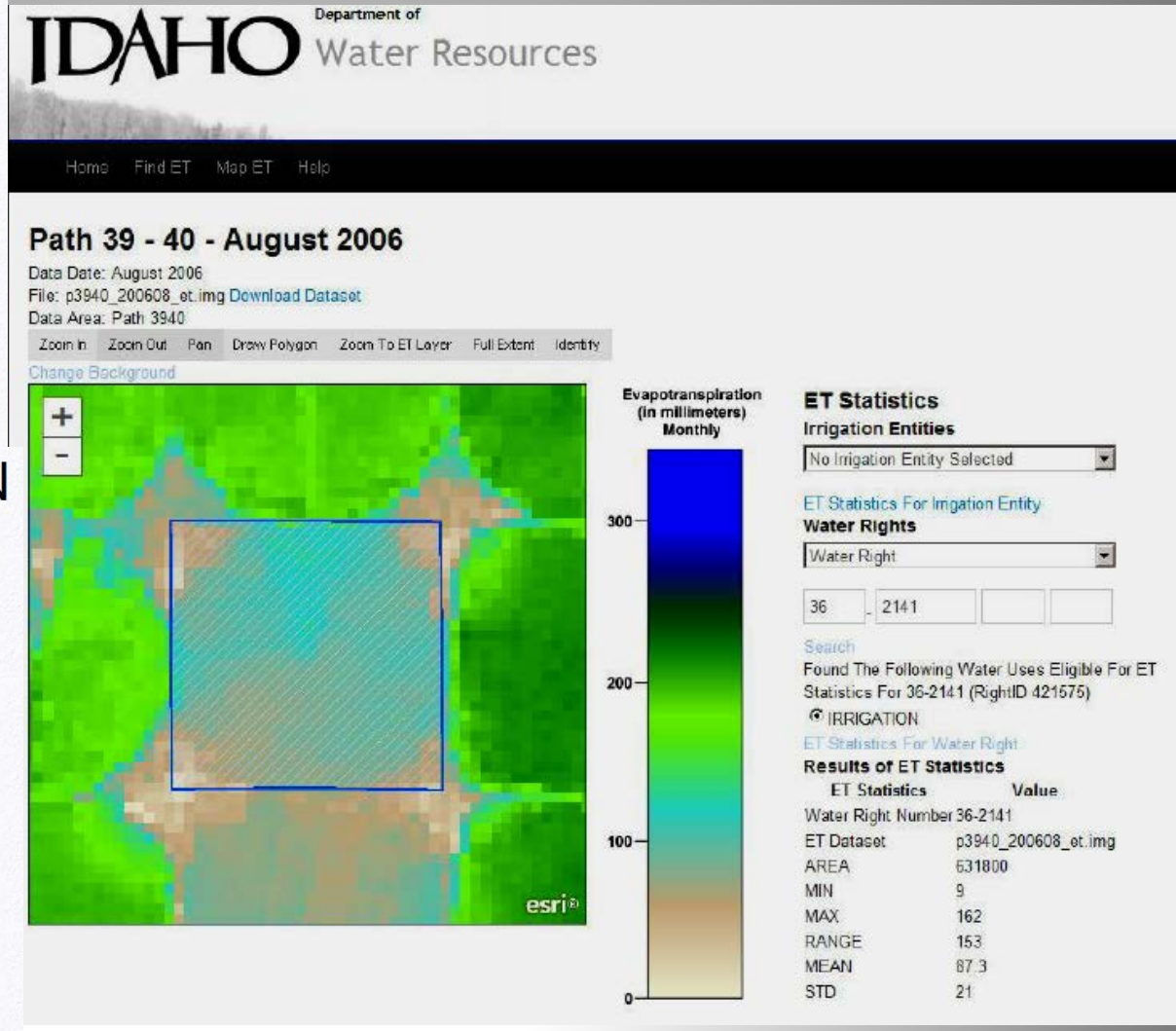
Idaho ET Applications

- 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

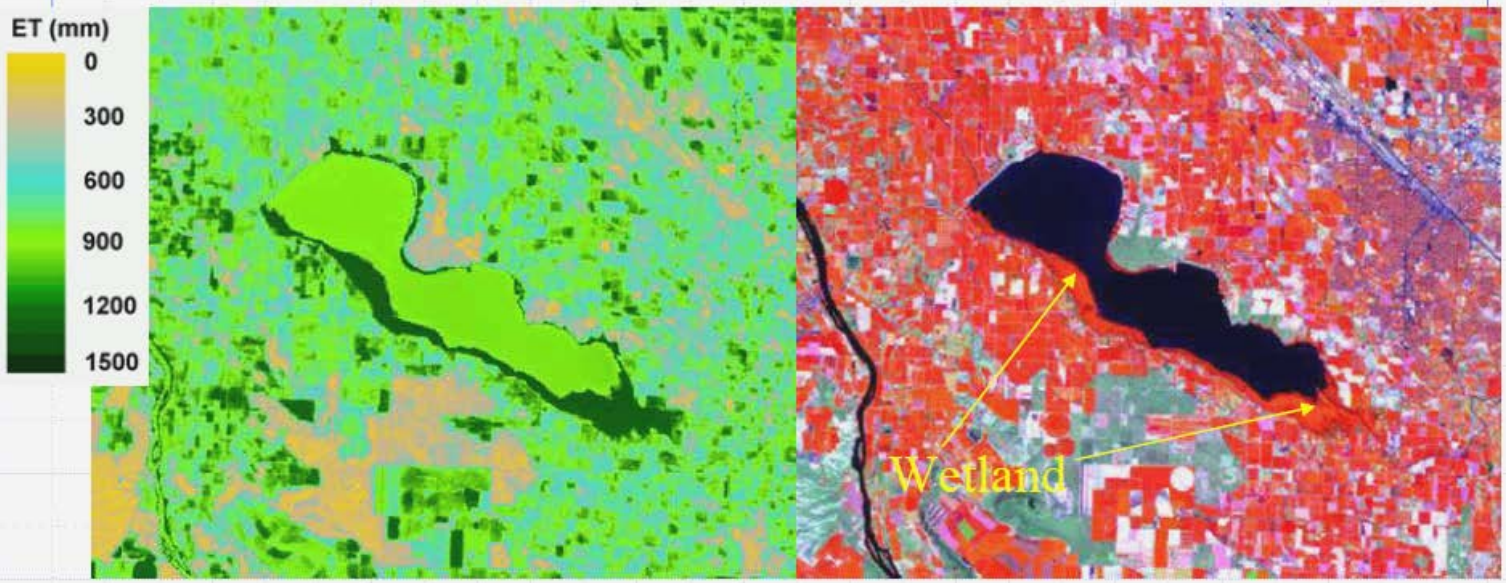
WATER ADMINISTRATION

Monitoring Water Rights Compliance

Irrigation Without a Water Right



Actual ET from wetlands and riparian systems

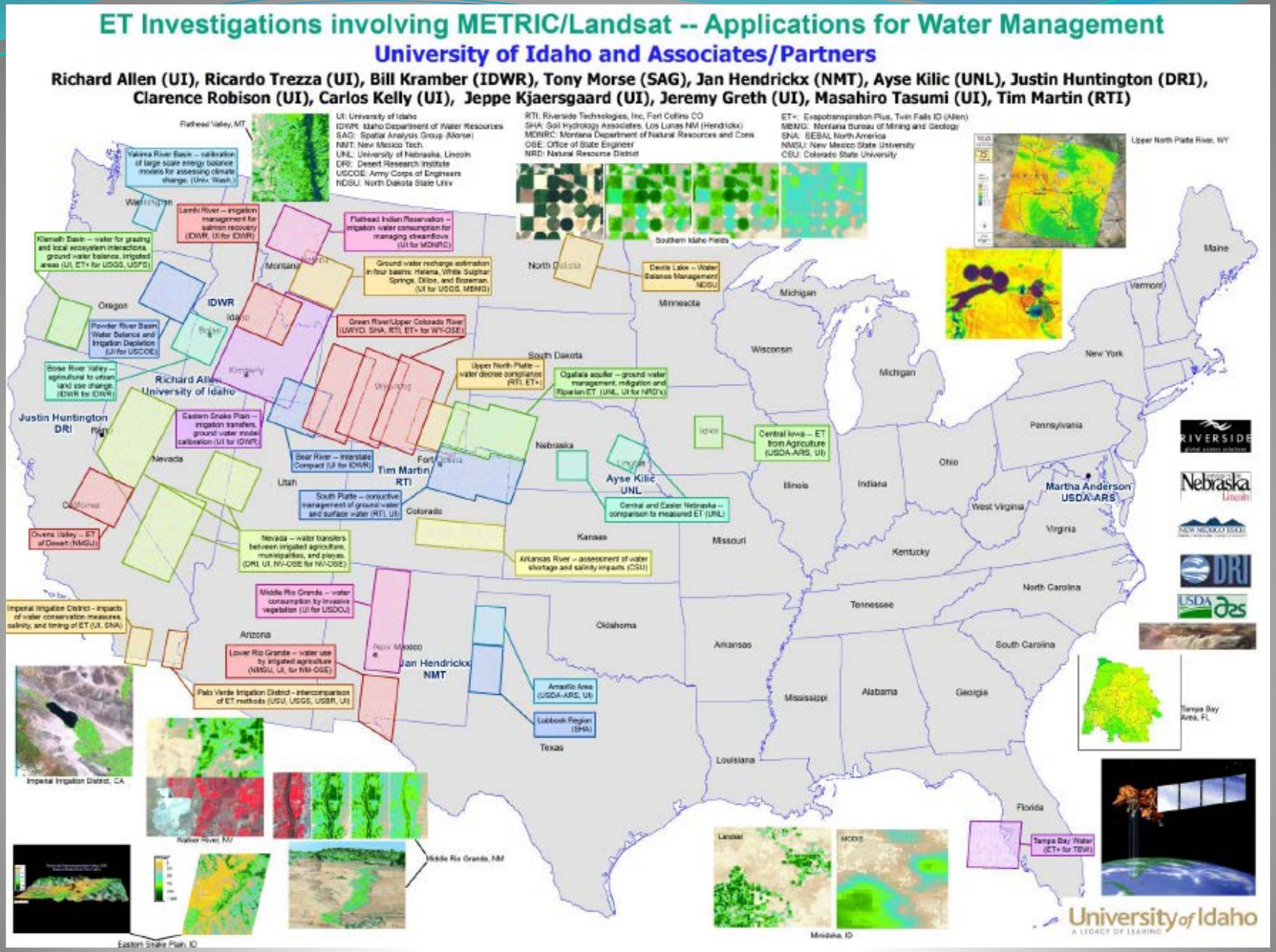


Boise Valley Seasonal ET 2000

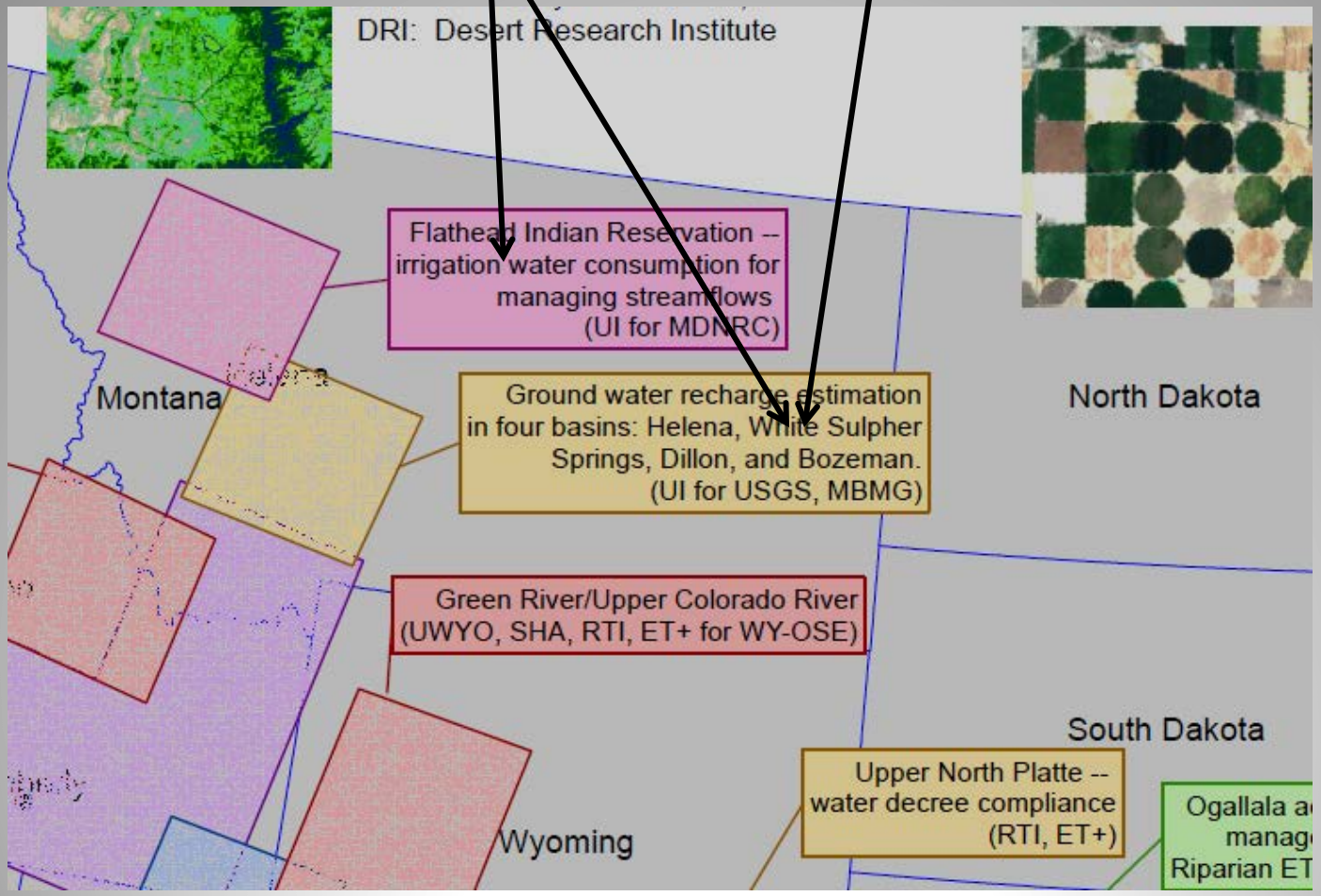
University of Idaho

Source: Rick Allen, University of Idaho

4. Surface-Energy Balance Methods

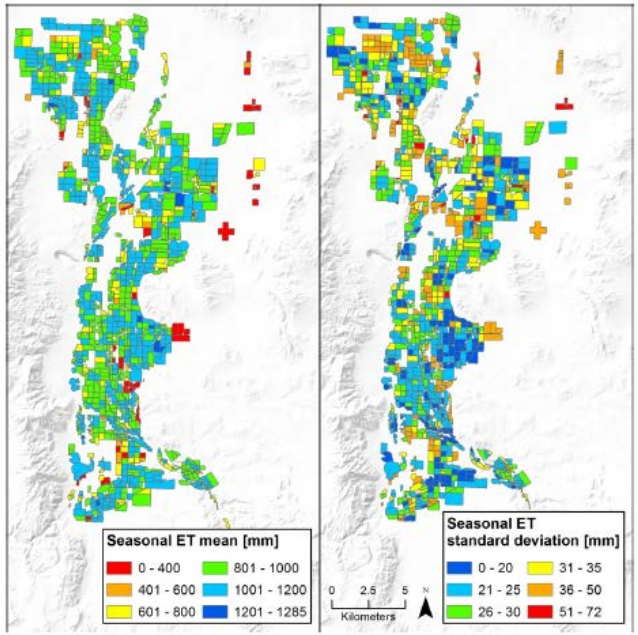


Montana METRIC and SSEB Applications



METRIC Automation Benefits

- Quickly generate ET estimates comparable to those from trained users
- Calculate calibration uncertainty of METRIC ET estimates
- Example of per field calibration variability in Mason Valley, NV



METRIC Automation Benefits

- DRI is collaborating with NASA Ames/Cal State Monterey Bay (Forrest Melton)
- Implement METRIC on the NASA Earth Exchange (NEX) high performance computer

Future direction ?

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

MONTANA WATER SUPPLY INITIATIVE

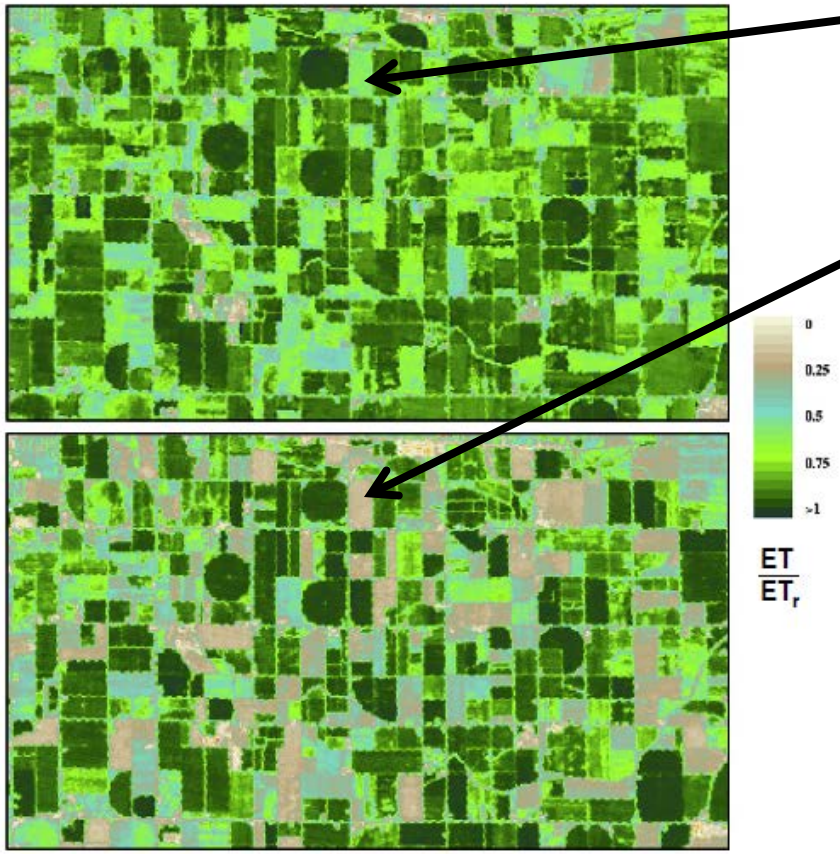
(DNRC-WRD 2015 update of State Water Plan)

Estimate statewide consumptive use at 4th code HUC scale: focus on irrigated agriculture

Method: Vegetation Index with thermal band adjustment

Vegetation Index methods may underestimate ET

M.C. Anderson et al. / Remote Sensing of Environment xxx (2012) xxx–xxx



METRIC shows irrigation

Vegetation Index: no irrigation

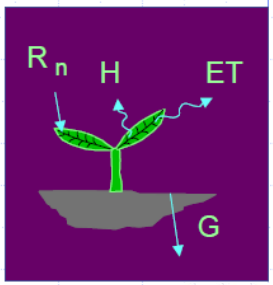
Fig. 4. Comparison of ET maps over an irrigated area in Idaho generated using the TIR-based METRIC approach (top), and using VI data only (bottom). The two approaches agree well for fields at very wet and dry conditions within the METRIC scene, but less well at intermediate moisture conditions. In these cases, the LST is too cold to be consistent with the low ET rates predicted by the VI method, presumably reflecting soil evaporation that is unaccounted for using VIs only.

$$ET = R_n - G - H$$

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

underlined terms are measurable by satellite

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

CIMEC = calibration using inverse modeling at extreme conditions

Source: Rick Allen, University of Idaho

References

Allen, R.G., M. Smith, L.S. Pereira, and A Perrier 1994
An Update for the calculation of reference evapotranspiration. ICID Bulletin, V. 43, Issue 2, pages 35-92

Allen, R.G., Luis S Pereira, Dirk Raes, Martin Smith 1998
Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome.

Allen, R.G., Ivan A. Walter, Ronald L. Elliott, Terry A. Howell, Daniel Itenfisu, Marvin E. Jensen, and Richard L. Snyder *2005*
The ASCE Standardized Reference Evapotranspiration Equation.

Allen, R. G., Tasumi, M., Morse, A. T., & Trezza, R. 2005
A Landsat-based energy balance and evapotranspiration model in western U.S. water rights regulation and planning. Journal of Irrigation and Drainage Systems, 19, 251–268.

Allen, R.G., Masahiro Tasumi, Ricardo Trezza 2007
Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. ASCE Journal of Irrigation and Drainage Engineering. V. 133, Issue 4 pages 380-394.

Allen, R. G., Tasumi, M., Morse, A., Trezza, R., Wright, J. L., Bastiaanssen, W. G. M., et al. (2007).
Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) — Applications. ASCE Journal of Irrigation and Drainage Engineering, 133, 395–406.

Allen, R.G., Luis S Pereira, Terry A Howell, Marvin E Jensen 2011
Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agricultural Water Management. V. 98, Issue 6, pages 899-920.

Allen, R.G., Irmak, Ayse, Trezza, Ricardo; Hendrickx, Jan M. H.; Bastiaanssen, Wim; Kjaersgaard, Jeppe *2011*
Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrological Processes, V. 25, Issue 26 http://dx.doi.org/10.1002/hyp.8408.

Kjaersgaard,J., R. Allen and A. Irmak (2011)
Improved methods for estimating monthly and growing season ET using METRIC applied to moderate resolution satellite imagery. Hydrol. Process. V. 25, pages 4028–4036.

Martha C. Anderson, Richard G. Allen, Anthony Morse, and William P. Kustas 2012
Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. Remote Sensing of Environment. V.122 pages 50-65

Pereira,L.S.; Richard G. Allen; Martin Smith; and Dirk Raes (2015)
Crop evapotranspiration estimation with FAO56: Past and future. Agricultural Water Management V. 147, pages 4-20.

Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, H., and Verdin, J. P 2013
Operational evapotranspiration mapping using remote sensing and weather datasets: a new parameterization for the SSEB approach,
J. Am. Water Resour. As., 49, 577–591, doi:10.1111/jawr.12057, 2013.