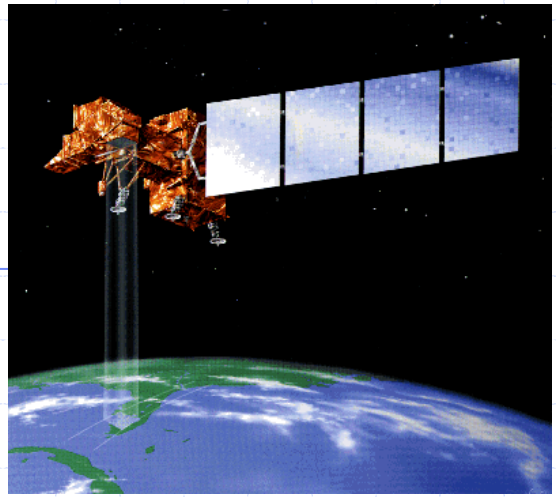
Satellite-based Evapotranspiration for Water Accounting
(or: *Peace through ET Data)*



Rick Allen, University of Idaho

Partners and Collaborators:

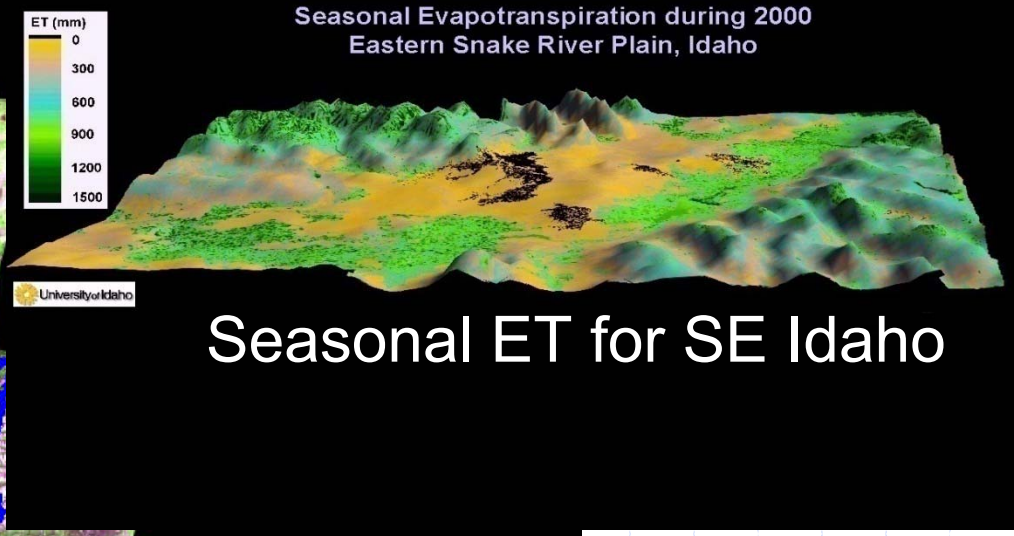
Dr. Magali Garcia, Dr. Jeppe Kjaersgaard, Clarence Robison, *Univ. Idaho*
Tony Morse, William Kramber, *Idaho Dept. Water Resources*
Dr. Ricardo Trezza, *Univ. Andes, Venezuela*
Dr. M. Tasumi, *Miyazaki University, Japan*
Dr. Wim Bastiaanssen – *WaterWatch*, Dr. J. Hendrickx – NMT
Dr. James Wright – USDA-ARS, Dr. Dave Toll – NASA

University of Idaho

USDA ARS

NASA

Vegetation, Water Availability and ET are variable in space and time

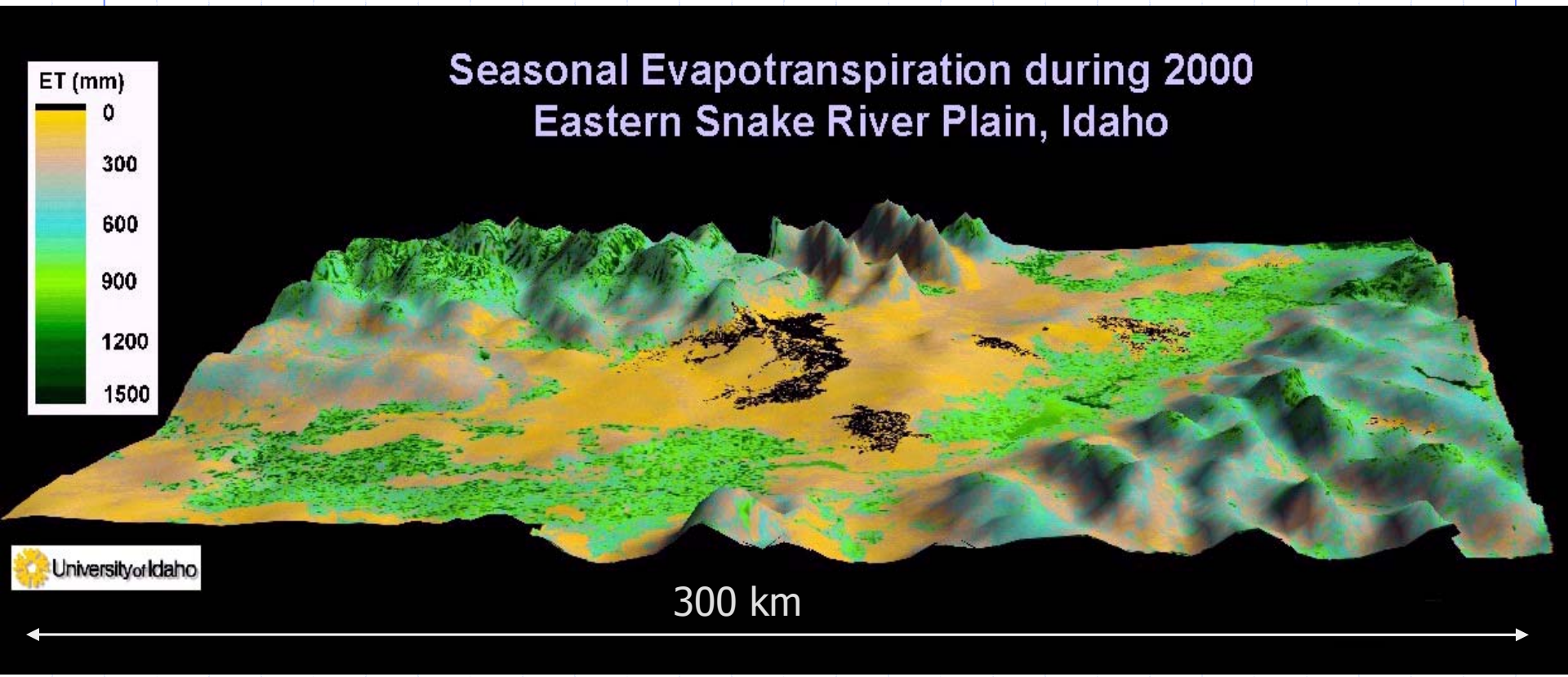


Seasonal ET for SE Idaho

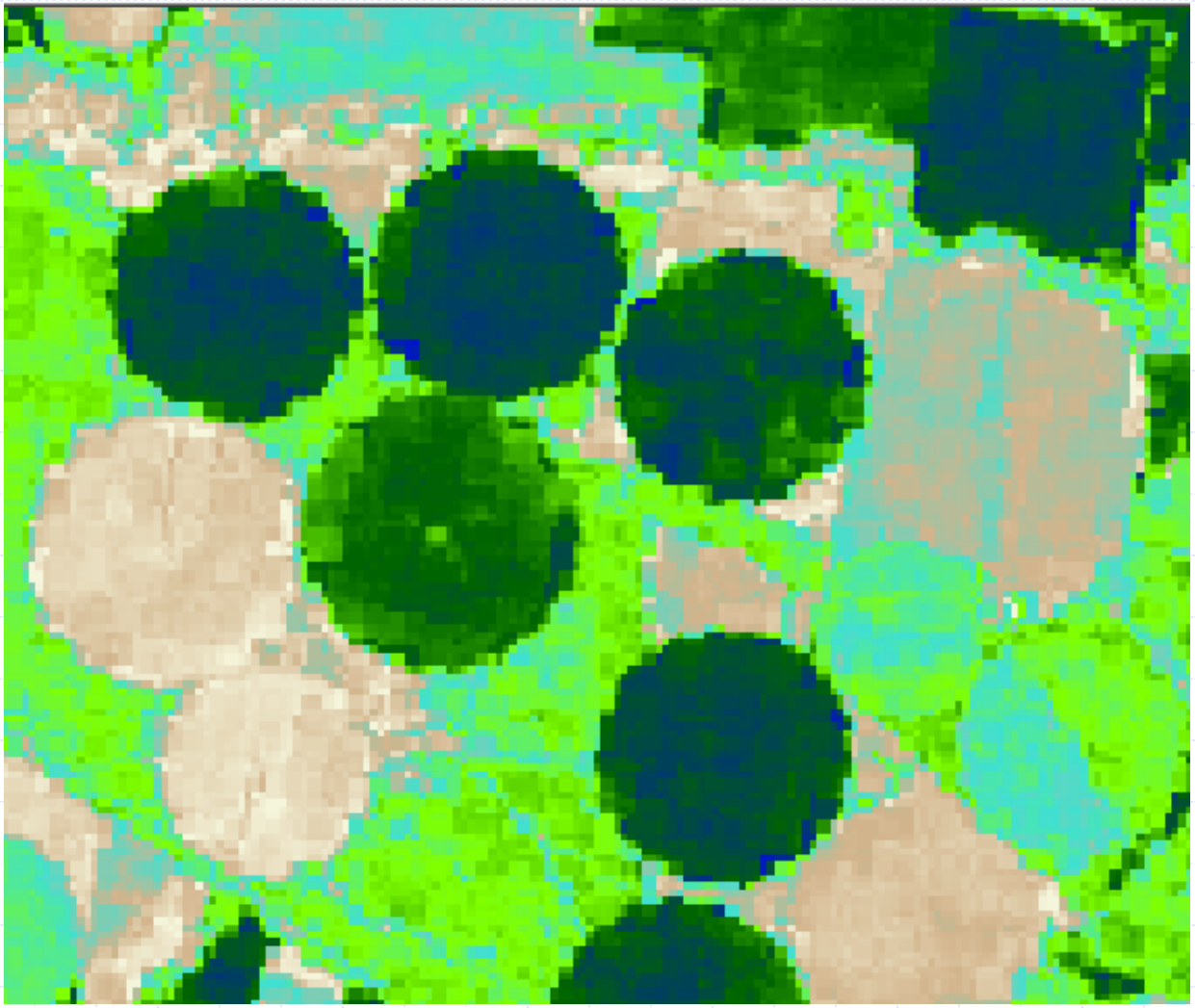
Idaho from Landsat

Major Irrigated areas in Idaho and areas of METRIC application

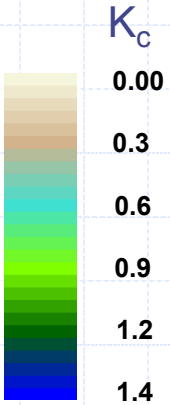
Integrated ET map from 20 Landsat images during 2000



Why use High Resolution Imagery?



ET from Landsat 5 with thermal sharpened to 30 m



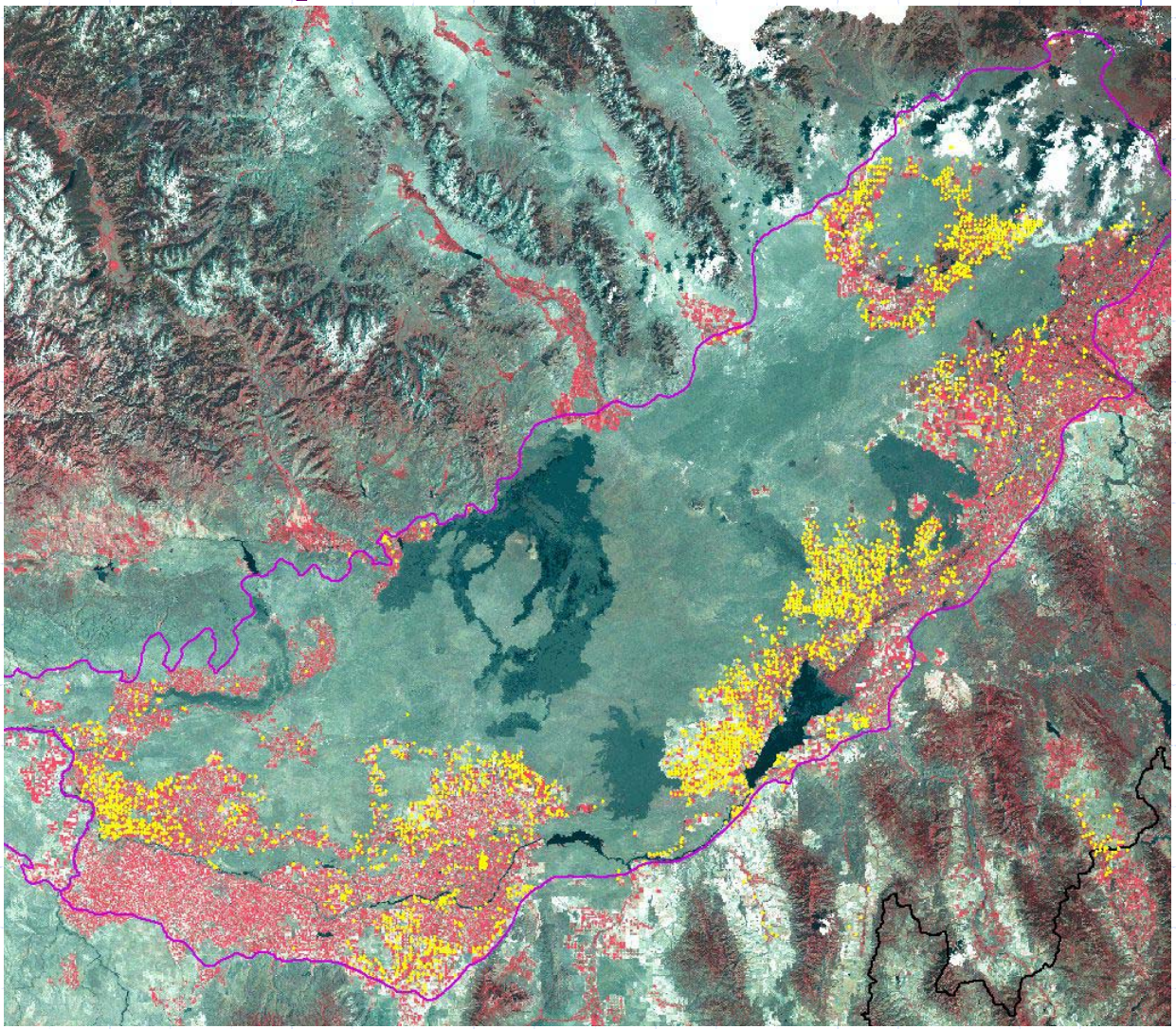
$(K_c = ET_{act} / ET_{ref})$

ET from individual fields is essential for: Water Rights, Water Transfers, Farm Water Management

--Barrax, Spain, Allen and Trezza, 2004

Why Quantify ET?

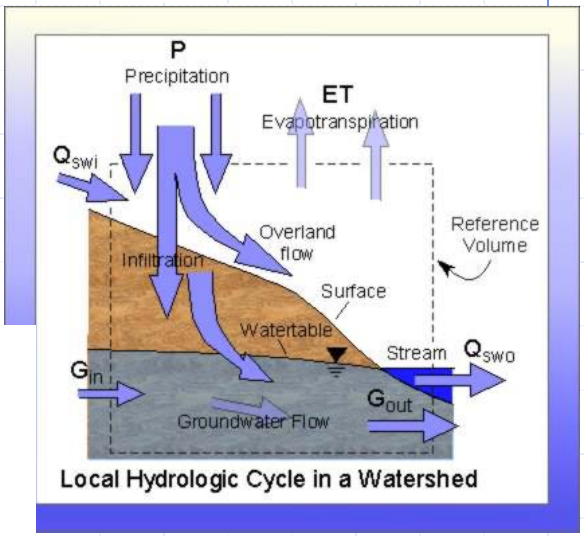
Net Depletion from Ground-water Pumping *(is largely unmeasured)*

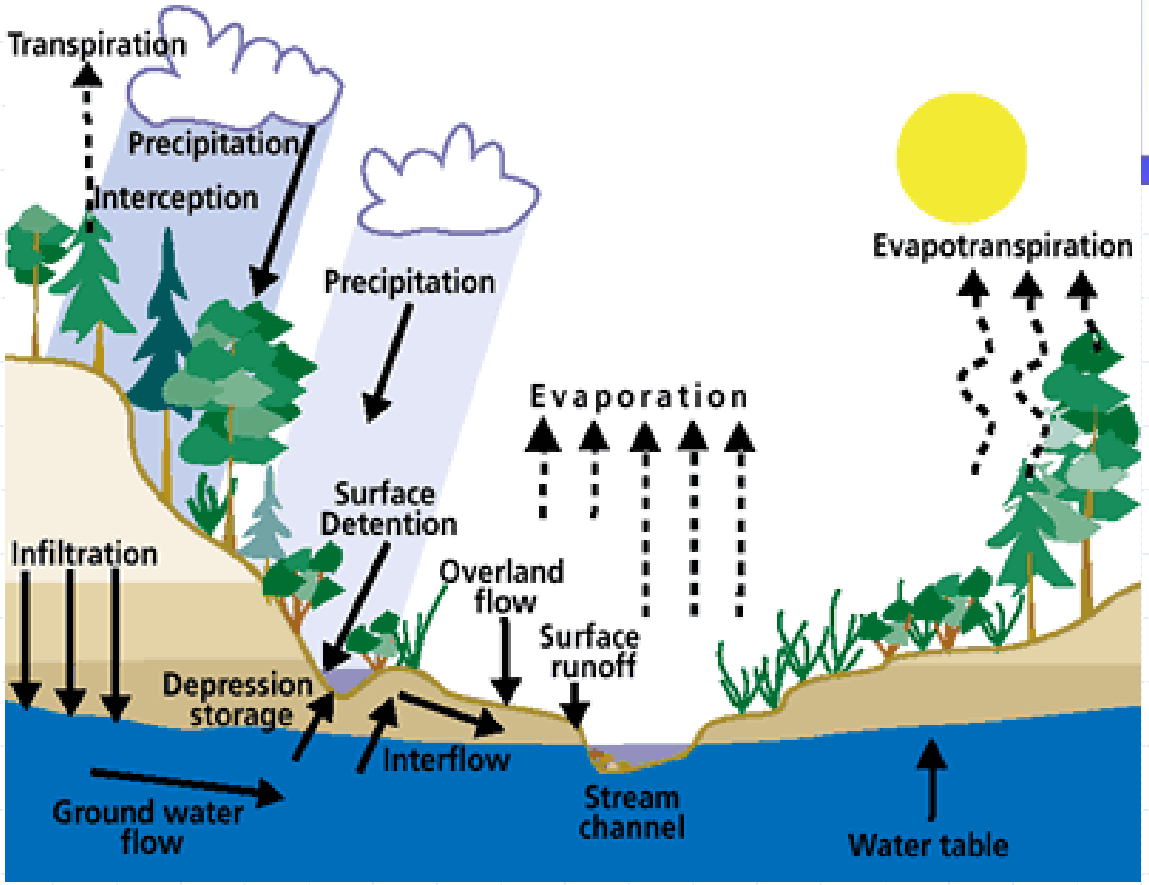


Yellow dots are irrigation wells

Why Quantify ET?

- Hydrologic Water Balances

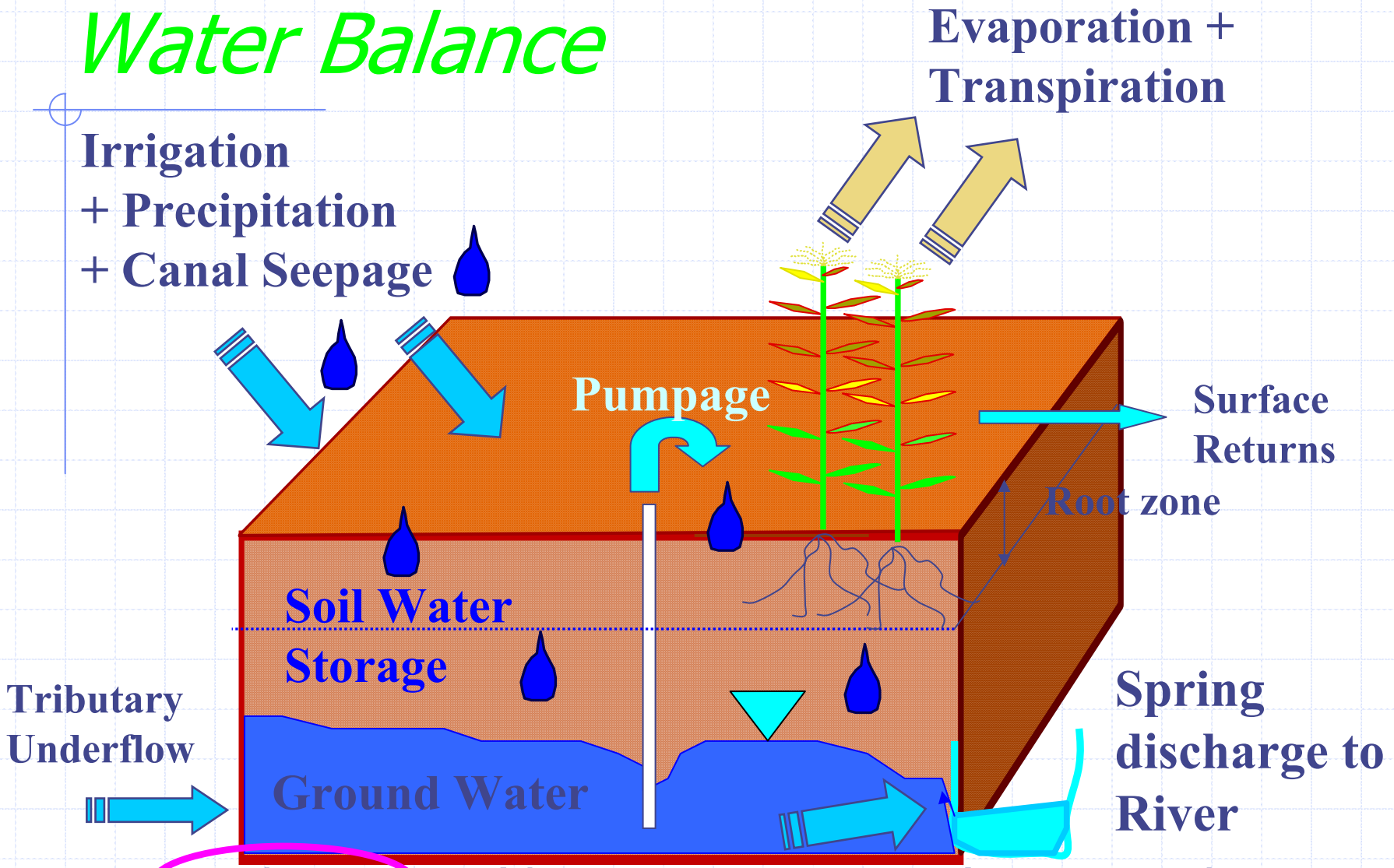




slide courtesy MNR, Ontario, Canada

Irrigated Hydrology:

Water Balance



Recharge = I (deliveries + seepage) + P + Trib_to_GW – Surf Returns – GW discharge – dStorage – ET

ET "mapping" with METRIC^{tm}

- Mapping EvapoTranspiration with high Resolution and Internalized Calibration

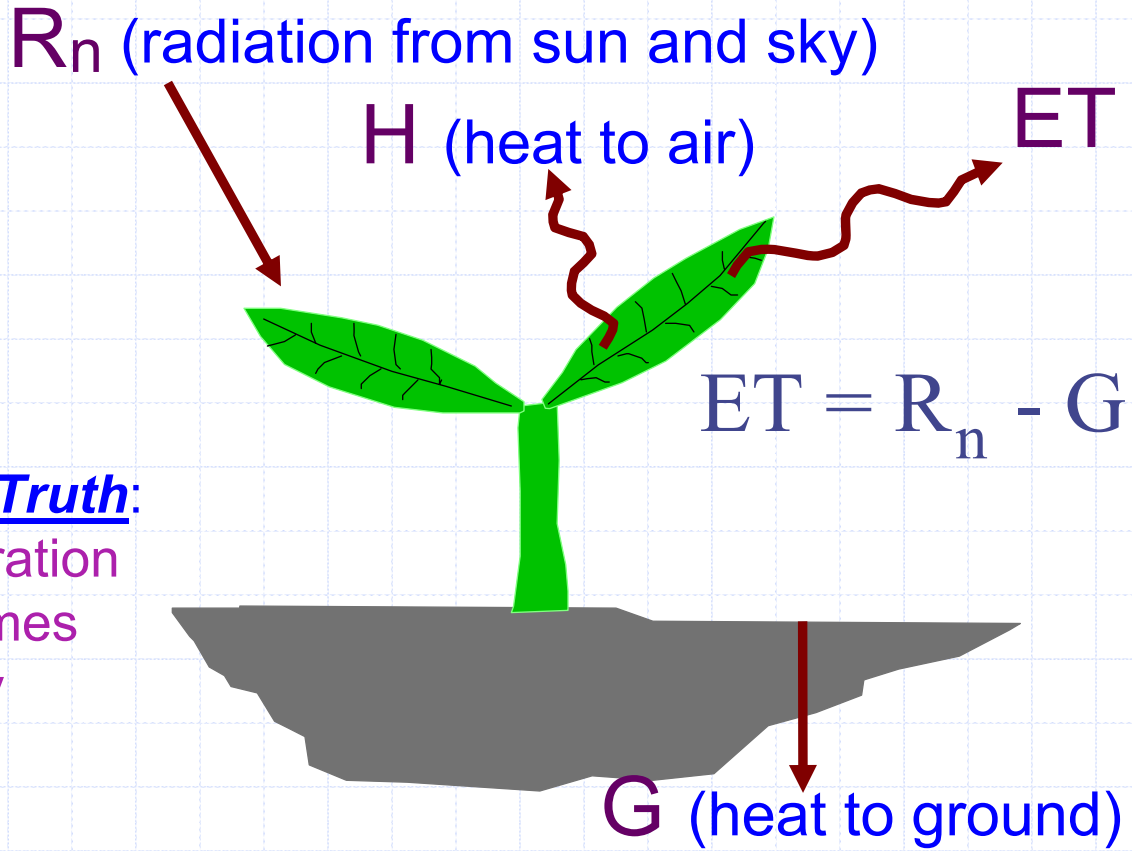
  Allen and Tasumi,
  University of Idaho, *Kimberly*
  – ***development began in 2000***
  – ***rooted in SEBAL^{2000}***

- Surface Energy Balance Algorithm for Land

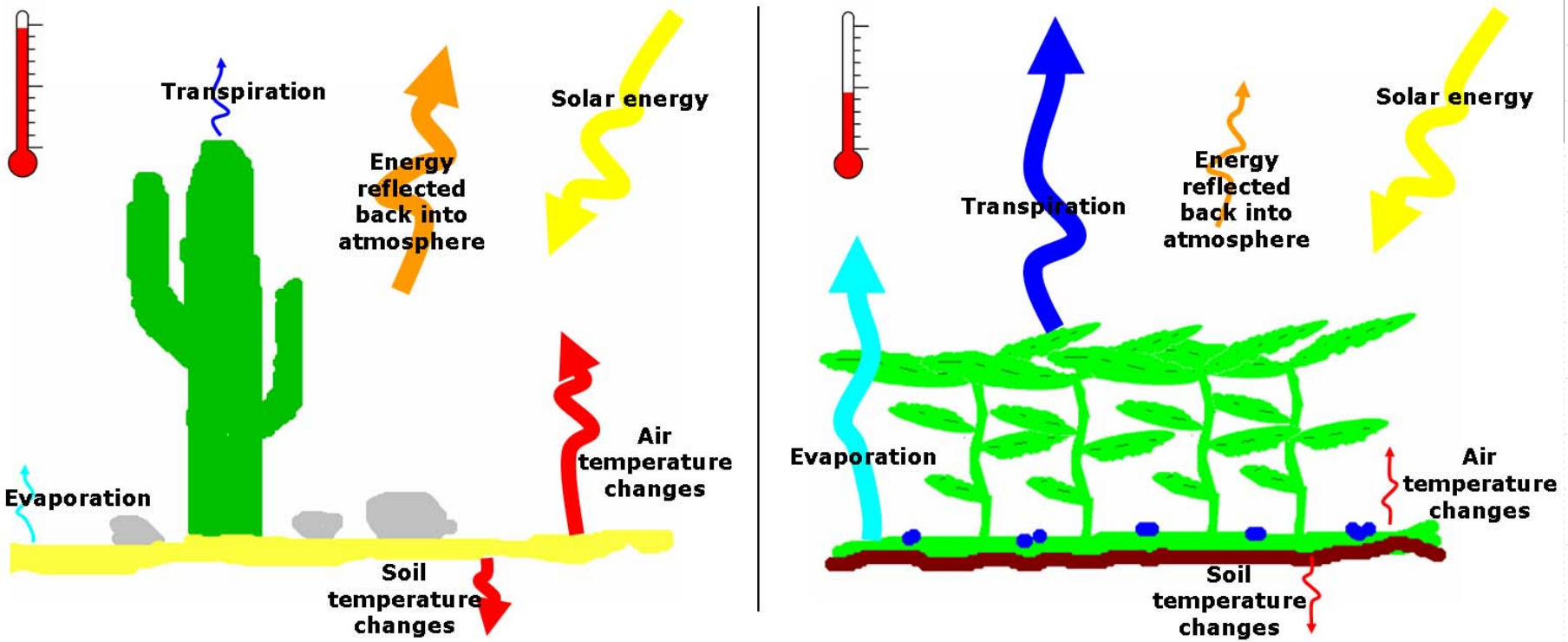
  Dr. Wim Bastiaanssen,
  WaterWatch, *The Netherlands*
  – *beginning in 1990*

Why Energy balance?

- ET is calculated as a "residual" of the energy balance



Basic Truth:
Evaporation consumes Energy



Courtesy of W. Bastiaanssen, WaterWatch

Energy balance gives us "actual" ET

EB can 'see' impacts on ET caused by:

- water shortage
- disease
- crop variety
- planting density
- cropping dates
- salinity
- management

- *(these effects can be converted directly into a crop coefficient)*

History of METRIC Development

- 2000 – Prof. Bastiaanssen came to Idaho to train UI and IDWR on *SEBAL*
- 2002 – ET_{ref} was used to calibrate energy balance process and "*SEBAL_Idaho*" was renamed *METRIC*
- 2002 – 2009 – *METRIC* and *SEBAL* applications in the US in more than 12 western states

Standardized Reference ET

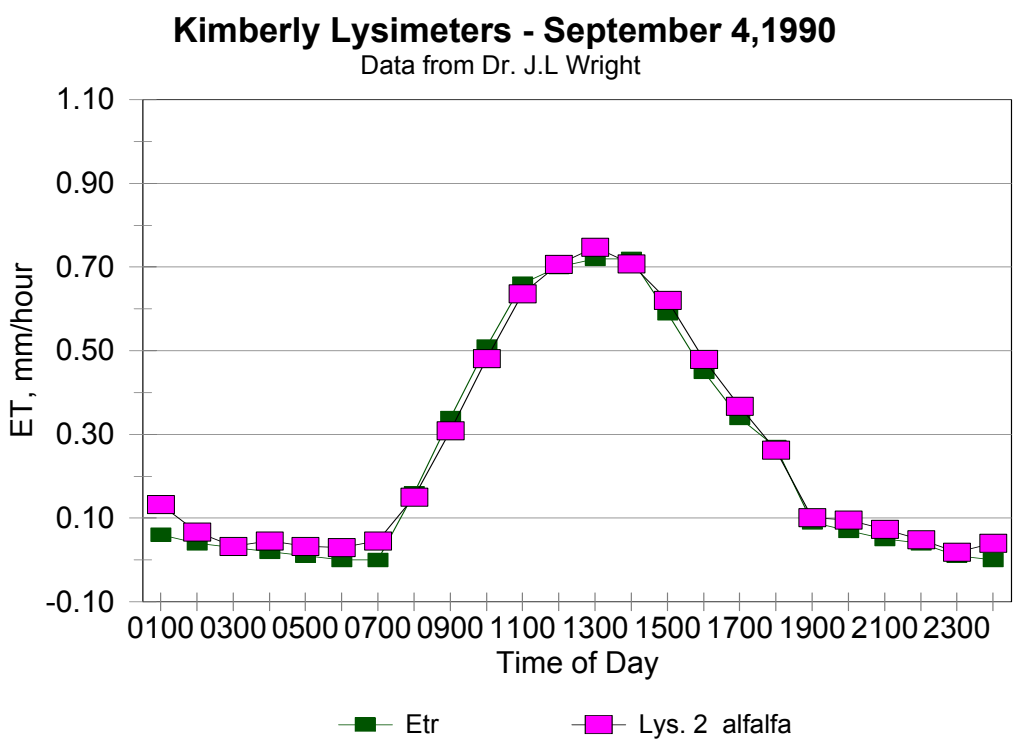
Penman-Monteith *equation applied to* ***alfalfa*** *for* ***hourly*** *application*

$$ET_{ref} = \frac{\Delta (R_n - G) + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right) \lambda}$$

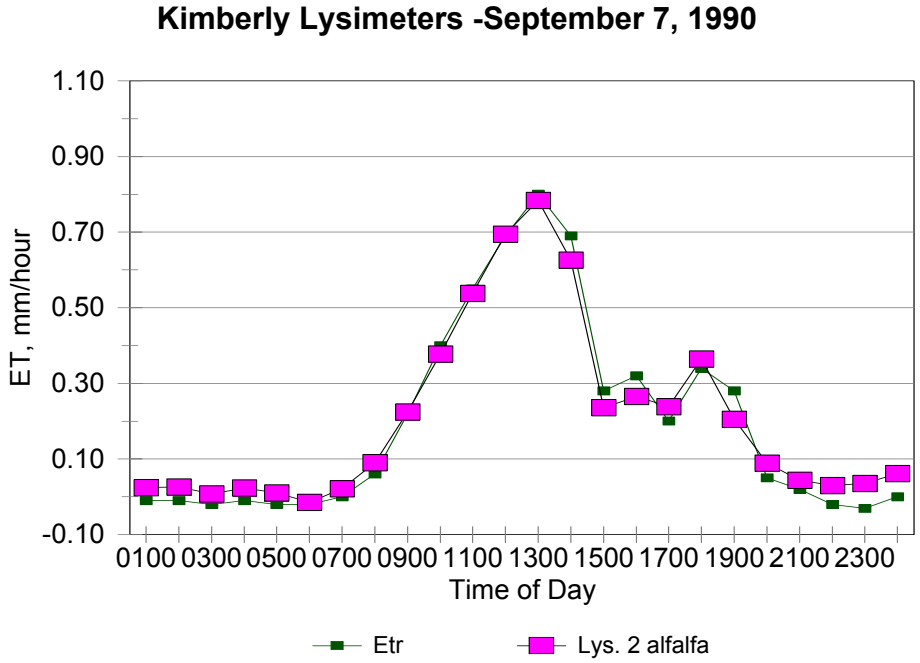
30 s m^{-1}
(daylight)

= f(0.5 m ht)

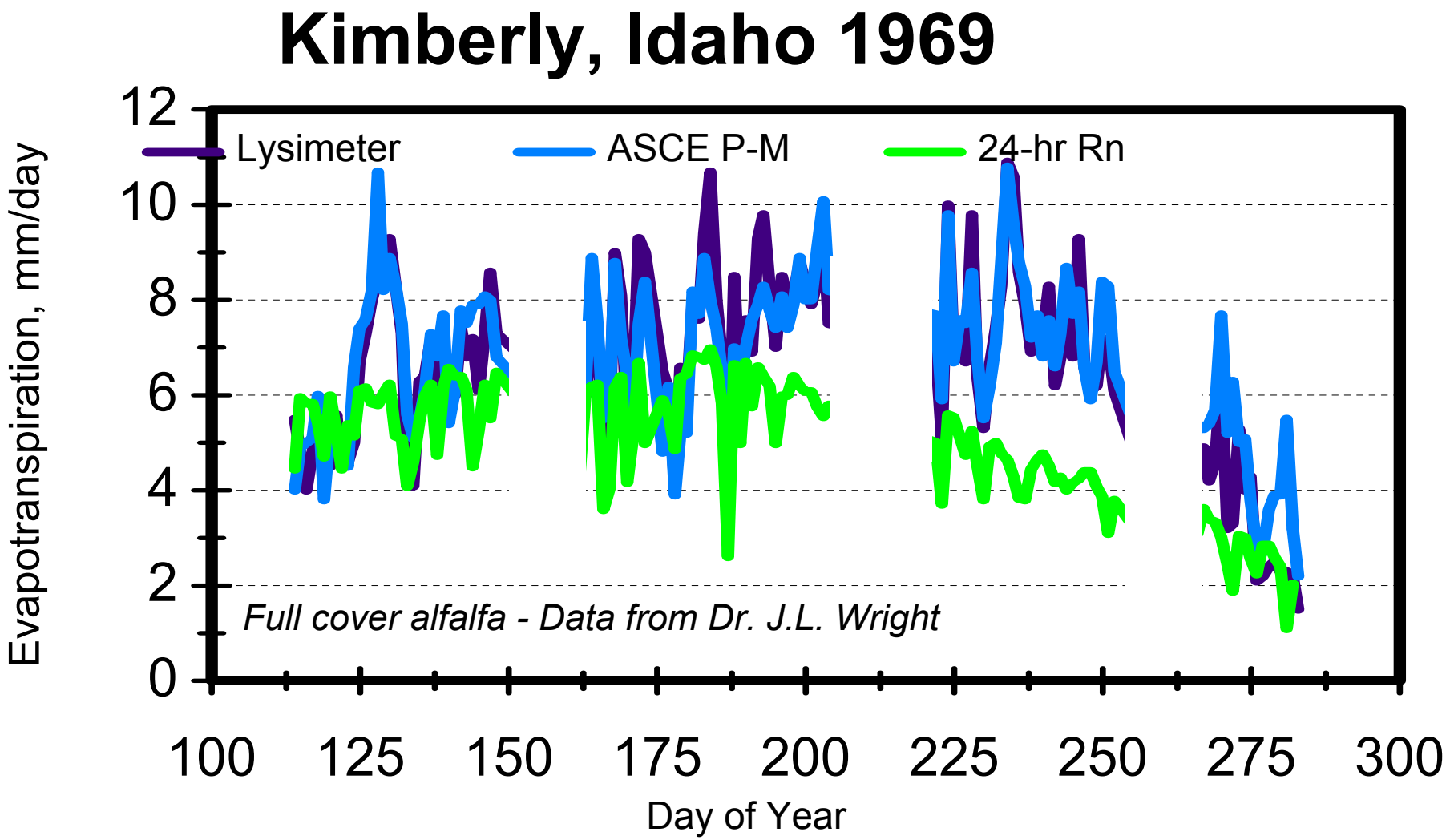
(ASCE-EWRI, 2005)


Kimberly Lysimeters - September 4,1990
Data from Dr. J.L Wright
1.10
0.90
0.70
0.50
0.30
0.10
-0.10
ET, mm/hour
0100 0300 0500 0700 0900 1100 1300 1500 1700 1900 2100 2300
Time of Day
Etr
Lys. 2 alfalfa

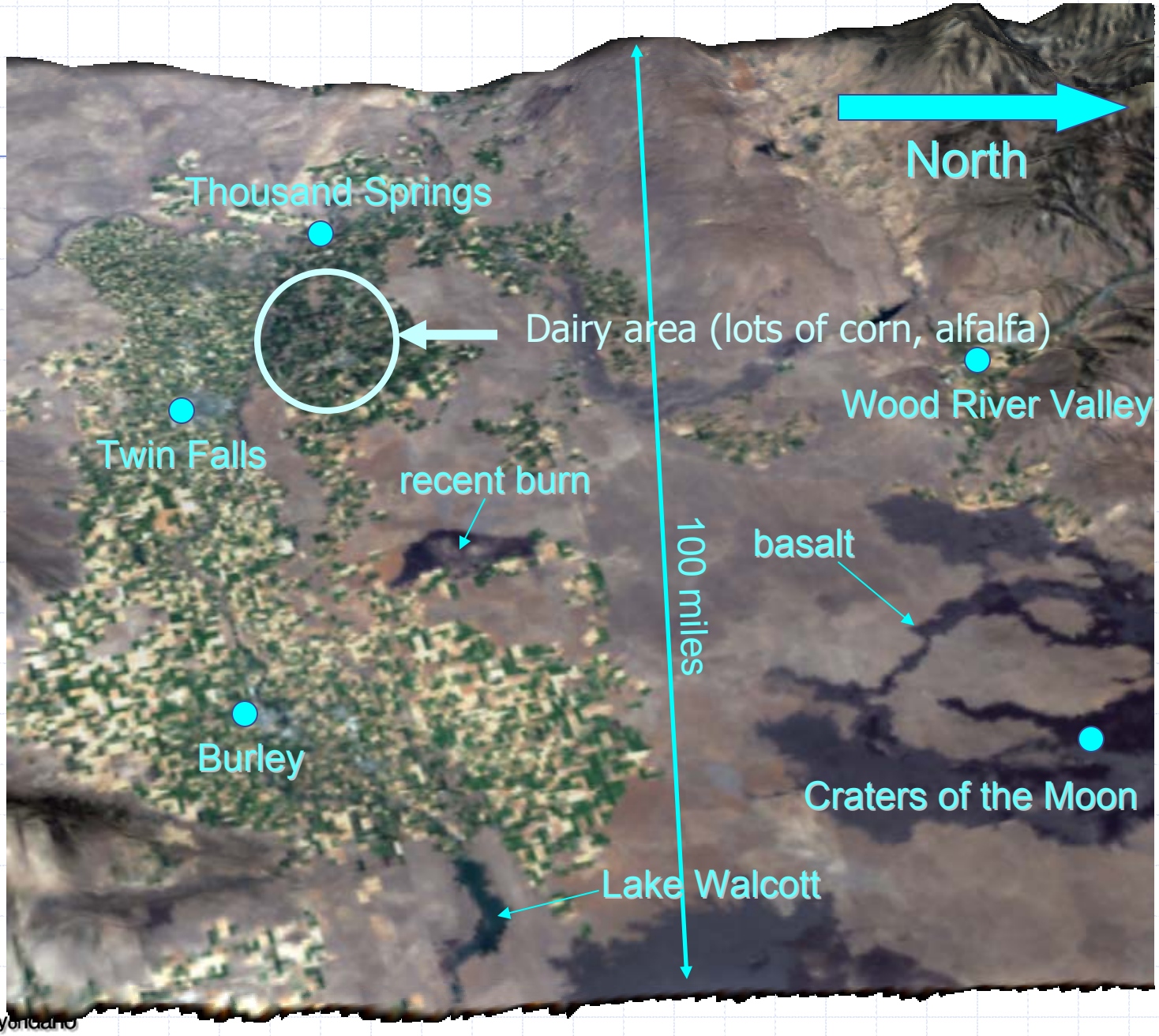

ASCE Standardized
Penman-Monteith
(alfalfa reference)
at Kimberly, Idaho
- hourly time step


Kimberly Lysimeters -September 7, 1990
1.10
0.90
0.70
0.50
0.30
0.10
-0.10
ET, mm/hour
0100 0300 0500 0700 0900 1100 1300 1500 1700 1900 2100 2300
Time of Day
Etr
Lys. 2 alfalfa

Period of strong advection of heat from desert

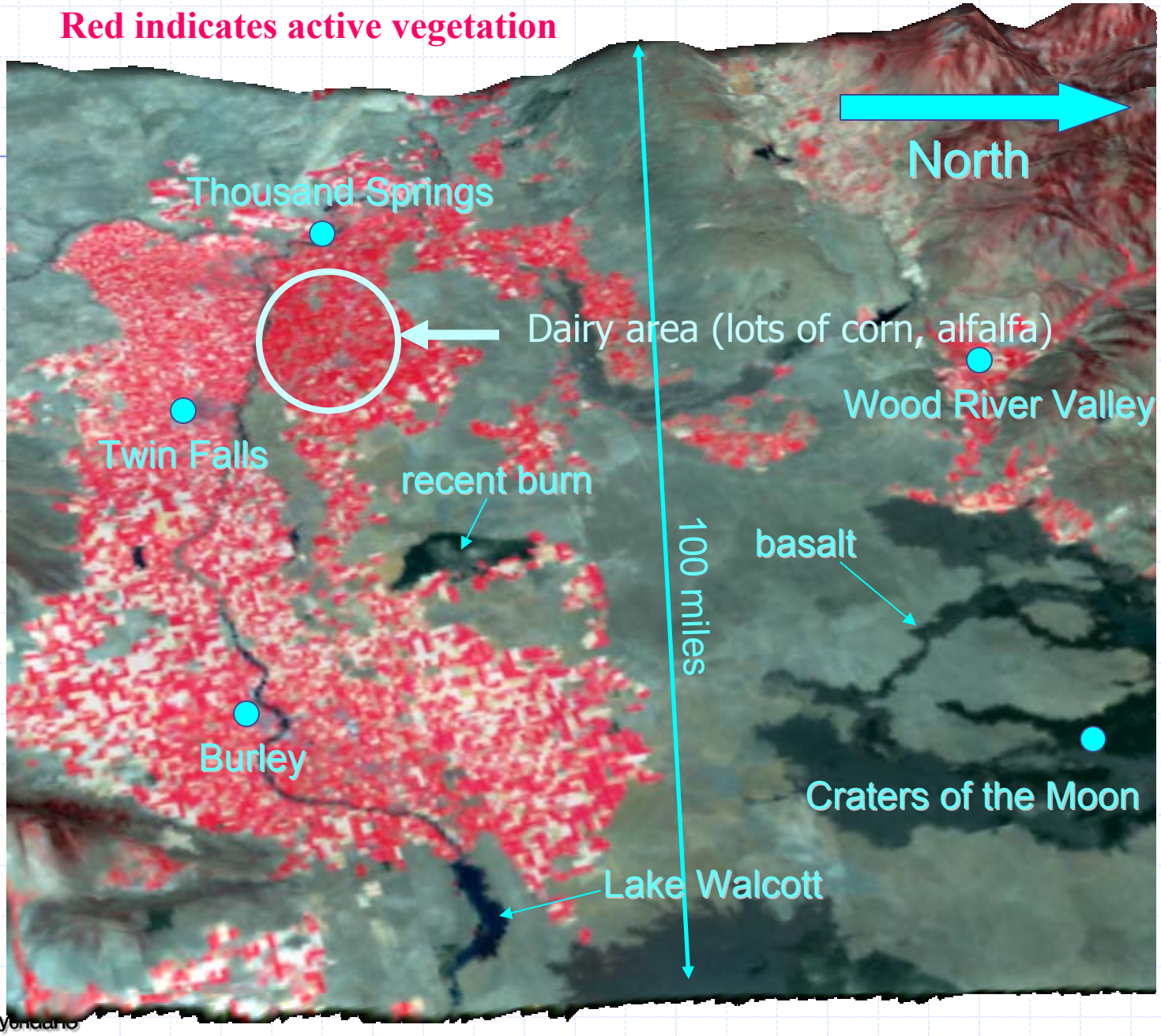


True Color – southcentral Idaho – August 14, 2000

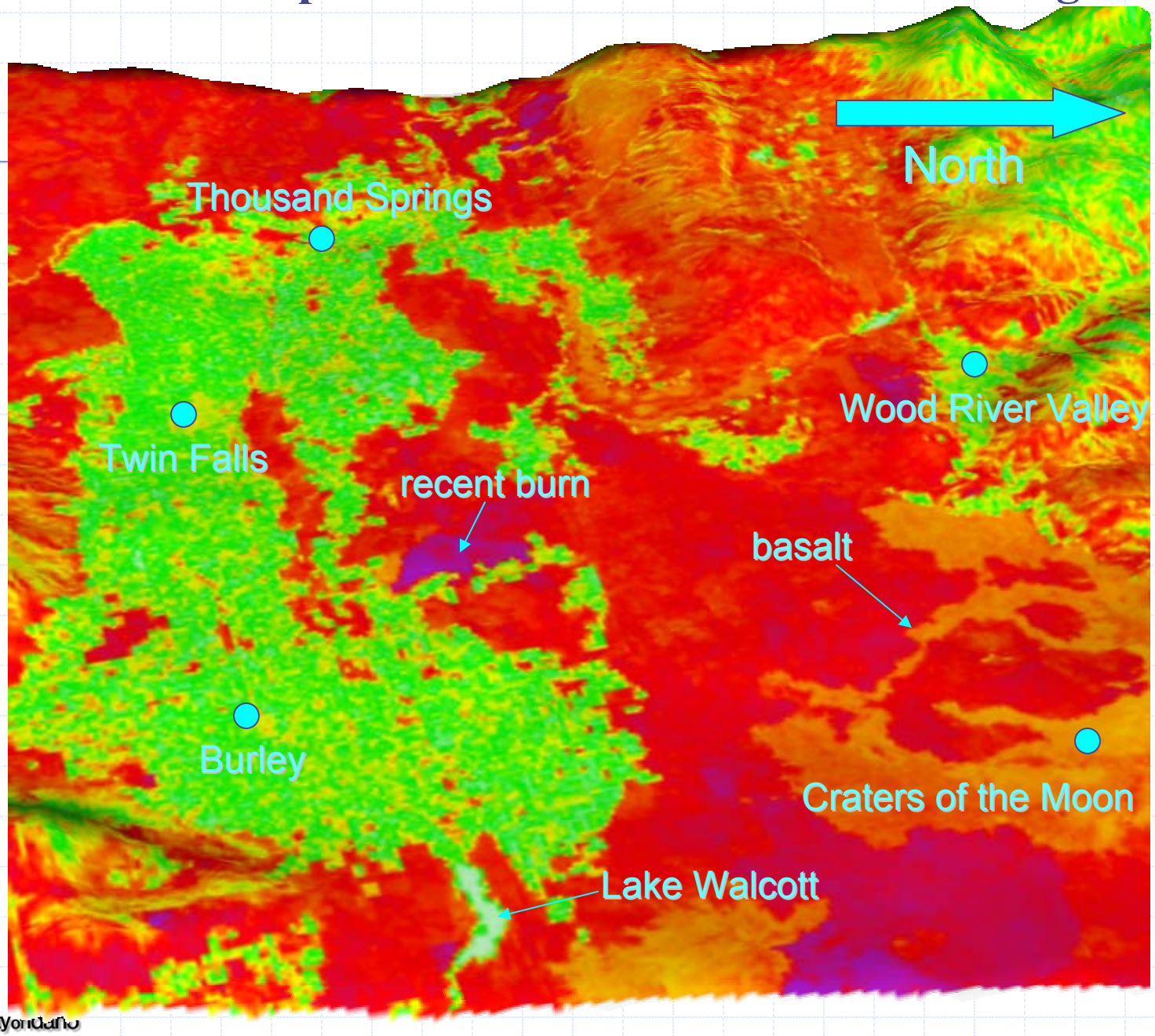


"False" Color – southcentral Idaho – August 14, 2000

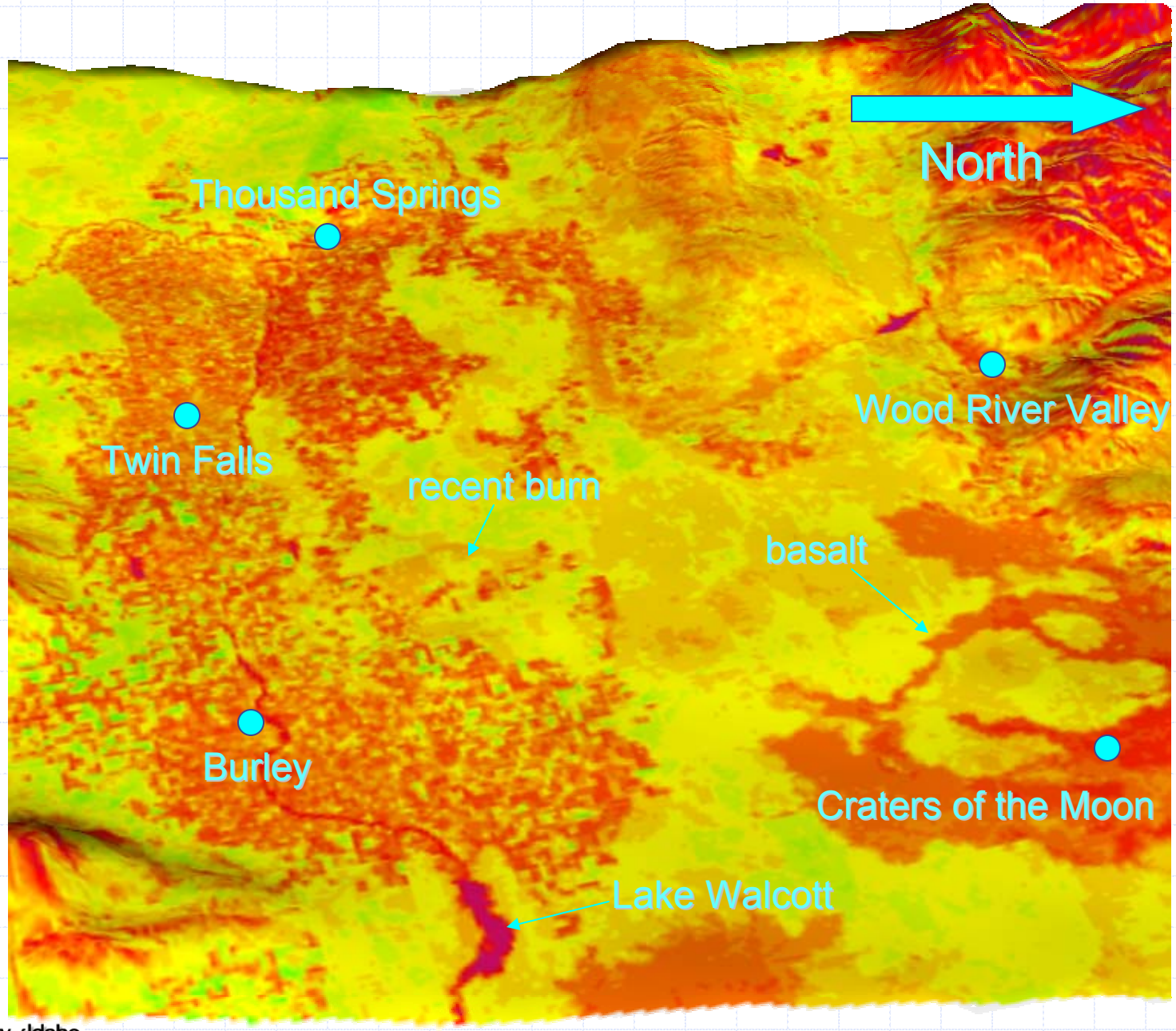
Red indicates active vegetation

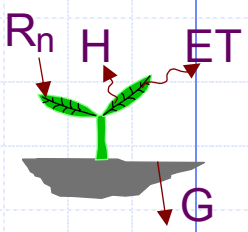


Surface Temperature – southcentral Idaho – August 14, 2000



Net Radiation – southcentral Idaho – August 14, 2000

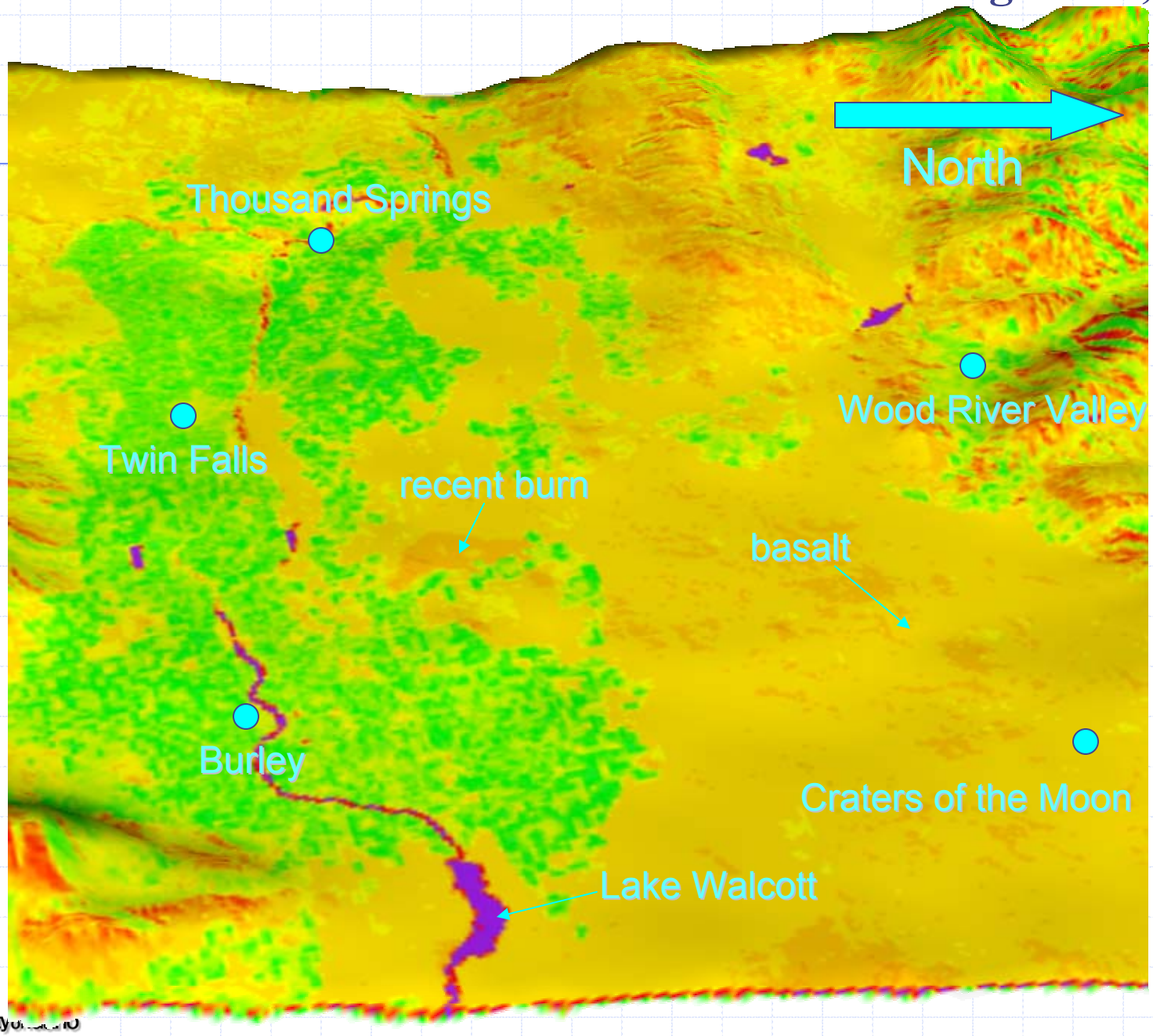


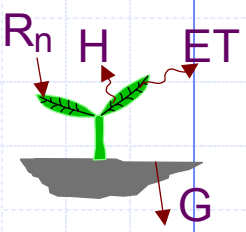


Net Radiation (W/m^2)

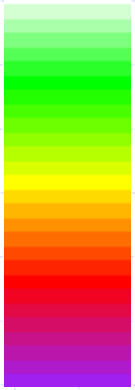
0
200
400
600
800+

Ground Heat Flux – southcentral Idaho – August 14, 2000

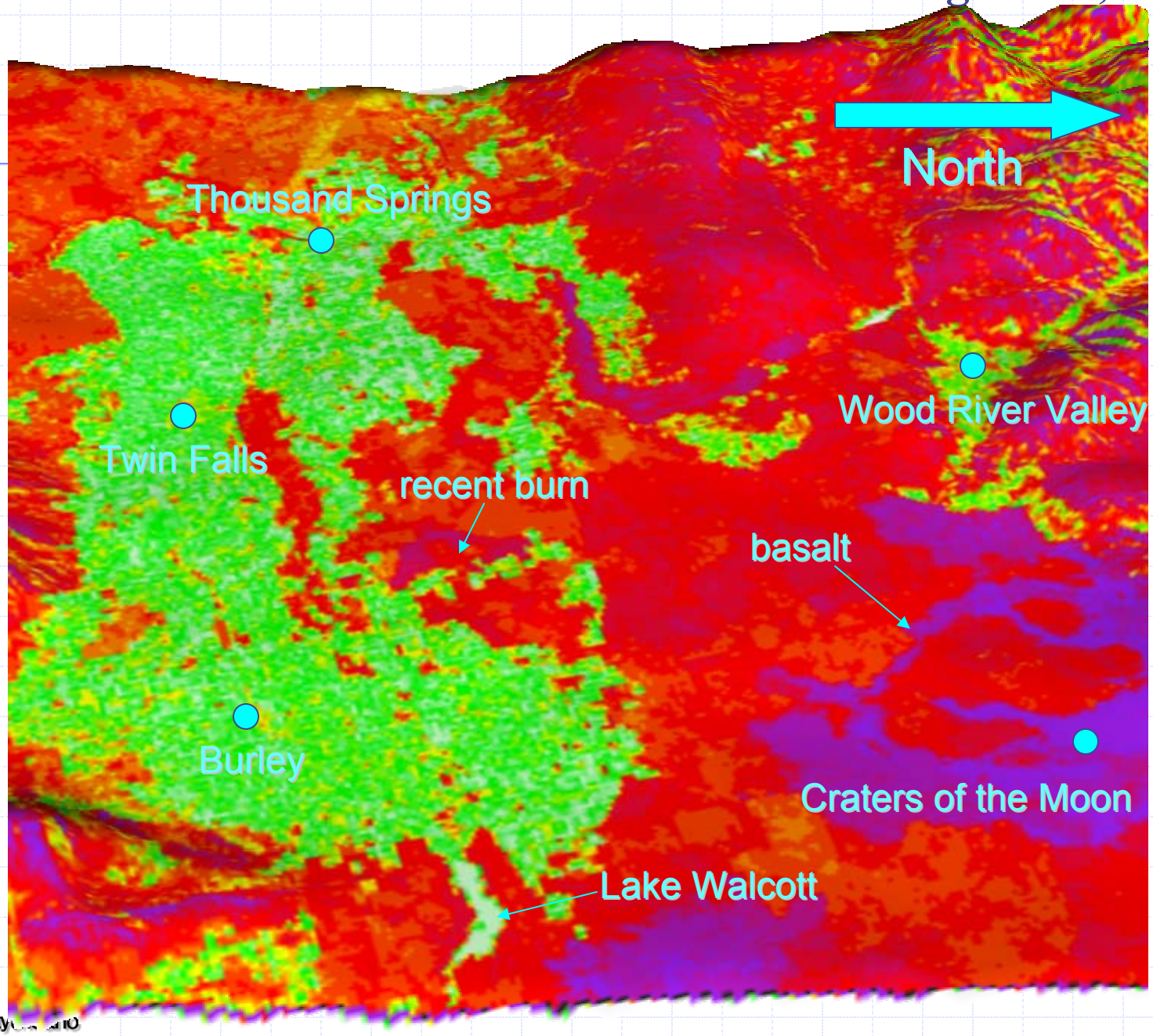


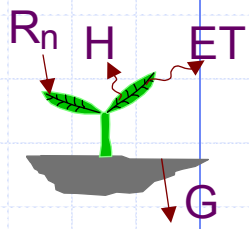


Soil Heat Flux (W/m^2)

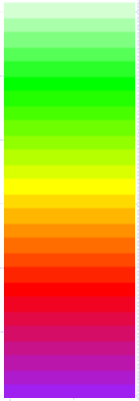


Heat Flux to Air – southcentral Idaho – August 14, 2000

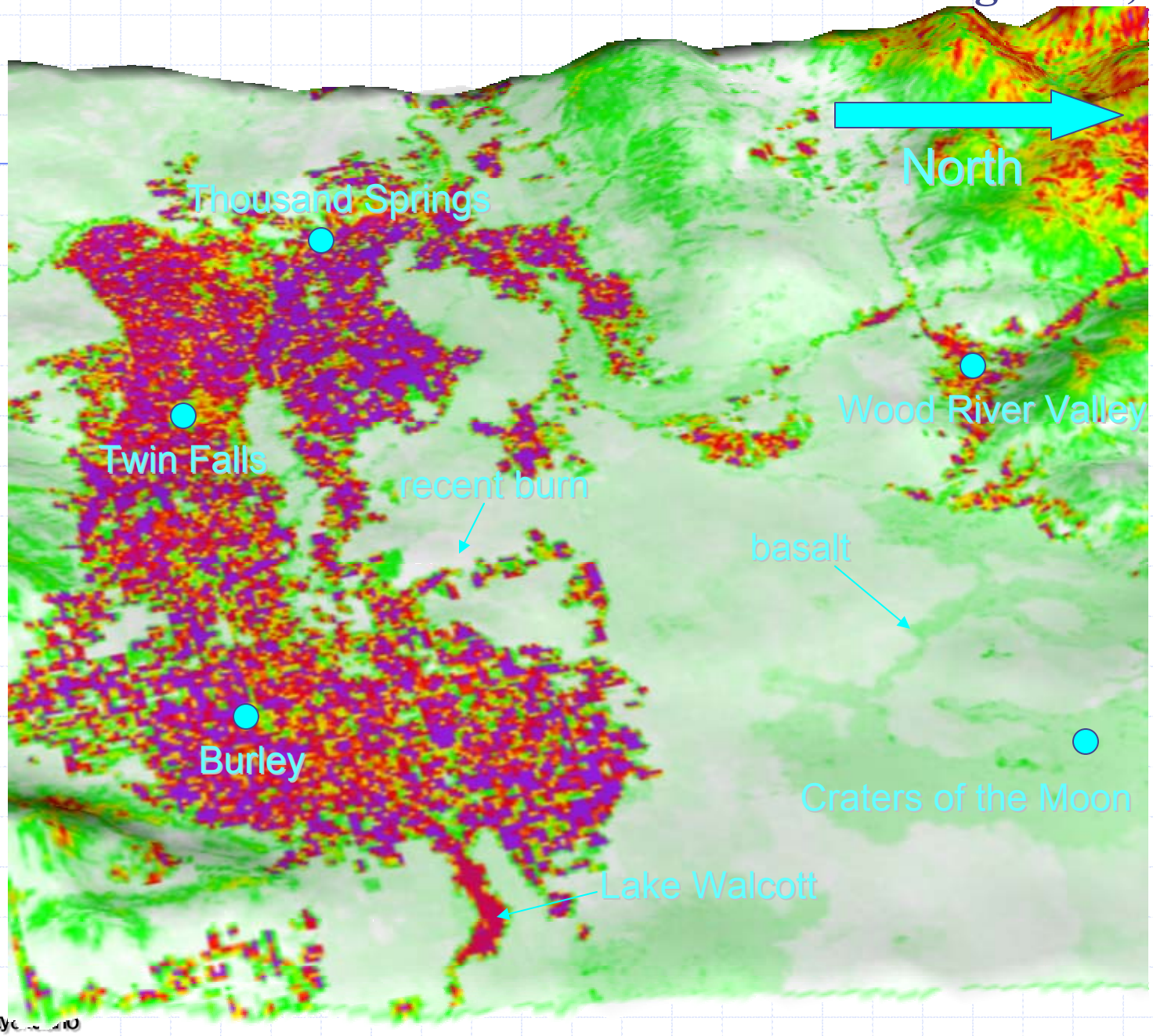


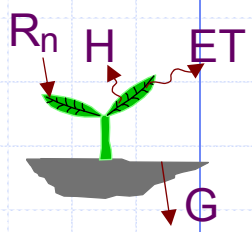


Sensible Heat (W/m^2)



Instantaneous ET – southcentral Idaho – August 14, 2000

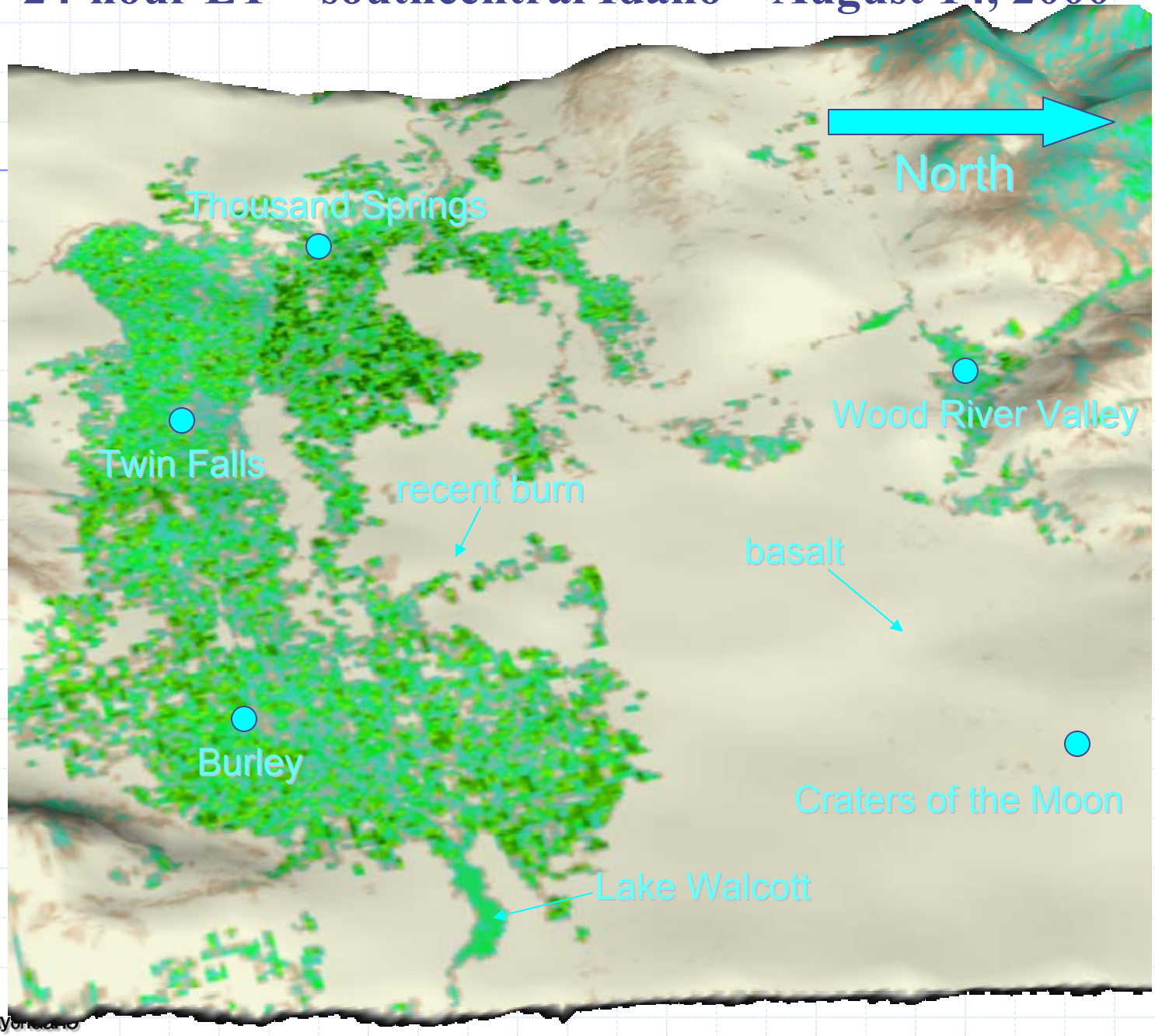




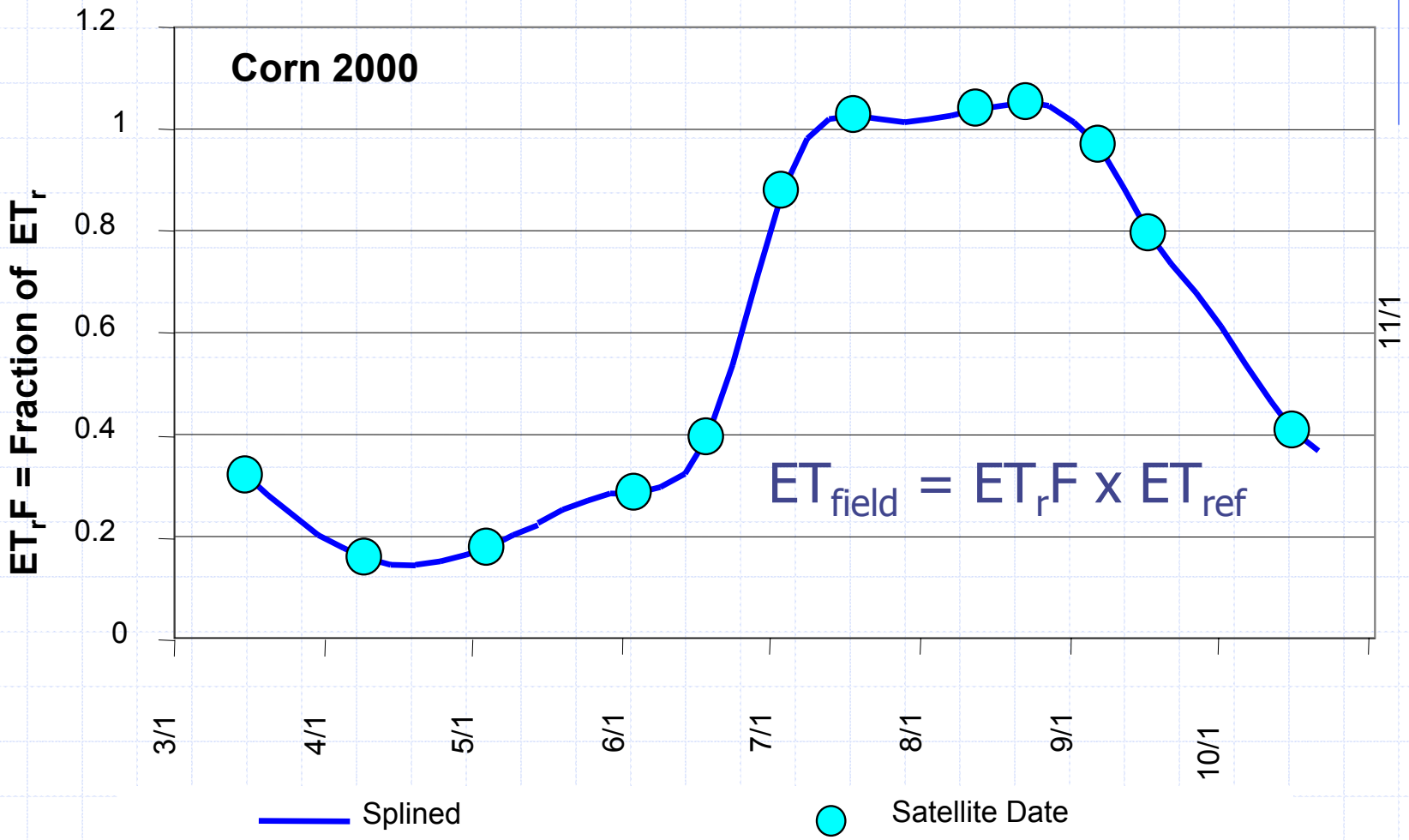
Latent Heat (W/m^2)

0
100
200
300
400+

24-hour ET – southcentral Idaho – August 14, 2000



Satellite-based EB can be used to create Kc curves for thousands of fields



METRIC Applications in American Water Management

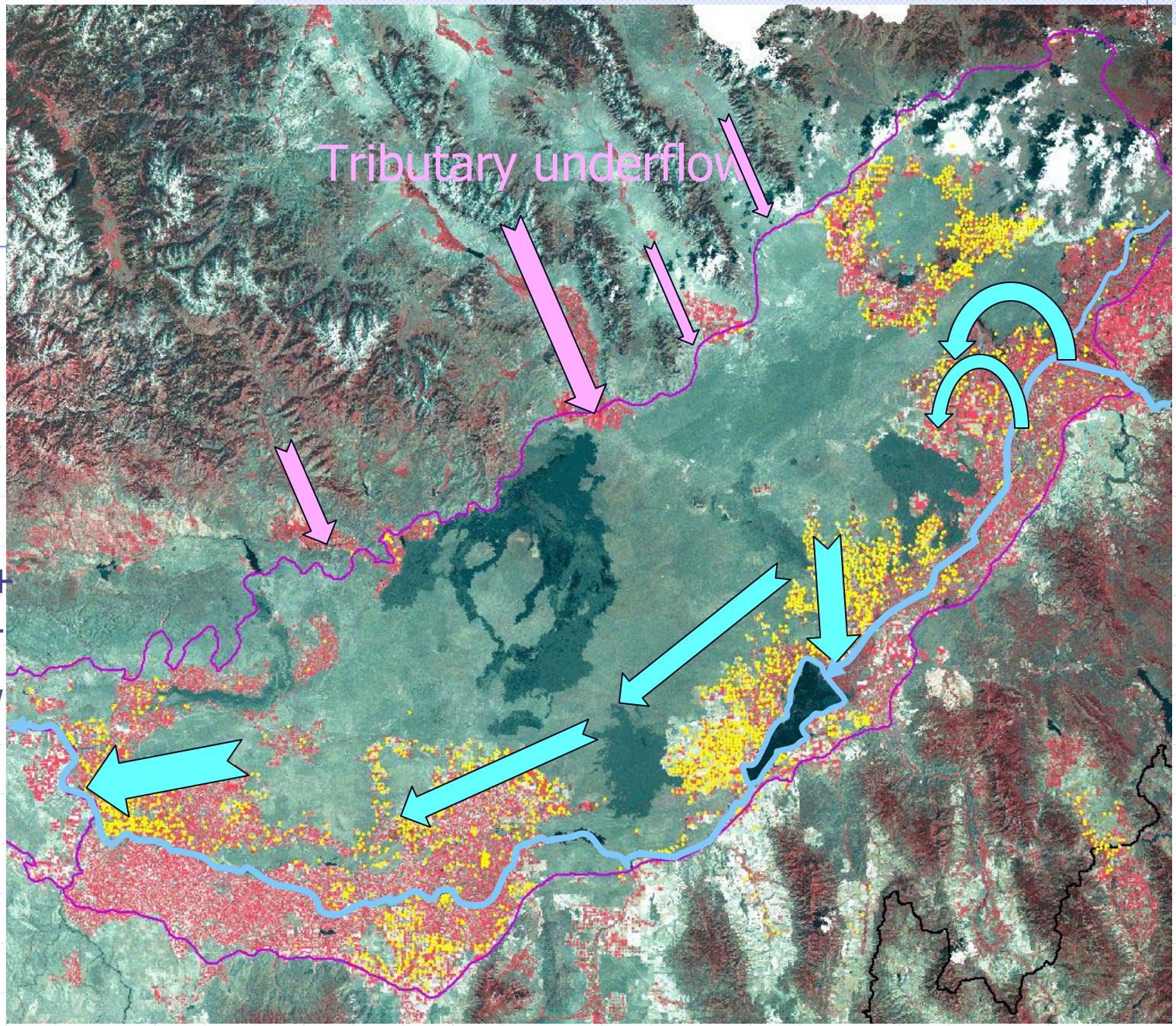
- **Idaho**
  - **Improved calibration of GW flow models in large aquifers by improving estimation of:**

$$\text{Recharge} = P + \text{Diversions}_{river} + \text{Inflow}_{trib.underflow} - ET - \text{Surface Returns}$$

  - Quantification of GW pumping using ET estimates (for water rights management)
  - Confirmation of Crop Coefficients used in water rights management
  - Assisting irrigation projects to reduce diversions by knowing the consumptive requirement (for endangered salmon management)
  - Distinguishing differences in ET between sprinkler and surface irrigation systems
  - Determining amount of 'injury' from water shortage caused by well interference

Water flow from Snake River to Aquifer and from Aquifer to River

Recharge = P + $Diversions_{river}$ + $Inflow_{trib.underflow}$ – ET – Surface Returns



Yellow dots are irrigation wells

METRIC Applications in American Water Management

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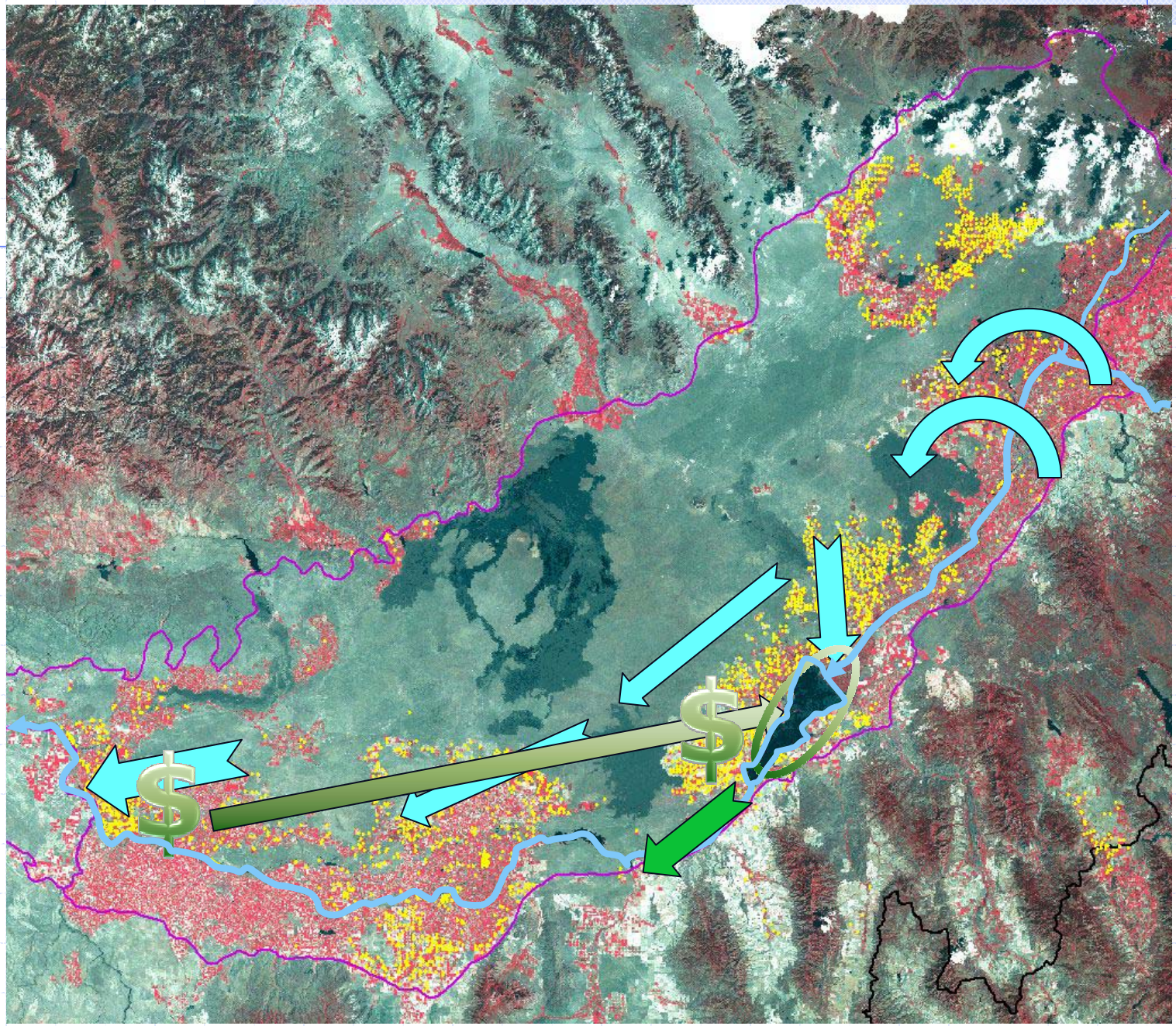
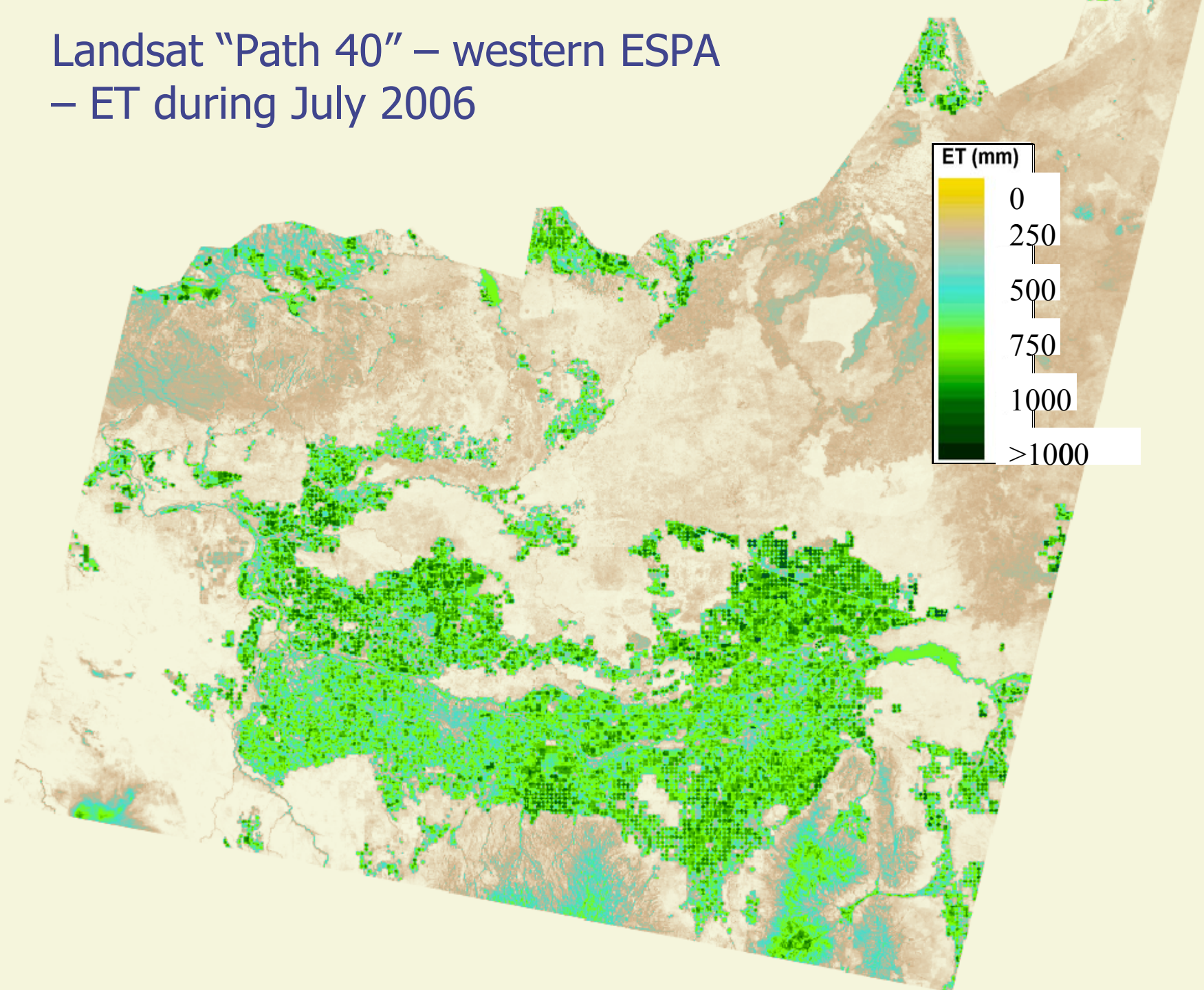
Water flow from Snake River to Aquifer and from Aquifer to River.

ET from satellite provides indication of $ injury by "junior" GW pumpers

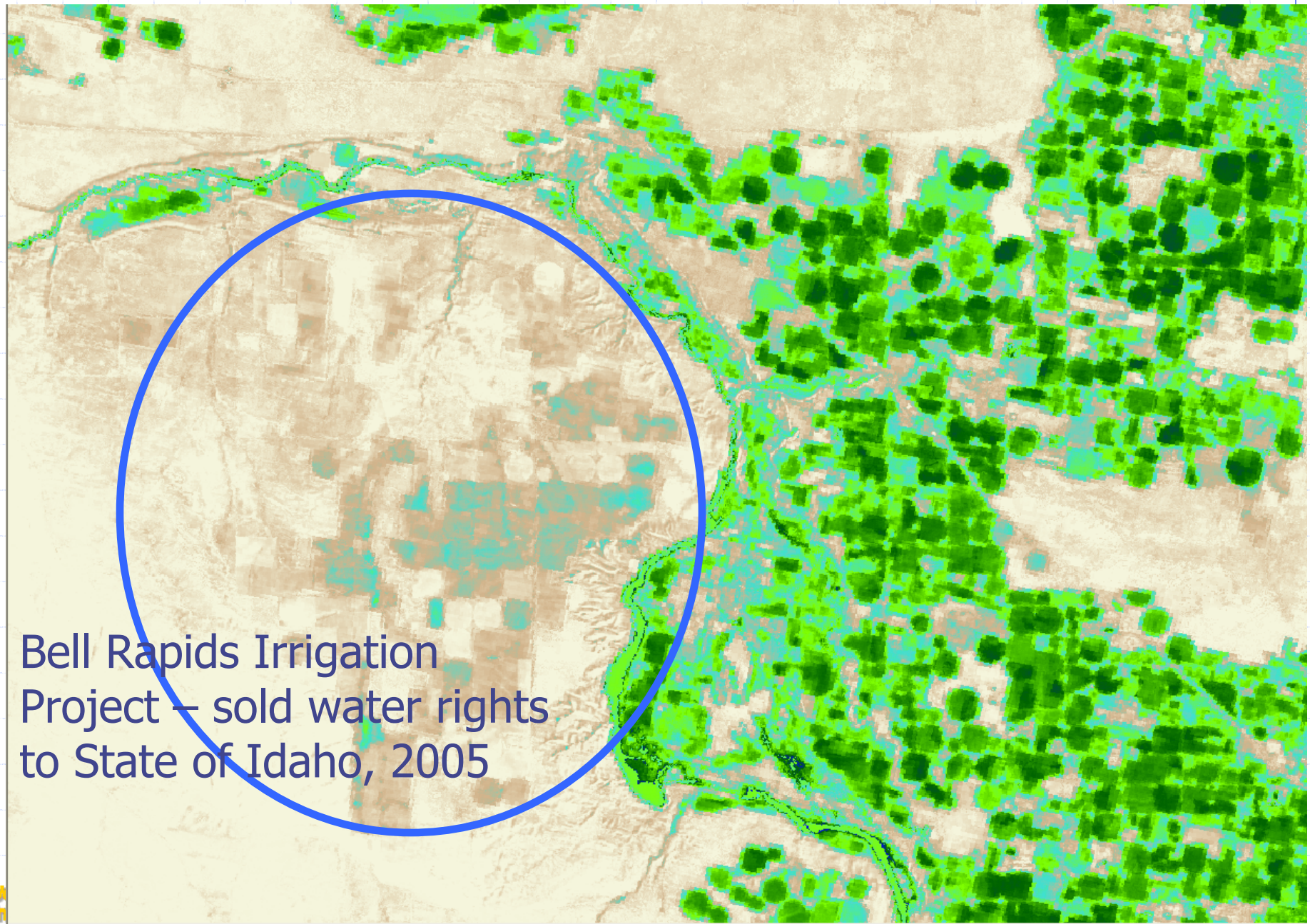


Yellow dots are irrigation wells

Landsat "Path 40" – western ESPA – ET during July 2006



Landsat – ET during July 2006 – Thousand Springs



METRIC Applications in American Water Management

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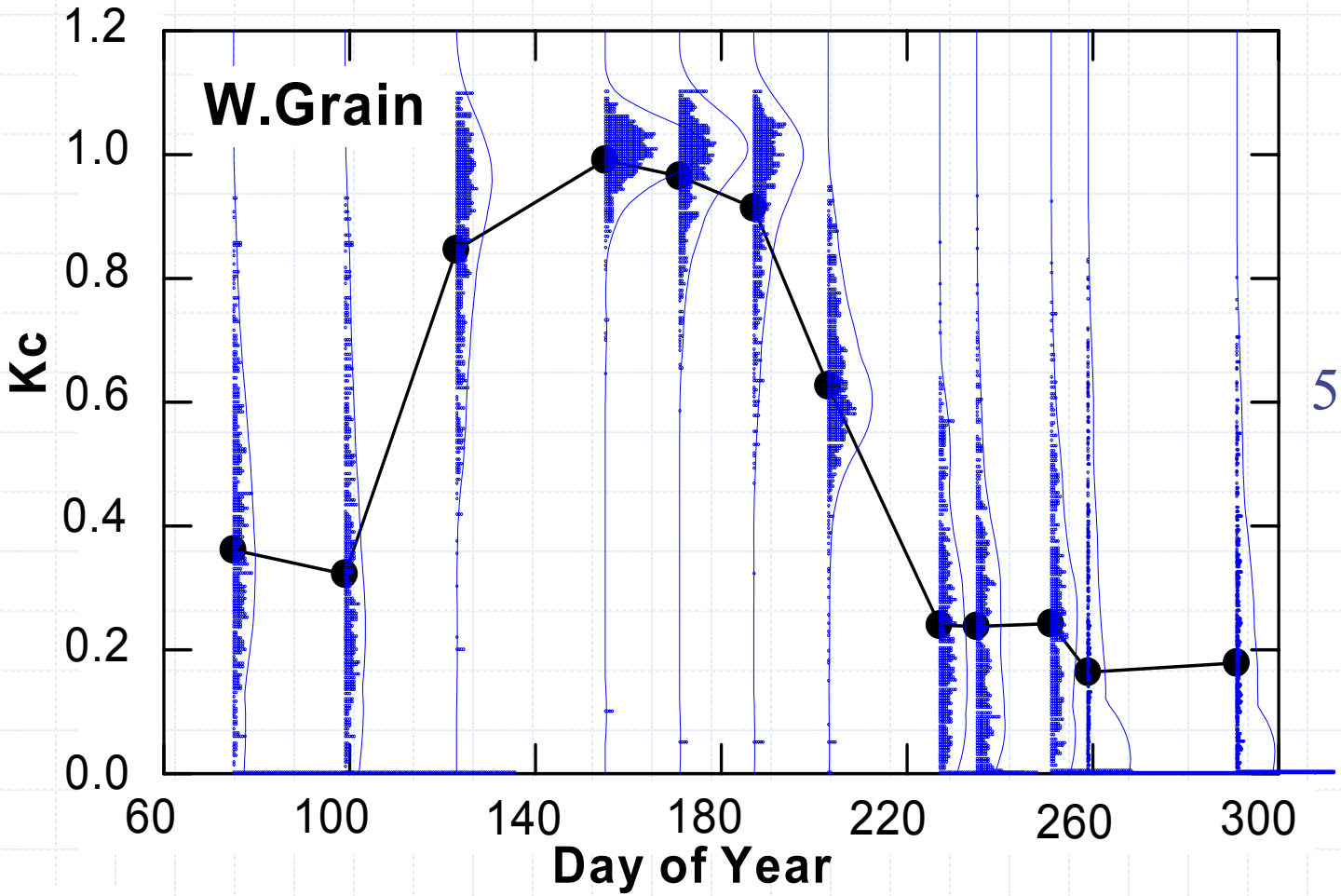
Develop better Crop Coefficient Curves

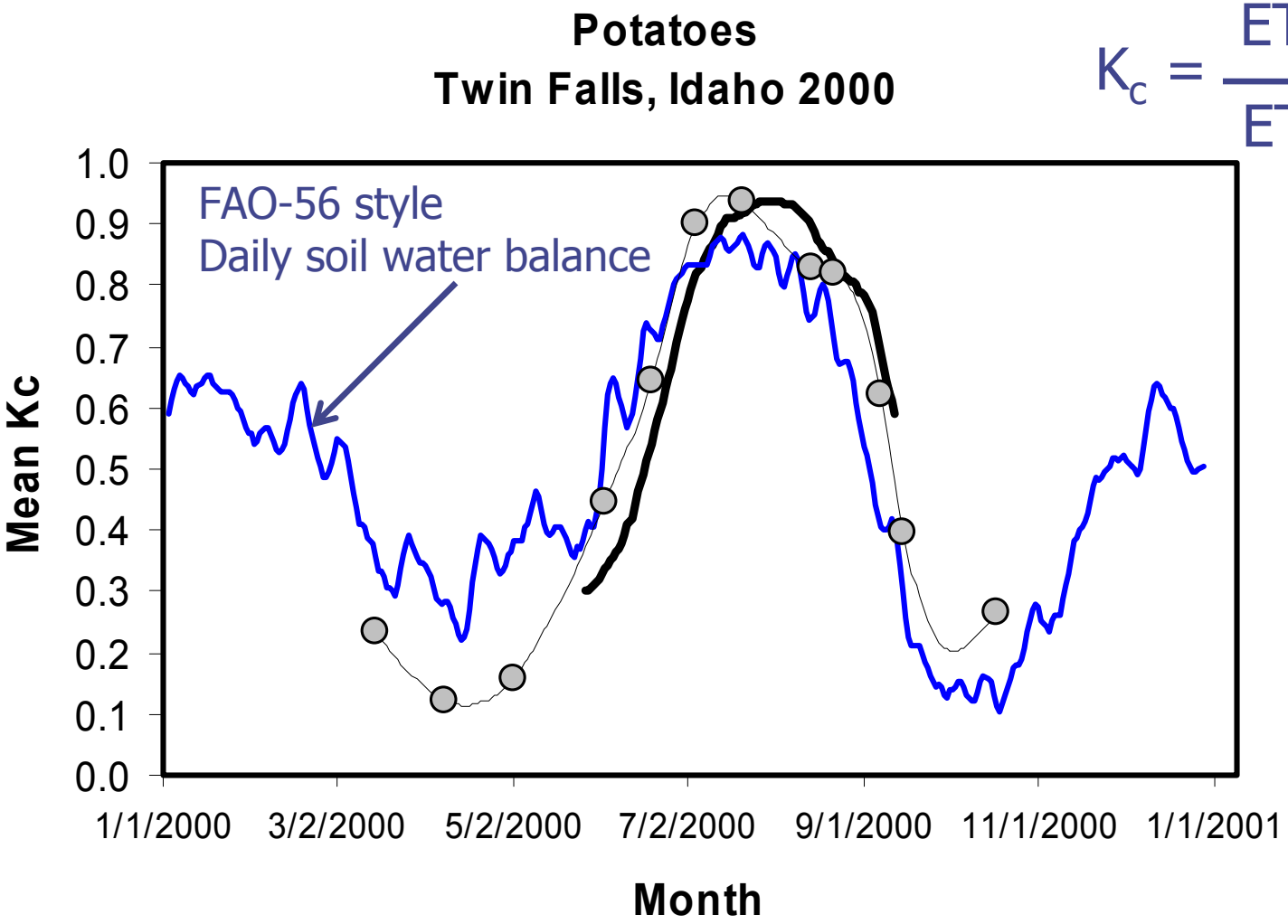
$$K_c = \frac{ET_{act}}{ET_{ref}}$$



564 fields

Comparing METRIC vs. traditional K_c ET_{ref} methods

$$K_c = \frac{ET_{act}}{ET_{ref}}$$



(relatively good agreement among very independent approaches, including during the 'shoulder' periods when ground has partial cover)

METRIC Applications in American Water Management

- **Idaho**
  - Improved calibration of GW flow models in large aquifers by improving estimated Recharge = P + $Diversions_{river}$ + $Inflow_{trib.underflow}$ – ET – Surface Returns
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  - **Assisting irrigation projects to reduce diversions by knowing the consumptive requirement (for endangered salmon management)**
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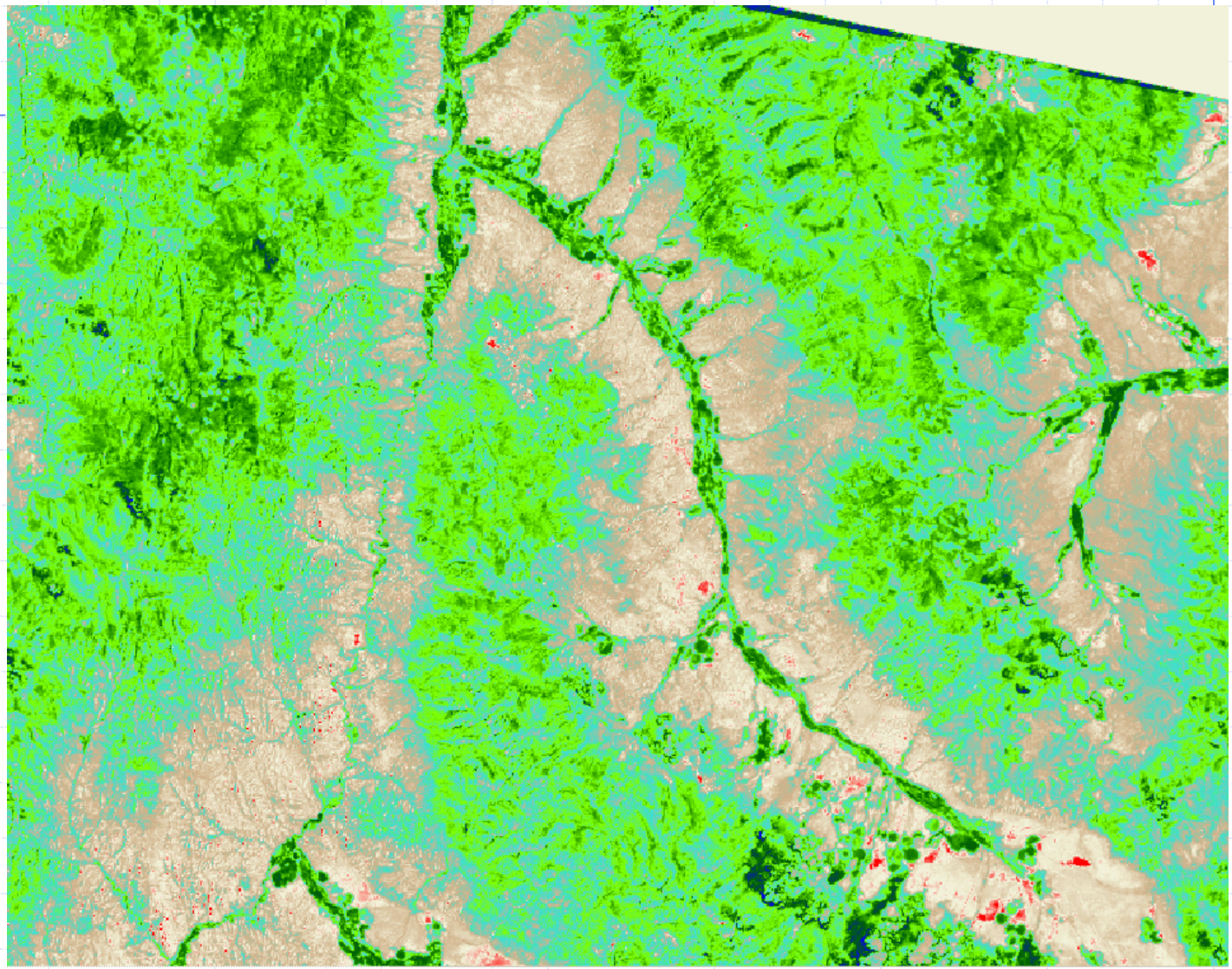
  - Determining amount of 'injury' from water shortage caused by well interference

Salmon, Idaho area -- July 2006

Quantify ET and Diversion requirements to leave more water in Mountain Streams for Salmon

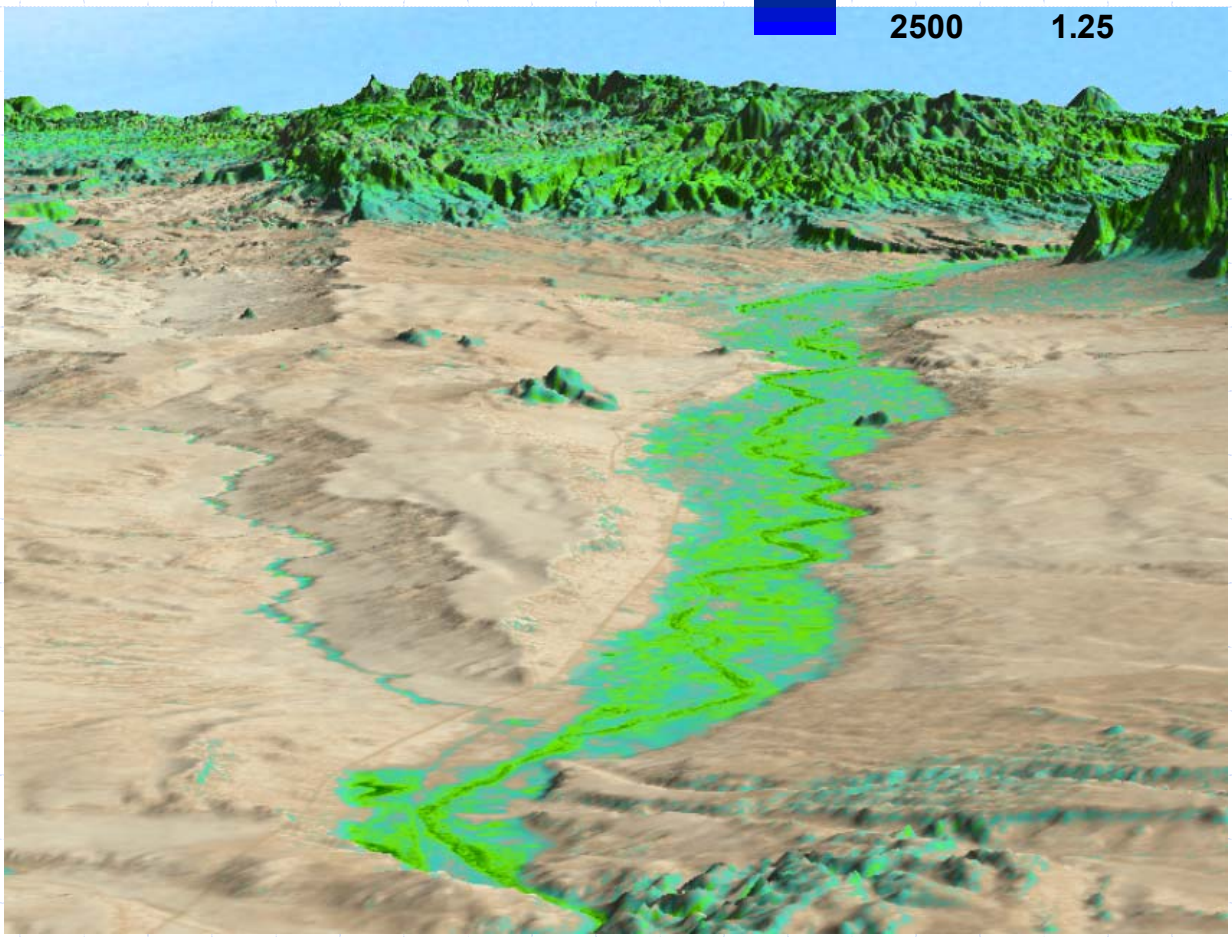


METRIC Applications in American Water Management

- New Mexico
  - **Water consumption by invasive vegetation along the Rio Grande (UI)**
  - **Water consumption by pecan orchards for water rights management by the State of New Mexico (AE)**
- Colorado
  - Conjunctive management of ground-water and surface water by State Engineer along the South Platte (RTI-UI)
  - Assessment of water shortage and salinity impacts along the Arkansa River (an independent application by CSU)
- Nebraska
  - Ground-water management and mitigation in the Ogallala Aquifer in western Nebraska (UI-UNL)
  - Testing against measured ET in central NE (w/SEBAL) (UNL)

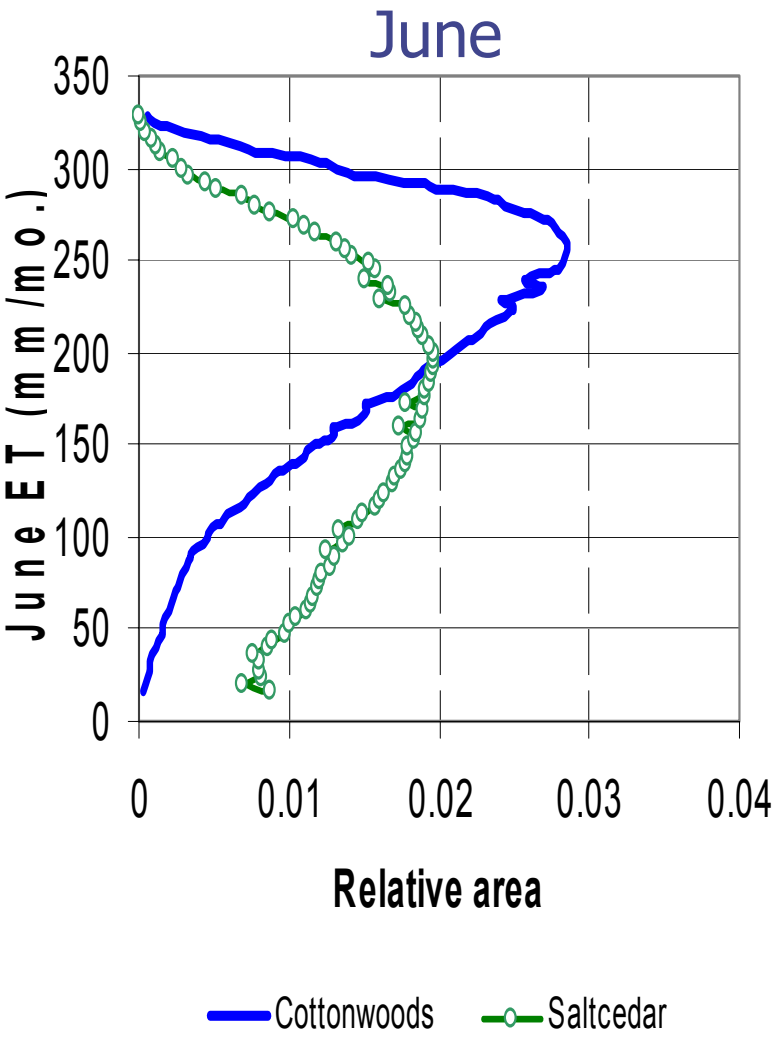
METRIC applications

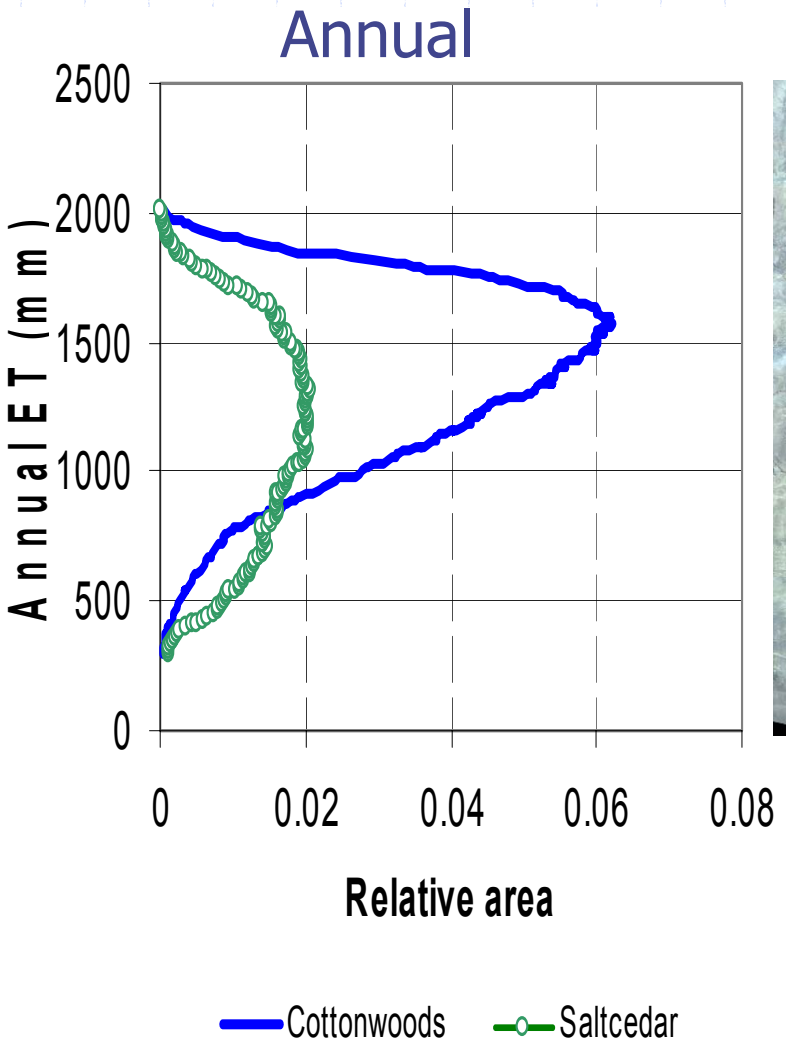
Middle Rio Grande of New Mexico

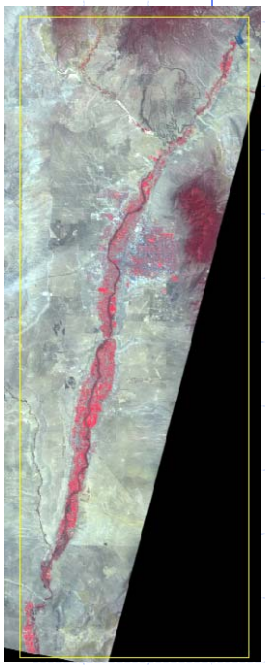


Frequency Distribution of ET

15,000 acres of cottonwood and salt cedar

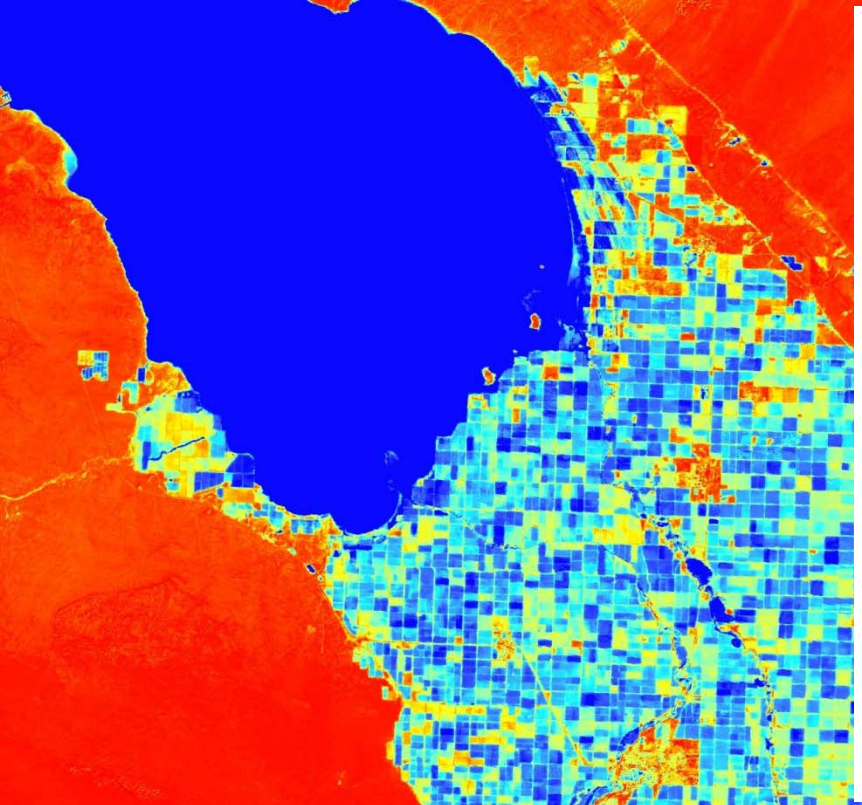


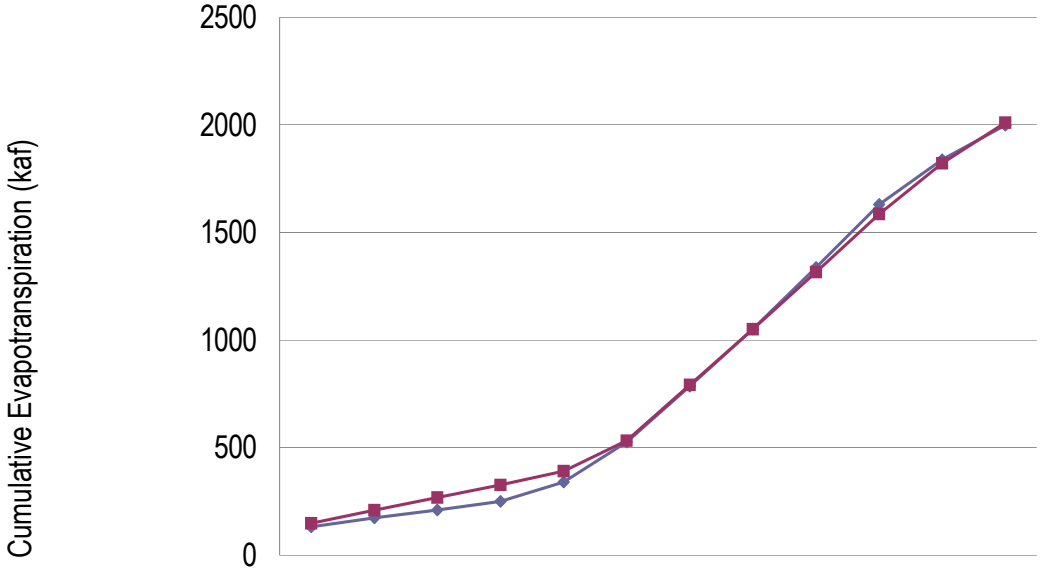




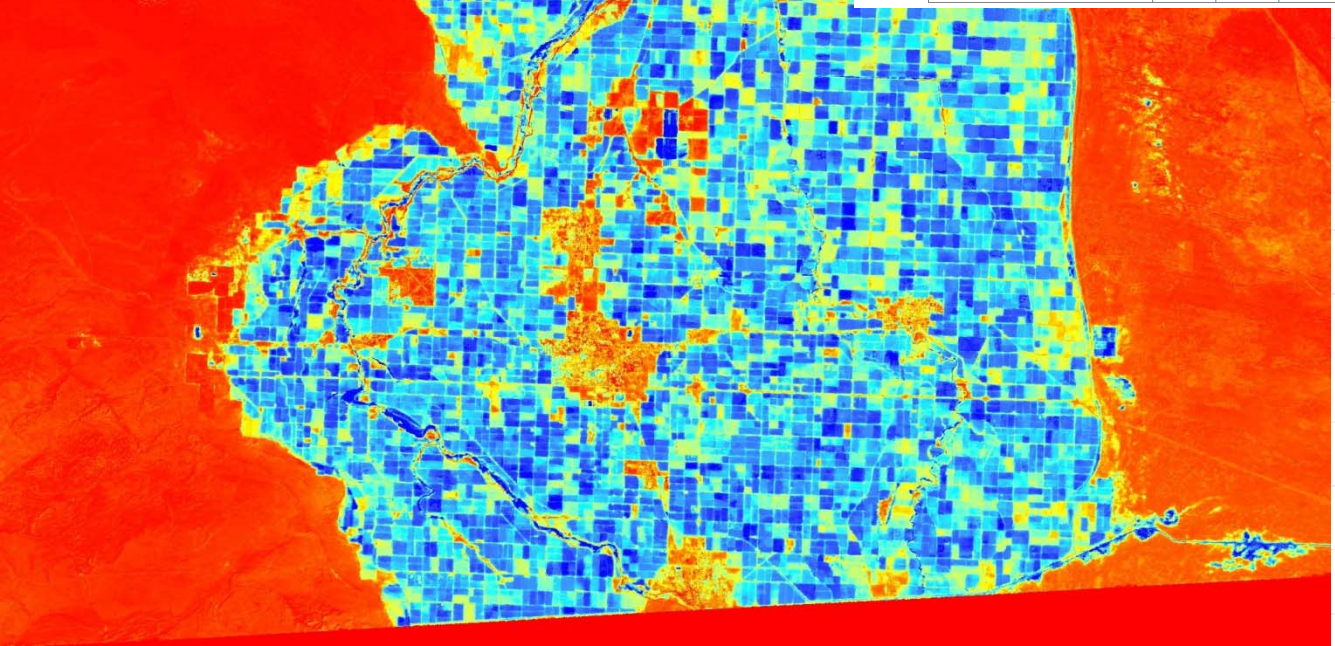
METRIC Applications in American Water Management

- Texas
  - Comparisons against lysimeter measured ET in N.Texas (by USDA-ARS) to use for GW management in High Plains Aquifer
- North Dakota
  - Improvement of farm water management (NDSU)
- Wyoming
  - Total water consumption along North Platte for compliance with Nebraska – Wyoming lawsuits (RTI)
- California
  - **Total water consumption in Imperial Irrigation District for negotiations with Cities needing water (METRIC** by **UI and SEBAL** by **WW)**
  - **Assessment of impacts of soil salinity on ET reduction (UI and WW)**





	Oct-97	Nov-97	Dec-97	Jan-98	Feb-98	Mar-98	Apr-98	May-98	Jun-98	Jul-98	Aug-98	Sep-98
Water Balance	132	173	209	250	340	526	785	1051	1337	1631	1838	1999
SEBAL	148	209	268	326	391	532	791	1049	1316	1586	1821	2010



Regional scale Validation California: ET from SEBAL vs. ET by water balance.

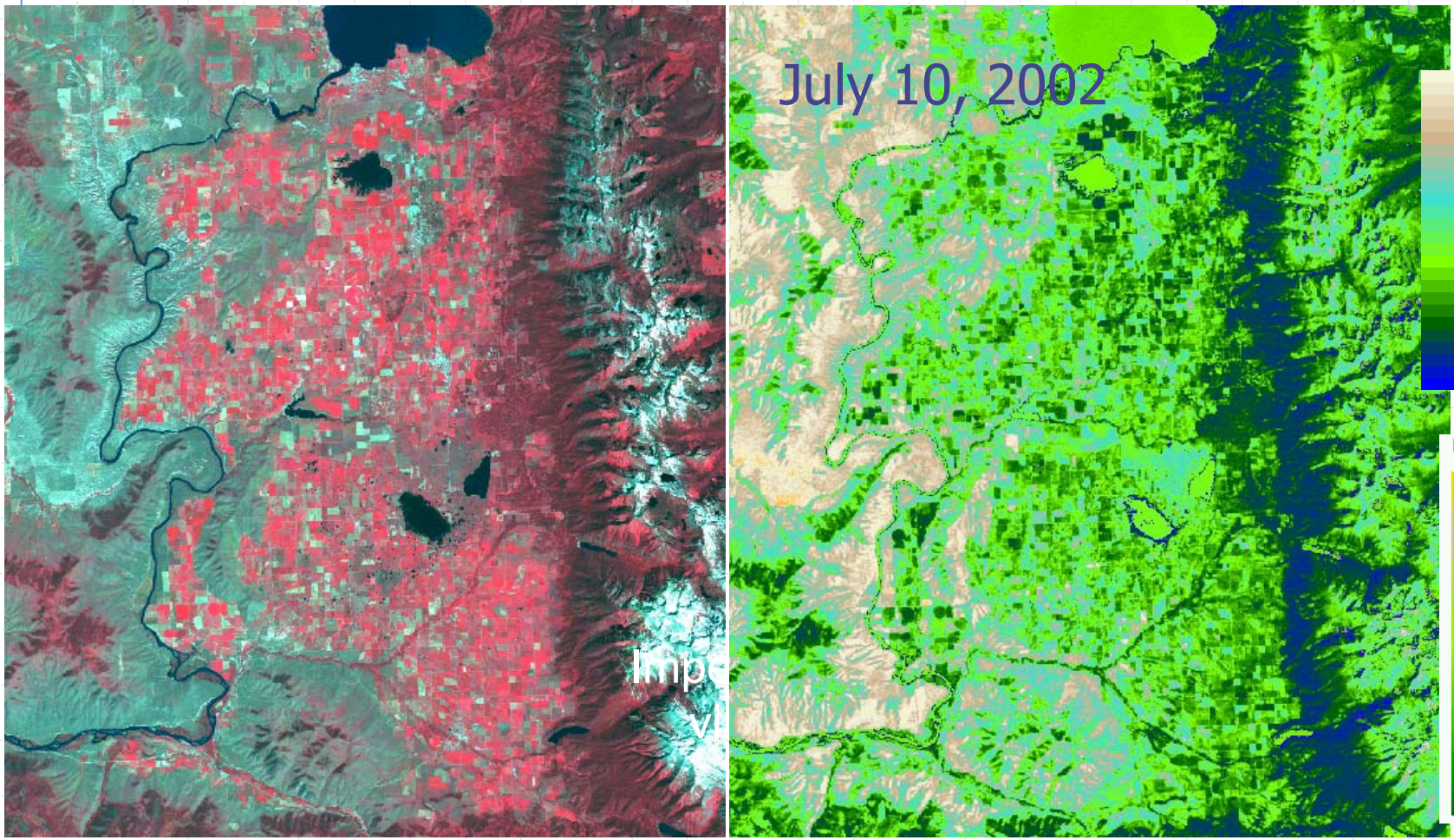
--from WaterWatch

METRIC Applications in American Water Management

- Oregon
  - Klamath Basin where Native American water rights, Salmon population health and Irrigation water consumption are in opposition (Oregon State Univ.)
- Washington
  - METRIC used as 'truth' for calibrating larger scale energy balance models to assess climate change (Climate Impacts Group-UW)
- Montana
  - **Quantification of water consumption on Flathead Indian Reservation for State and Federal Water Rights mitigation (UI)**
- Federal
  - improve performance of the US Bureau of Reclamation RiverWare and AWARDS programs for operating large river systems (UI)
  - Calibrate a more simple large scale EB model (USGS).

METRIC applications

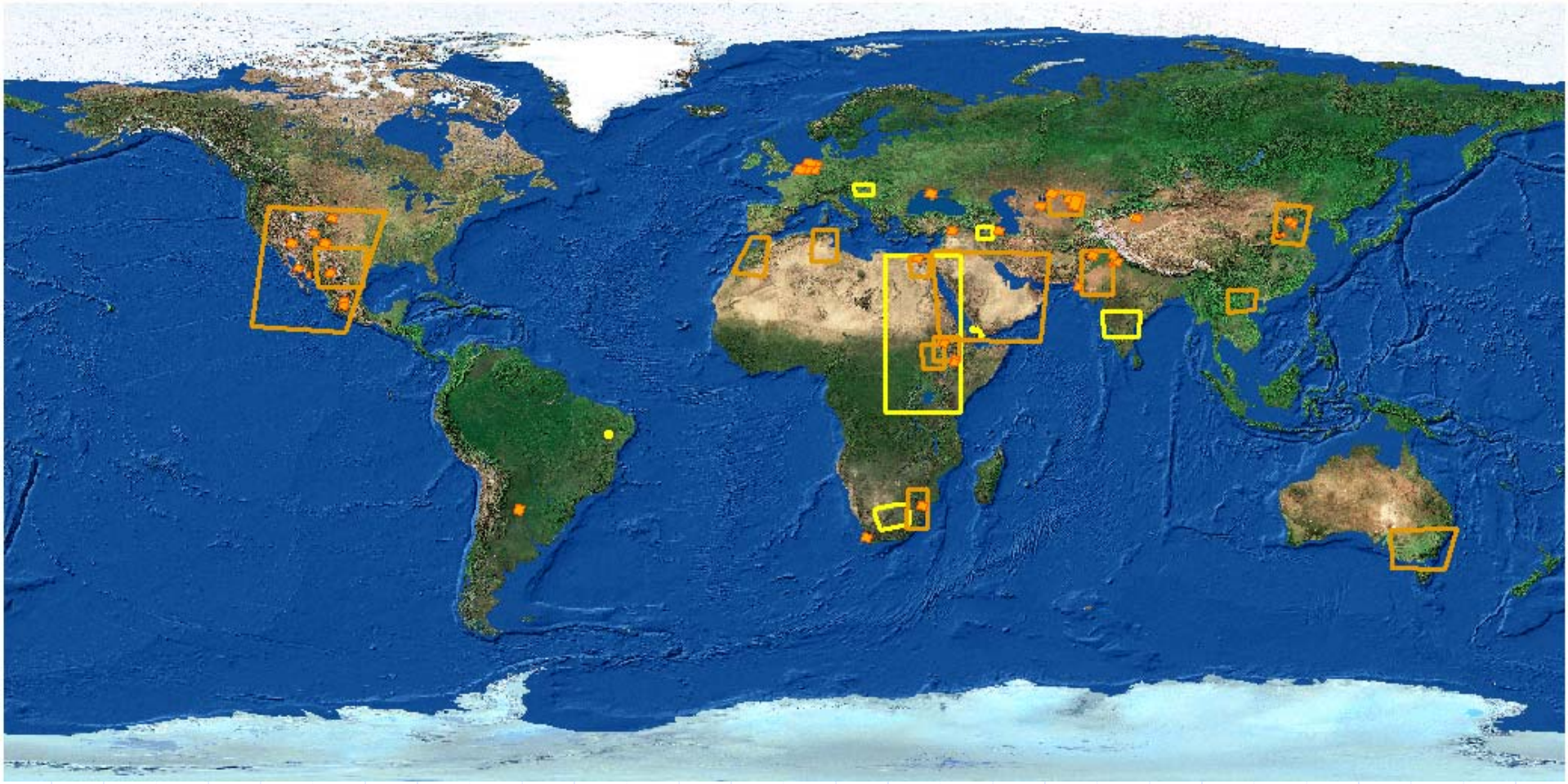
Flathead Indian Reservation, MT)



SEBAL Applications in American Water Management

- SEBAL North America and WaterWatch
  - a number of States
  - a number of types of application
  - a number of objectives

- Applications by Hendrickx of New Mexico Tech.



Global Applications of SEBAL by WaterWatch

(--from WaterWatch 2009)

University of Idaho

SEBAL VALIDATION PARTNERS

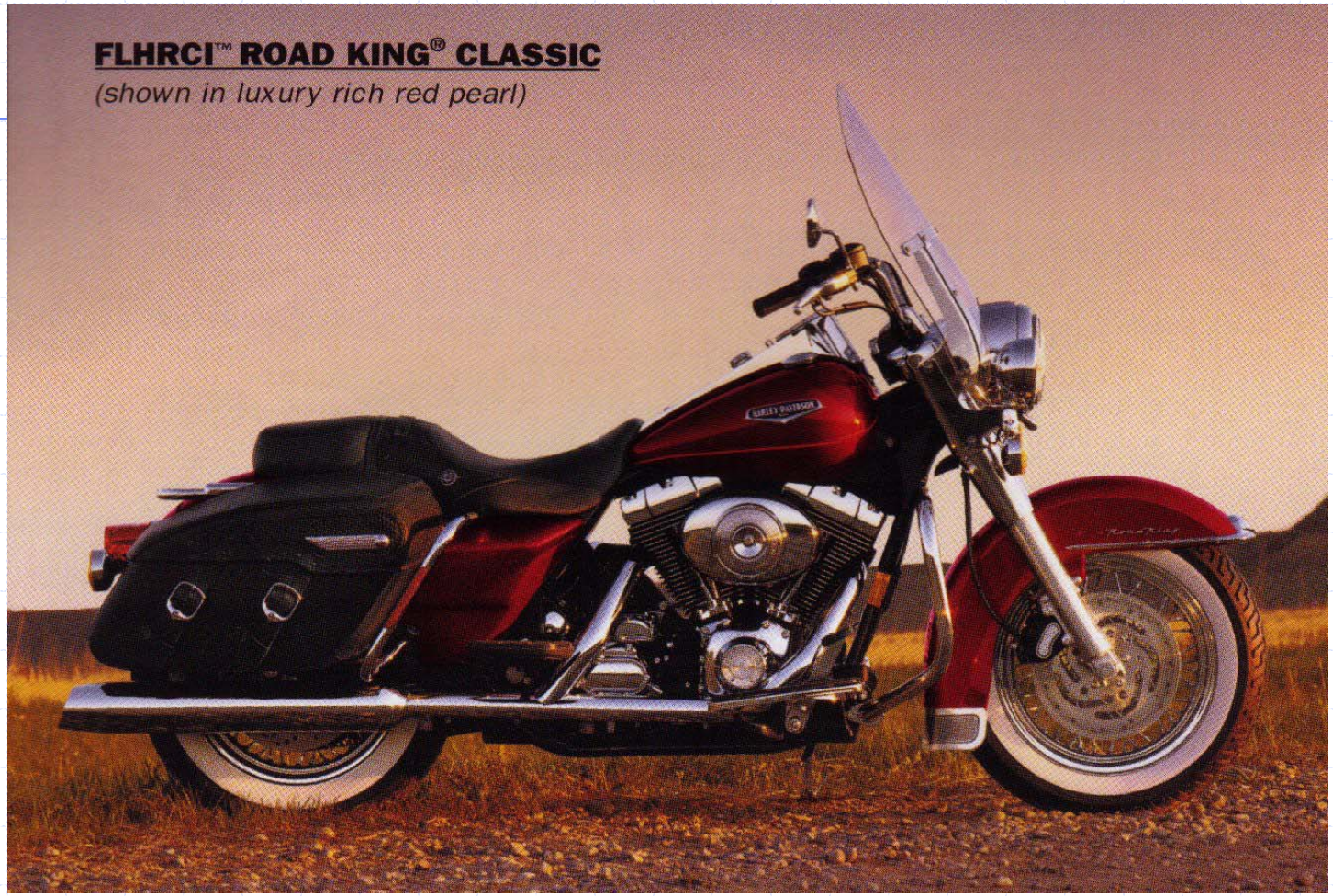
- University of Idaho – Idaho, USA
- USDA – Oklahoma, USA
- International Water Management Institute (IWMI) – Gediz Basin, Turkey/Sri Lanka
- Royal Netherlands Meteorological Institute (KNMI) – Cabauw, Netherlands
- INRA – Provence, France
- Chinese Academy of Sciences – Gansu, China
- Wageningen University – Marrakesh, Morroco
- IHE – Sudd wetland, Sudan
- ITC – Okavango delta, Botswana
- ITSON – Sonora, Mexico
- EMBRAPA – Sao Francisco, Brazil
- USDA – California / Oklahoma
- Imperial Irrigation District / California
- CSIR / DoA- South Africa
- CSIRO / SKM – Australia
- New Mexico Tech

(--from WaterWatch 2009)

Table 1. Recent Published Comparisons of SEBAL2008 Seasonal ET_a to Ground-Based Measurements

Comparison Technique	Location	Duration	Landscape	Difference	Reference
Weighing Lysimeter	California	7 months	Peach	5%	Cassel (2006)
Weighing Lysimeter	California	7 months	Alfalfa	2%	Cassel (2006)
Water Balance	California	12 months	Irrigated Agriculture	1%	Soppe et al (2006)
Water Balance	Pakistan	12 months	River basin	1%	Bastiaanssen et al. (2002)
Water Balance	Sri Lanka	12 months	River basin	1%	Bastiaanssen et al. (2003)

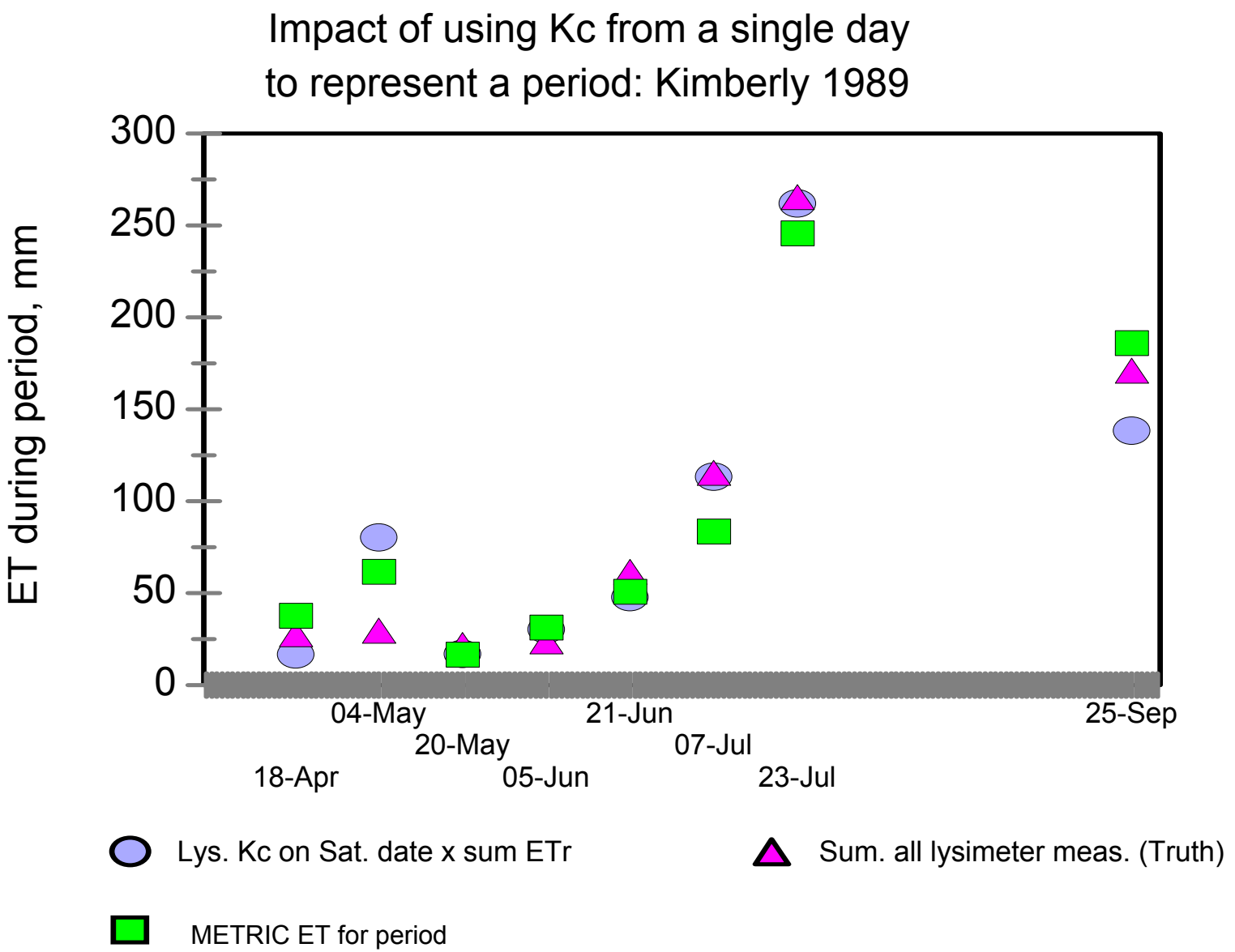
(--from WaterWatch 2009)

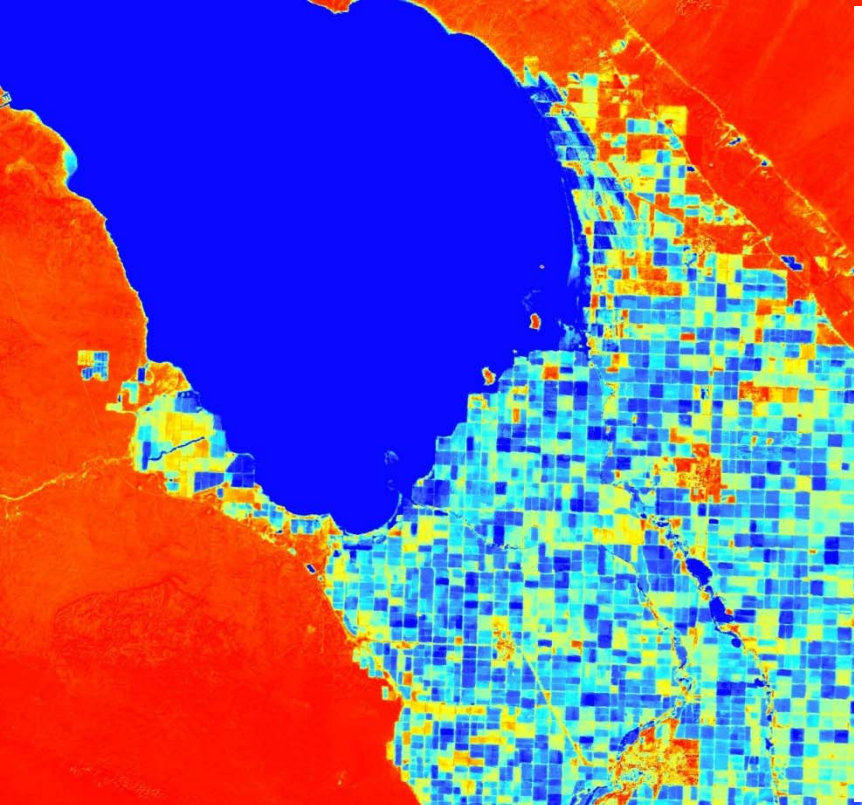

FLHRCI™ ROAD KING® CLASSIC
(shown in luxury rich red pearl)

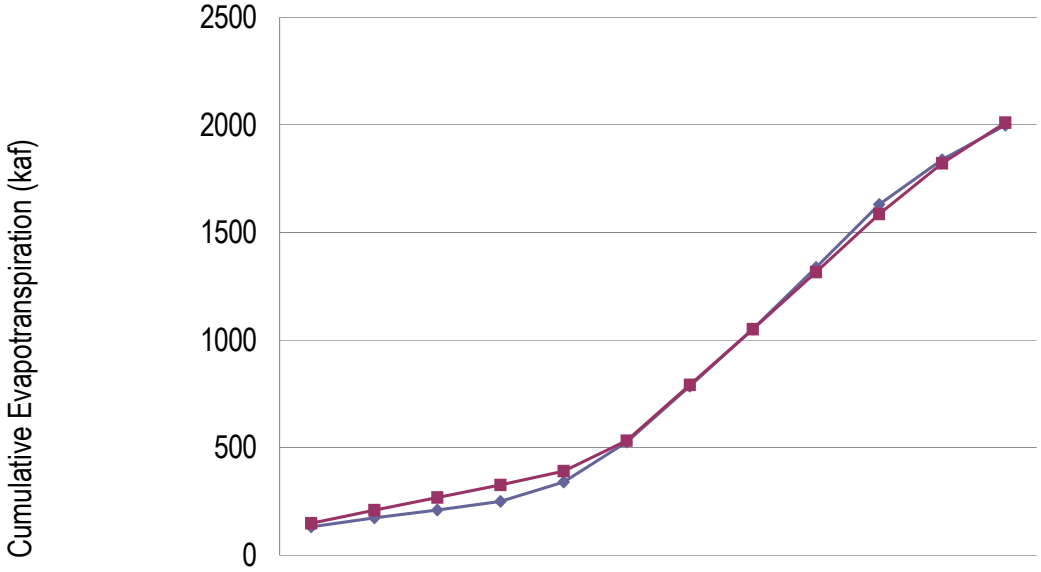
Comparison with Lysimeter Measurements:

1968-1991

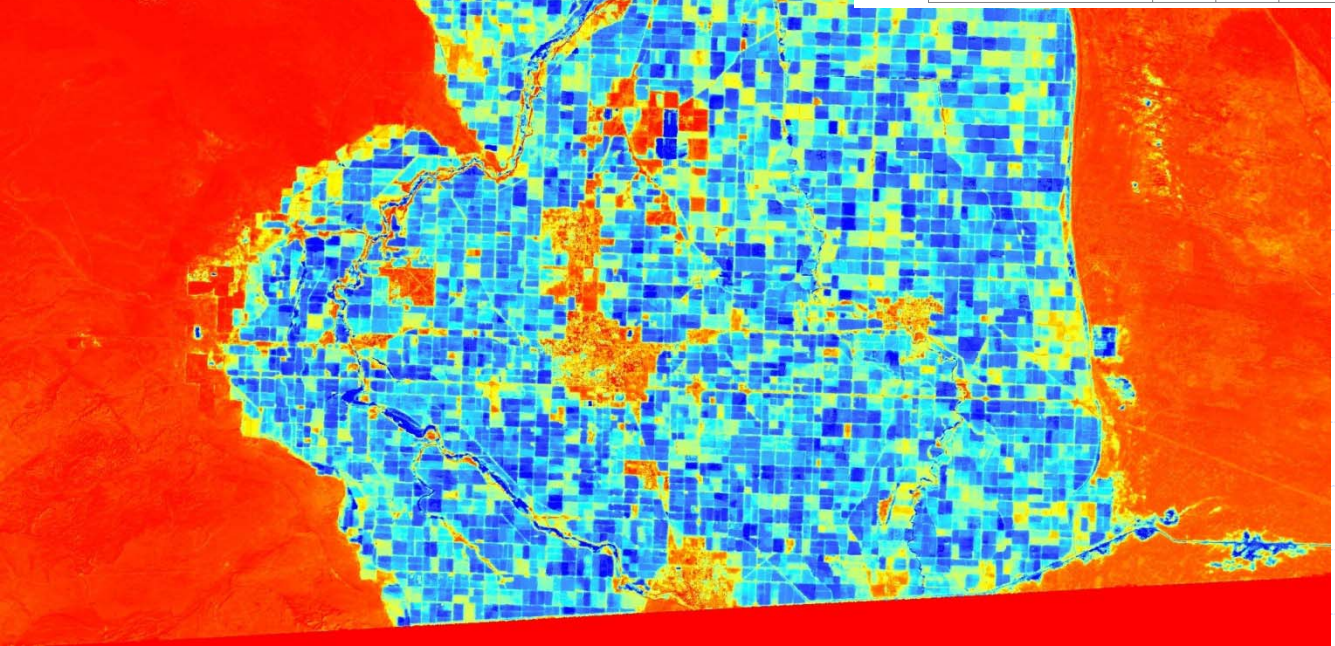
Kimberly, Idaho – Periods between Satellites







	Oct-97	Nov-97	Dec-97	Jan-98	Feb-98	Mar-98	Apr-98	May-98	Jun-98	Jul-98	Aug-98	Sep-98
Water Balance	132	173	209	250	340	526	785	1051	1337	1631	1838	1999
SEBAL	148	209	268	326	391	532	791	1049	1316	1586	1821	2010



Regional scale Validation California: ET from SEBAL vs. ET by water balance.

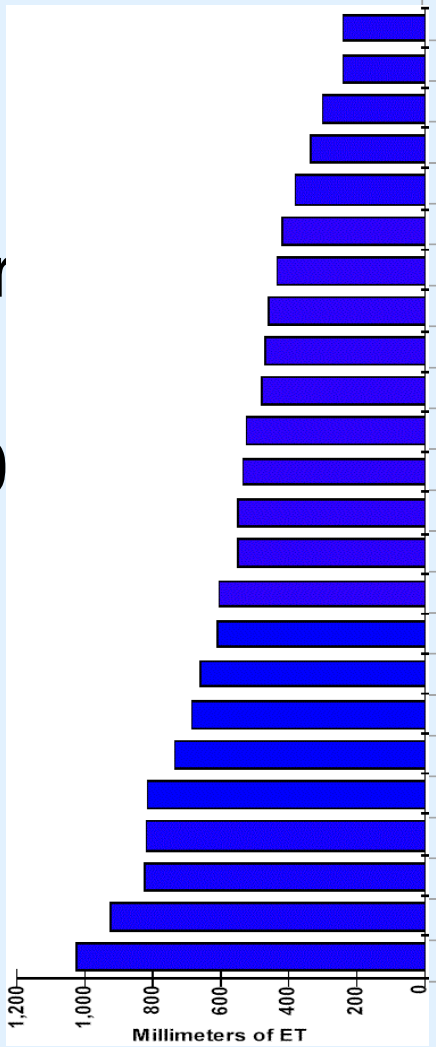
--from WaterWatch

Other Applications of ET "maps"

Boise River Valley, Idaho

ET BY LAND USE CLASS

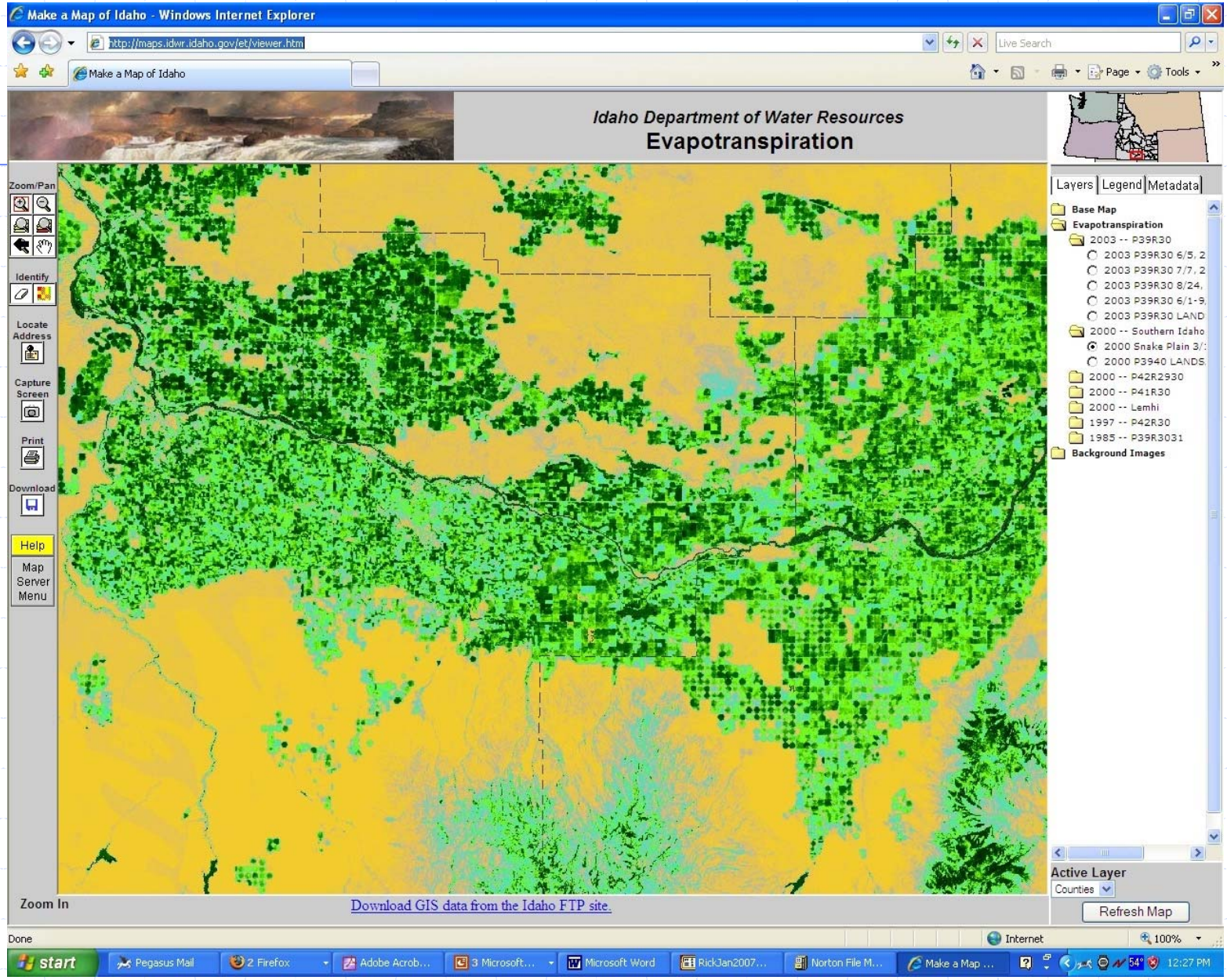
- Benefit:
  New Infor
- Cost:
  ±$70,000



Class Name	ET in mm
Petroleum Tank Yards	237
Rangeland	242
Unclassified	298
Barren	335
Commercial / Industrial	380
Transportation	420
Idle Agriculture	436
Abandoned Agriculture	459
Junk Yard	467
Feedlot	479
Dairy	524
Other Agriculture	536
Public	548
Sewage	552
New Subdivision	606
Farmstead	609
Rural Residential	657
Urban Residential	684
Canal	731
Irrigated Crops	812
Perennial	820
Recreation	826
Water	924
Wetland	1,025

Courtesy of W. Kramber and T. Morse, IDWR

(ARC-IMS serving ET for Idaho)

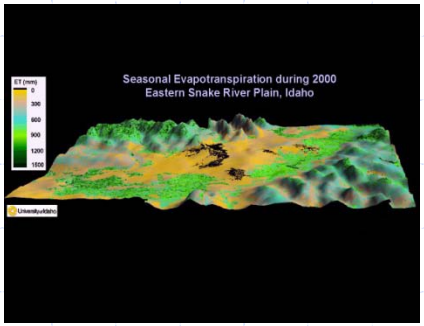


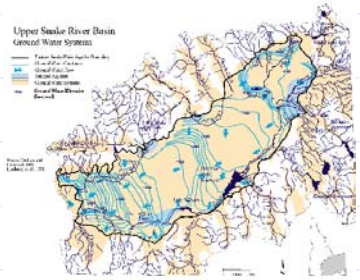
http://maps.idwr.idaho.gov/et/

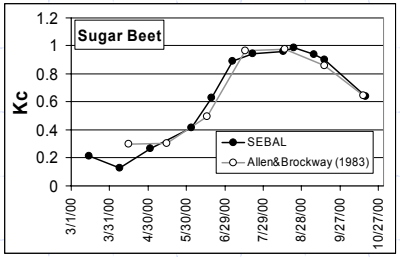
University of Idaho

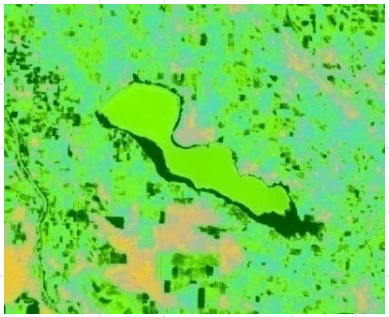
Conclusions

- ET maps are valuable for:
  - Determining **Actual** ET
  - Ground-water Management
  - Water Rights Conflicts
  - Consumption by Riparian Vegetation
  - Refining Crop Coefficient Curves



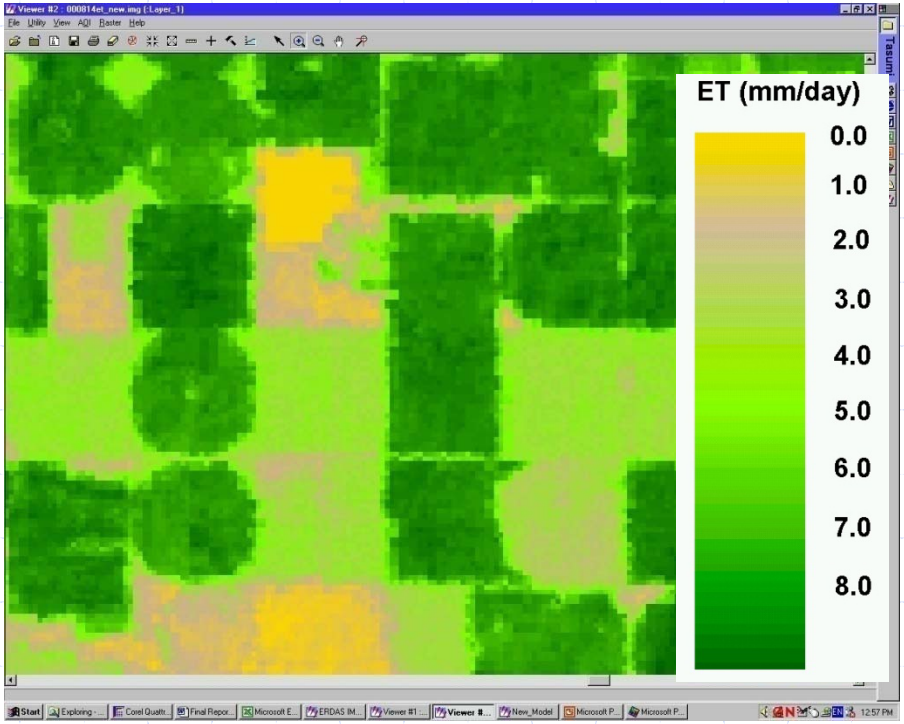






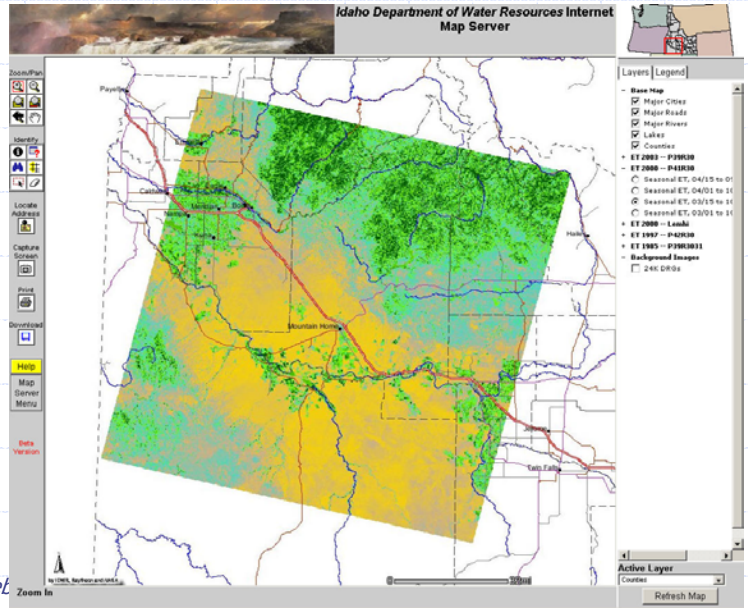
Requirements for METRIC^{tm}

- Satellite images with **Thermal Band**
  - High resolution (*Landsat*) is needed for field scale maps
- Good quality weather data for best calibration
- **Experienced, thinking human at the controls (determination of ET conditions at calibration pixels)**

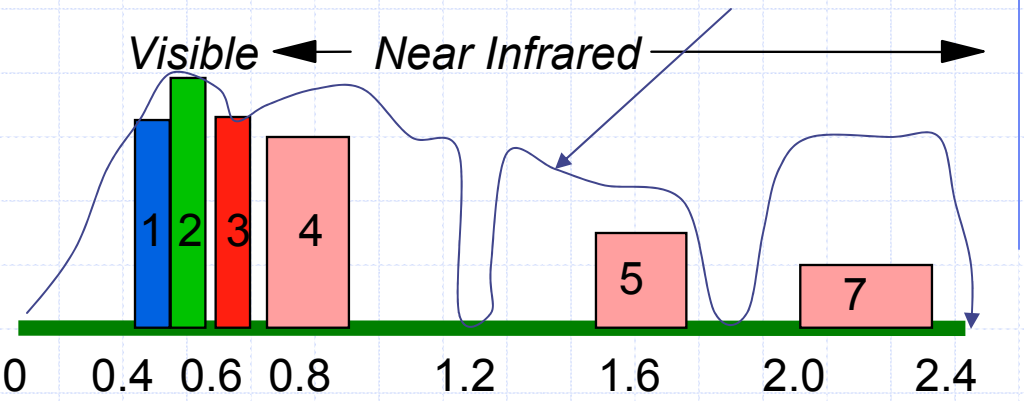


More information at:

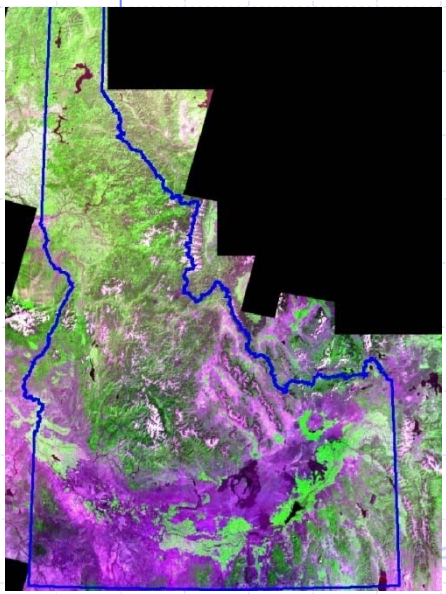
- www.kimberly.uidaho.edu/water/ (METRIC^{tm})
- http://www.idwr.idaho.gov/gisdata/et.htm
- http://maps.idwr.idaho.gov/et/

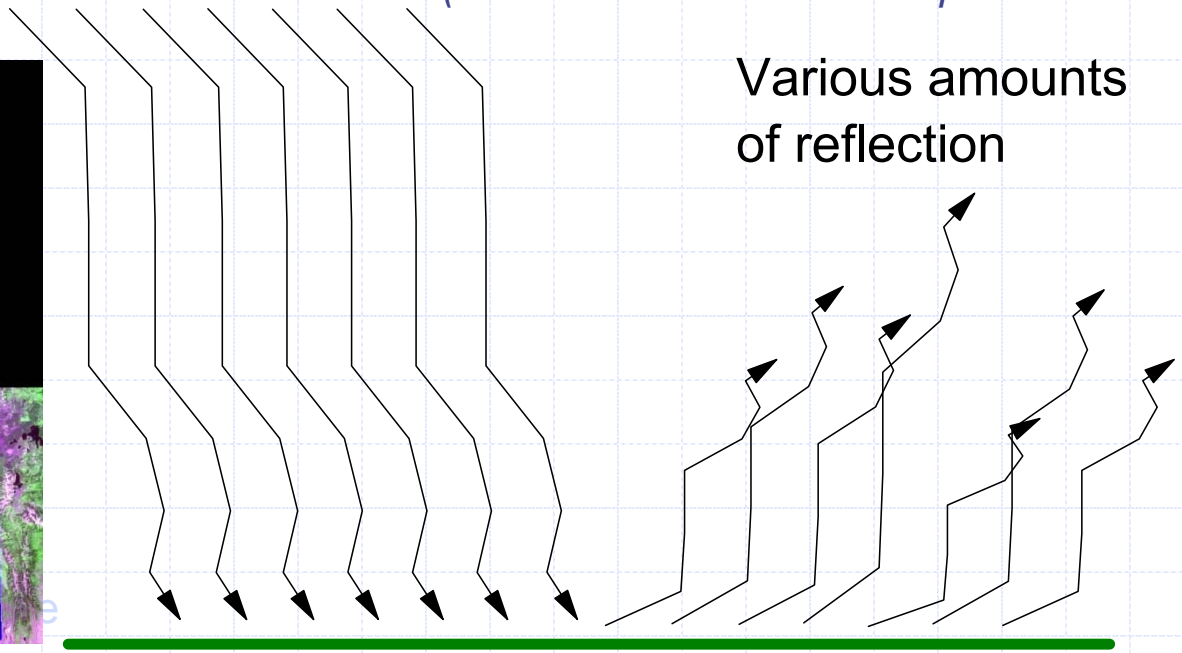


What Landsat sees



(Band 6 is the surface temperature band (not shown))





Sensible Heat Flux (H) – using CIMEC modeling

(**C**alibration using **I**nverse **M**odeling of **E**xtreme **C**onditions)

$$H = (\rho \times c_p \times dT) / r_{ah}$$

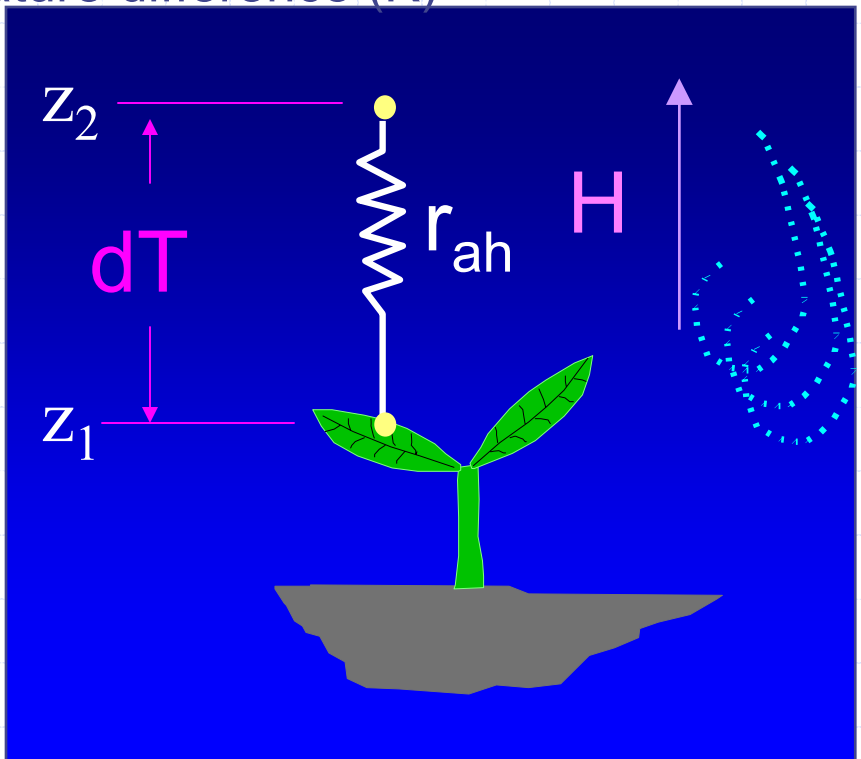
Advantage:
dT is inverse calibrated (simulated) (free of T_{rad} vs. T_{aero} vs. T_{air})

dT = "floating" near surface temperature difference (K)

r_{ah} = the aerodynamic resistance from z_1 to z_2

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

u_* = friction velocity
k = von karmon constant (0.41)

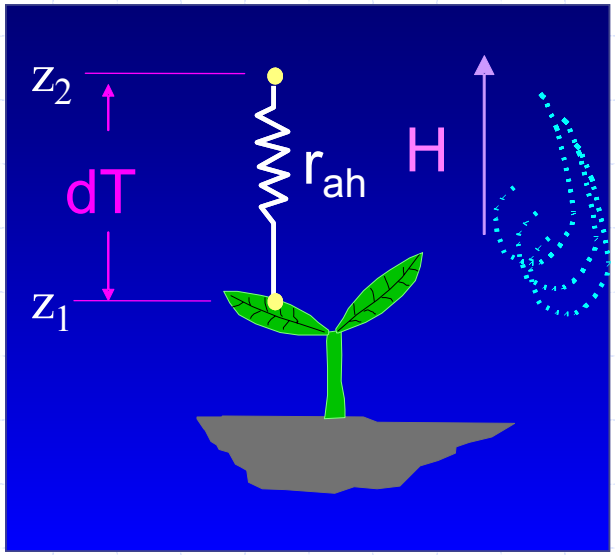


Near Surface Temperature Difference (dT)

- To compute the sensible heat flux (H), define near surface temperature difference (dT) for each pixel

$$\textit{Classical:}\ dT = T_{surface} - T_{air}$$

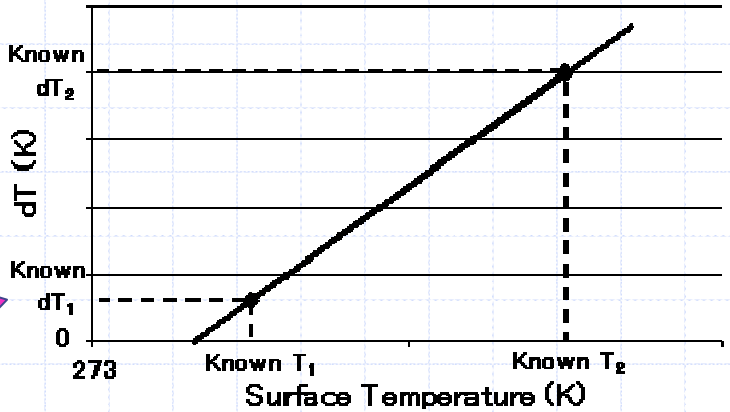
$$\textit{SEBAL/METRIC:}\ dT = T_{z1} - T_{z2}$$



- T_{air} is unknown and unneeded
- SEBAL and METRIC^{tm} assume a linear relationship between T_s and dT:

$$dT = b + aT_s$$

Bastiaanssen ingenuity



- T_s is used only as an index and can have large bias and does not need to represent aerodynamic surface temperature

METRIC Energy Balance

Mapping EvapoTranspiration
with high Resolution and Internalized Calibration

- **METRIC** is a sort of "hybrid" between pure remotely-sensed energy balance and weather-based ET methods
- **Combines** the strengths of energy balance from satellite and accuracy of ground-based reference ET calculation:
  - **satellite-based energy balance** provides the spatial information and distribution of available energy and sensible heat fluxes over a large area (and does most of the "**heavy lifting**")
  - **reference ET calculation** "**anchors**" the energy balance surface and provides "reality" to the product.

Weather Data

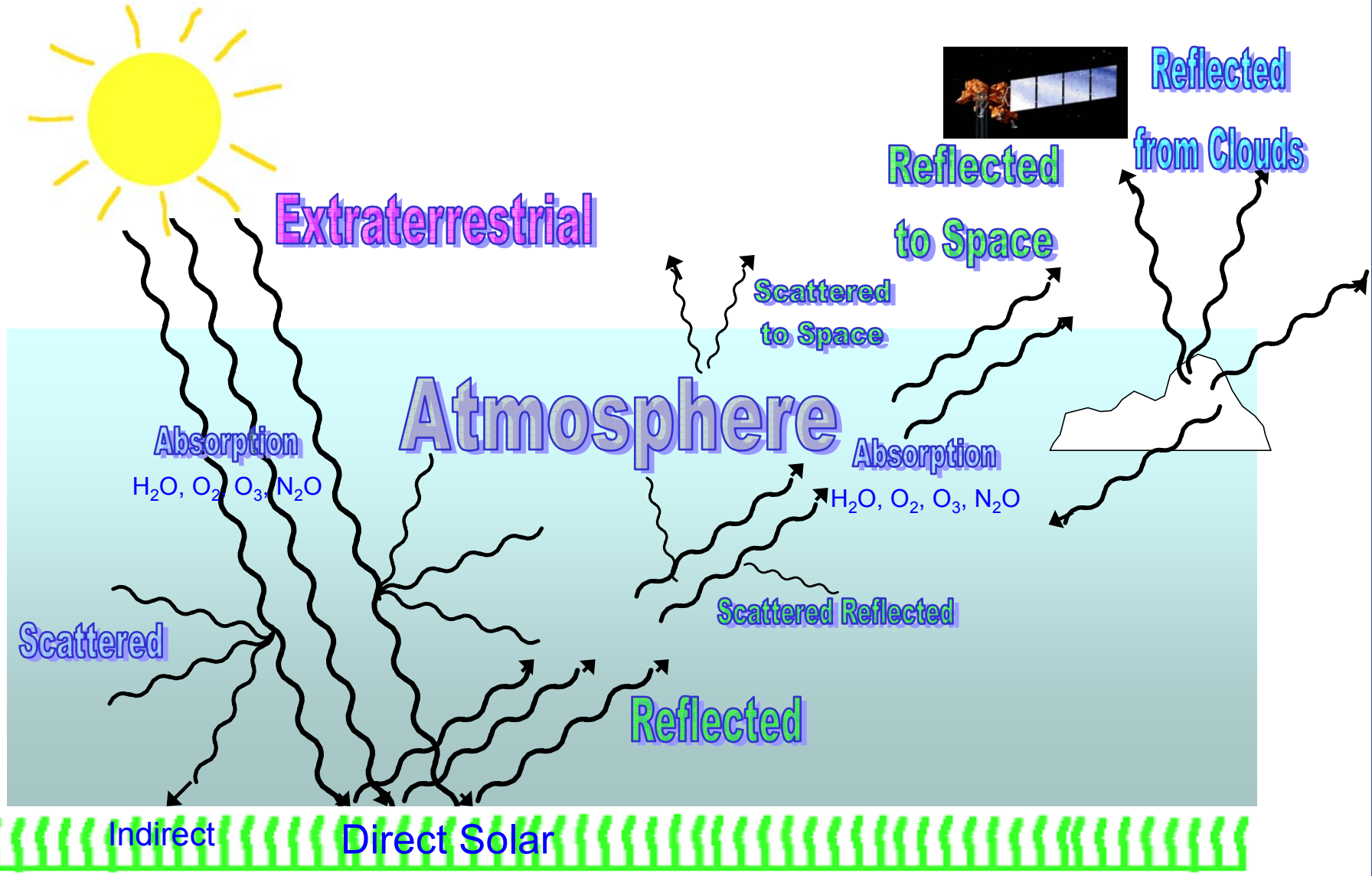
In METRIC, Weather Data are used for:

- *Wind speed* for sensible heat flux calculation

- *Reference ET* for Calibrating the Energy Balance

- *Reference ET* to Extrapolate ET over:
  - 24-hour period
  - Days between Images

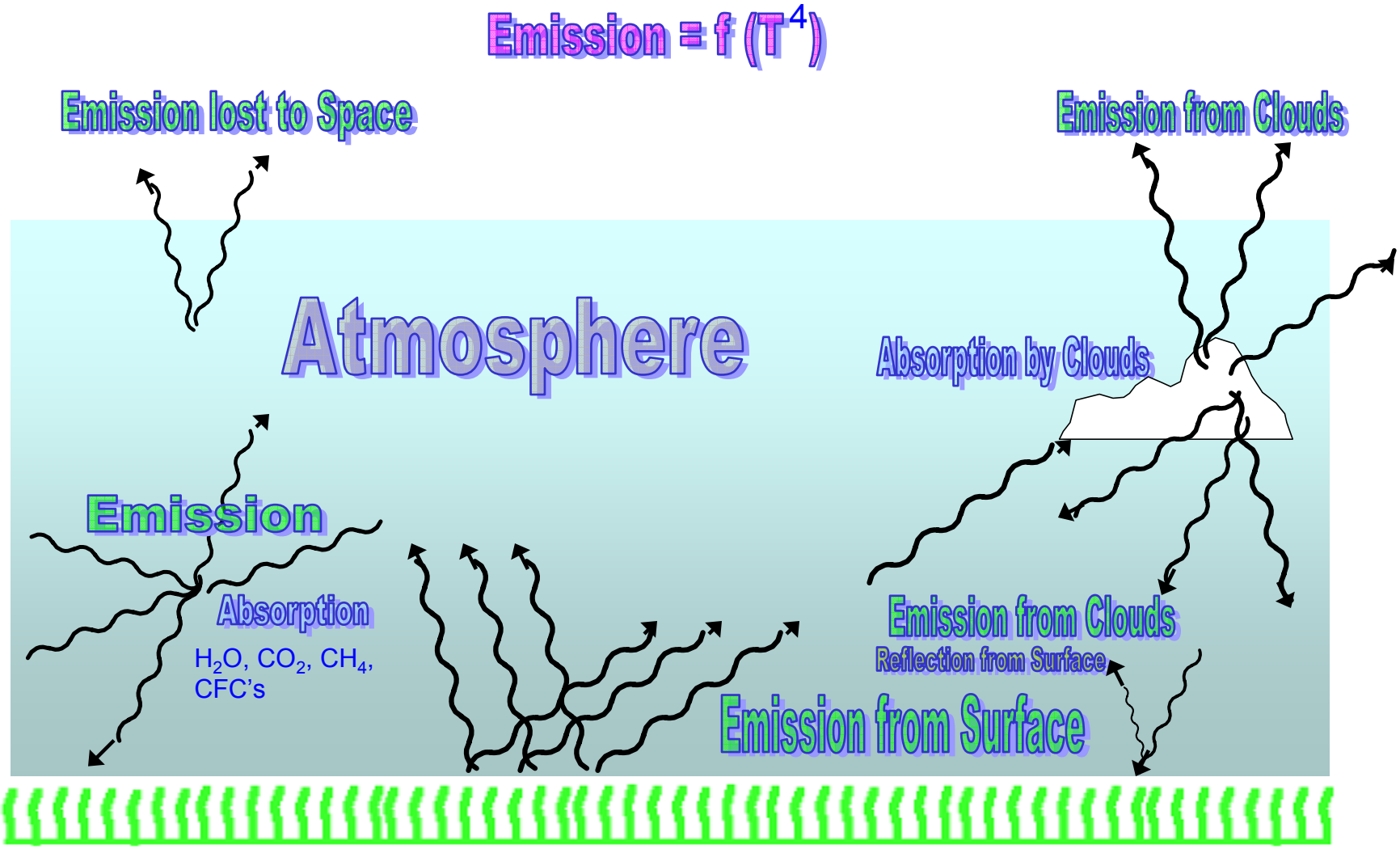
Disposition of Solar Radiation in the Atmosphere



$$\rho_{s,b} = \frac{\rho_{t,b} - \rho_{a,b}}{\tau_{in,b} \cdot \tau_{out,b}}$$

$$\tau_{in,b} = C_1 \exp\left[\frac{C_2 \cdot P_{air}}{K_t \cos\theta_h} - \frac{C_3 W + C_4}{\cos\theta_h}\right] + C_5$$

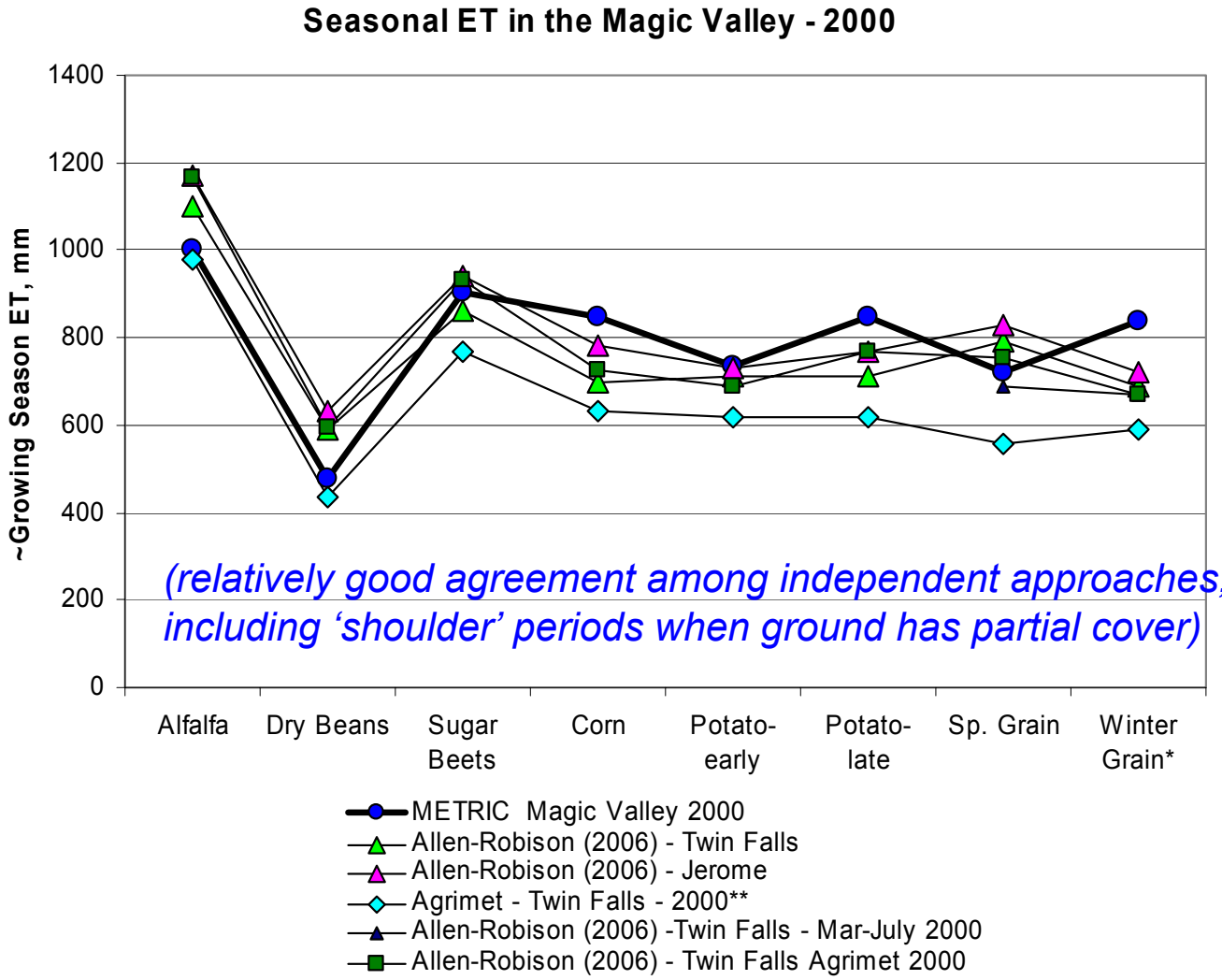
Longwave (Infrared) Radiation in the Atmosphere



Alternative to Satellite-based EB

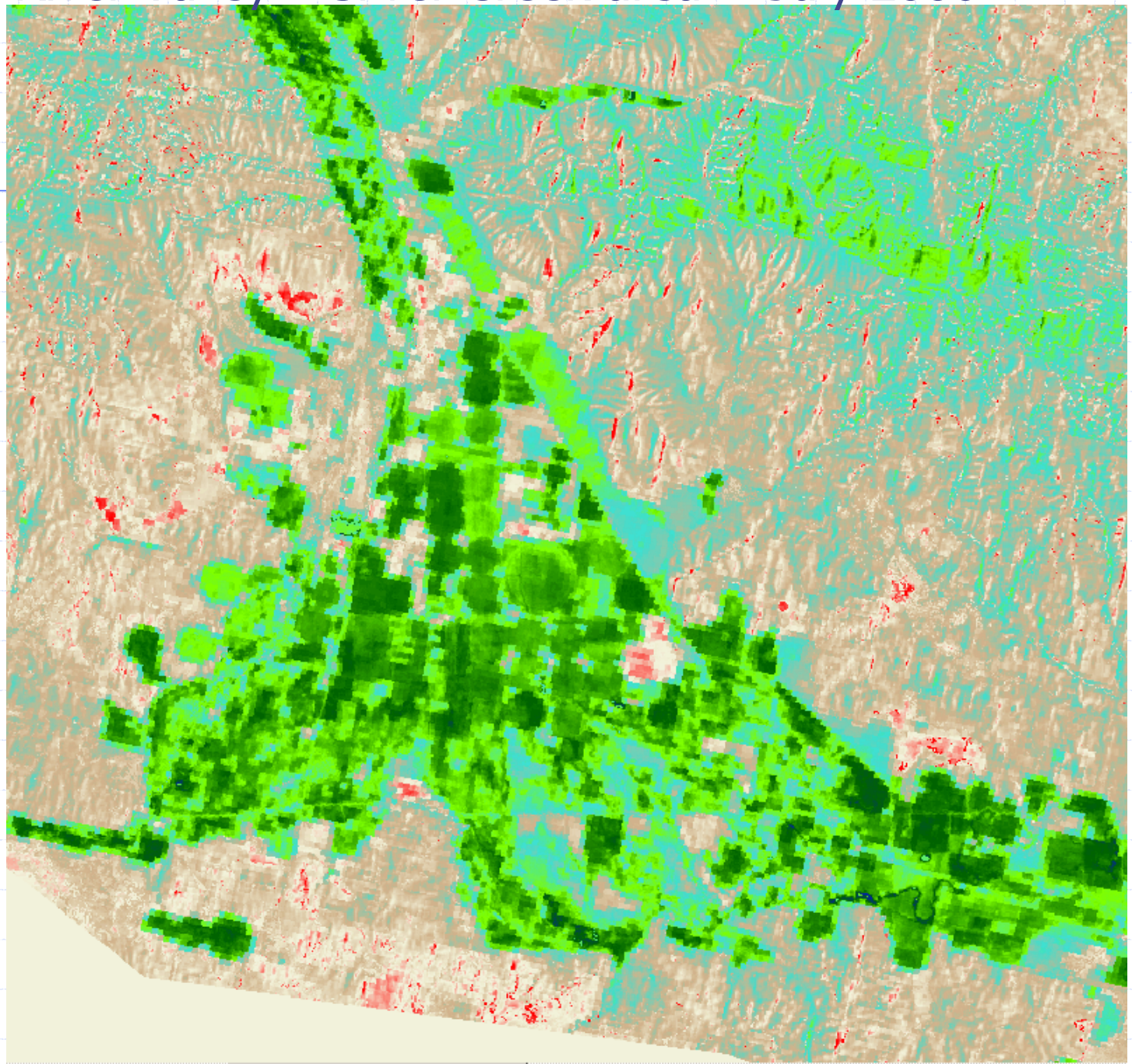
- Traditional Crop Coefficient approach:
  - $ET_{field} = K_c \times ET_{ref}$
    - ET_{ref} = reference ET from weather data
    - K_c = a potential value for high production and management *(always true?)*
  - However:
    - Acreages of each crop are needed
      - (METRIC does not require crop type information)
    - Differences in ET between sprinkler and surface irrigation are unknown
    - ET from desert (range) systems is uncertain

Comparison of traditional K_c ET_{ref} calcs with Satellite-based Energy Balance (METRIC)



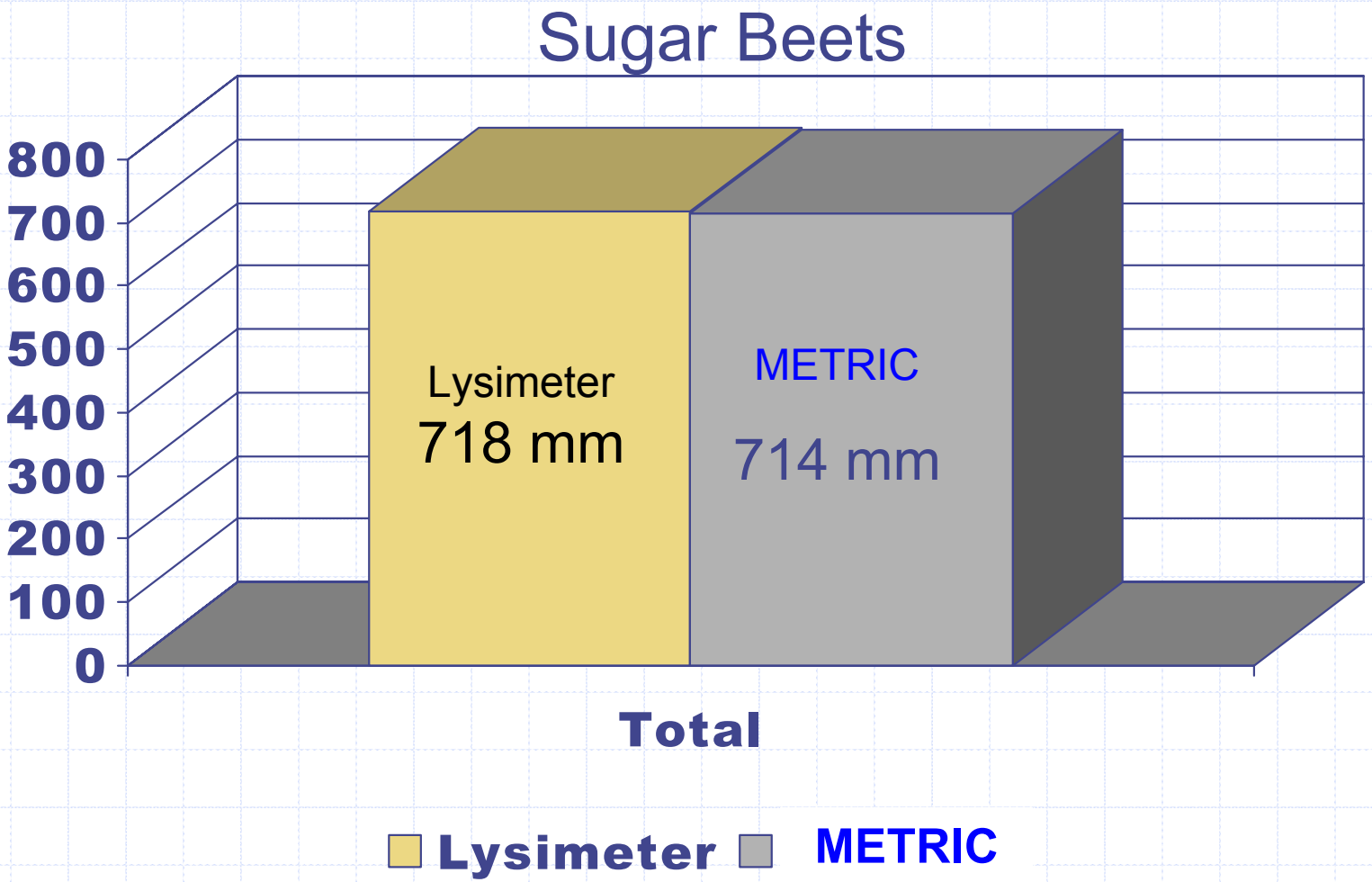
Wood River Valley – Silver Creek area -- July 2006

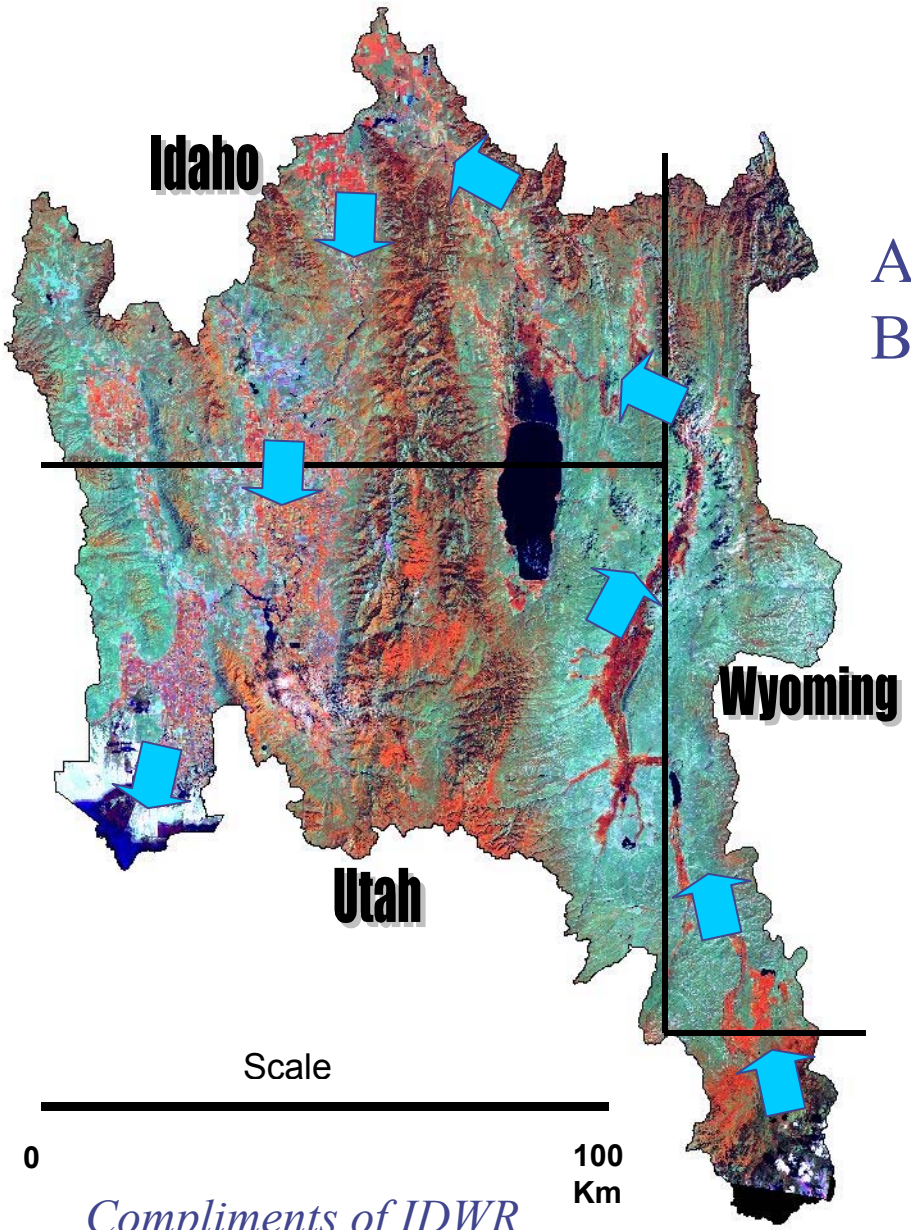
GW study: ET needed for recharge estimate



Comparison of Seasonal ET by METRIC^{tm} with Lysimeter

ET (mm) - April-Sept., *Kimberly, 1989*





Compliments of IDWR

Application to the Bear River Basin

Bear River Compact

Three USA States

Need ET maps for:

- Total "depletion" by each state
- Total hectares of development
- Monitoring

ET by METRIC with Lysimeter – Irrigated Forages

ET (mm) - July-Oct., *Montpelier, ID 1985*