Estimating ET from Irrigated Agriculture and Groundwater Discharge Areas with Remote Sensing and Weather Station Data

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Division of Water Resources
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RECLAMATION
Managing Water in the West

Introduction

- What is the majority of water being used for in the West?

  West Wide ~80-85% is used for Agriculture

Introduction

- Western States are dry
- Western States are growing fast
- Most urbanized states in the nation (most of states' population living in cities… i.e. Las Vegas)
- Low PPT + High Growth Rates in Urban Areas = Water Transfers from Agriculture and Natural Groundwater Discharge Areas to Urban Areas

Introduction

- Big need to estimate potential consumptive use. Example:

Question: How much water is needed to grow a healthy crop?

- Big need to estimate actual historical agricultural consumptive use. Example:

Question: How much water can actually be realized over the long term for a potential water transfer if crops are fallowed?

Potential Consumptive Use vs. Actual Consumptive Use

Potential Consumptive Use

- ET that occurs under optimal conditions
- Assumes crop is well watered
- Derived from reference ET
- Traditional ETr * Kc approach
- Crop types and planting and harvest dates need specified
- Primary use is for irrigation design, scheduling, water rights, and water transfers

Actual Consumptive Use

- ET that actually occurs
- Can be very different from the potential consumptive use due to water limitations, stress, management, etc.
- Primary use is for water budget estimation, modeling, water rights, water transfers, and compliance

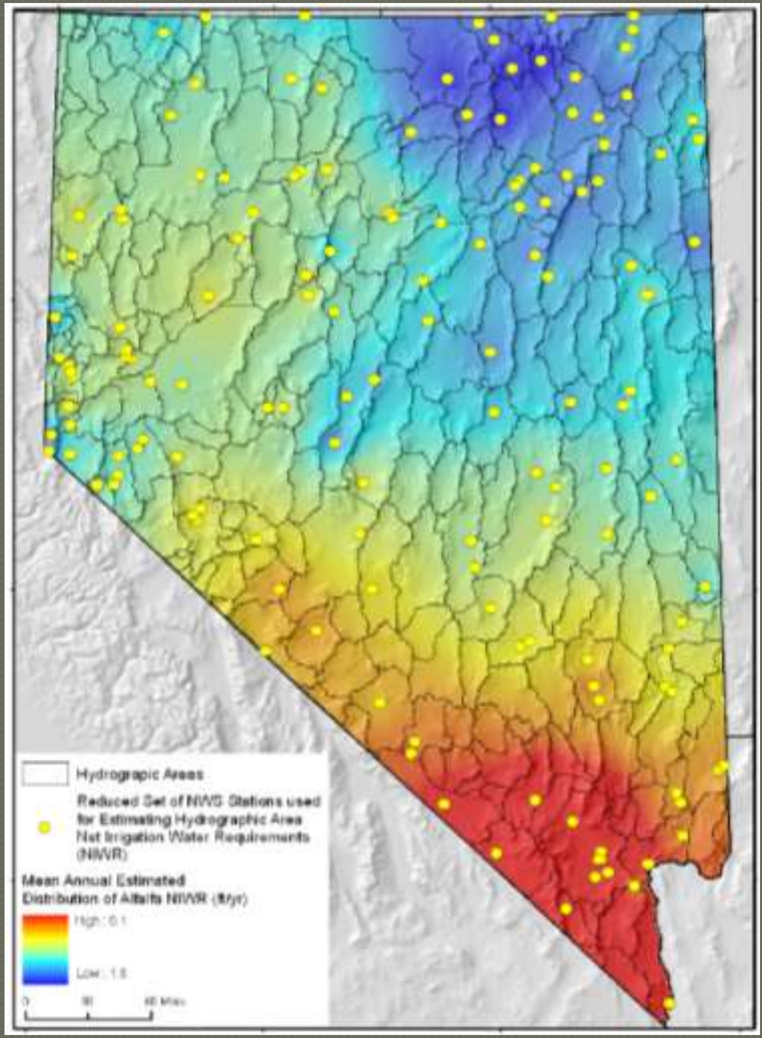
Potential Net Consumptive Use Example

- In Nevada, the limit of irrigation water right allowed for transfer to a new use is the mean annual "Net Irrigation Water Requirement"

  AKA "Potential Net Consumptive Use"

  $NIWR = ET_{act} - (PPT - RO - Dp)$

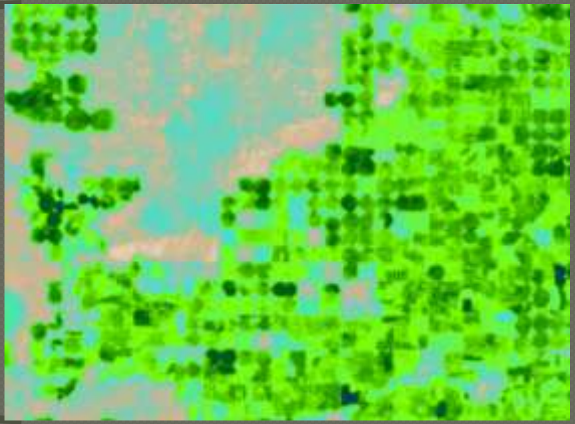
- Irrigation water rights (and past transfers to municipal) range from 3ft – 5ft (North – South)
- New Penman-Monteith based NIWR estimates range from 1.6ft – 6.1ft
- Provides water right holders information on irrigation requirements, and water rights potentially available for transfer
- This approach assumes perfect crops and water supply, requires estimates of planting and harvest dates using thermal units or static dates, and crop types and acreages must be known to compute volumes *(not so with remote sensing)*



Huntington and Allen, 2010

Use of Remote Sensing for "Actual Consumptive Use"

- Remote sensing using Landsat is likely the only way to estimate the "actual consumptive use" at field scales over large areas



- Recent Landsat Science News Clip (April 12, 2010) - *Landsat can be an Impartial Arbitrator in Water Conflict Issues* – Article highlights Nevada Governor Brian Sandoval's thoughts, and DRI's work in Nevada and California

  "Access to accurate ET maps produced using a widely accepted approach allows water resource managers to assess water use on a field by field basis in an objective way where everyone is treated equally."

  "With equality of data for everyone, disputes over data or lack of data are reduced, which is a big change in how water conflicts have been dealt with in the past."

2 Common Approaches for Remote Sensing of Actual Consumptive Use

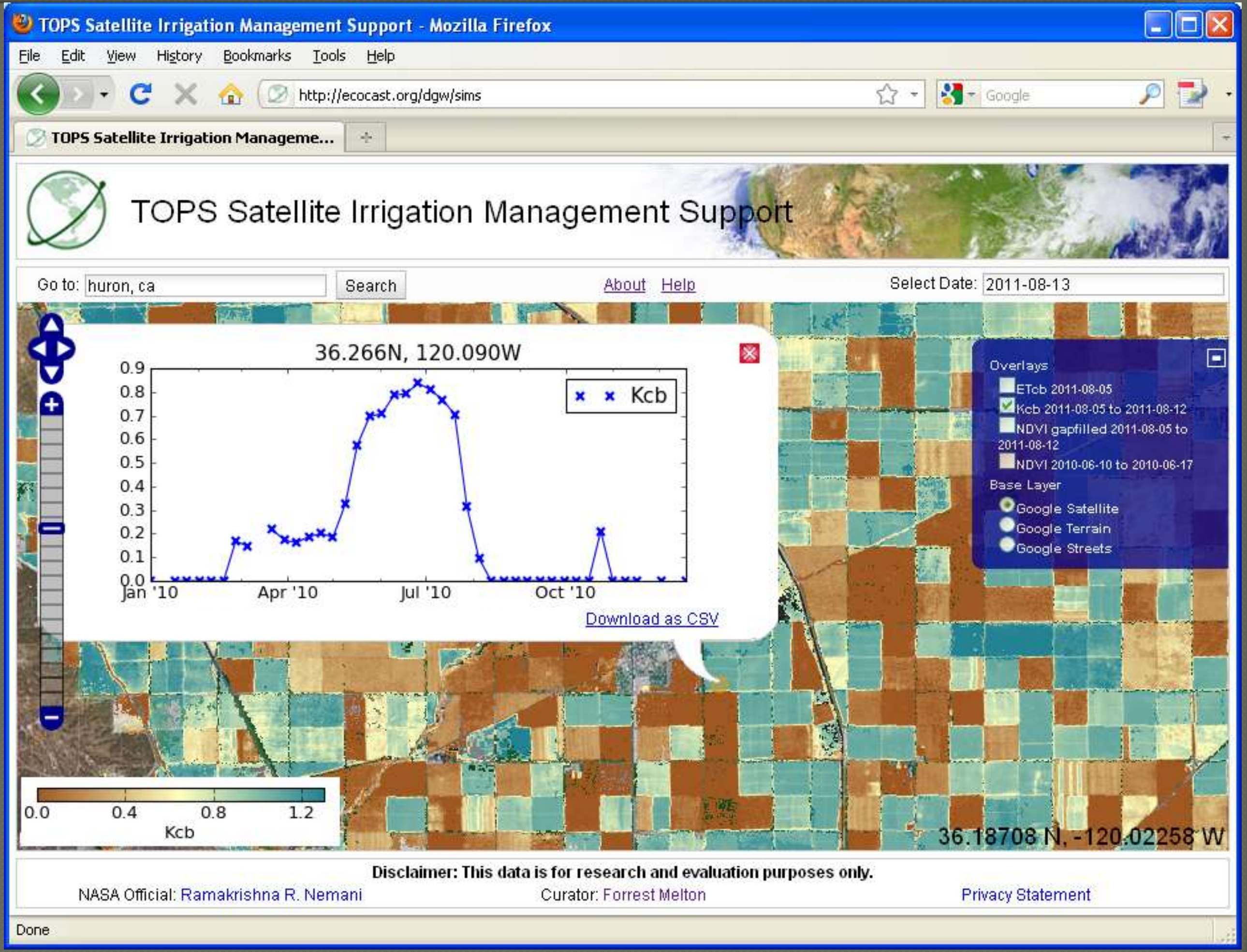
- Vegetation Indices
  - Relies on reflected light of near infrared and red wavelengths
  - Plants reflect near infrared light and absorb red light

    NDVI = (NIR – Red) / (NIR + Red)

- Energy Balance
  - Largely relies on thermal infrared
  - Basic premise - Evaporation consumes heat thereby cooling the surface

Current Work in California using VIs

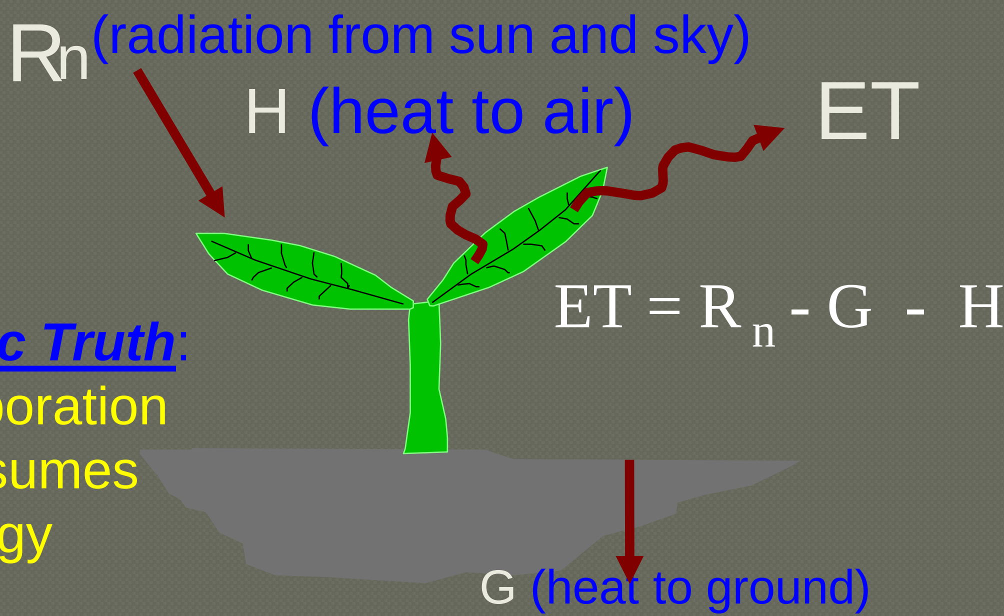
- Transform NDVI into fraction of cover, and from fraction of cover to crop coefficient (Kc)
- ET is computed as ET = ETref * Kc
- Approach has several advantages over others, and some disadvantages



Courtesy of Forrest Melton, NASA Ames

Energy Balance

- Calculates ET as a “residual’ of the energy balance
- METRIC - **M**apping **E**vapo**t**ranspiration at high **R**esolution using **I**nternalized **C**alibration (Allen et al., 2007)
- SEBAL – **S**urface **E**nergy **B**alance **A**lgorithm for **L**and (Bastiaanssen, et al., 1998)
  - METRIC won Harvard’s Best Innovations in American Government Award in 2009
  - EB approach is supported by the Western States Water Council and Western Governors Association



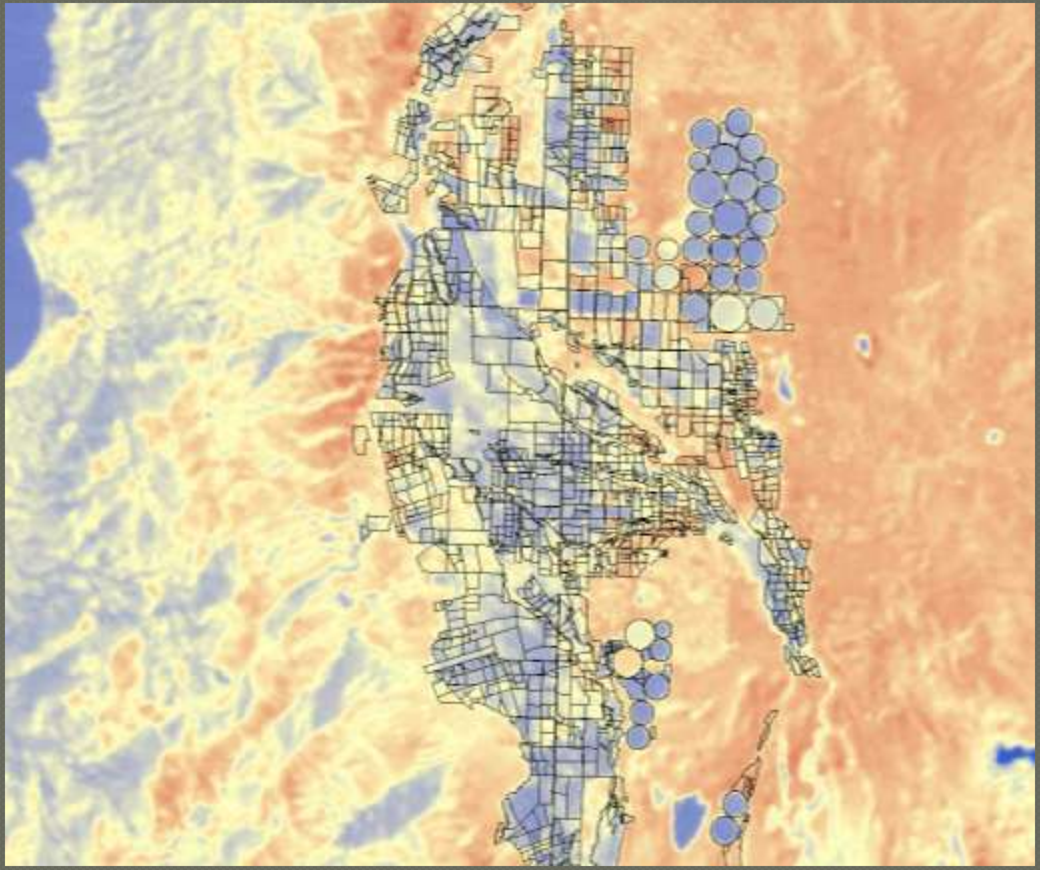
$$ET = R_n - G - H$$

Basic Truth: Evaporation Consumes Energy

The energy balance includes all major sources (R_n) and consumers (ET, G, H) of energy

Energy Balance Based on Thermal Imagery

Agriculture cooler due to "evaporative cooling" – energy consuming!



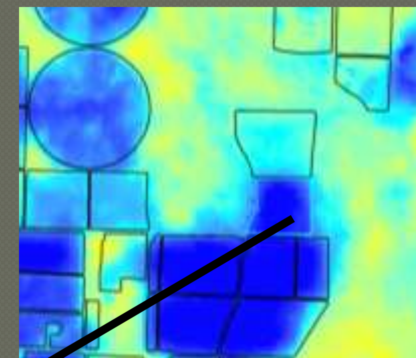
Carson Valley, CA / NV

8/15/2009

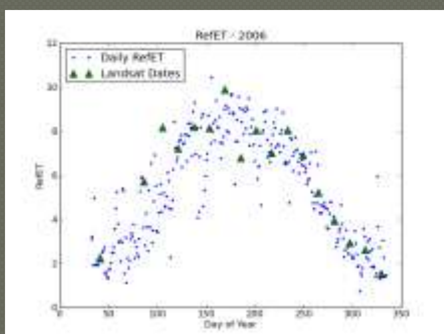
Surface Temperature (Deserts ~ 125°F – Agriculture ~80°F)

Mechanics of VI and EB to Estimate Seasonal ET – Interpolation and Integration

- Once we estimate the fraction of daily reference ET (Kc) using either VIs or EB based daily ET from the satellite overpass, we need to interpolate and integrate to estimate the seasonal ET

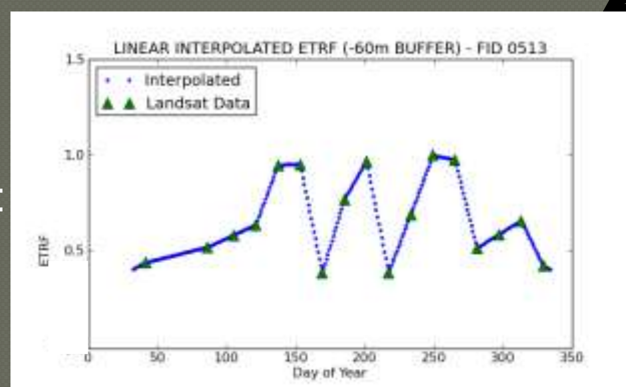


Time Series of Reference ET (ETr)



x

Kc = fraction of reference ET



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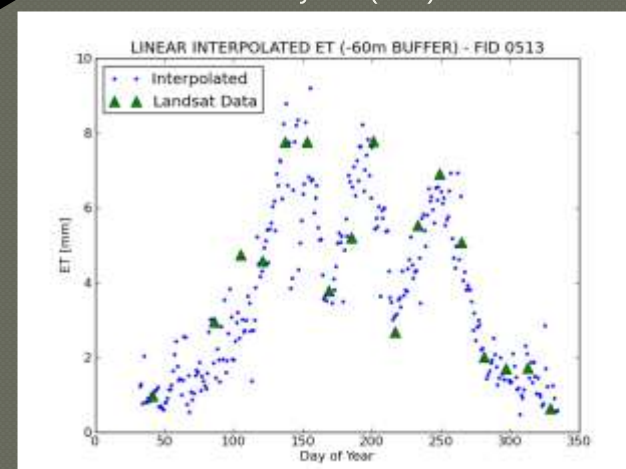
Total Daily ET (mm)



- By using Reference ET, we account for daily variations in solar radiation, temperature, humidity, windspeed!!

Advantages of Energy Balance to Estimate Actual ET

Pros: We can 'see' impacts on ET caused by:

- evaporation from bare soil
- short and long term water shortage
- disease
- crop variety
- cropping dates
- salinity
- management

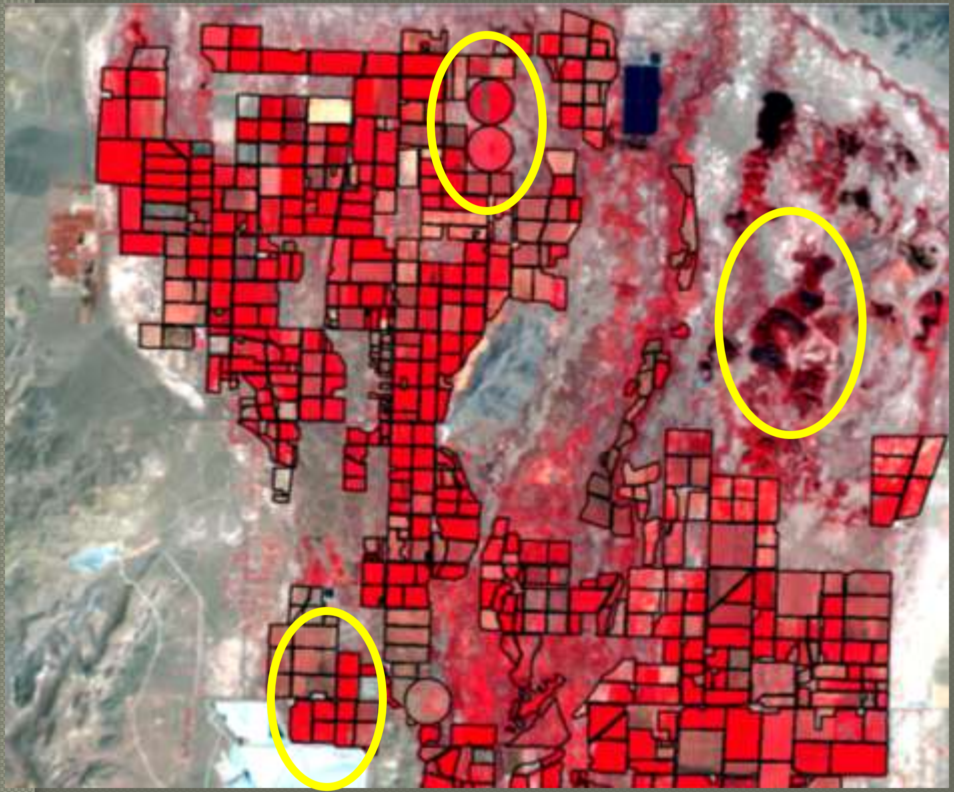
Combines strengths of EB with accuracy of ground based reference ET calculations which "anchors" the energy balance surface and provides "reality" and accuracy to the product

Cons:

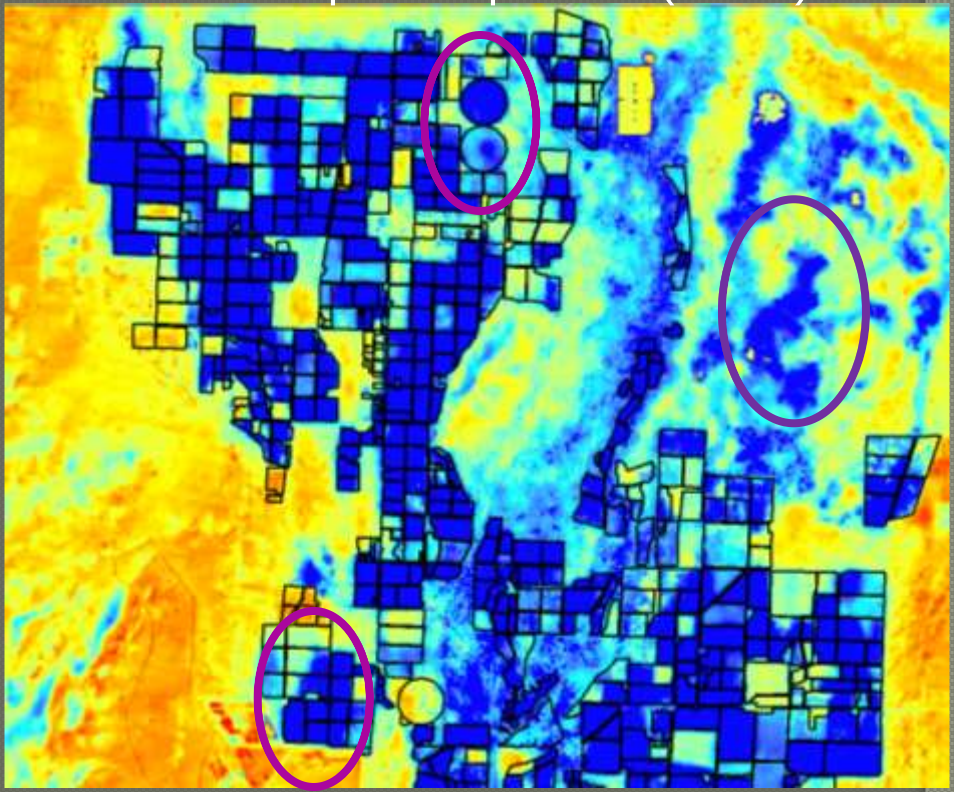
- Is fairly time consuming
- Takes a human to control
- Is currently not a fully automated process

Energy balance gives us "actual" ET from many different land uses

False Color Infrared



Evapotranspiration (mm/d)



Mason Valley CA / NV, 7/25/2008

- EB "sees" evaporation from soil and marsh areas where as reflectance data does not
- EB "sees" stress where NDVI has a hard time with acute stress

Advantages of VIs to Estimate Actual ET

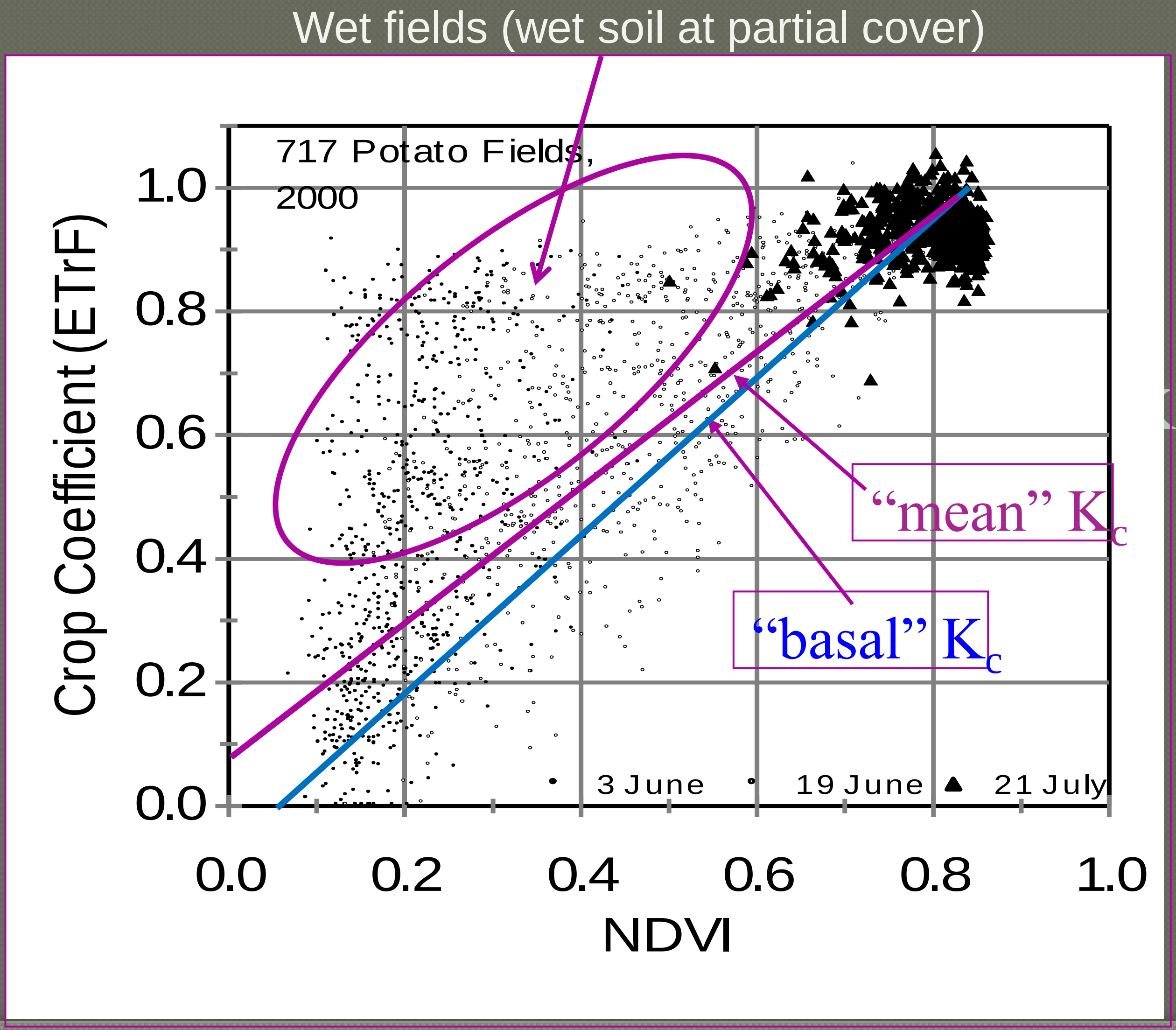
Pros:

- Relatively accurate over a season and over large areas
- Rapid processing
- Easy automation
- Can be easily calibrated

Cons:

- Can not directly see bare soil evaporation or mixed open water riparian ET
- Does not perform well seeing short term water stress
- Difficulties estimating ET in riparian areas due to stomatal control reducing ET *(Glenn, Nagler, et al.)*
- Is currently not a fully automated process

NDVI vs EB estimated Kc



Courtesy of Rick Allen, U of Idaho

NDVI vs EB estimated Kc

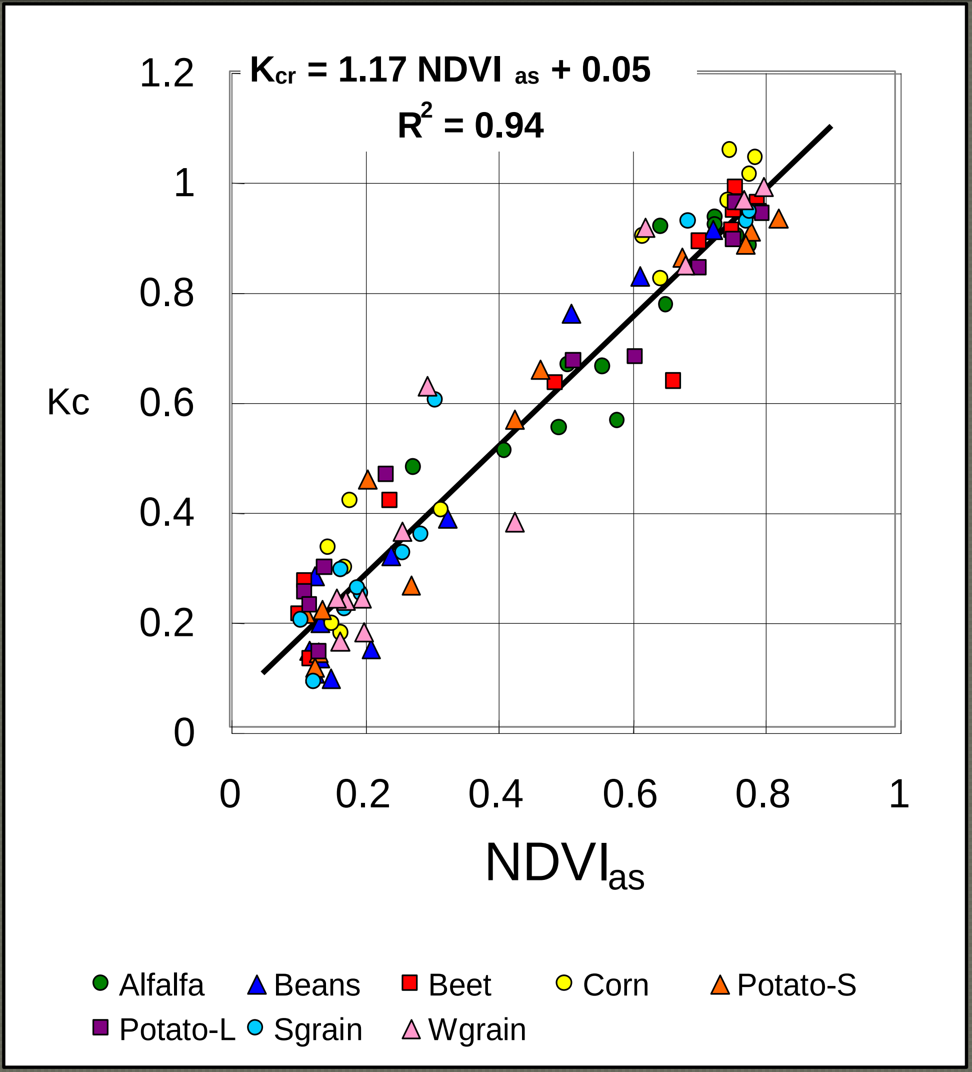
Well Watered Crops in Magic Valley, ID

X = NDVI

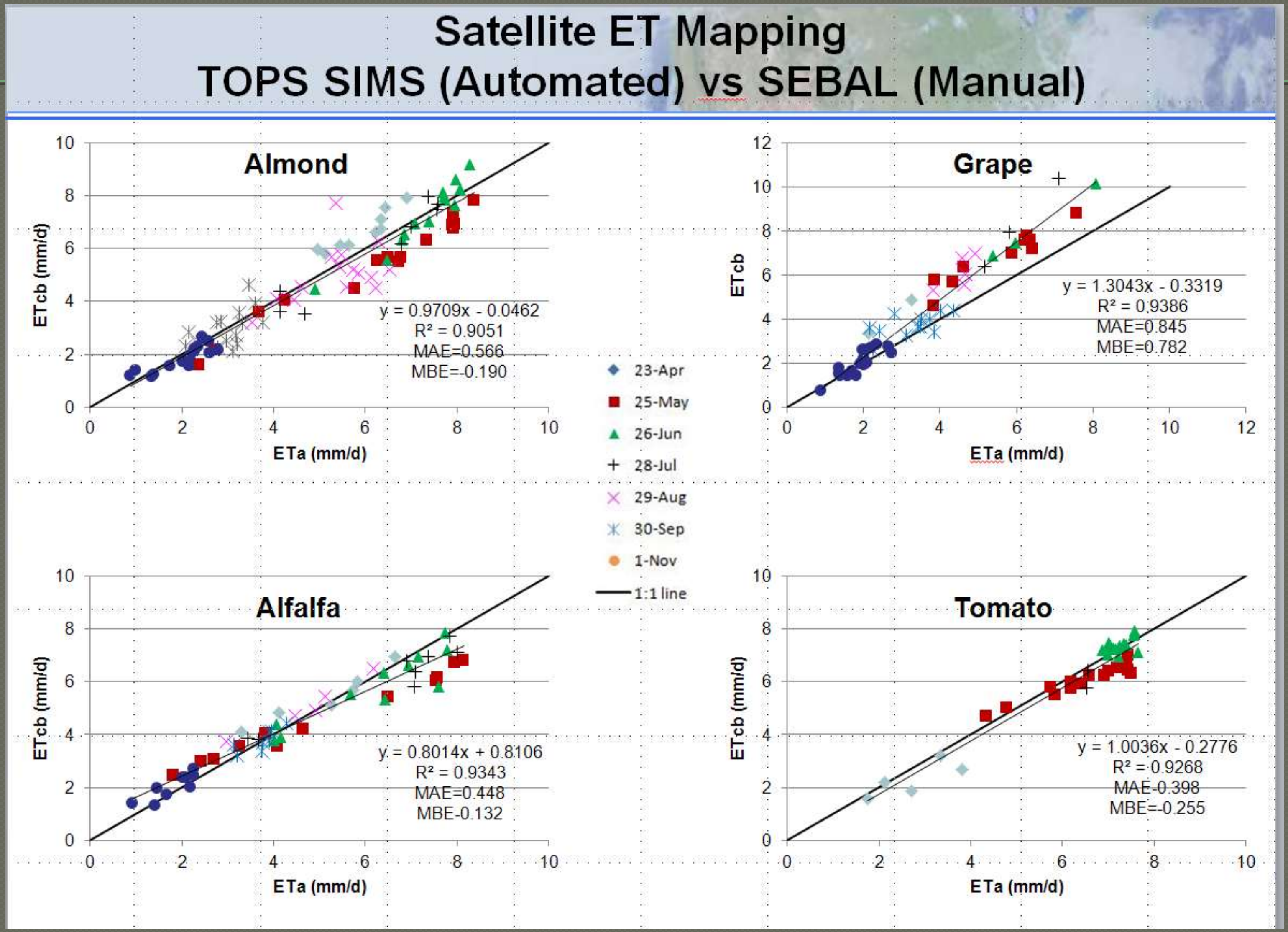
Y = EB derived Kc averaged over all field types for all images dates for 2000

Scatter among fields collapses and NDVI EB derived Kc relationship not too bad

Courtesy of Rick Allen, U of Idaho



NDVI vs EB estimated ET



Courtesy of Forrest Melton, NASA Ames, CSUMB

Accuracy Matters for Water Rights/Transfers: Example for NV / CA / UT

- **Goal:** Refine estimates of actual historical crop consumptive use over last 10yrs and provide information towards refining water budgets and support water rights transfers throughout NV and boarder basins with CA and UT

- Nevada is actively using EB (METRIC) in agricultural areas due legal issues surrounding water transfers from ag. to municipal and wildlife, and the need for accurate "*individual field*" estimates

- However, we are working towards using NDVI when and where possible such as for *"basin wide"* estimates when the error among field largely cancels out over the entire basin

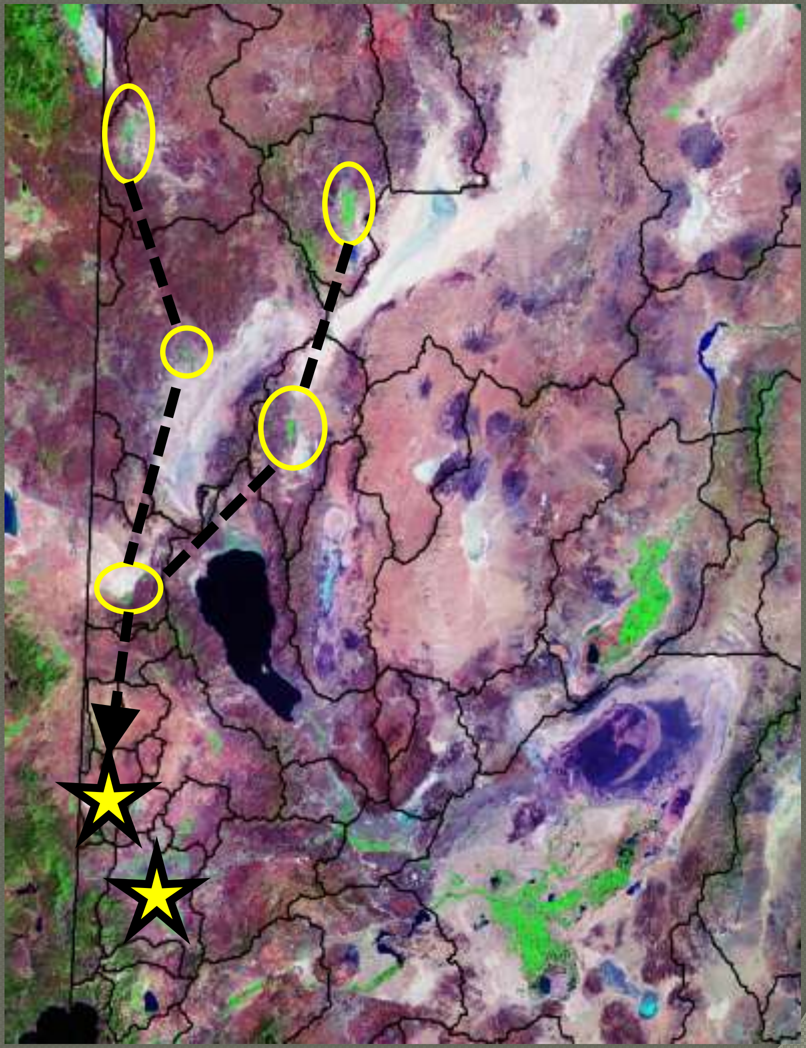
Example of Nevada Water Transfer

- Nevada water law allows for existing water rights to be transferred to a new location and/or use
  - Example: Export groundwater irrigation water rights out of a basin and use it for municipal purposes in a basin needing the water

~$10K per ac-ft
~$70,000 per ac-ft in 2007

One 125 acre center pivot @ 4ac-ft/acre

= $5,000,000 !! per center pivot
= 35,000,000 !! per center pivot

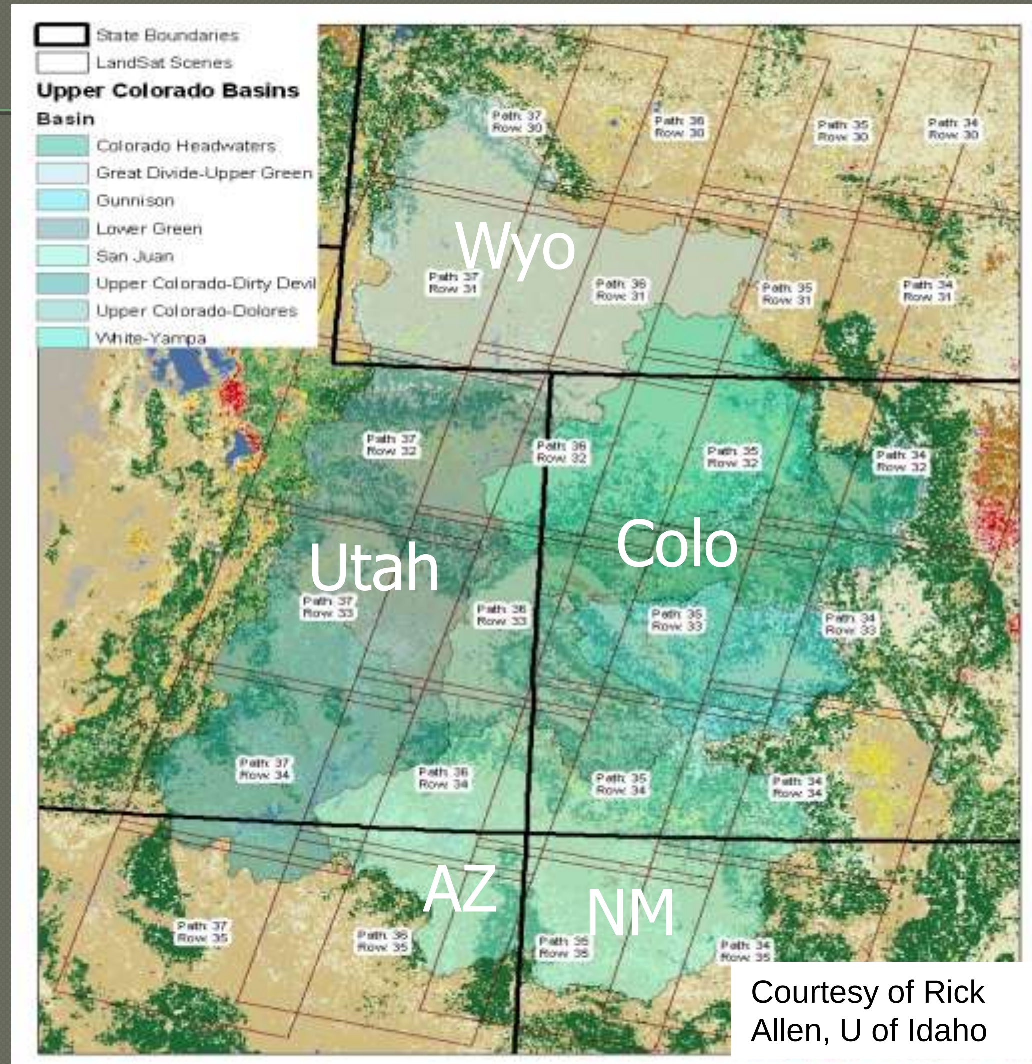


Upper Colorado River Basin

- A VI / EB combination approach would be attractive for the Colorado River basin for estimating tributary basin scale ET in an automated fashion and in near real time

Proposition:

- Derive a NDVI Kc relationship from EB
- Apply the NDVI Kc relationship in an automated mode
- Recalibrate the relationship every couple of years due to changes in crop varieties and management
- Apply EB when individual field scale estimates are needed for water rights transfers / legal and compliance issues

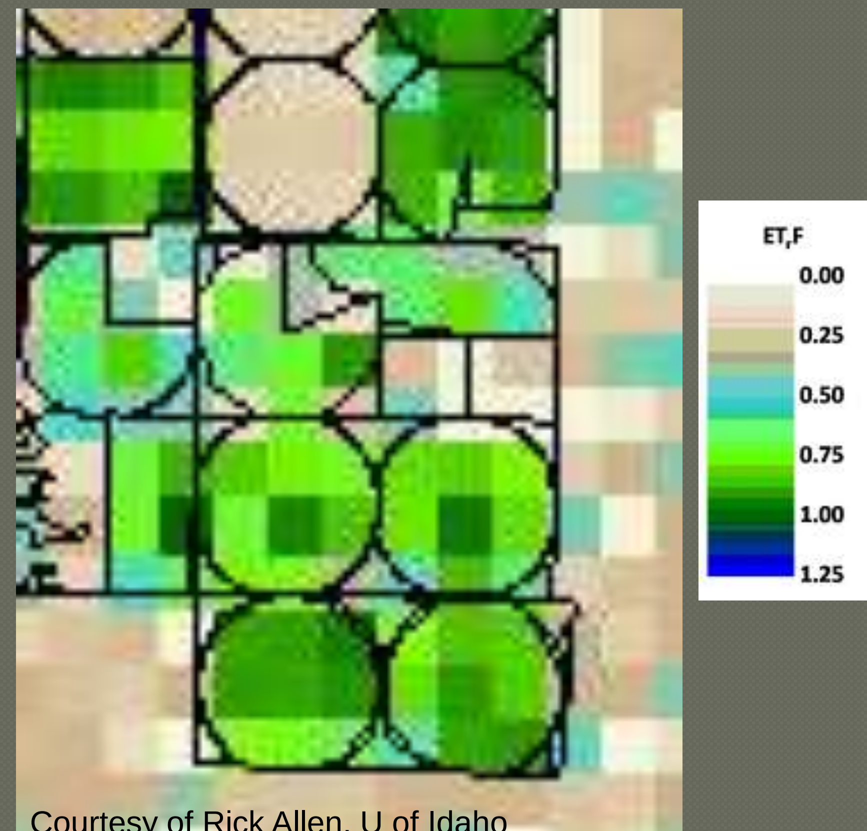


Overlays of Landsat path and rows over the upper Colorado River Basin
24 total path / rows
100 x 100 miles per path / row

Regardless of VI or EB
Field Scale (30-100m) is a Must!

ET based on Landsat 30 m

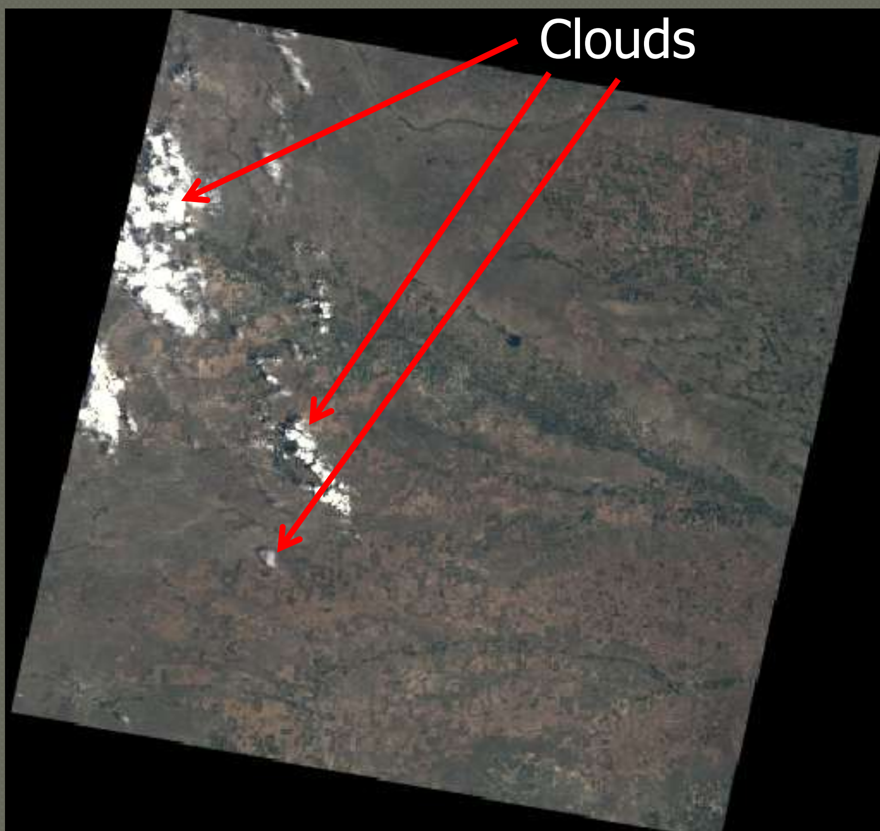
ET based on MODIS 250 m

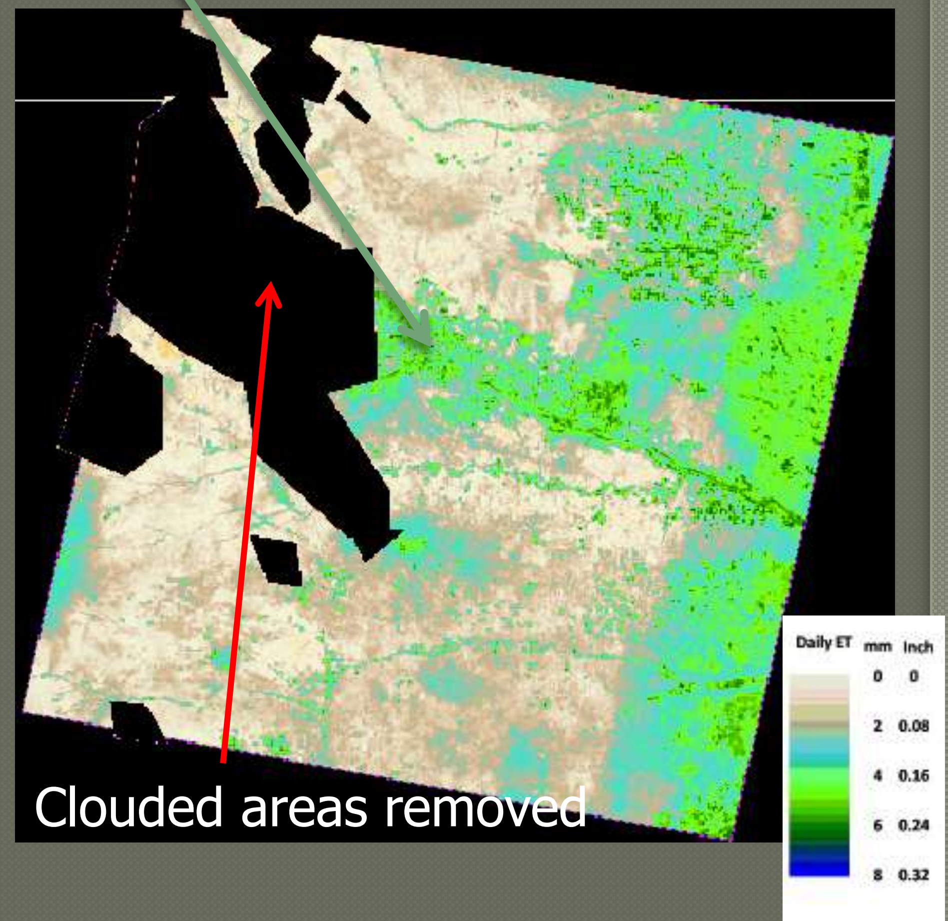


Bell Rapids Irrigation District, Idaho, 2002

Regardless of VI or EB
Cloud Mitigation is a Must!

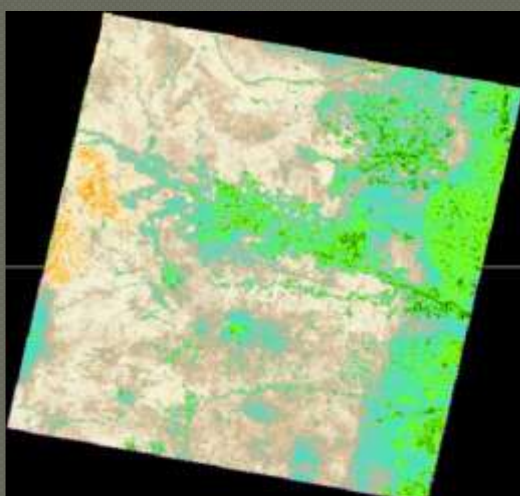
Automatic Landsat cloud detection (ACCA & FMASK) is not all that accurate… misses thin clouds and other types… masks must be manually digitized and eventually gap filled using like pixels or other image dates



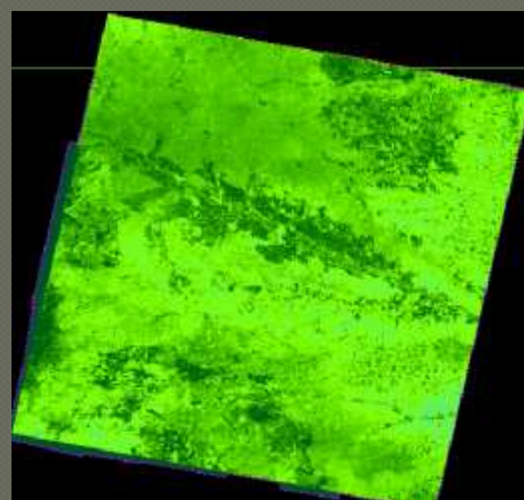


Regardless of VI or EB

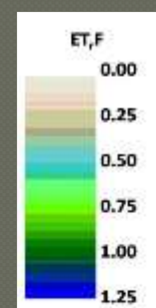
- Accurate time integration and accounting for evaporation from precipitation events in between Landsat overpass dates is needed in many regions where precipitation occurs frequently during the growing season
- Accomplished using a gridded daily evaporation process model to estimate evaporation from precipitation (Kjaersgaard, Allen, Irmak, 2012)

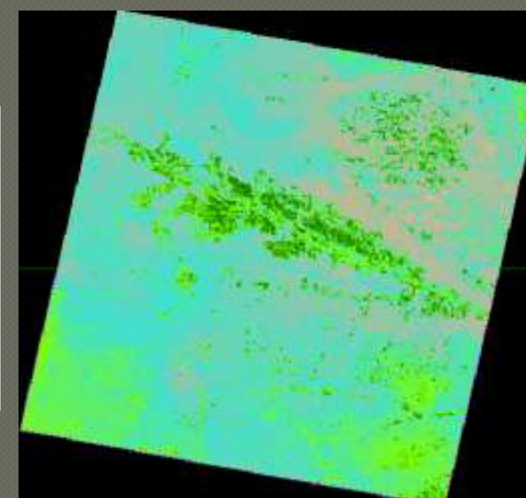


ET from July 12 1997



ET from August 13 1997 after rain and before adjustment

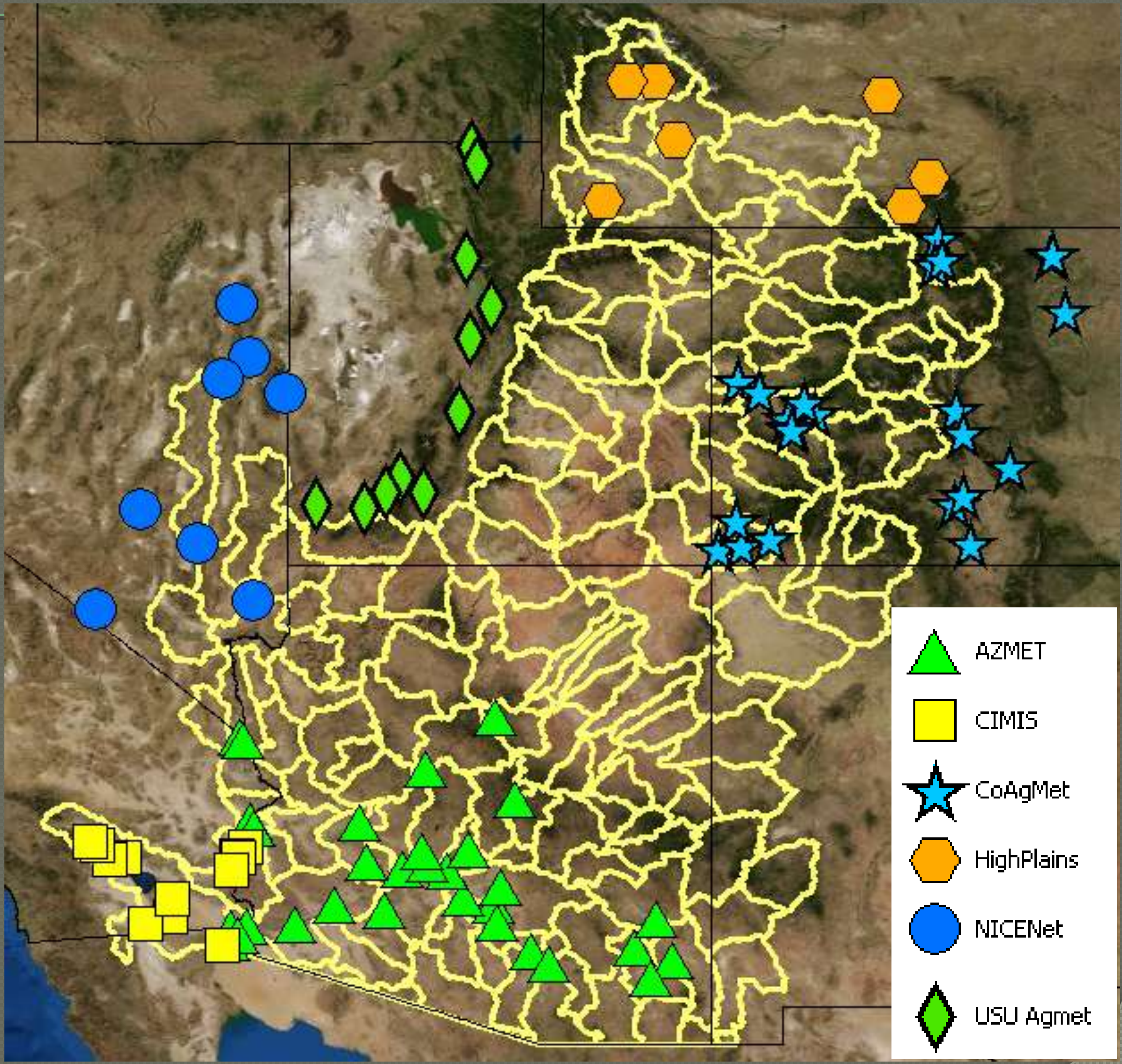




ET from August 13 1997 adjusted for background evaporation

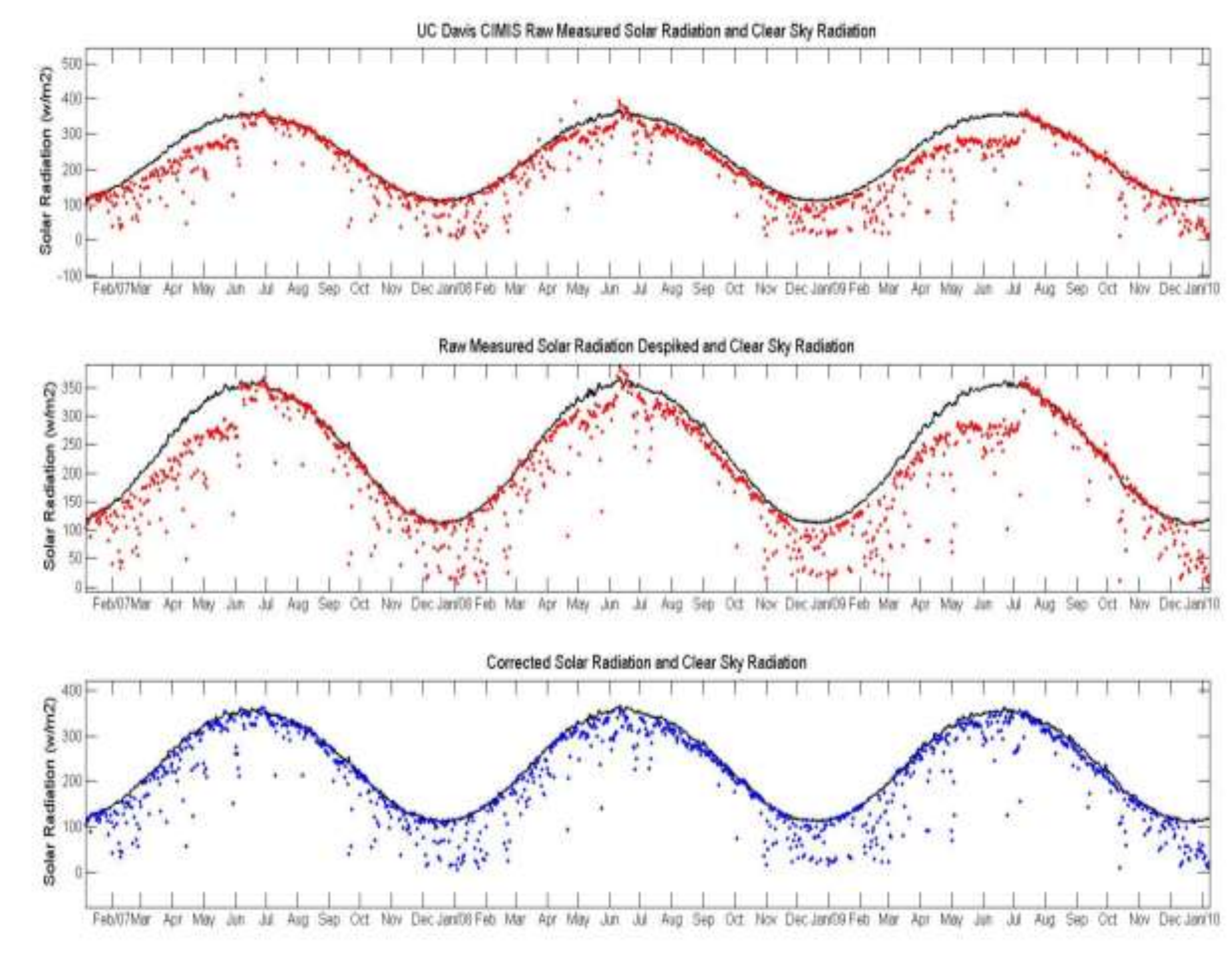
Regardless of VI or EB
Accurate Ag. Weather Data is a Must!

- Accurate reference ET is a must for time integration of daily ET maps
- DRI and U of Idaho have recently developed semi-automated algorithms and tools to QAQC
- We have just completed QAQC compiled accurate reference ET for all agricultural stations that exist in and around the Colorado River Basin (CRB)!
- Currently using QAQC'd data to estimate potential consumptive use using the Penman-Monteith across the CRB (and Western States, funded through Reclamation)
- Aim to utilize these QAQC'd data for remote sensing purposes in the CRB in the near future



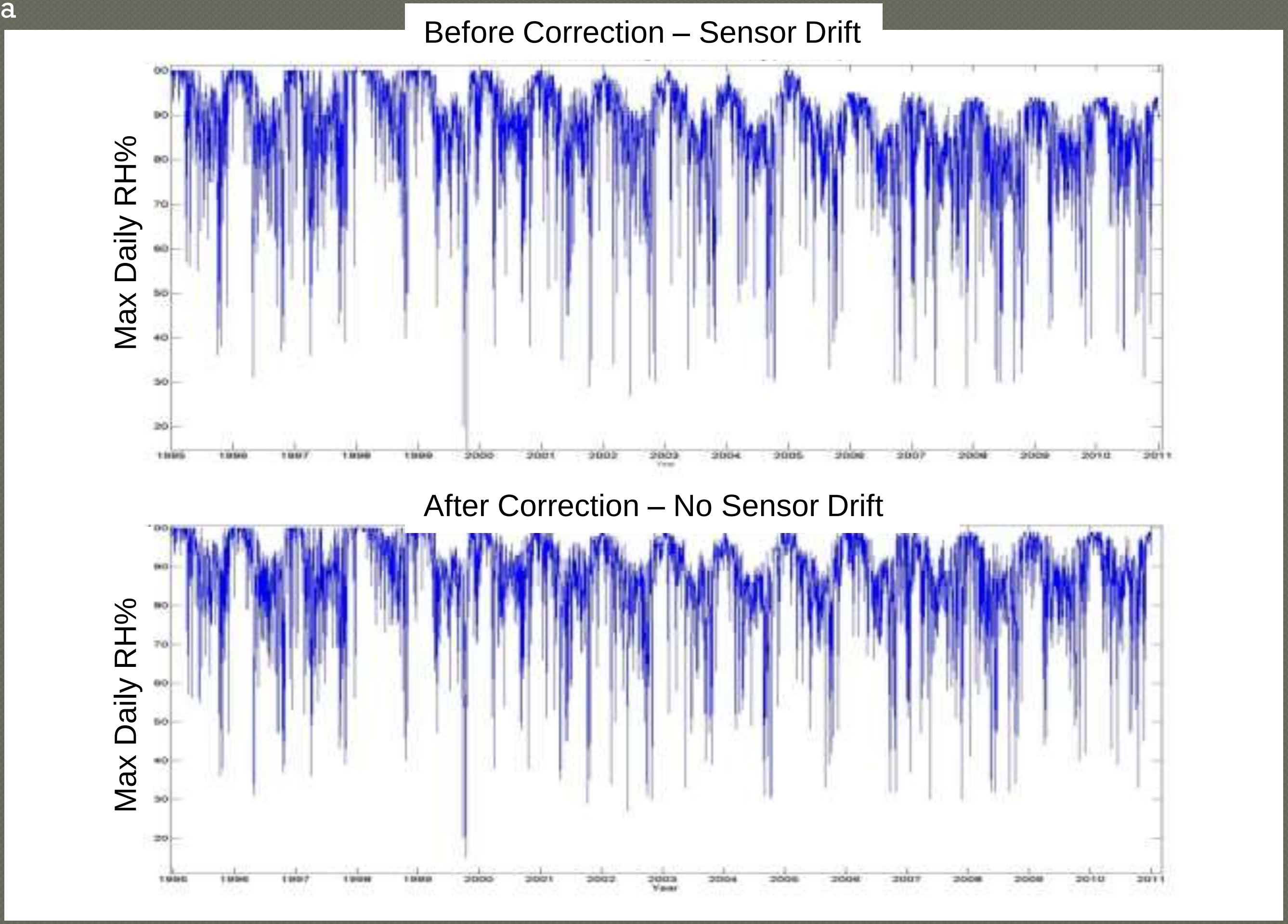
Regardless of VI or EB
Accurate Ag. Weather Data is a Must!

- Example of QAQC process of Solar Radiation at UC Davis CIMIS station
  - Base adjustments on ratios between theoretical clear sky solar radiation and top percentiles of measured data



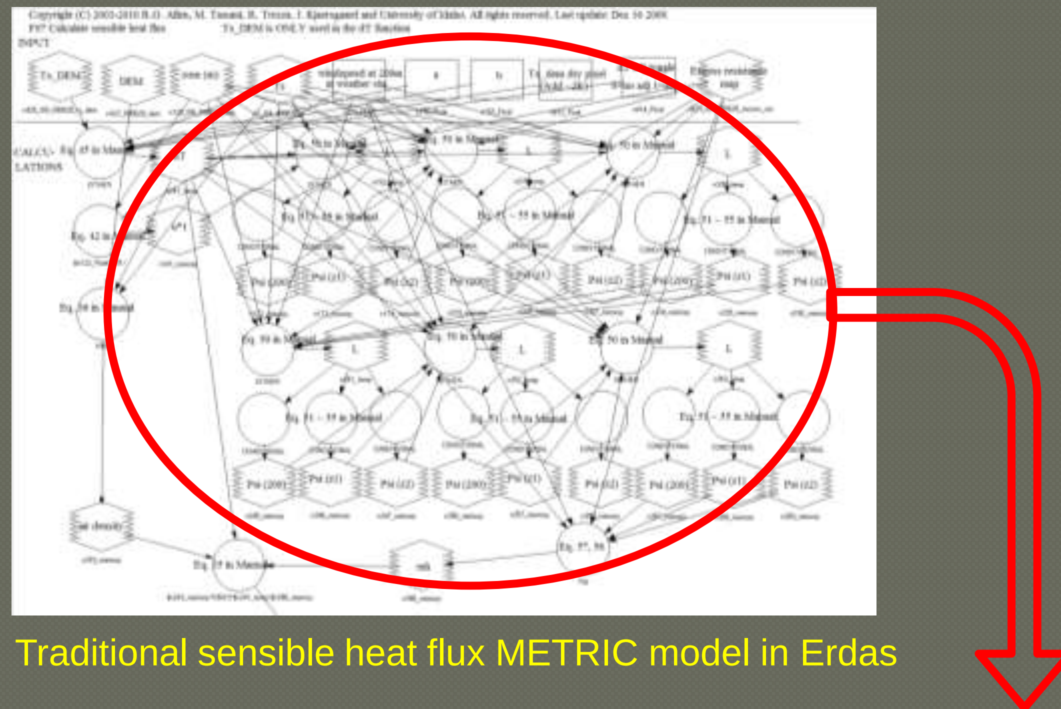
Regardless of VI or EB
Accurate Ag. Weather Data is a Must!

- Example of QAQC process of Max. Daily RH% at UC Davis CIMIS station
  - Base adjustments on ratios between theoretical clear sky solar radiation and top percentiles of measured data



Future Directions – Python Version of METRIC Energy Balance Code & Automation

- DRI recently coded METRIC in Python (open source open platform software)
- Enhanced productivity, reduced cost, and reduced time required to estimate ET
- Working with NASA Ames (Forrest Melton) to implement and test a automated version of METRIC Python for the Central Valley
  - Funded through Nevada EPSCoR NASA Space Grant

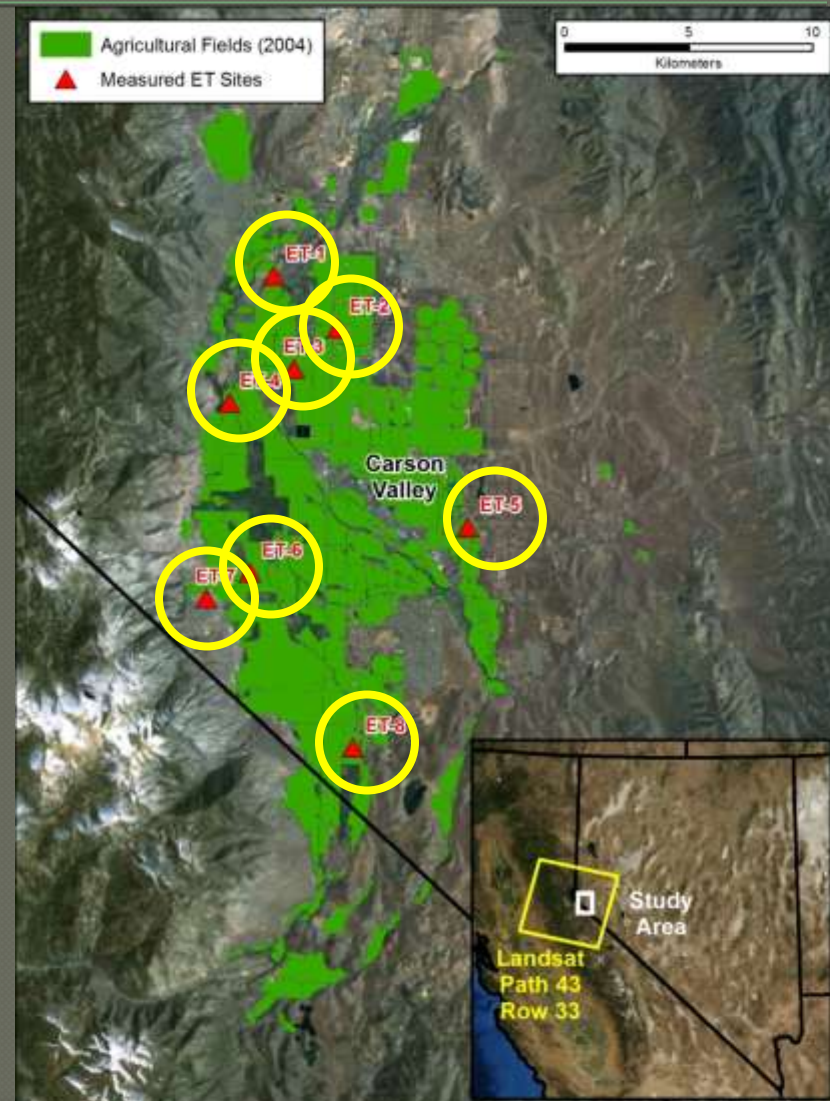


Traditional sensible heat flux METRIC model in Erdas

Clipped Python version of METRIC sensible heat flux model

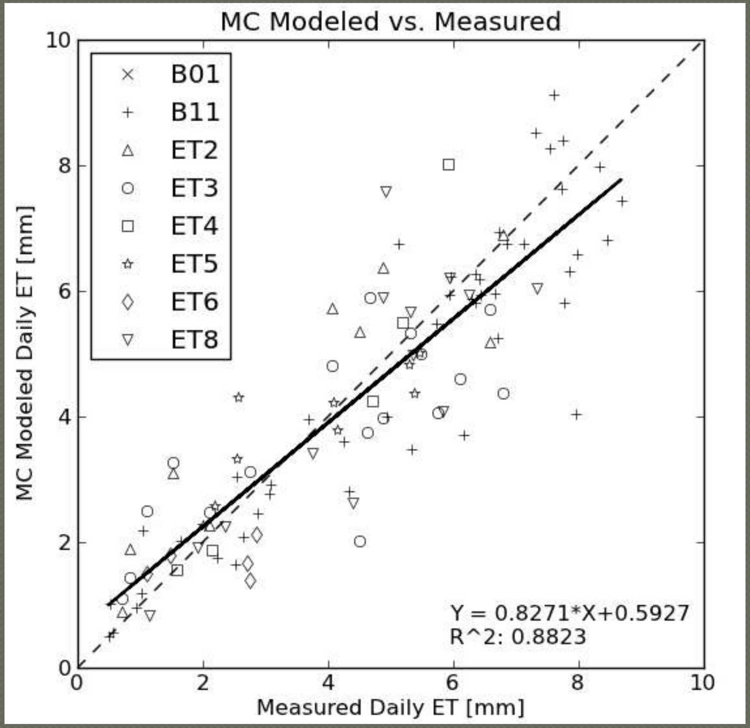
```
for i in range(6):
    u*(u, z, zom, psi_z3)
    rah(z, psi, u*, ex_res)
    l(dt, u*, Ts, rah)
    psi_z3(l, z3)
    psi_z2(l, z2)
    psi_z1(l, z1)
    if stable(): break
```

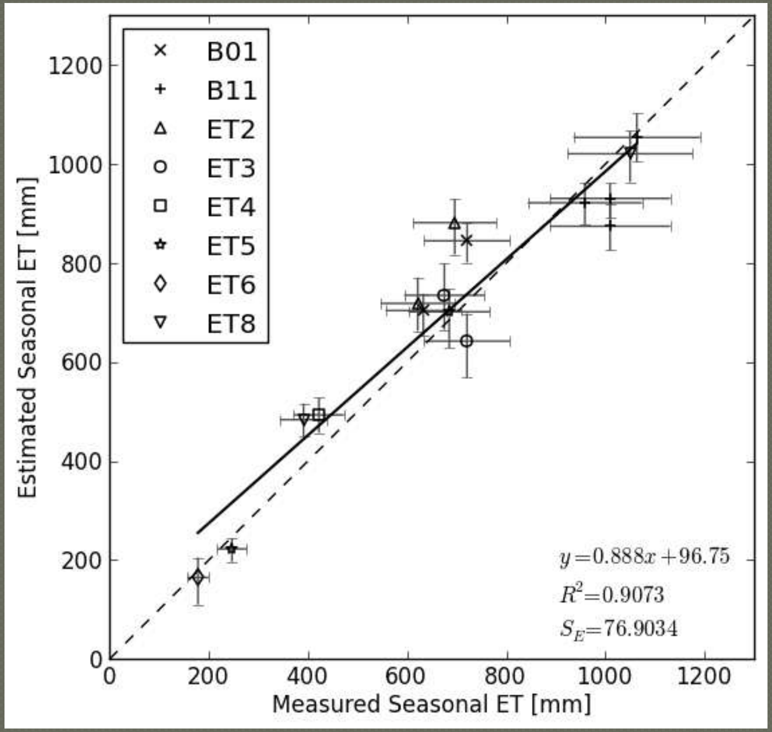
Blind Comparison of Automated Daily ET to Measured Daily ET in Carson and Mason Valley, NV / CA



Blind Comparison of Users and Automated ET to Measured ET

- Daily error is not bad when considering the error in measured daily ET is ~ +/- 20%
- Whiskers on X = +/- 12% USGS estimated uncertainty in measured ET, Y = +/- 95% confidence interval of 100 automated estimates of ET using different input parameters
- Over a season the error in daily estimates largely cancels out

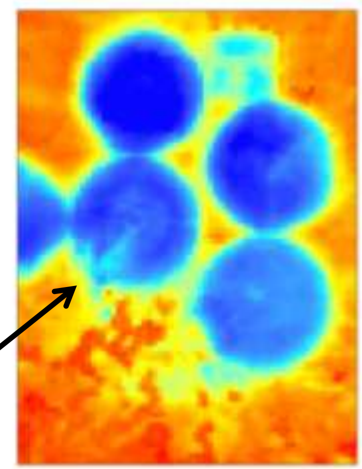




Nevada Division of Water Resources (NDWR) is using DRI Python Version of METRIC In house

NDWR commitment to remote sensing of ET:

- Motivated by using the best science available
- Need for in-house capabilities
  - Calculate actual consumptive use
  - Revise basin water budgets
  - Review work by others
- Anchored by a cooperative partnership with DRI



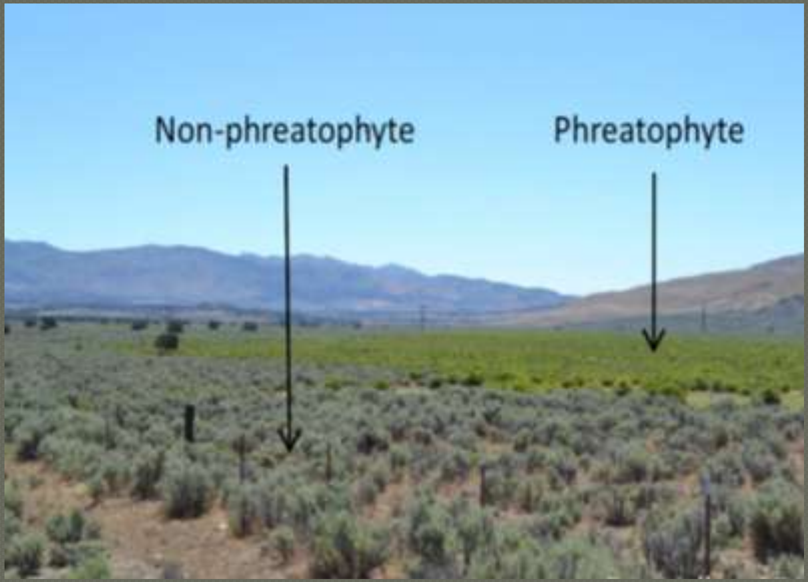
Which way are the pivots moving?…pretty cool! Evaporation!!

Groundwater Discharge via ET from Phreatophytes - Remote Sensing is Key

- Several major recent evidentiary exchanges and subsequent water right rulings in Nevada that impact water resources of the CRB have heavily relied on Landsat derived ET from phreatophytes
- Why? - The need to prove the hydrographic basins *Perennial Yield*
- Nevada Water Law - "*Perennial yield* is the maximum amount of groundwater that can be salvaged each year over the long term without depleting the groundwater reservoir. The perennial yield cannot be more than the natural recharge of the groundwater reservoir and is usually limited to the maximum amount of natural discharge" (i.e. groundwater mining is not allowed)
- Capturing the natural groundwater discharge and putting this water to beneficial use is the basis for groundwater appropriation in many Western States

Groundwater Discharge via ET from Phreatophytes - Remote Sensing is Key

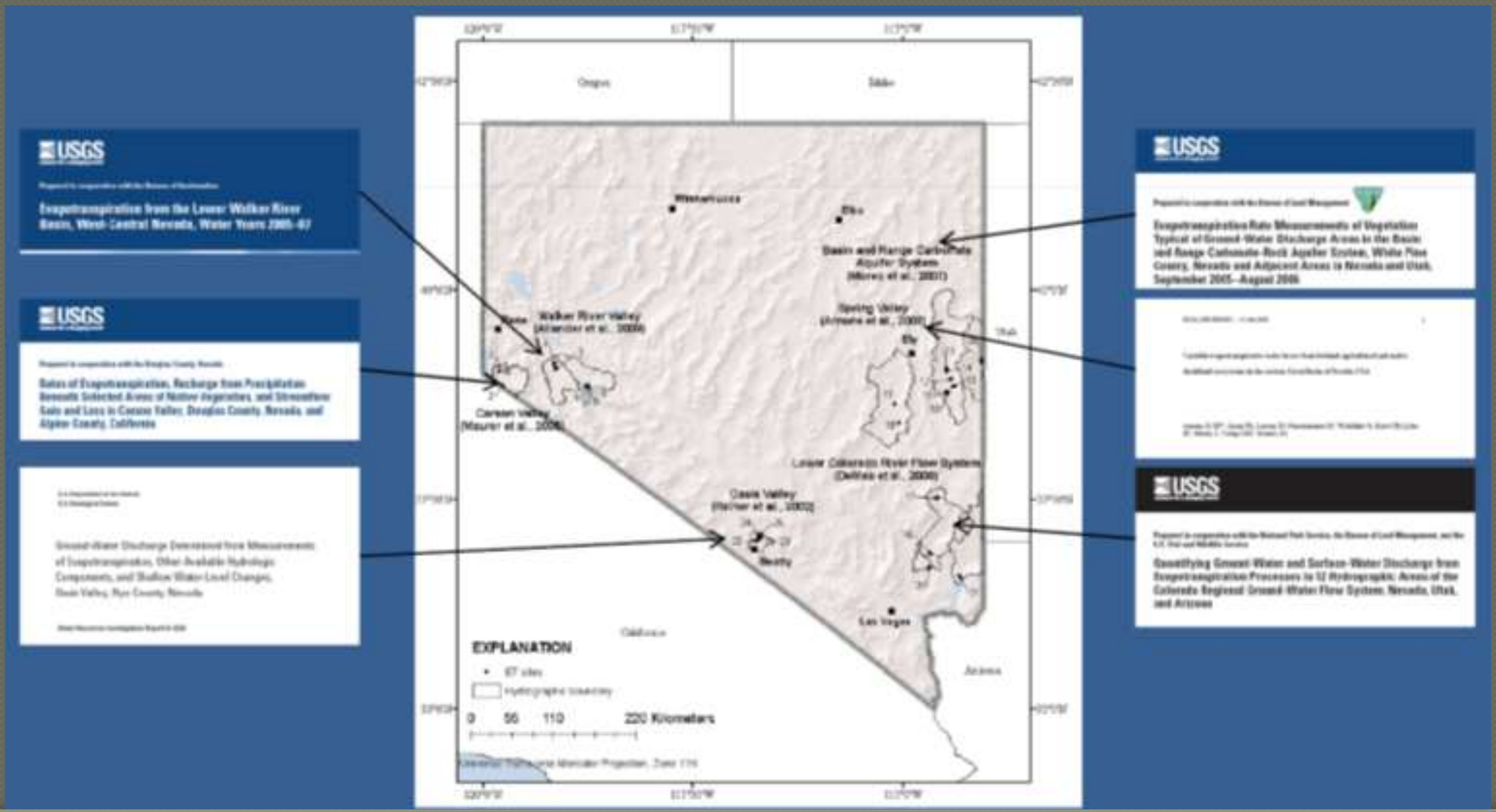
- In many Great Basin hydrographic areas, recharge is largely naturally discharged by via ET by phreatophyte vegetation which tap the shallow aquifer
  - Common phreatophytes are greasewood, salt grass, sagebrush, cotton woods, willows



- Easier to estimate groundwater ET than groundwater recharge, so for decades, groundwater ET from phreatophyte areas has been used to help define perennial yield

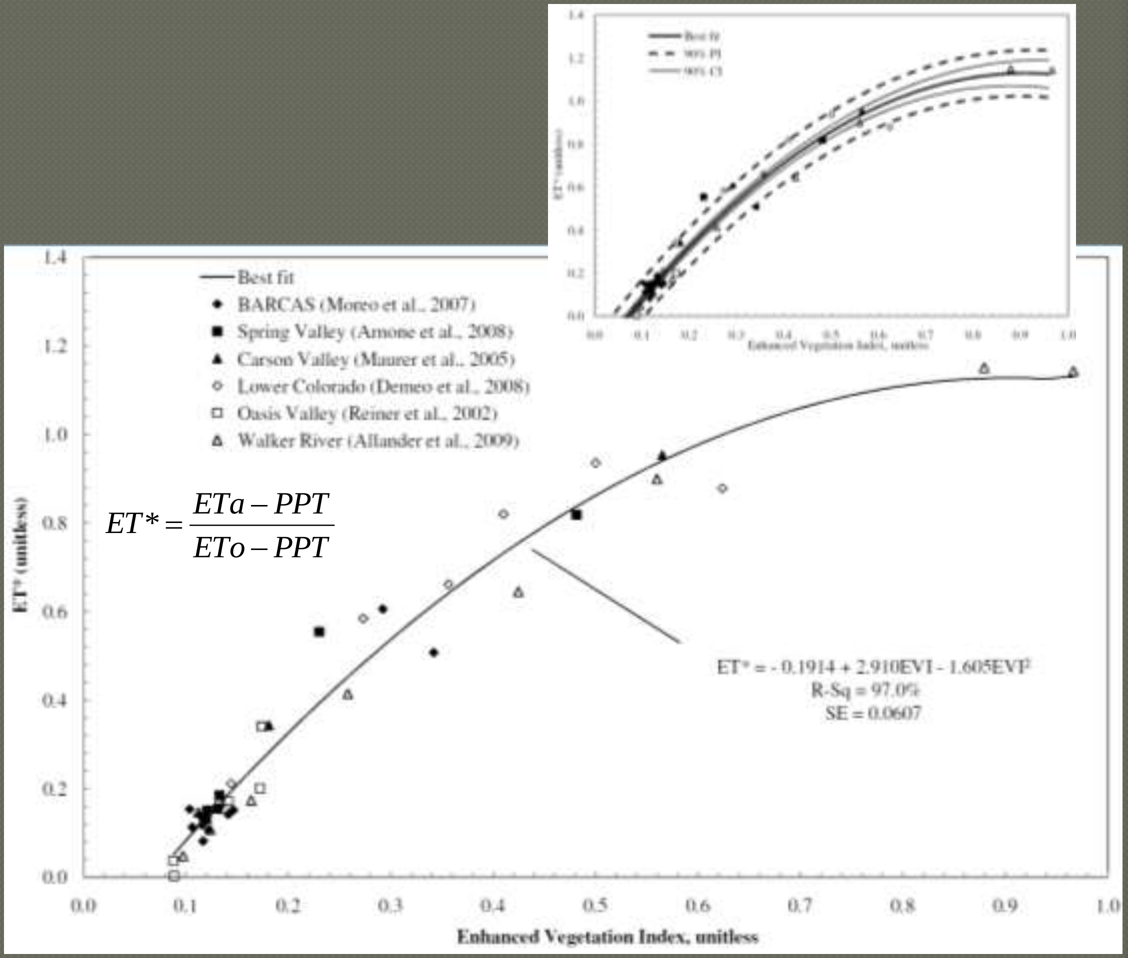
Compilation of Phreatophyte ET Measurements in Nevada

- Relating annual ET to remotely sensed vegetation indices is advantageous
  - Approach: Upscale point measurements of annual ET to the total discharge area using peak seasonal VIs
- Compiled data from 26 flux towers for a total of 40 site years
- Developed empirical function using EVI and 40 flux station years of ET data(26 flux sites multiple years)



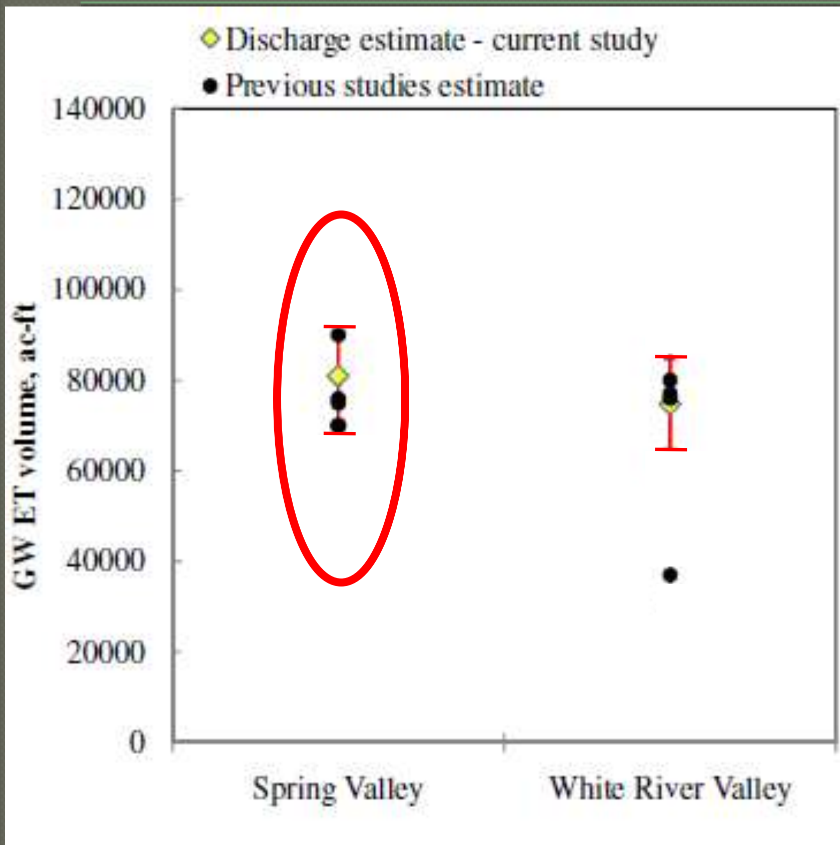
Towards Using Vegetation Indices for Estimating GWET from Phreatophytes

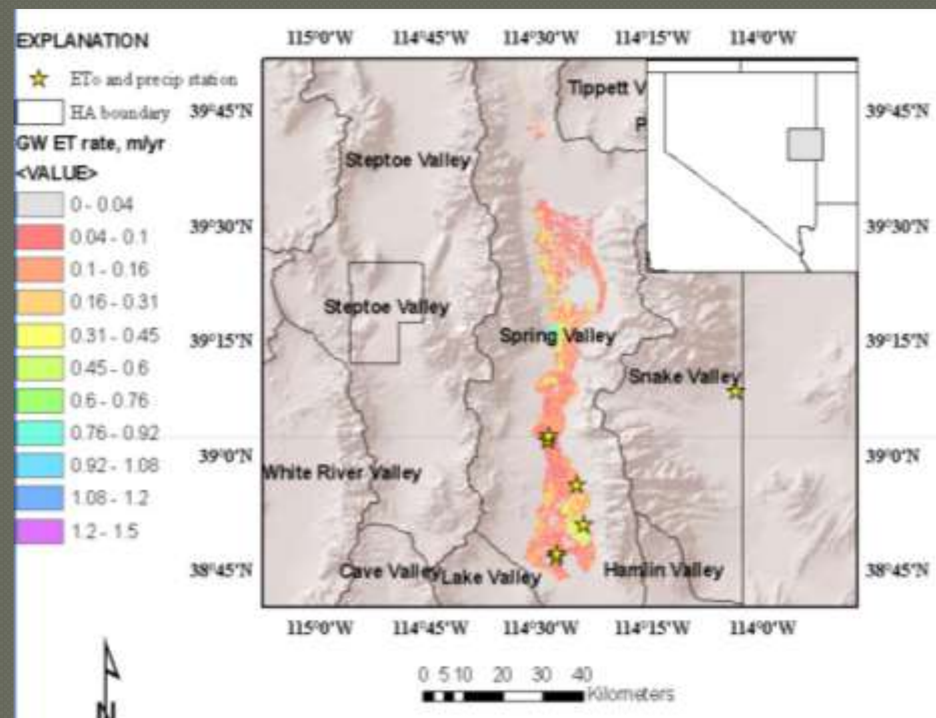
- Computed Landsat derived EVI from pixels around ET sites
- Developed function that is normalized (ET*) to transfer from one basin to another by accounting for ETo and PPT
- Computed 90% confidence and prediction intervals to assess uncertainty
- The Nevada State Engineers Office is actively utilizing this approach to independently asses expert evidence and provide alternative estimates that are bounded by measurements, and that have a measure of uncertainty



Beamer et al., (2012)

Spring Valley Groundwater ET





Landsat scale resolution (30-60m) is critical for these types of applications, as many basins and phreatophyte areas are small and highly variable

Beamer et al., (2012)

Summary and Recommendations

- Field scale (30-60m) resolution ET mapping is, and will become, more and more critical for water accounting as supplies decline and demands increase
- The use of Landsat for computing EB and VI derived ET separately, and in combination, provide robust solutions *now* for water and ecological management needs

Things to invest in to improve accuracy and reduce cost:

- Automation of EB and VI based ET estimates, improved time integration, cloud, and gap filling
- Representative weather station data for computing reference ET (not nearly enough quality weather station data to use, however people demand estimates of ET that are accurate!)
- Gridded reference ET and potential consumptive use estimates at < 1Km resolution to provide consistent estimates across all Western States
- Buoy weather station network for estimating open water evaporation
- **Landsat 9**

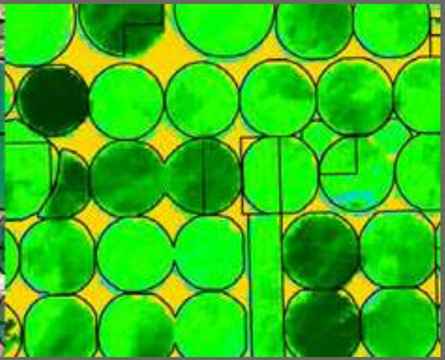
Stampede Reservoir, CA, Truckee River Basin

Summary

- Further development and application of VIs and EB, traditional ET approaches, and future instillation and maintenance of weather stations, will provide the ability to estimate historical actual and potential consumptive use using “the best available science”
  - refine basin water budgets
  - hydrologic and ecological modeling
  - water rights transfers and compliance
  - pumpage/crop/water use inventories
  - water leasing agreements
  - **<u>negotiation</u> and hopefully not litigation**

Water Rights Polygons

Seasonal ET



Questions?

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Many thanks to:

Nevada Division of Water Resources
USGS
Reclamation
NASA Ames
Cal. State University, Monterey Bay
Truckee River Operating Agreement Staff
University of Idaho
Spatial Analysis Group
Landsat Water Mapping Inc.

Winnemucca Lake (Truckee River Basin)