Evapotranspiration: long-term studies of ecohydrology and biometeorology along the Middle Rio Grande

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Acknowledgements

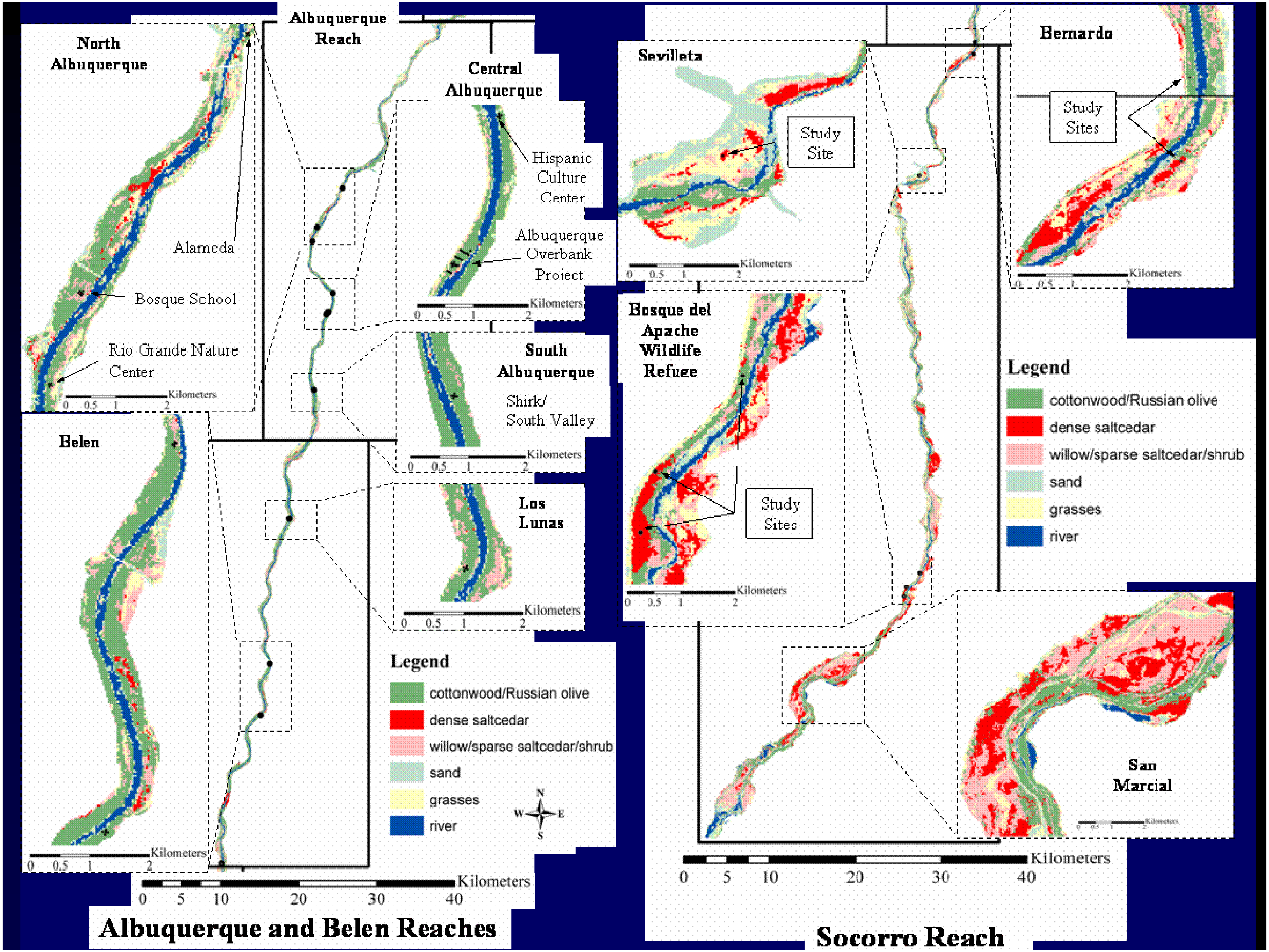
- NASA award NAG5-6999
- Bosque Initiative/Bosque Improvement Grant
- Interstate Stream Commission
- US Bureau of Reclamation/Endangered Species Workgroup
- US Army Corps of Engineers
- US Fish and Wildlife Service/Bosque del Apache NWR
- NM House Bill 2
- NSF/EPSCoR RII-2

- UNM Hydrogeoecology
- UNM Sevilleta LTER
- NM ET Workgroup
- NM Bosque Hydrology Group

- City of Albuquerque Open Spaces Division
- Middle Rio Grande Conservancy District
- NM State Land Office
- Bosque del Apache NWR
- Sevilleta NWR
- Rio Grande Nature Center

Major Basin Characteristics

- 320 km of riverine corridor
- 1672.9 m elevation in the north (Otowi) to 1262.2 m elevation in the south (Elephant Butte)
- 39,220 km^2 drainage
- Discharge gauge records from 1895 (Otowi) and 1915 (Elephant Butte)
- Major Biotic Communities: Great Basin grassland, semi-desert grassland, Chihuahuan desert scrub
- 20 – 31 cm annual precipitation (from north to south)


Albuquerque Reach
North Albuquerque
Alameda
Bosque School
Rio Grande Nature Center
Central Albuquerque
Hispanic Culture Center
Albuquerque Overbank Project
South Albuquerque
Shirk/ South Valley
Los Lunas
Belen
Legend
cottonwood/Russian olive
dense saltcedar
willow/sparse saltcedar/shrub
sand
grasses
river
N
W
E
S
Kilometers
0 0.5 1 2
0 5 10 20 30 40
Albuquerque and Belen Reaches
Sevilleta
Study Site
Bernardo
Study Sites
Bosque del Apache Wildlife Refuge
San Marcial
Socorro Reach

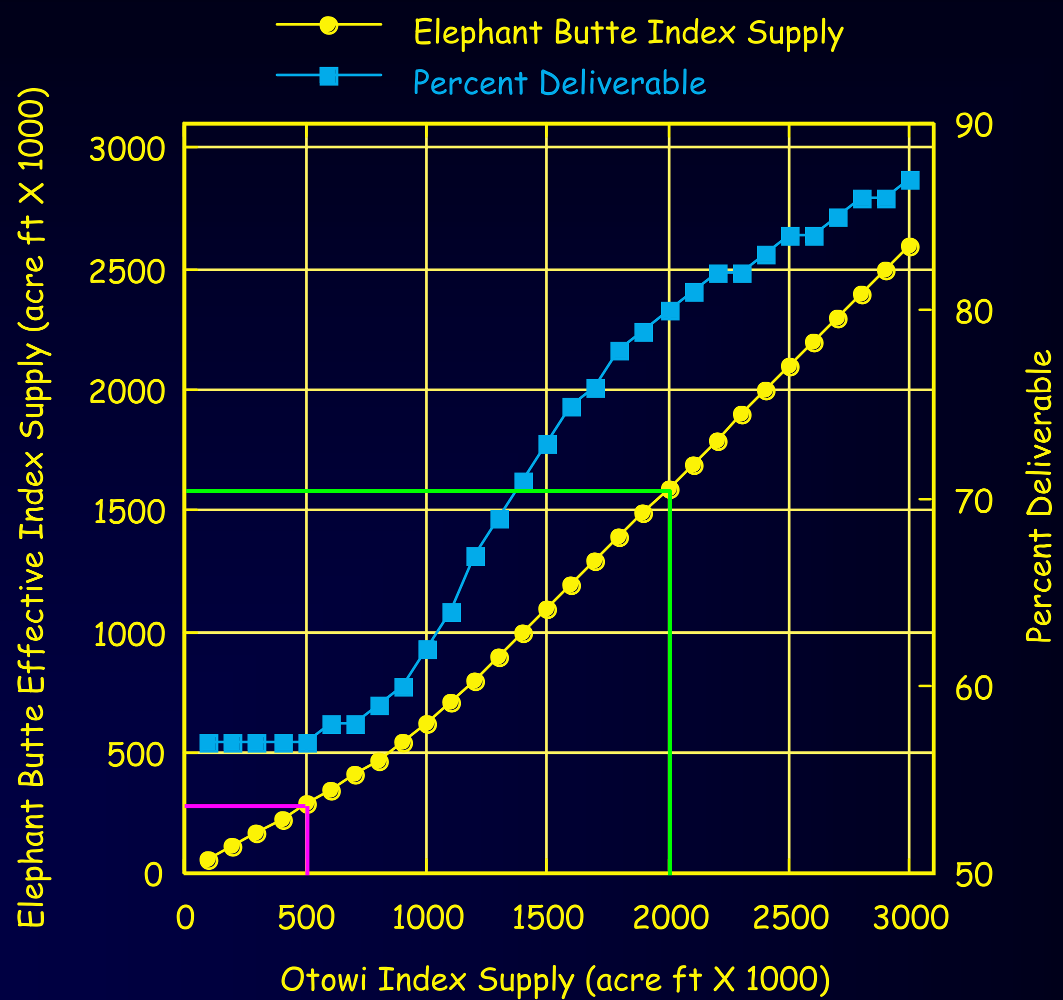
Water Budget:

A summary that shows the balance in a hydrologic system between water supplies (inflow) to the system and water losses (outflow) from the system

‖

Depletions are the difference between inflow at Otowi and outflow at Elephant Butte

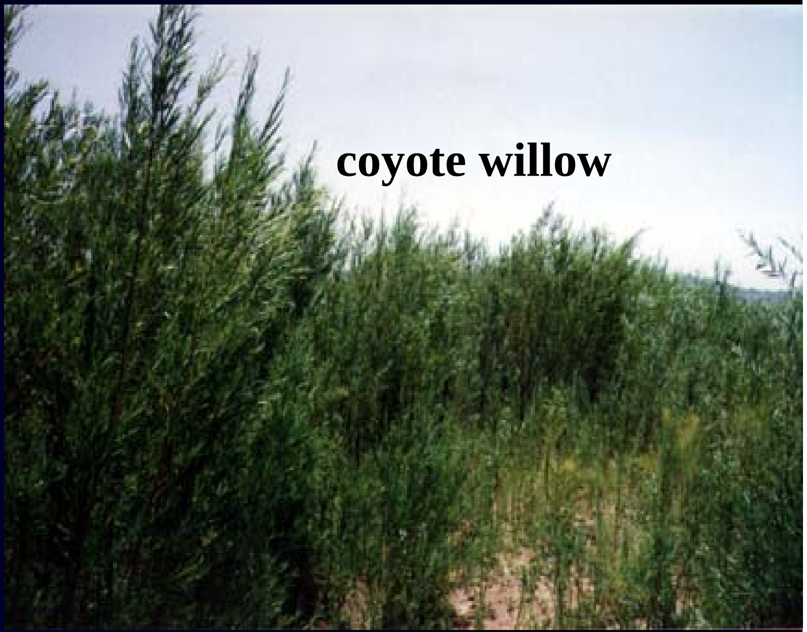
NM Legal Obligation



http://www.fws.gov/southwest/mrgbi/Resources/RG_Compact/rg_compact.pdf

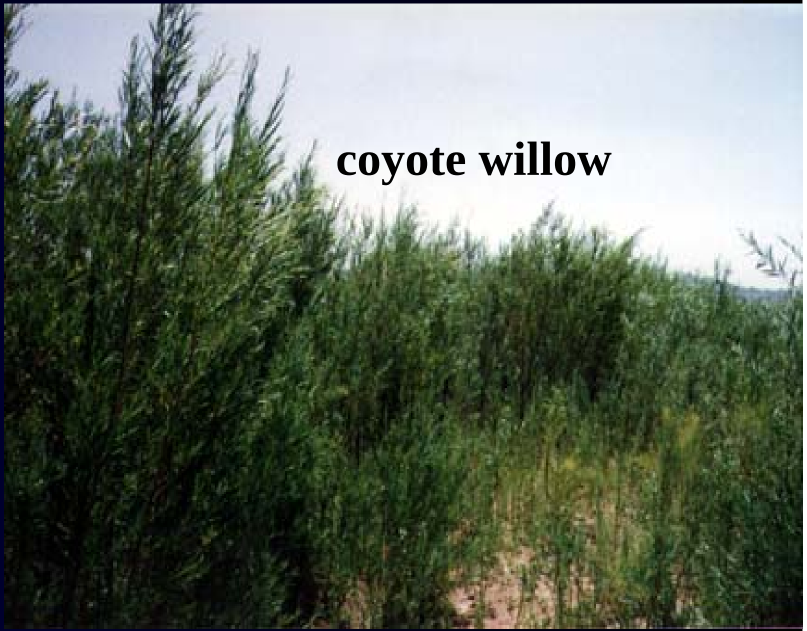
Major Depletions

- Evaporation
- Transpiration
- Agriculture
- Urban Use
- Groundwater Recharge

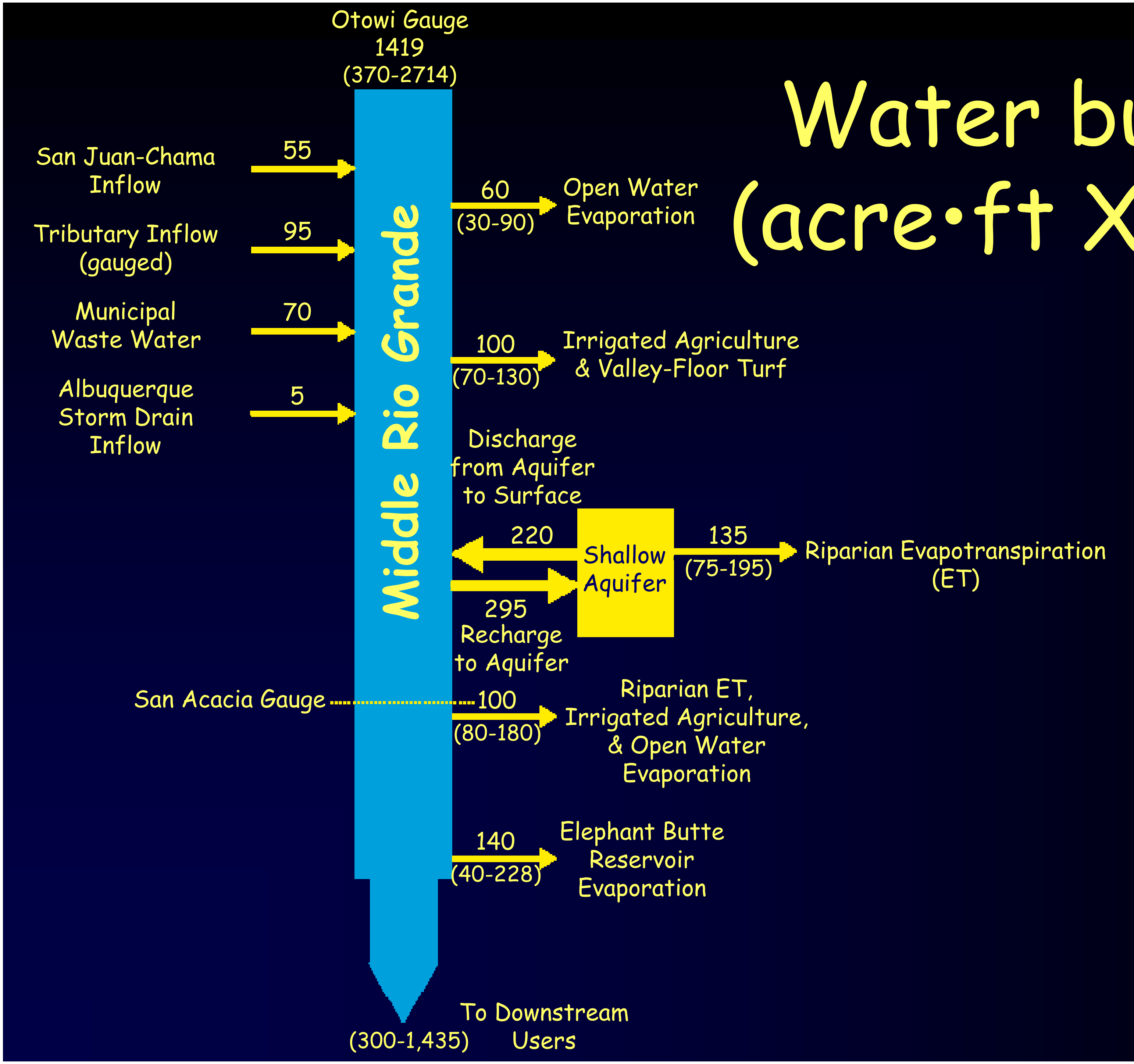


Major Depletions

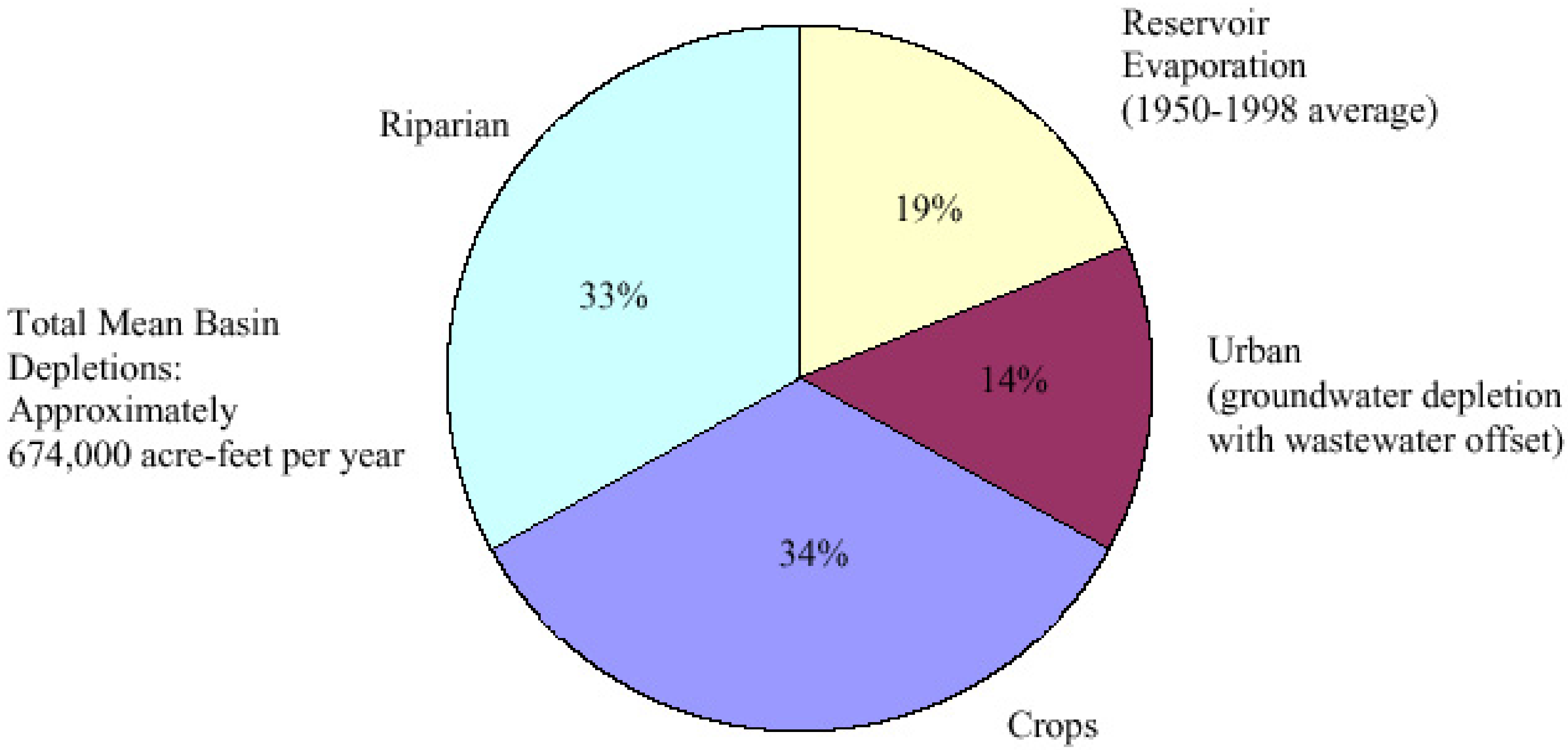
- Evapo-transpiration
- Agriculture
- Urban Use
- Groundwater Recharge



Water budget (acre•ft X 1000)



b) Mean total Middle Rio Grande depletions (including depletion from groundwater storage),under present land use and groundwater development conditions



Populus deltoides ssp. *wislizenii*
(cottonwood)

Dominant Riparian Vegetation

Interflood Interval	Saltcedar	Cottonwood
Short	connected non-native	connected native
Long	disconnected non-native	disconnected native

Molles *et al*. 1998

Tamarix ramosissima
(saltcedar)

Native | Exotic

Populus deltoides ssp. *wislizenii*
(Rio Grande Cottonwood)

Elæagnus angustifolia (Russian Olive)

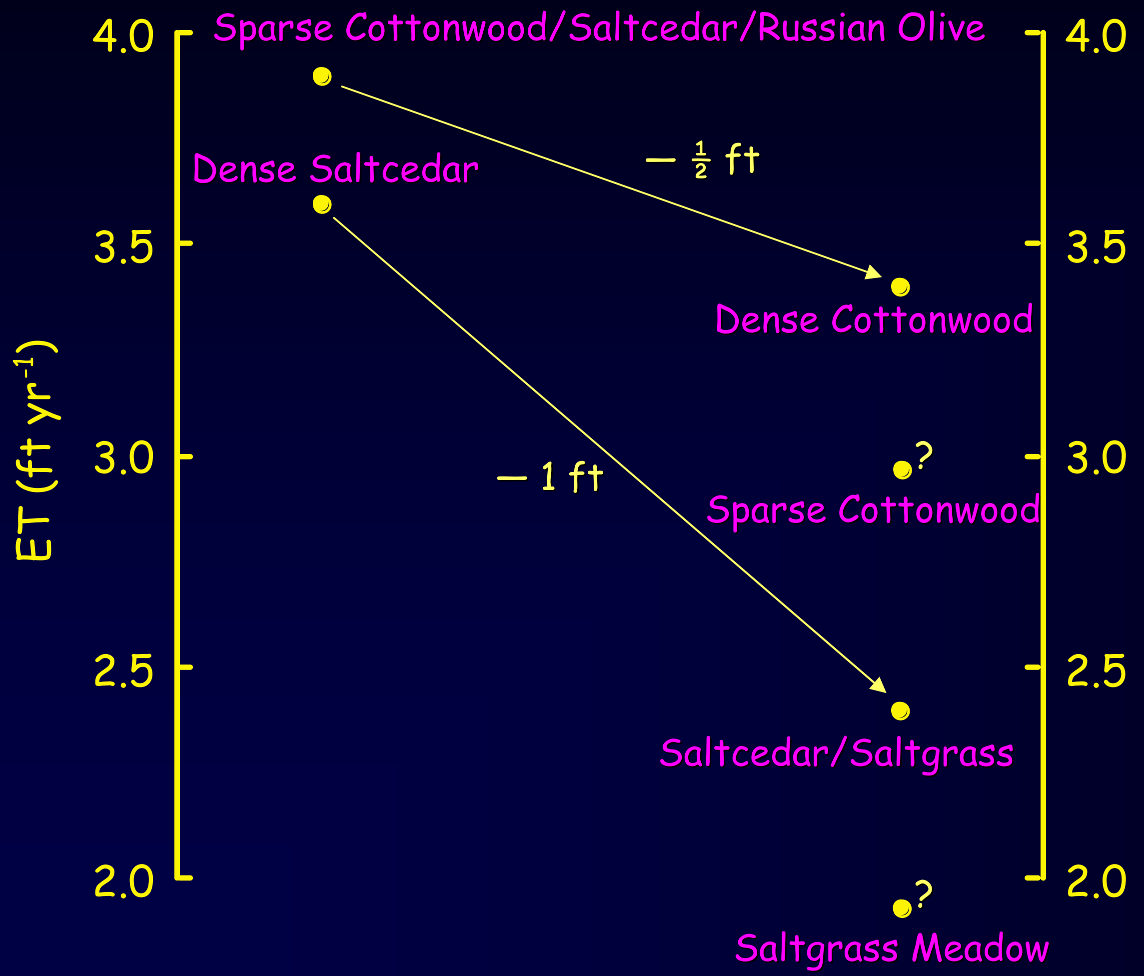
Tamarix chinensis (Saltcedar)

EPSCoR New Mexico

Restoration hypotheses

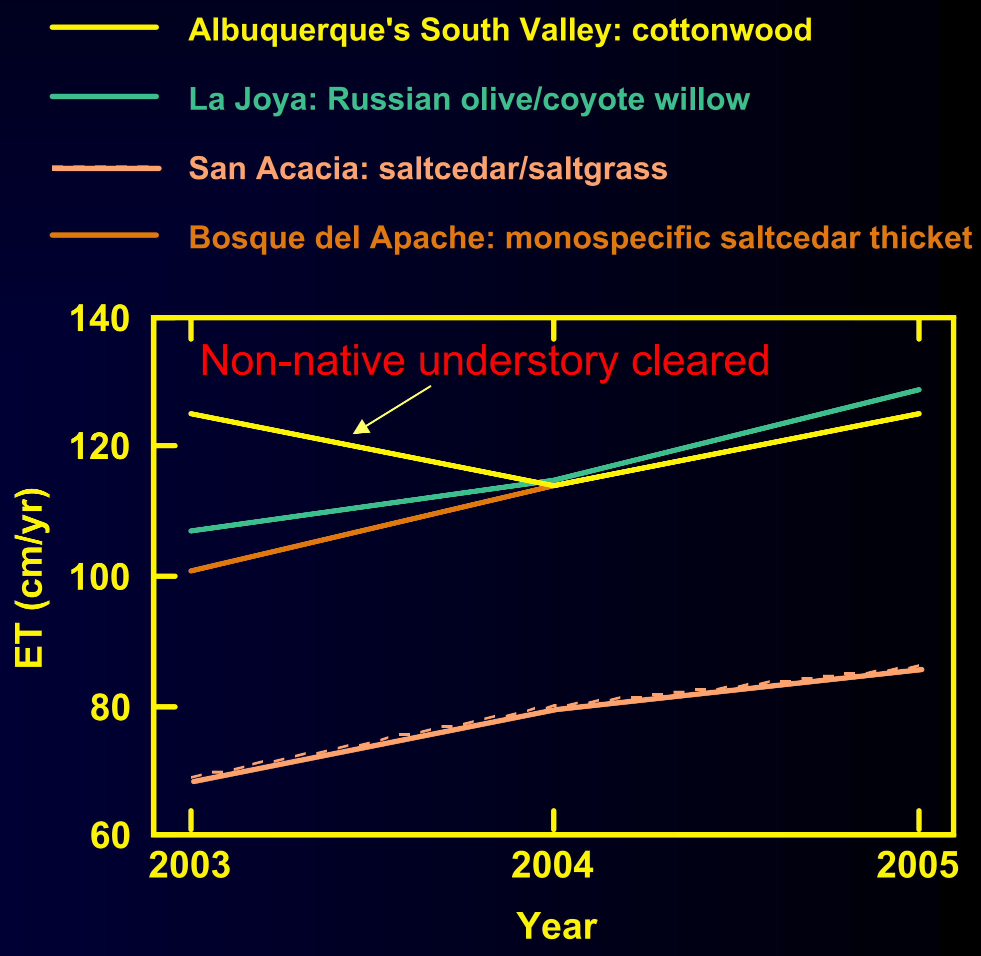
- Saltcedar removal from Cottonwood forests is predicted to be associated with a water savings
- High water usage when saltcedar develops high LAI

Restoration – comparative

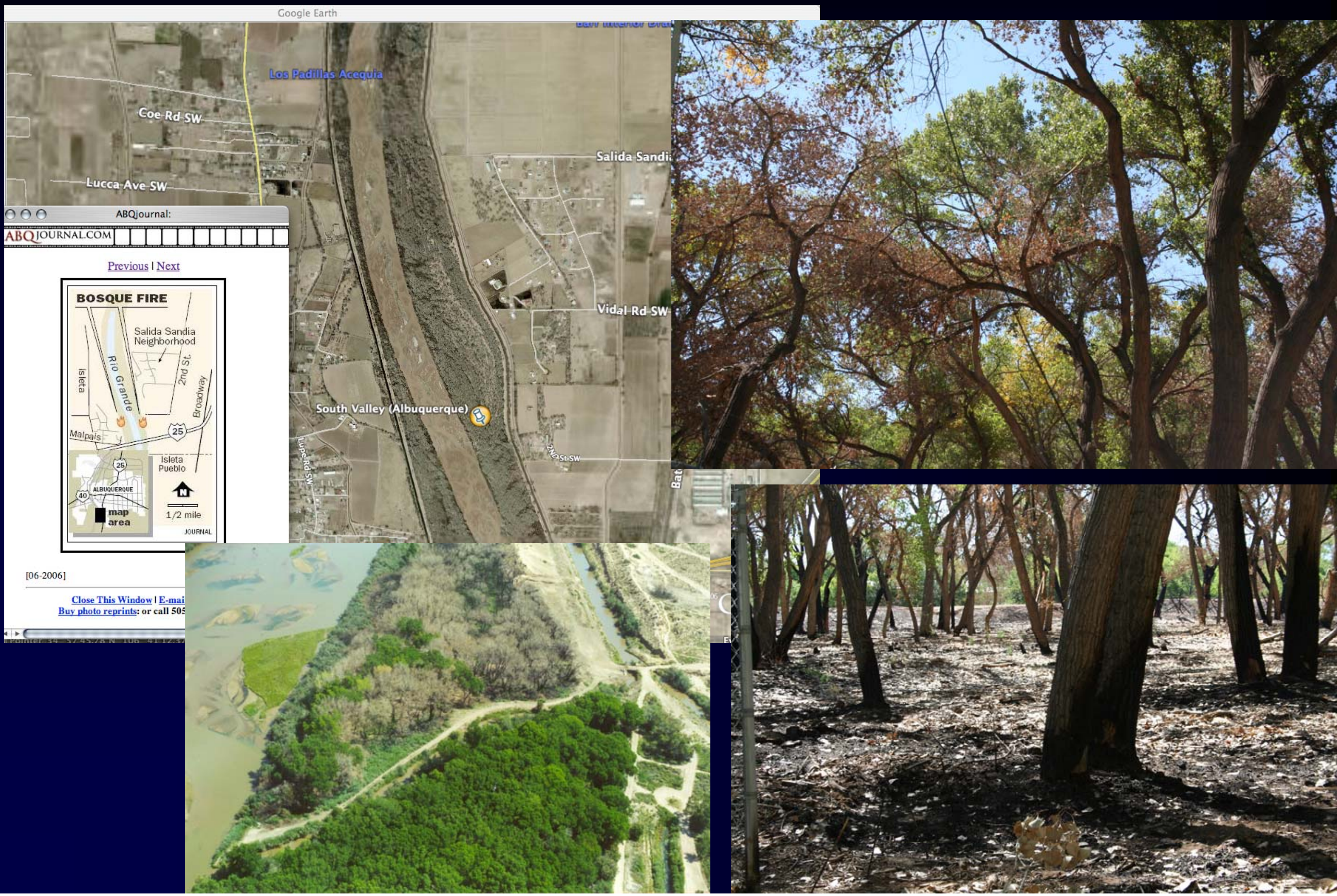


Restoration water salvage

- Understory Russian olive and saltcedar removed from South Valley Albuquerque cottonwood forest between 2003 and 2004 growing seasons
- First year reduction in ET of 9% while other sites increasing by 12% (total = -21% or -26 cm/yr)
- Second year increase matched increase at other sites: 0 cm/yr



Bosque Fire



Google Earth
Los Padillas Acequia
Coe Rd SW
Lucca Ave SW
Vidal Rd SW
South Valley (Albuquerque)
ABQjournal:
ABQJOURNAL.COM
Previous | Next
BOSQUE FIRE
Salida Sandia Neighborhood
Isleta
Rio Grande
2nd St.
Broadway
Malpais
25
Isleta Pueblo
ALBUQUERQUE
40
map area
1/2 mile
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Short Interflood Interval < 2yrs (flood site)

Long interflood interval > 10yrs (nonflood site)

EPSCoR New Mexico

Ecohydrology

- Parameterization of the interactions between terrestrial ecosystems and the water cycle
- Key papers:

Newman, B.D. et al., 2006. The ecohydrology of arid and semiarid environments: a scientific vision. Water Resources Research.

Pataki, D.E., Bush, S.E., Gardner, P., Solomon, D.K. and Ehleringer, J.R., 2005. Ecohydrology in a Colorado River riparian forest: Implications for the decline of Populus fremontii. Ecological Applications, 15(3): 1009-1018.

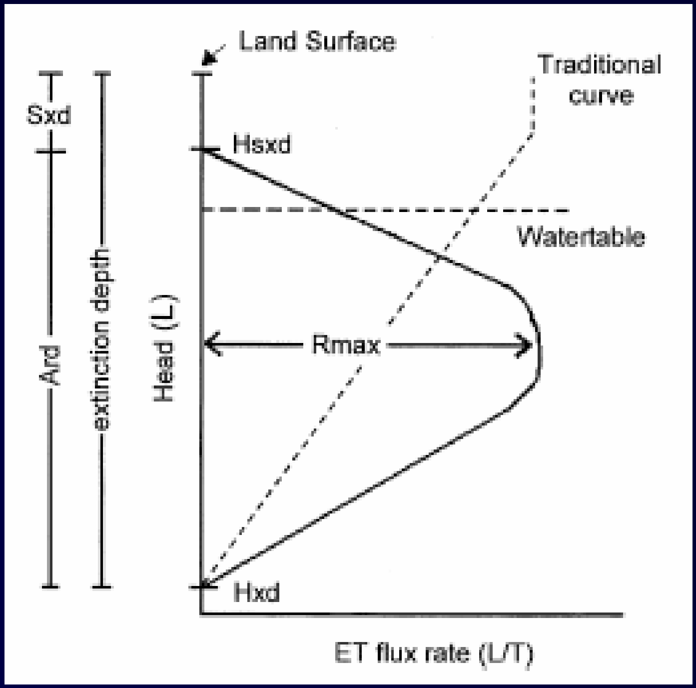
Huxman, T.E. et al., 2005. Ecohydrological implications of woody plant encroachment. Ecology, 86(2): 308-319.

Wilcox, B.P. and Newman, B.D., 2005. Ecohydrology of semiarid landscapes. Ecology, 86(2): 275-276.

Cleverly, J.R., Dahm, C.N., Thibault, J.R., McDonnell, D.E. and Coonrod, J.E.A., 2006. Riparian ecohydrology: regulation of water flux from the ground to the atmosphere in the Middle Rio Grande, New Mexico. Hydrological Processes.

Ecohydrology Parameters

- ET:PPT
- T:ET
- GW (MODFLOW)



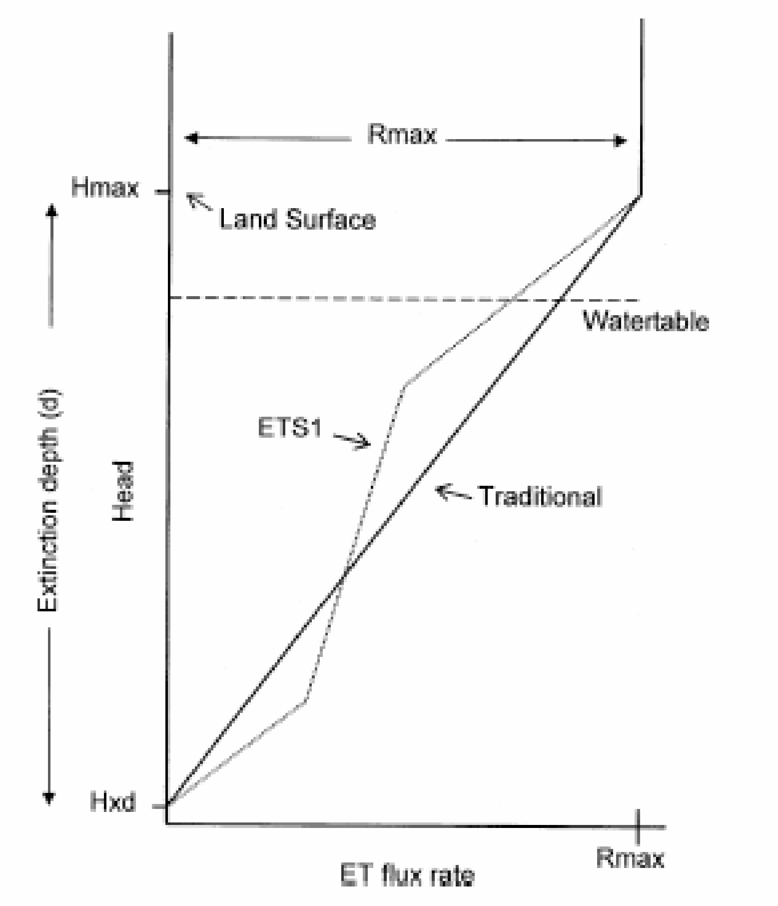


Fig. 1. Traditional linear (MODFLOW 96) and ETS1 segmented function (MODFLOW 2000) ET curves. Hxd, extinction depth elevation; *d*, extinction depth; Rmax, maximum ET rate; Hmax, maximum ET surface elevation.

Populus deltoides ssp. *wislizenii*
(Rio Grande Cottonwood, native)

- Strongly dependent upon groundwater:
  - $ET_{surface}$ ≈ 3 m, $ET_{extinction}$ ≈ 5 m (Horton 2001)
  - Only cottonwoods growing along ephemeral streams have shown uptake of soil water/precipitation (Stromberg & Pattern 1996, Snyder & Williams 2000)
  - Crown dieback occurred during the drought at locations with a deep water table

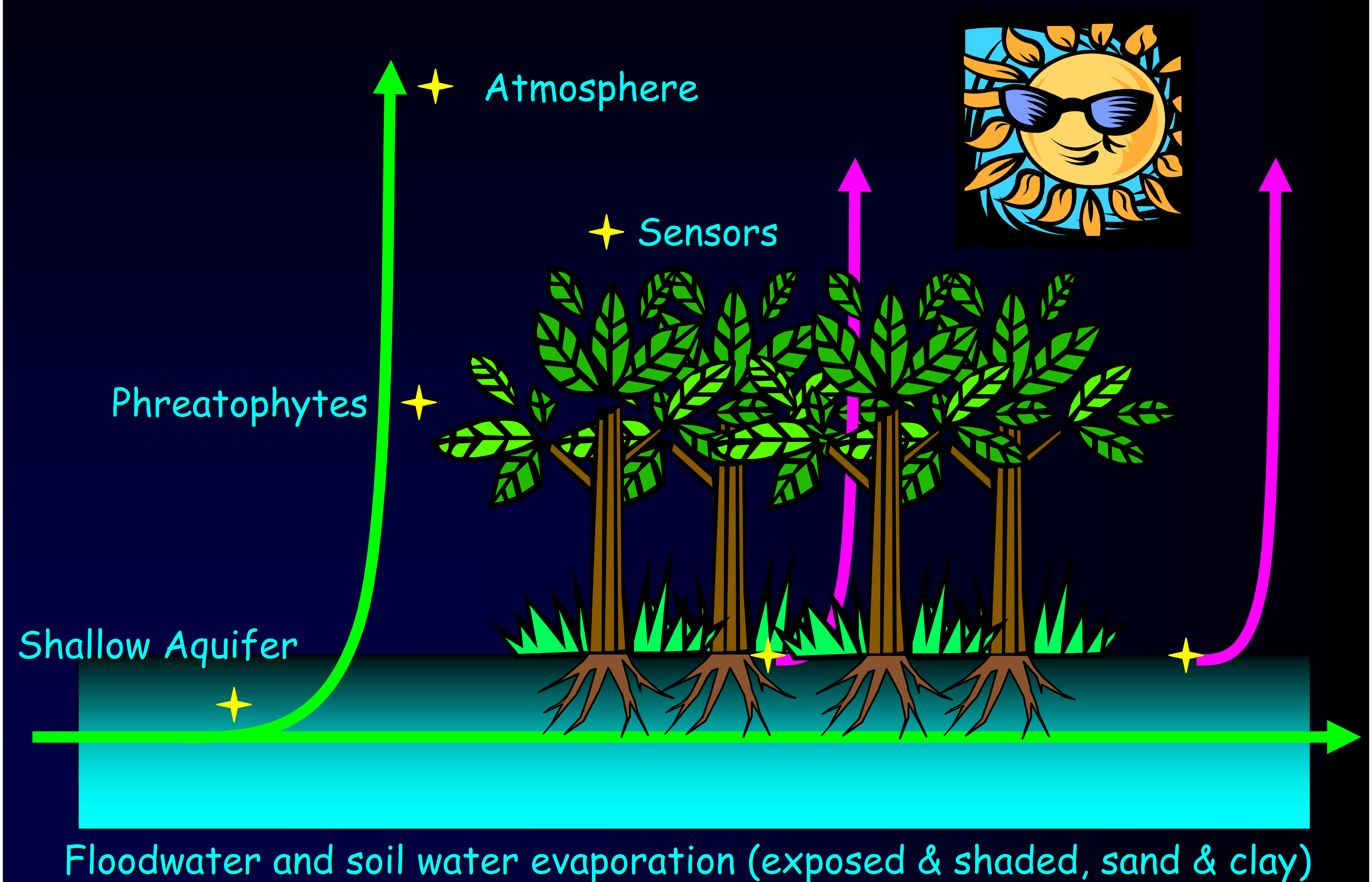
Elæagnus angustifolia
(Russian Olive, non-native)

- Relationship with groundwater?:
  - $ET_{surface}$ & $ET_{extinction}$ unknown
  - Found in a wide range of habitats (Katz & Shafroth 2003)
  - Seldom found in a monoculture along the MRG
  - Water use typically equivalent to monospecific saltcedar & native cottonwood forest

Tamarix chinensis
(Saltcedar, non-native)

- Relationship with groundwater?:
  - $ET_{surface}$ deeper than 10-m (Horton 2001) or 25-m (Gries et al 2003)
  - $ET_{extinction}$ undefined
  - Known facultative phreatophyte with hydraulic properties similar to other xeroriparian spp. (Busch et al 1995; Pockman & Sperry 2000)
  - Variations in transpiration explained solely by fluctuations in leaf-to-air VPD
  - Found preferentially in habitats with variable water table depth (Lite & Stromberg 2005)

Evapotranspiration



Reference Evapotranspiration

- Semi-empirical formulations
  - Measurements of associated conditions; e.g., Radiation
  - Blaney-Criddle, Jensen-Haise, Priestley-Taylor, Aerodynamic, Penman, Penman-Monteith
  - SCS, FAO, Grass standard
  - Crop/calibration coefficient:

$$ET_a = k \cdot ET_0$$

- Energy Balance
  - Bowen ratio, OPEC

Temperature: Blaney-Criddle-SCS 1950

$$u = k_t k_c \ddot{A}$$

k_t: monthly consumptive use coefficient for temperature; $k_t = 0.0173T_a - 0.314$, °F

k_c: monthly crop coefficient

f: monthly consumptive use factor;

$$\ddot{A} = \frac{T_a p}{100}$$

p: mean monthly percentage of annual daytime hours

Combination: Penman

$$ET_0 = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} E_A$$

Δ: slope of the saturation water vapor curve at a given temperature

R_n: net radiation (downwelling solar+thermal radiation less upwelling)

E_A: drying function (wind and humidity)

γ: psychrometric coefficient;

$$\gamma = \frac{C_P P}{\varepsilon \lambda_v}$$

Combination: Penman-Monteith 1965

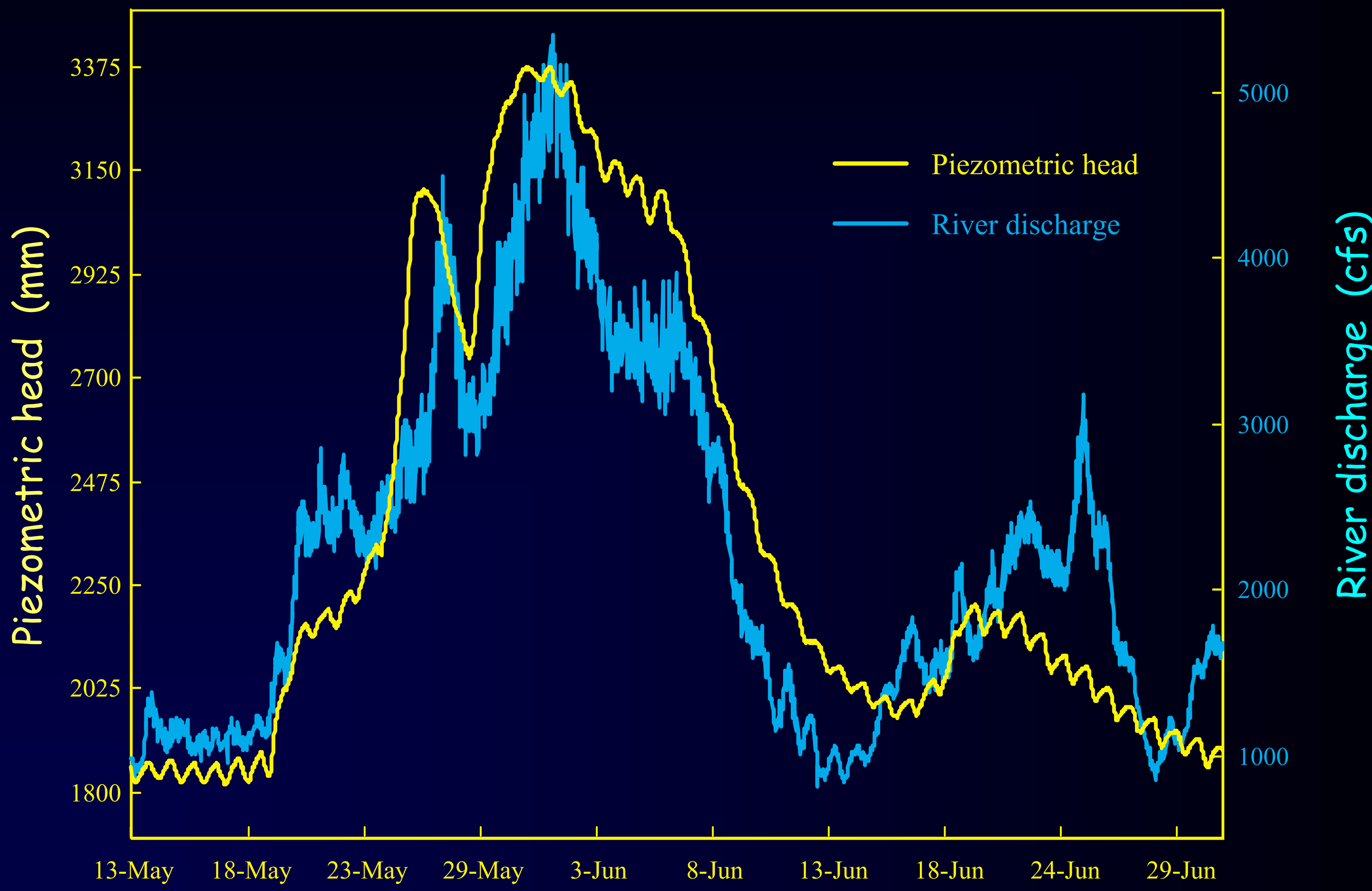
$$\gamma^{*} = \gamma\left[1 + \frac{r_c}{r_a}\right]$$

r_c: canopy resistance (stomatal resistance, LAI)

r_a: aerodynamic resistance;

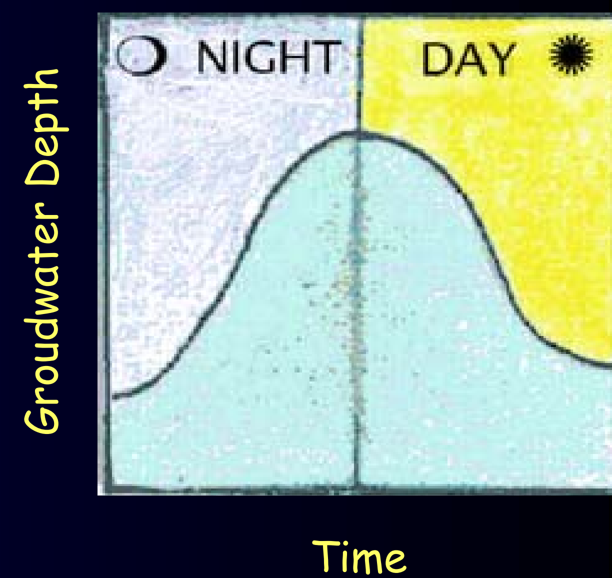
$$r_a = \frac{\ln\left[\frac{z_w - d}{z_{0m}}\right]\ln\left[\frac{z_p - d}{z_{0v}}\right]}{(0.41)^2 u}$$

Hydrology

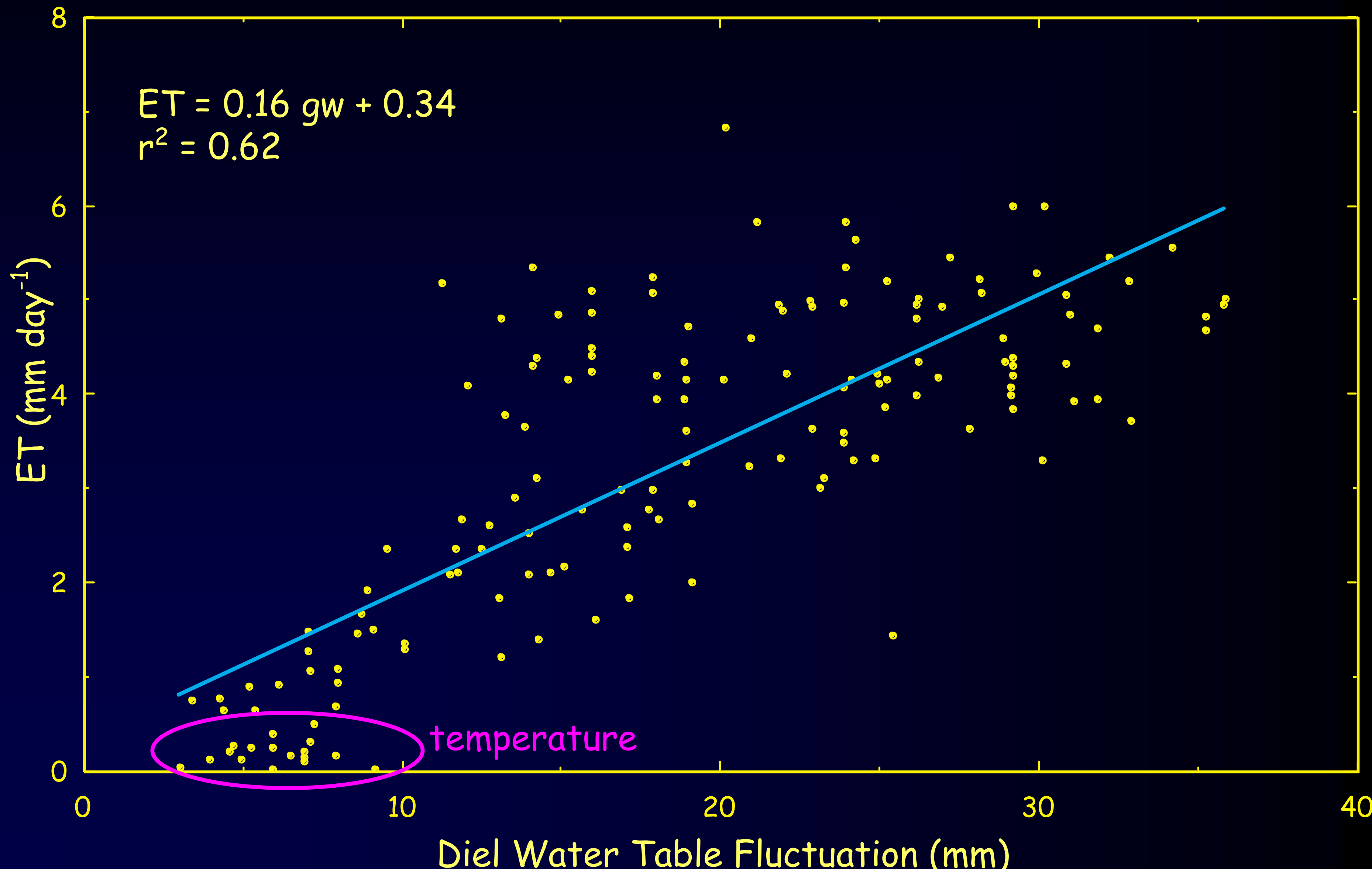


Piezometric head
River discharge
Piezometric head (mm)
River discharge (cfs)
3375
3150
2925
2700
2475
2250
2025
1800
5000
4000
3000
2000
1000
13-May
18-May
23-May
29-May
3-Jun
8-Jun
13-Jun
18-Jun
24-Jun
29-Jun

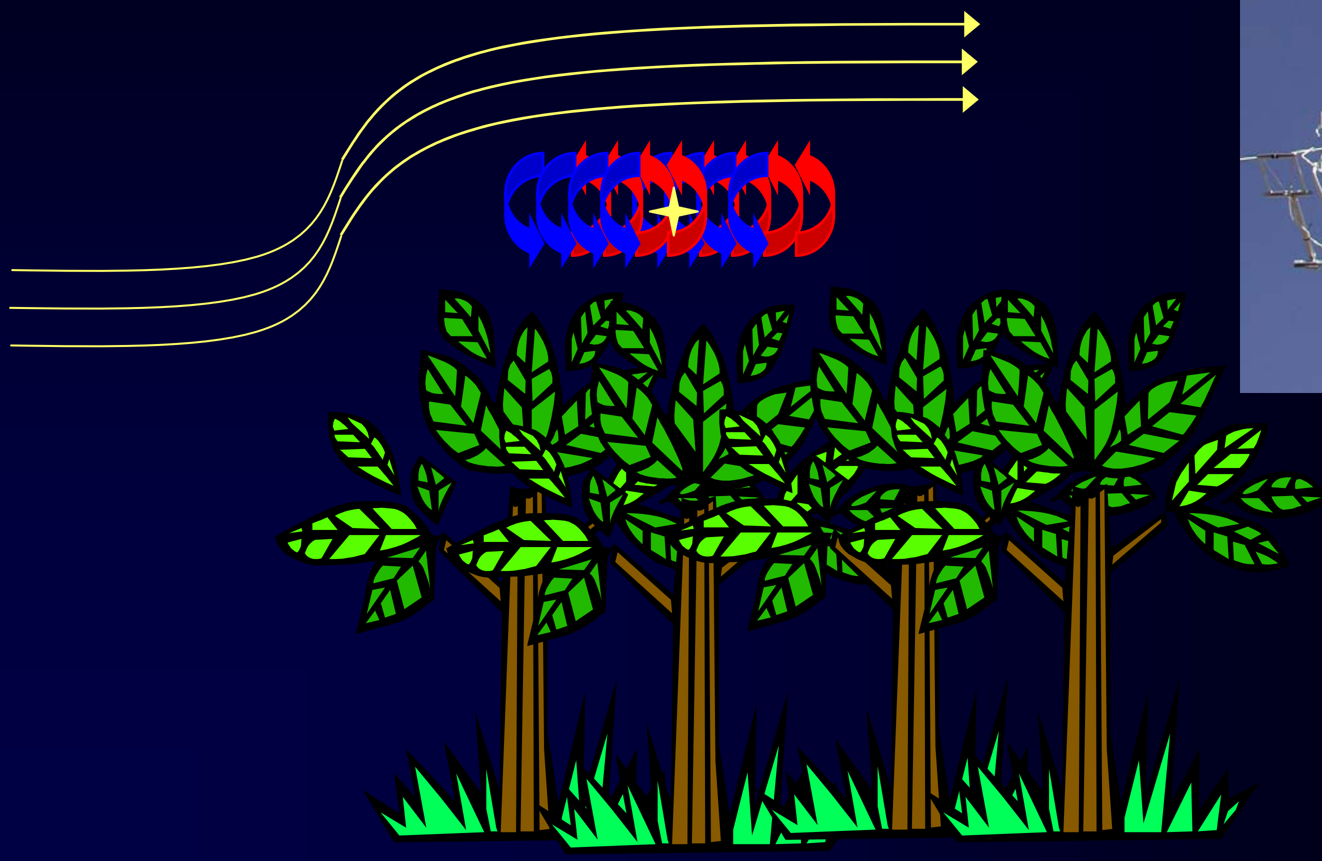
Diel GW fluctuations



Diel Groundwater — ET



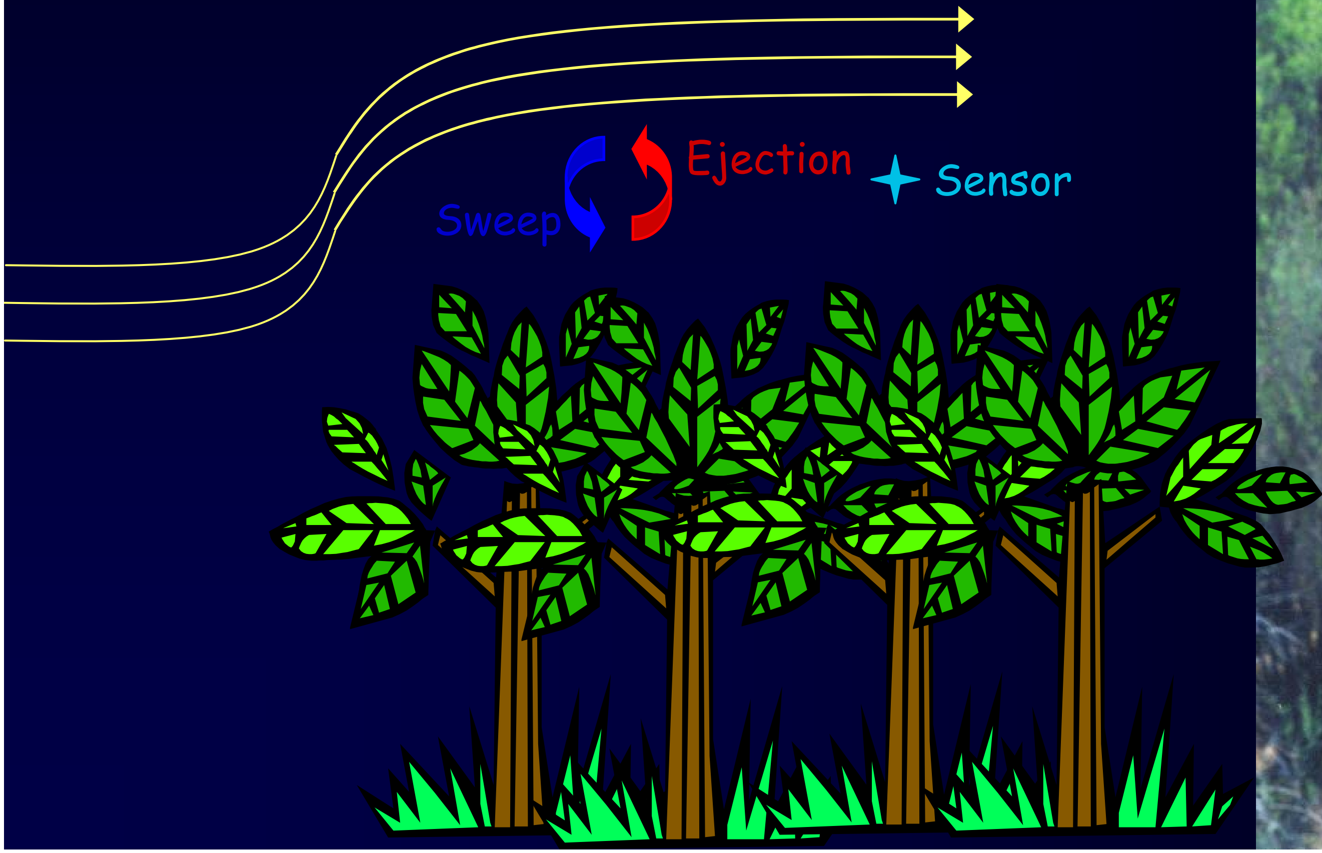
Surface Layer



3-D Eddy Covariance

Video: P Sprott

- Direct measurement of ET
- Self-test for accuracy
- Consistent with the application of atmospheric physics



Energy and Water Fluxes

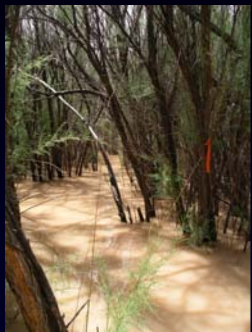
- Core Measurements: 3-D Eddy Covariance
  - Sonic anemometer
  - Hygrometer/IR Gas Analyzer
  - Temperature-Relative Humidity
  - Net Radiation
  - Ground heat flux
  - Soil temperature
  - Soil water content
  - Barometric pressure
  - Precipitation
  - Cellular/WiFi communications

$$R_n + G + LE + H = 0$$

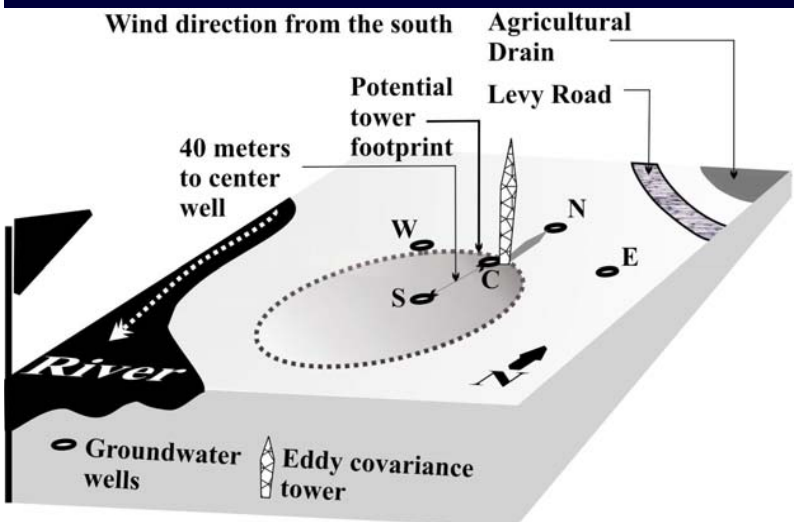
$$\lambda\ Cov(wq) = \lambda\ \overline{w'q'} = LE$$

$$\rho\ c_p\ Cov(wT) = \rho\ c_p\ \overline{w'T'} = H$$

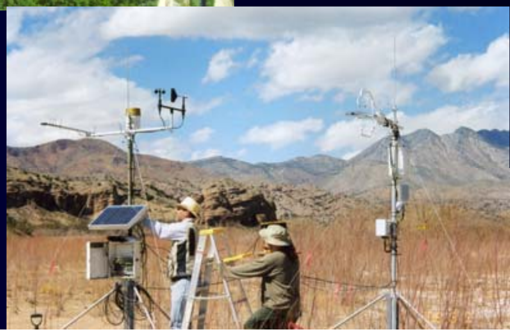
EPSCoR New Mexico



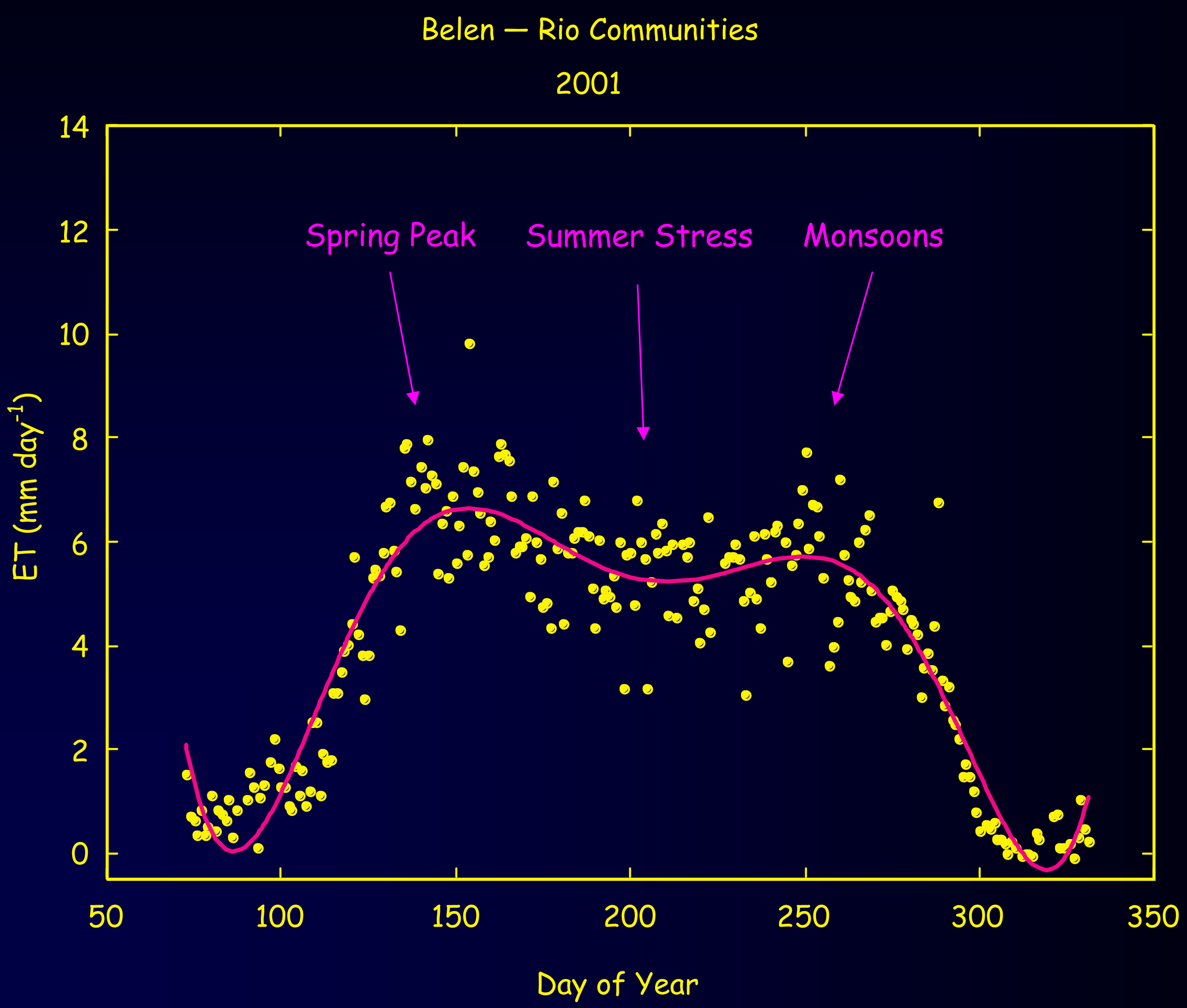
Rio Chama
Rio Grande
Jemez River
Rio Puerco
Rio Salado
New Site:
Rio Salado
Bare Soil
Albuquerque's South Valley
Cottonwood + Saltcedar/Russian olive understory
Understory removed 2004 / Partially burned 2006
Belen near Rio Communities
Cottonwood, mostly native understory
Site decommissioned 2004 following vandalism
La Joya State Game Refuge
Russian olive/coyote willow
established in 2003
Sevilleta National Wildlife Refuge
Saltcedar/Saltgrass
New Site:
San Acacia village
Alfalfa
Bosque del Apache National Wildlife Refuge
Dense monospecific saltcedar
Elephant Butte Reservoir



Wind direction from the south
Agricultural Drain
Potential tower footprint
Levy Road
40 meters to center well
W
N
E
S
C
River
N
Groundwater wells
Eddy covariance tower

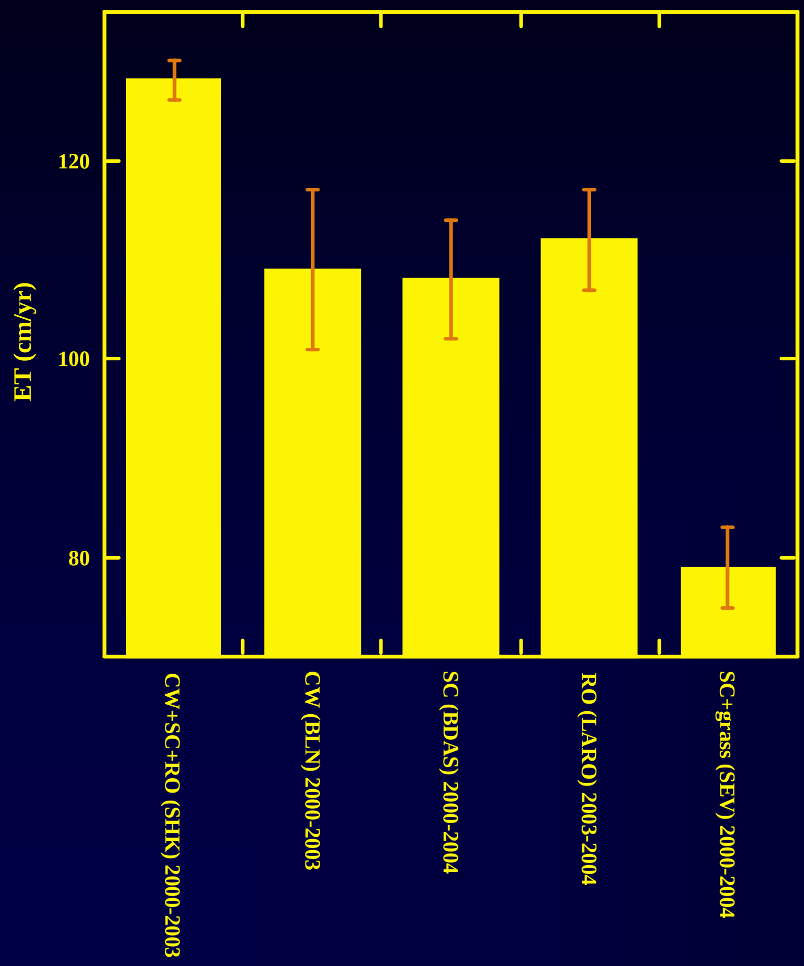


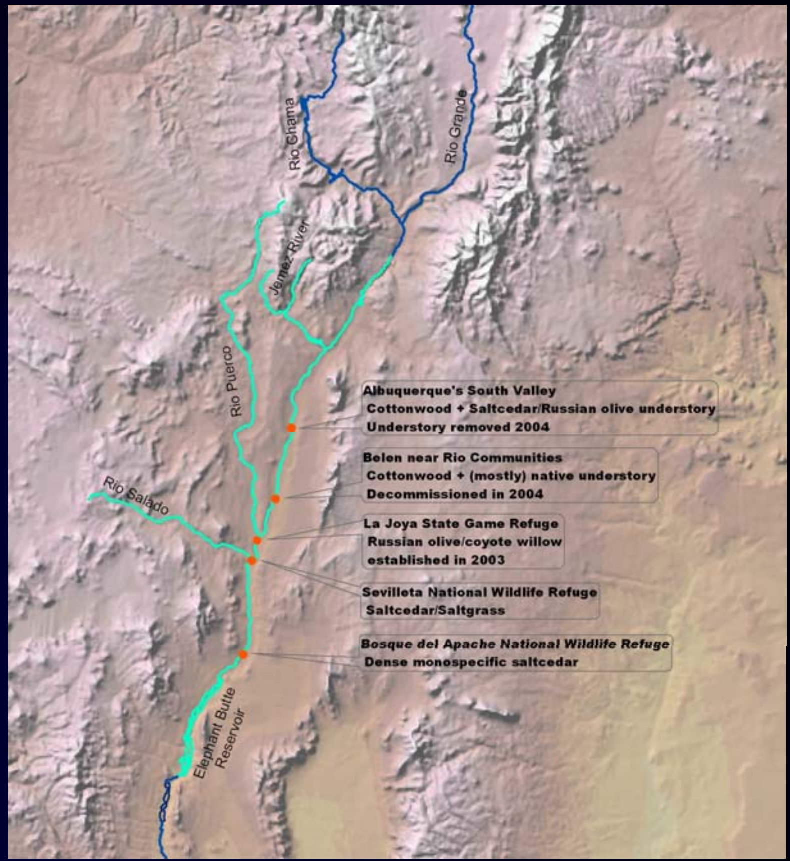
Seasonal ET



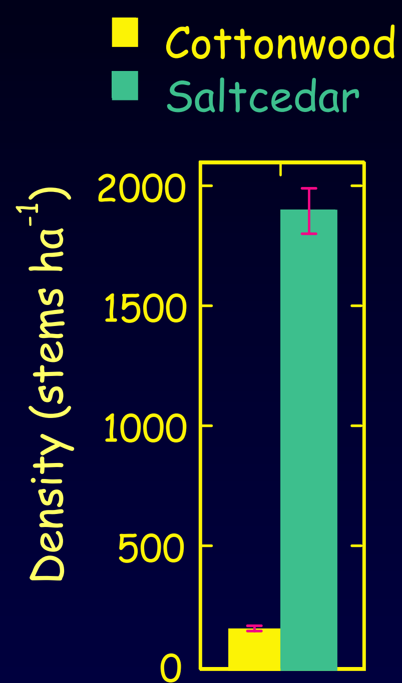
Belen — Rio Communities
2001
Spring Peak
Summer Stress
Monsoons
ET (mm day-1)
Day of Year
0
2
4
6
8
10
12
14
50
100
150
200
250
300
350

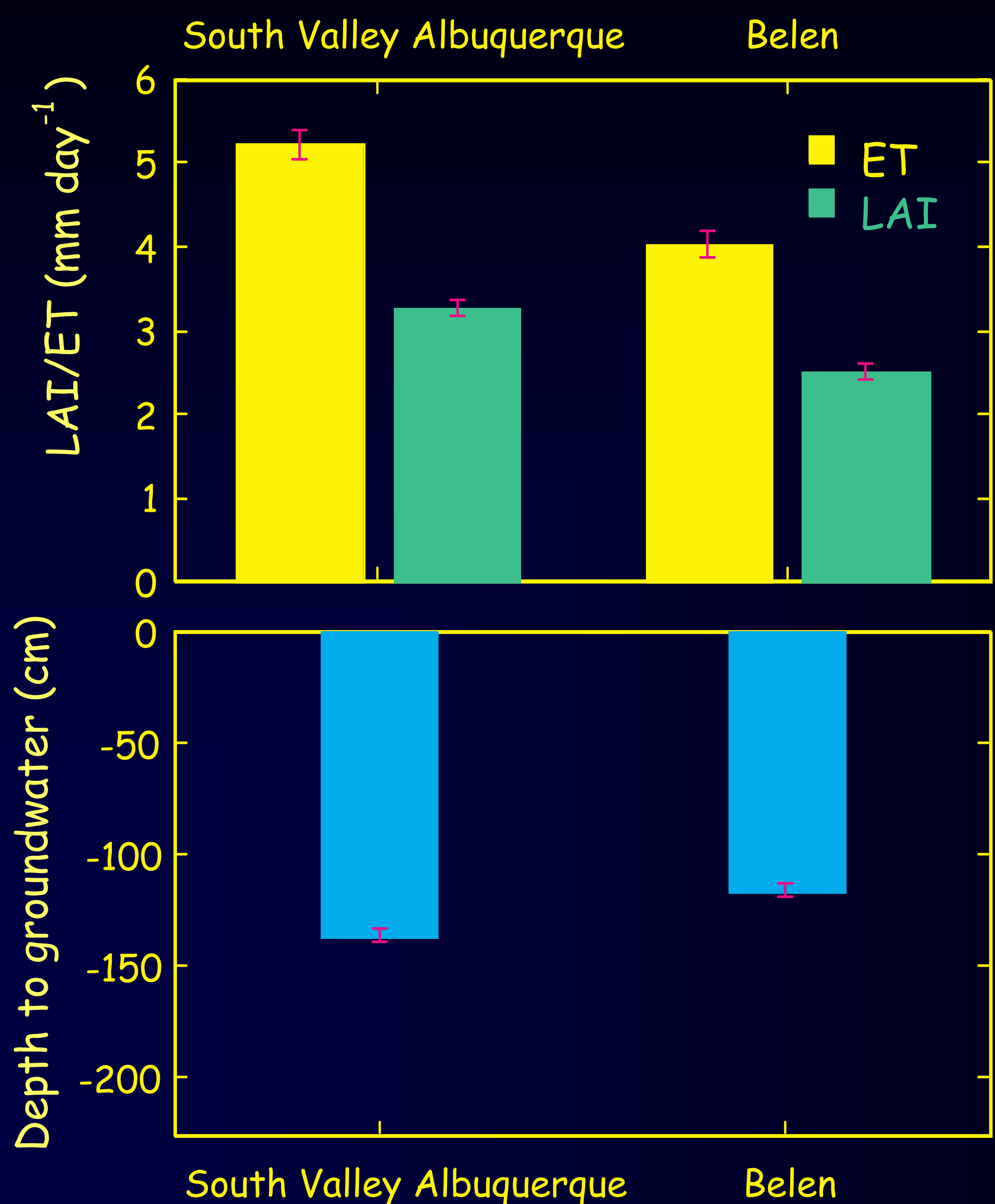
Average evapotranspiration

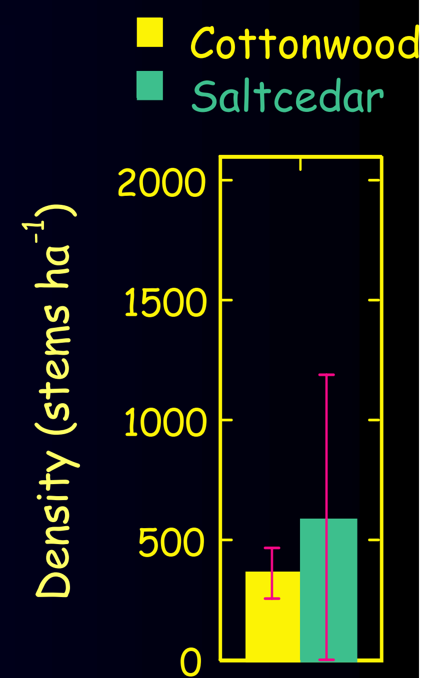


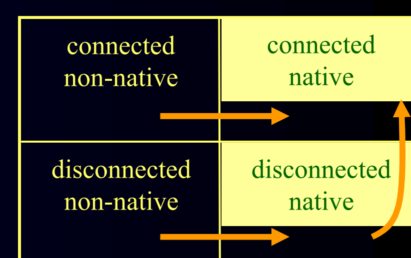


Cottonwood Mixed Communities

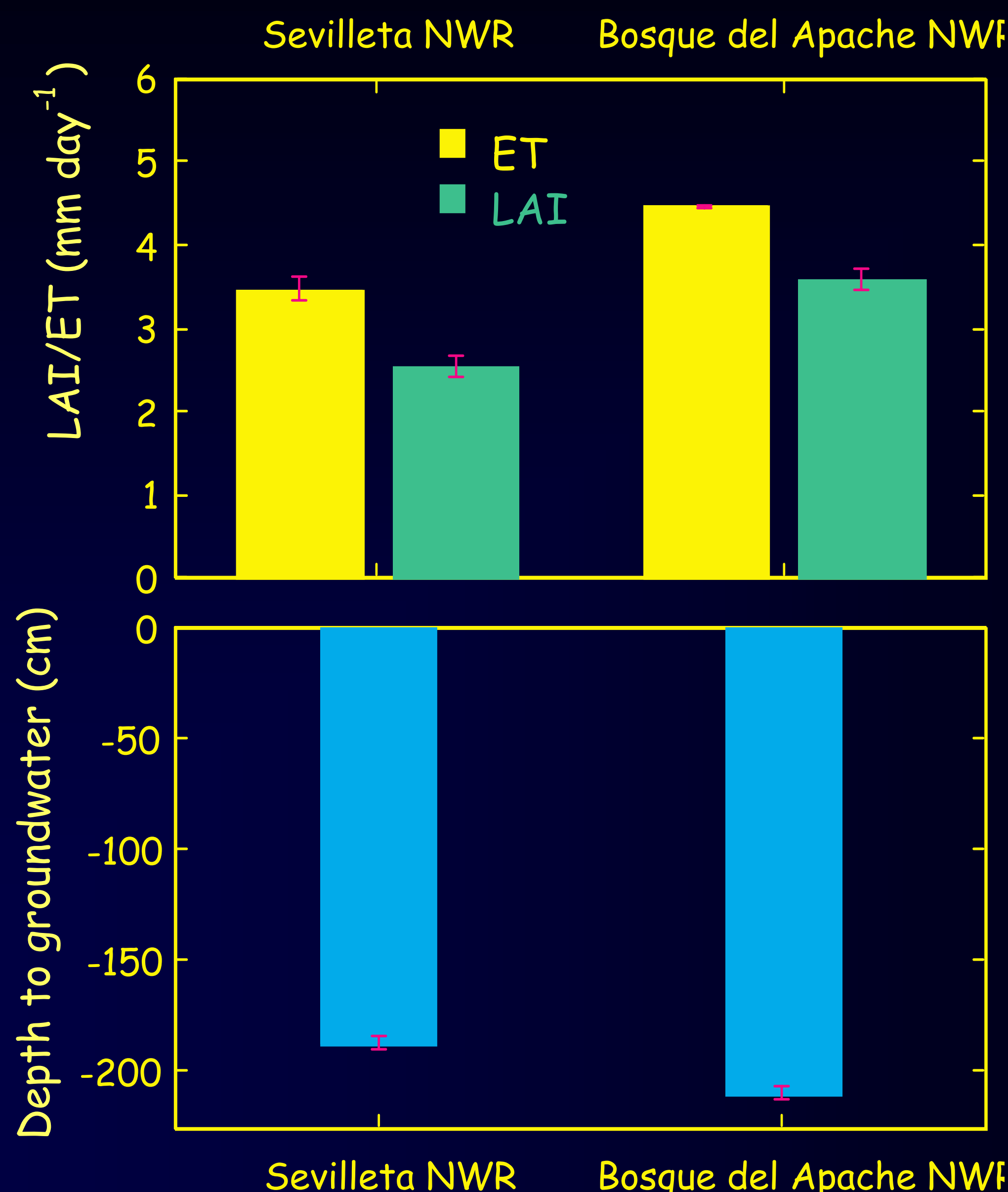


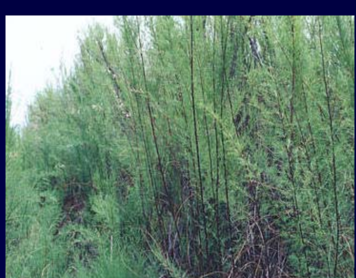


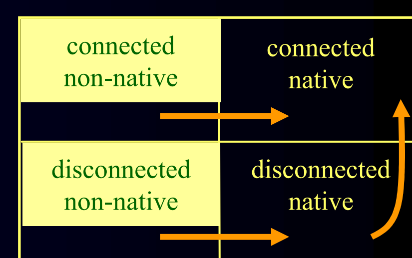




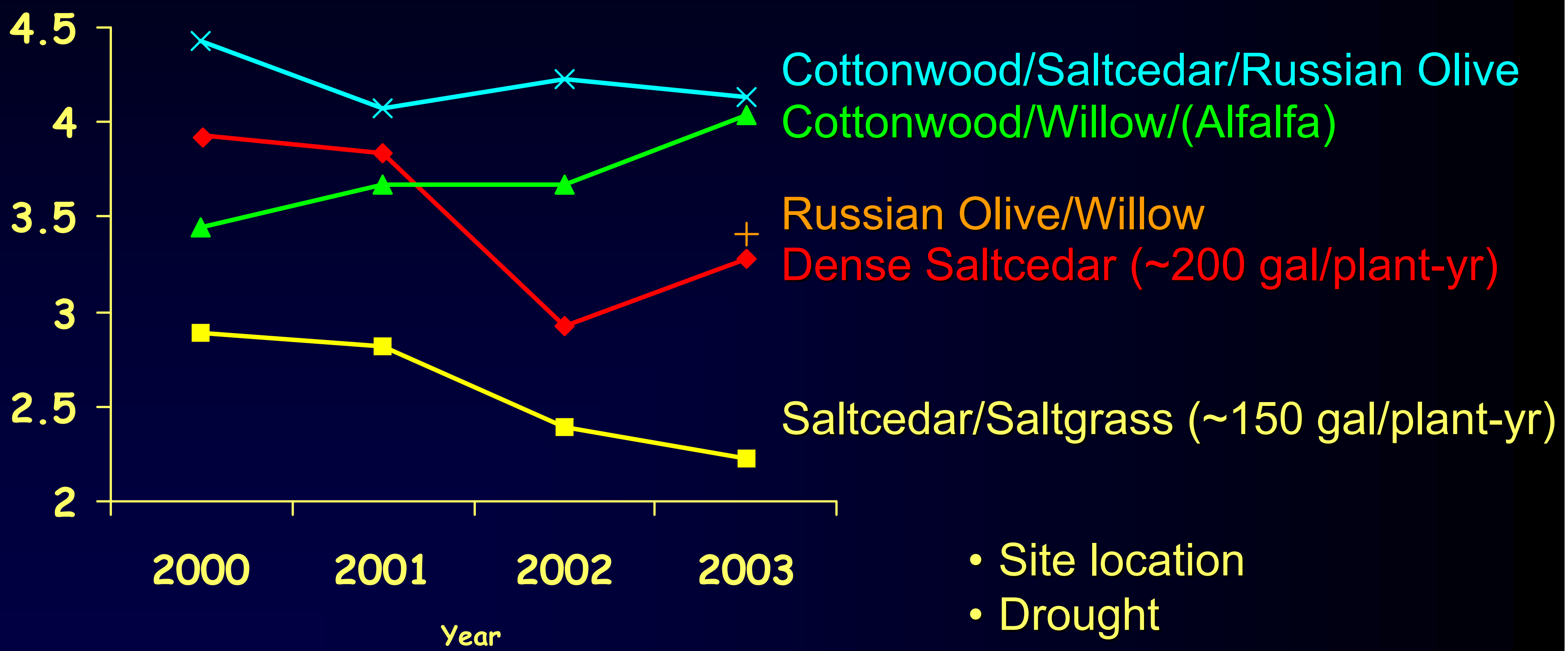
Saltcedar Communities







Annual ET

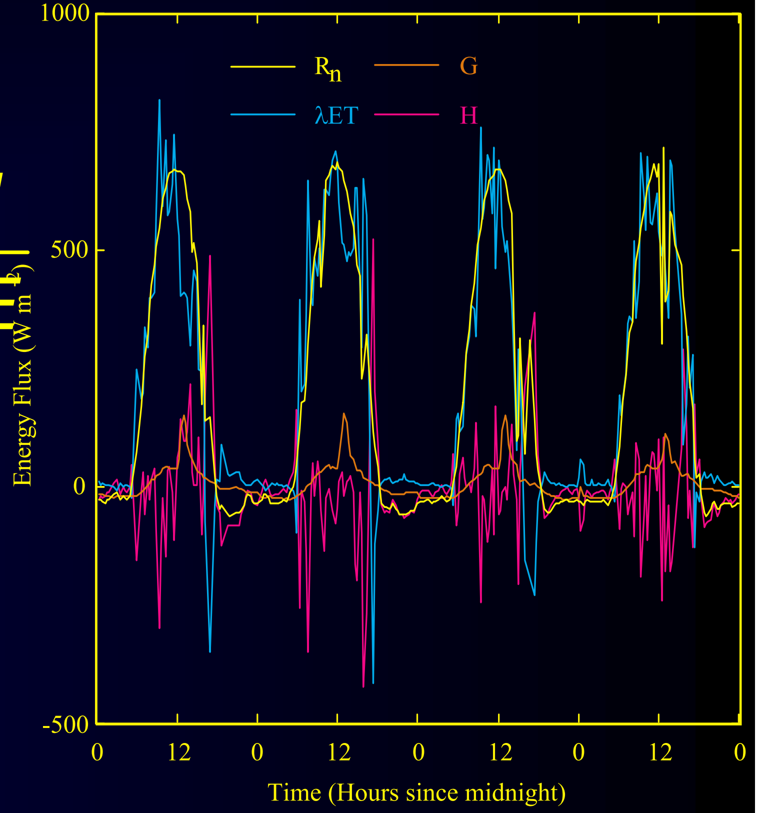


- Site location
- Drought
- Vapor Pressure Deficit
- Groundwater

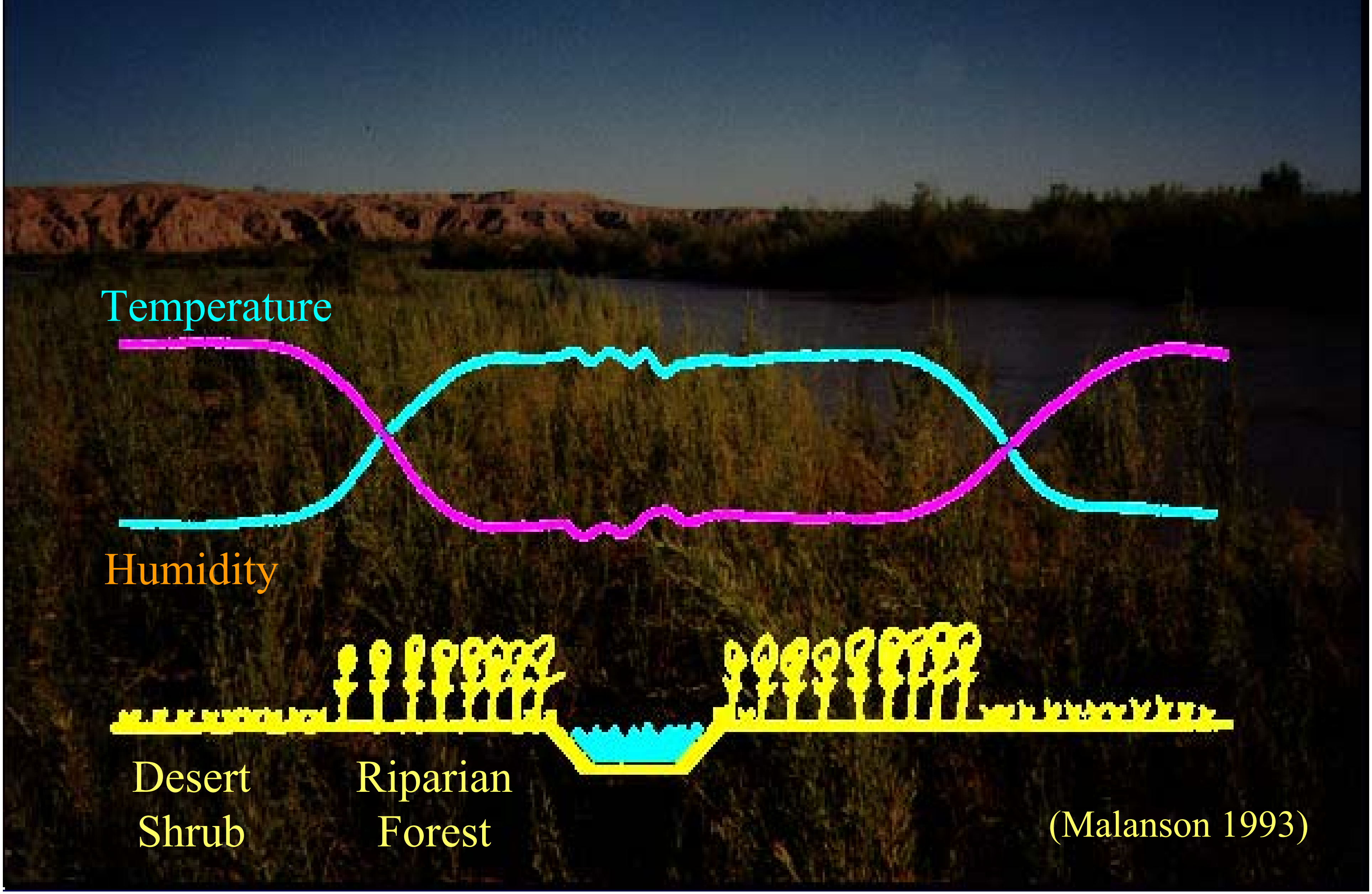
Bowen Ratio Energy Balance

$$\beta = \frac{PC_P\left(T_2 - T_1\right)}{\lambda_v \varepsilon\left(e_2 - e_1\right)} = \frac{H}{LE}$$

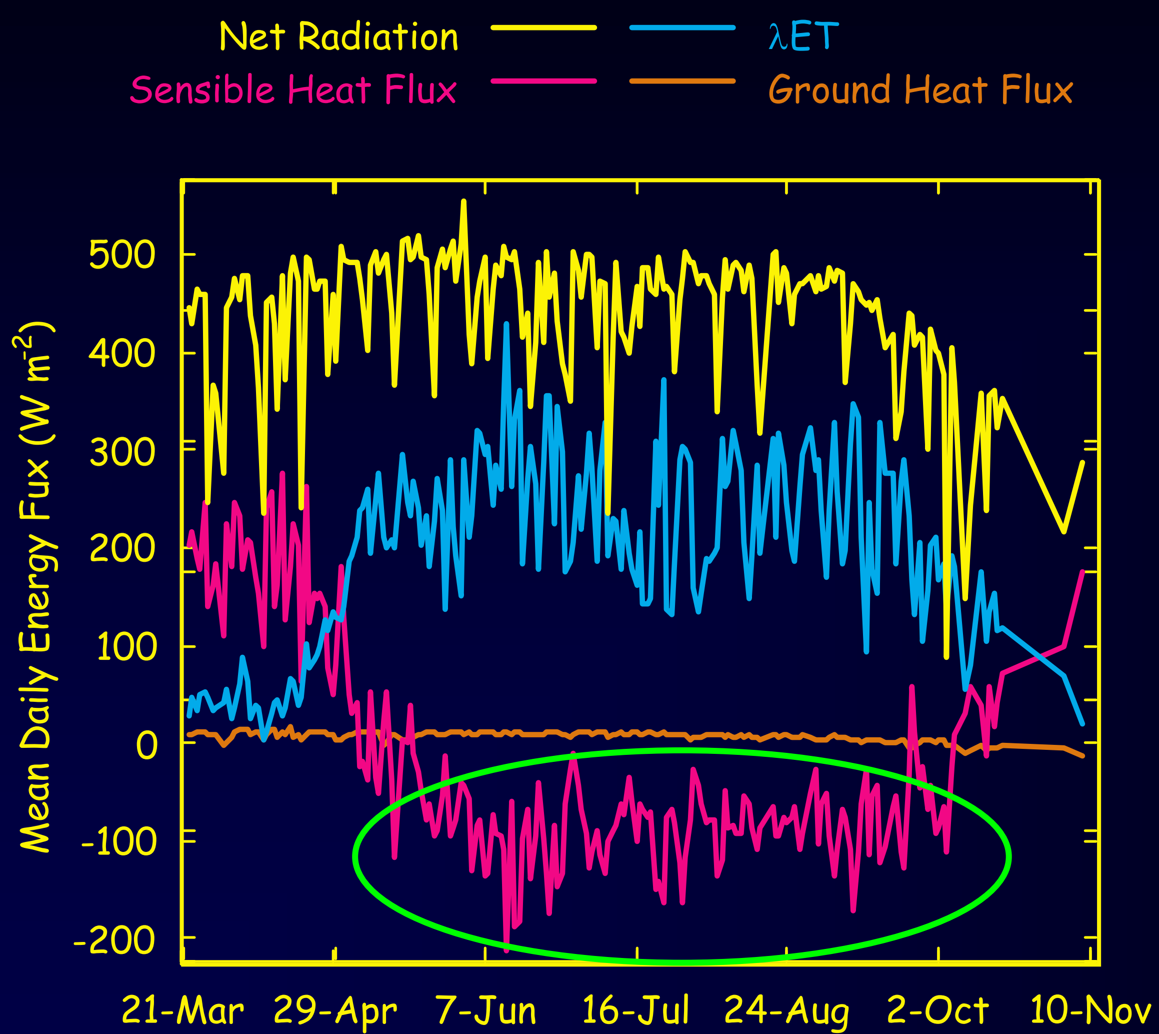
$$R_n = G + H + LE + S$$



Desert floodplain ecosystems



Sensible Heat Advection



- - H indicative of sensible heat input from adjacent desert
- + H observed over saltcedar towers (2000) and Sevilleta saltcedar tower (1999, 2000, & 2001)
- Cottonwood: 25-30 m
- Saltcedar: 4-6 m

Time lag

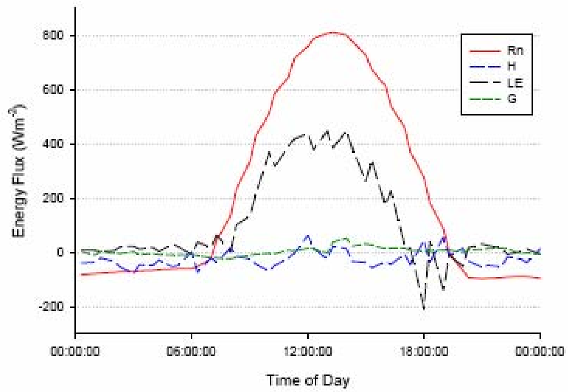


Figure 1: Comparison of energy fluxes on a sunny day, June 22, 2003, at the Belen site, dominated by *P. deltoides* with a native understory.

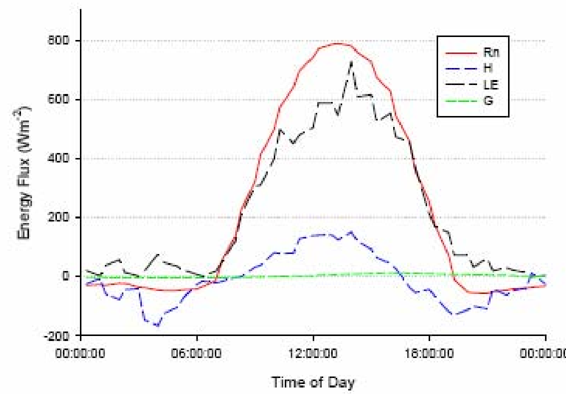


Figure 2: Comparison of energy fluxes on a sunny day, August 8, 2004, at the Bosque del apache site, a monospecific stand of the invasive species *T. ramosissima*.

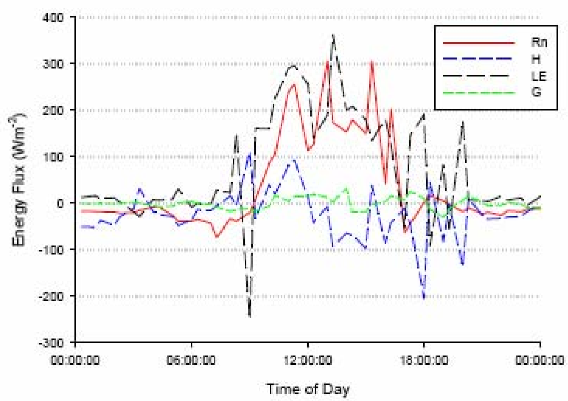


Figure 3: Comparison of energy fluxes on a cloudy day with precipitation, August 15, 2003, at the Belen site.

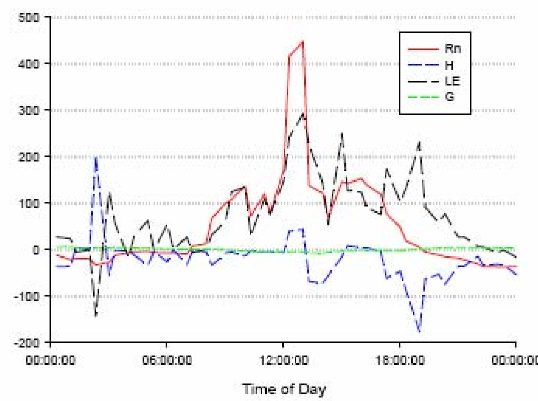


Figure 4: Comparison of energy fluxes on a cloudy day with precipitation, September 4, 2004, at the Bosque del Apache site.

Closure error

$$R_n = G + H + LE + closure$$

$$frac_{closure} = \frac{|H| + |LE|}{R_n - G}$$

Table 4. Summary of energy balance closure error using uncorrected and corrected fluxes.

Site	$frac_{closure}$ uncorrected	$frac_{closure}$ corrected
2000:		
Albuquerque	0.89 ± 0.01	0.88 ± 0.01
Belen—Rio Communities	0.81 ± 0.01	0.74 ± 0.01
Sevilleta NWR	0.86 ± 0.01	0.86 ± 0.01
Bosque del Apache NWR	0.82 ± 0.01	0.82 ± 0.01
2001:		
Albuquerque	0.86 ± 0.01	0.85 ± 0.01
Belen—Rio Communities	0.81 ± 0.02	0.76 ± 0.02
Sevilleta NWR	0.83 ± 0.01	0.84 ± 0.01
Bosque del Apache NWR	0.87 ± 0.01	0.89 ± 0.01
2002:		
Albuquerque	0.92 ± 0.01	0.90 ± 0.01
Belen—Rio Communities	0.91 ± 0.02	0.85 ± 0.02
Sevilleta NWR	0.81 ± 0.01	0.81 ± 0.01
Bosque del Apache NWR	0.87 ± 0.01	0.88 ± 0.01
2003:		
Albuquerque	0.86 ± 0.01	0.86 ± 0.01
Belen—Rio Communities	0.80 ± 0.02	0.75 ± 0.02
Sevilleta NWR	0.84 ± 0.01	0.83 ± 0.005
Bosque del Apache NWR	0.80 ± 0.01	0.82 ± 0.01

What is the upper limit?

550 W/m^2 for 12 hrs/day, 250 days/yr:
7.96 acre-ft/acre = ~ 432 gallons/(plant-yr)

Advection

150 W/m^2 for 12 hrs/day, 250 days/yr:
2.17 acre-ft/acre = ~ 118 gallons/(plant-yr)

6000 plants/acre at Bosque del Apache

Photo: bhg.fws.gov

Time Series

(with John Preuger, Larry Hipps, Bill Eichinger, & Dan Cooper)

Wavelets:

q', T', w'

- Continuous 1-D wavelet transformation[*]

Wavelet Half Planes: Covariance

$\overline{w'T'}, \overline{w'q'}, \overline{T'q'}$

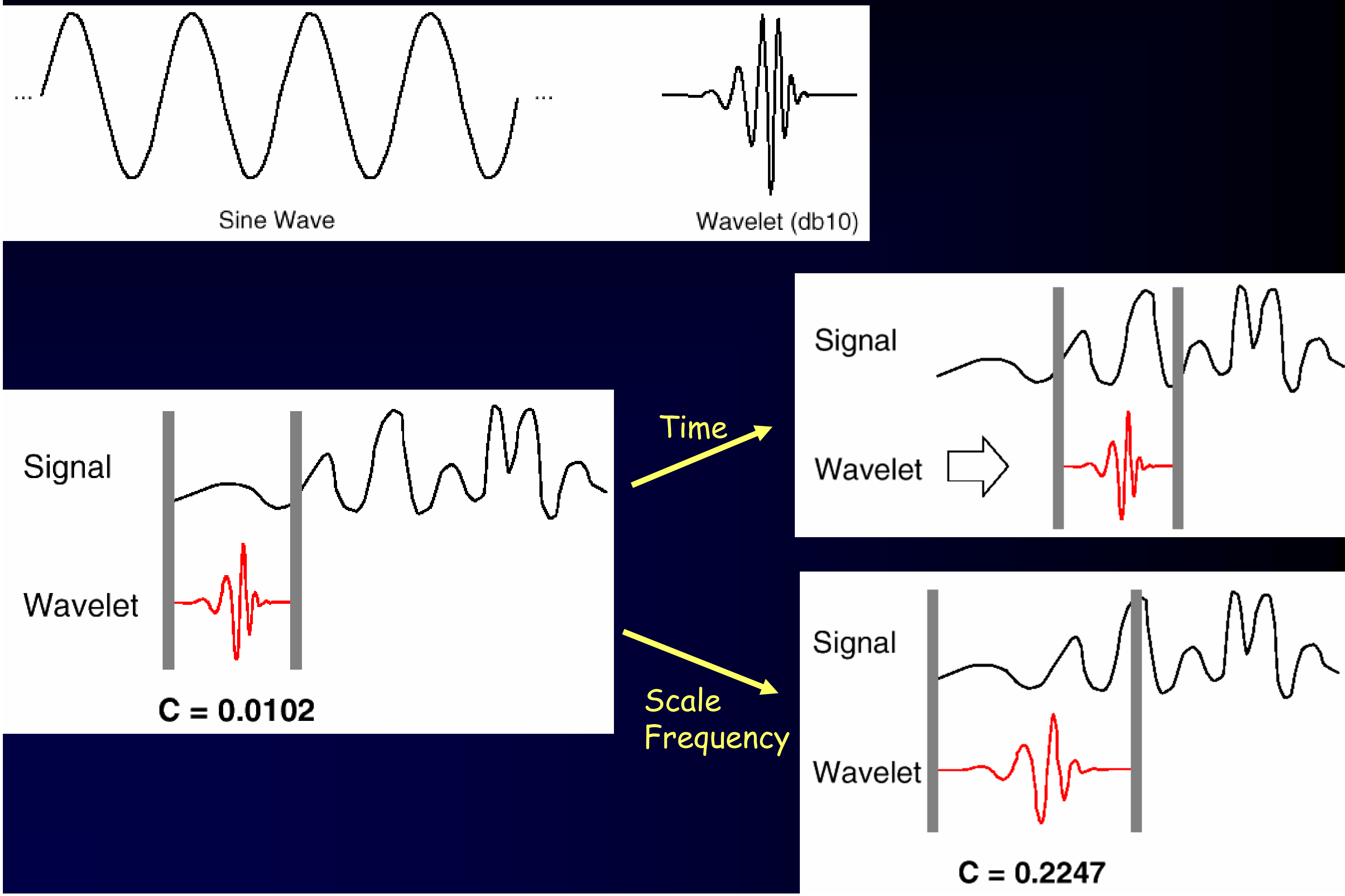
- Discrete 1-D wavelet transformation[**] (WaveletTransform[data, d1, 16])
- Array multiplication of coefficients[**]
- Synthesize new signal[**] (InverseWaveletTransform[wtdata, d1])
- Continuous 1-D wavelet transformation[*]

* Matlab

** Matlab (up to 2^{12}), Mathematica (full analysis, 2^{16})

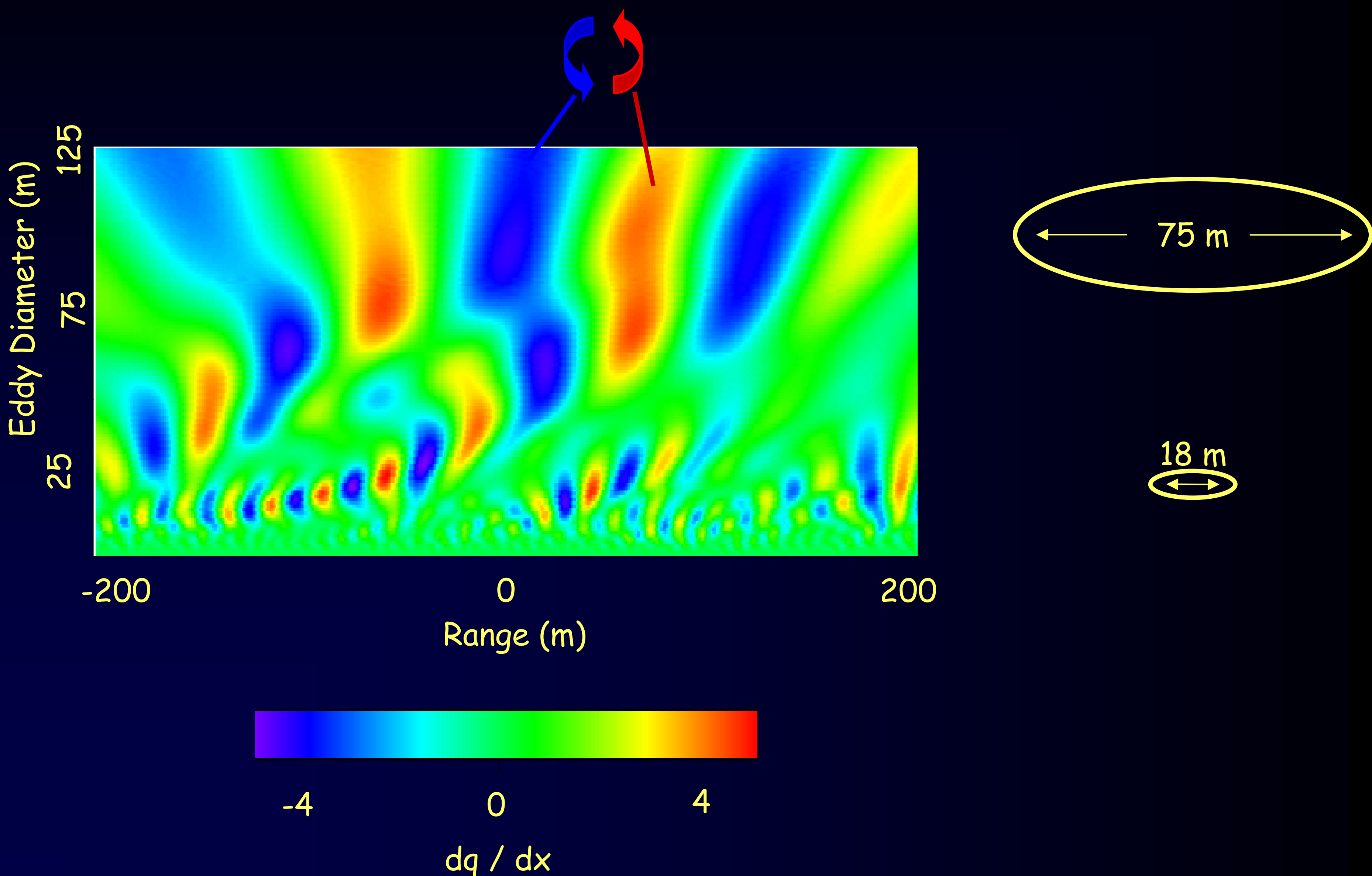
(Scanlon & Albertson In Review)

Wavelets



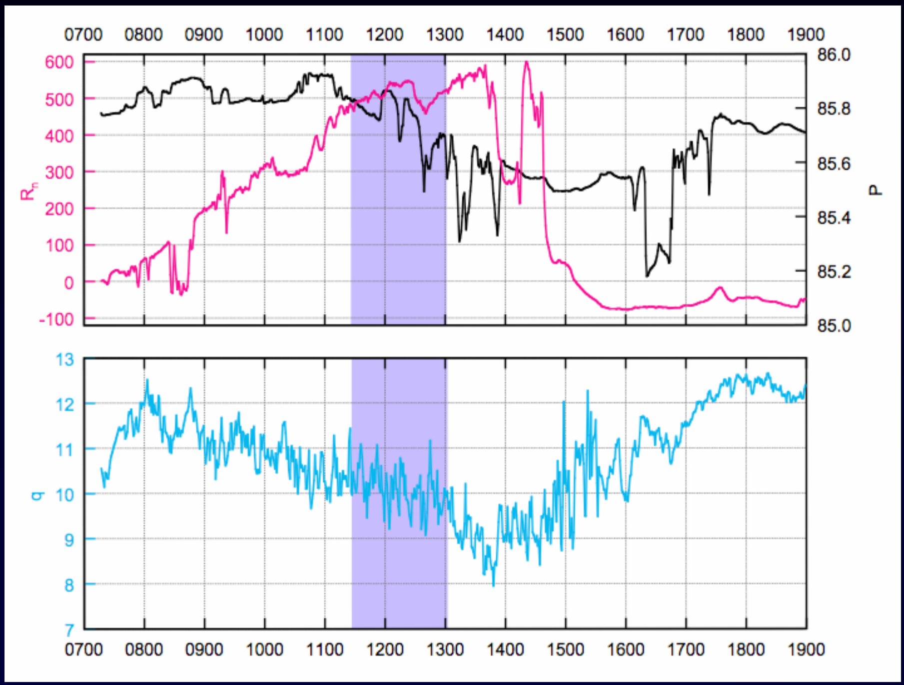
Sine Wave
Wavelet (db10)
Signal
Wavelet
C = 0.0102
Time
Scale
Frequency
Signal
Wavelet
Signal
Wavelet
C = 0.2247

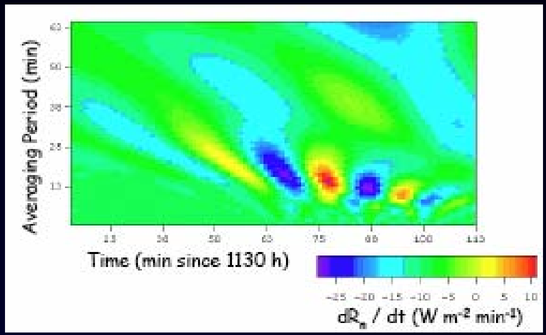
Space Series & Eddy Size

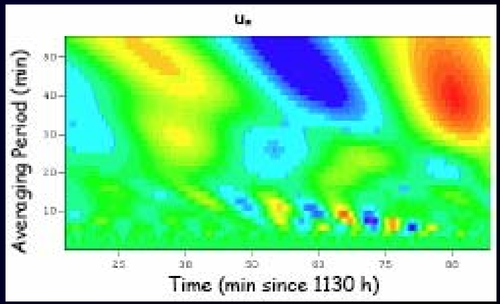


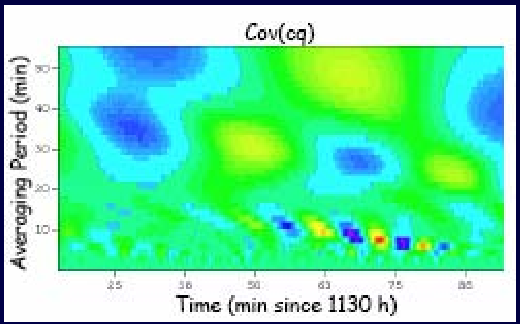
LIDAR data courtesy DI Cooper

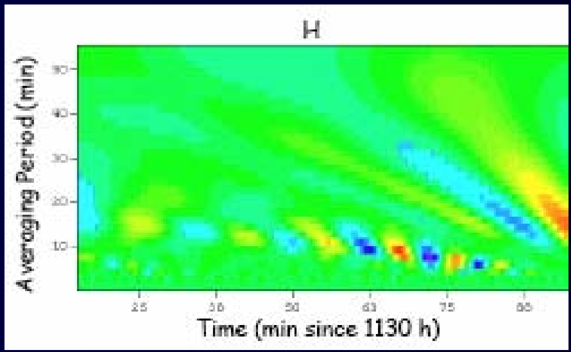
Monsoon dynamics

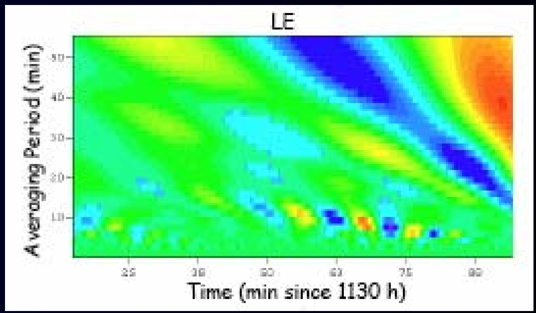




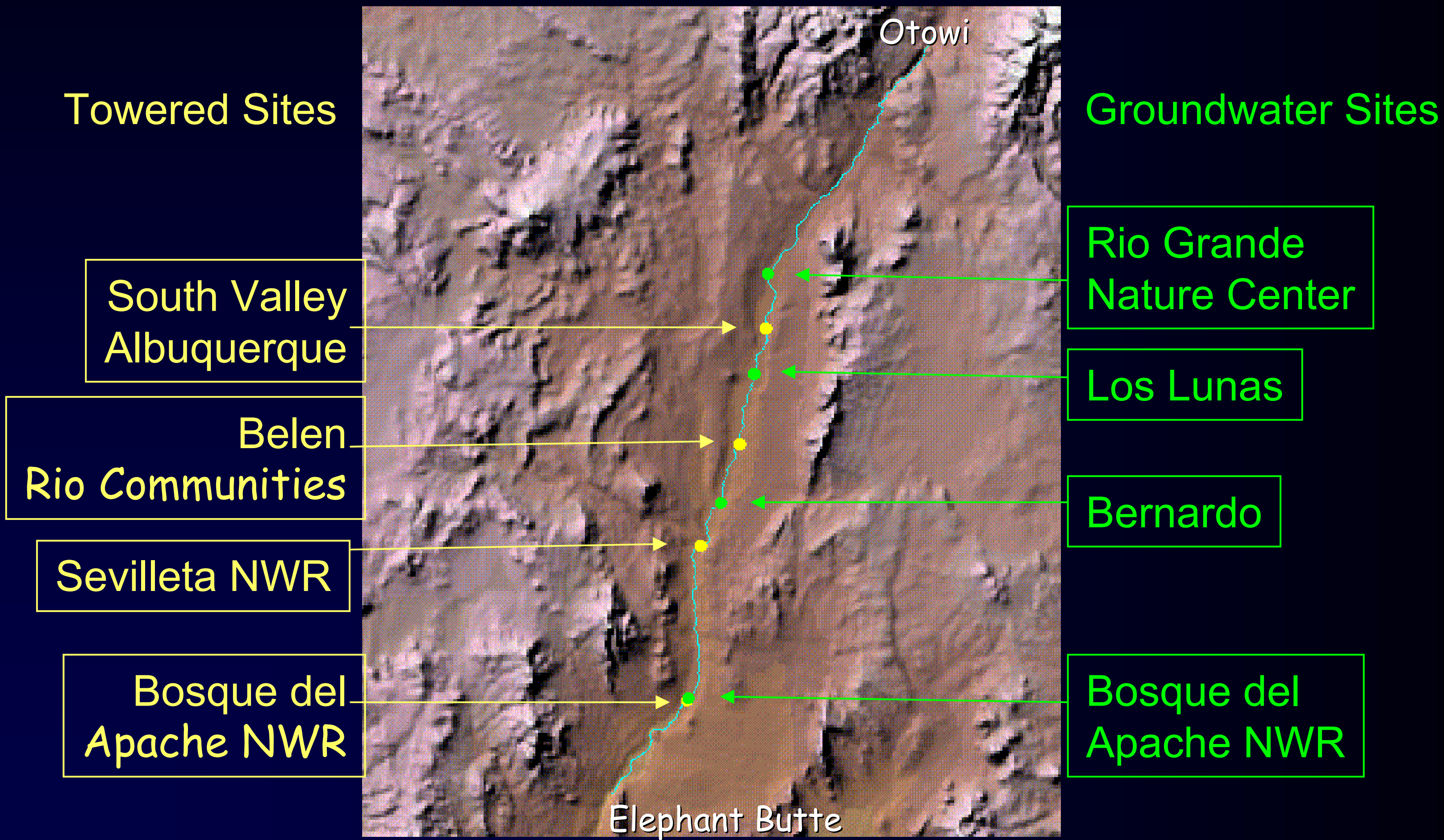






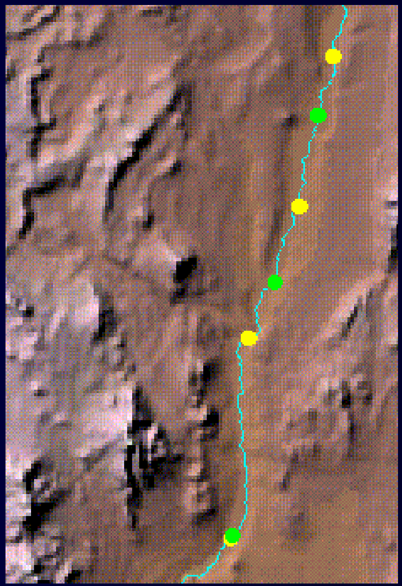


Basin Topography



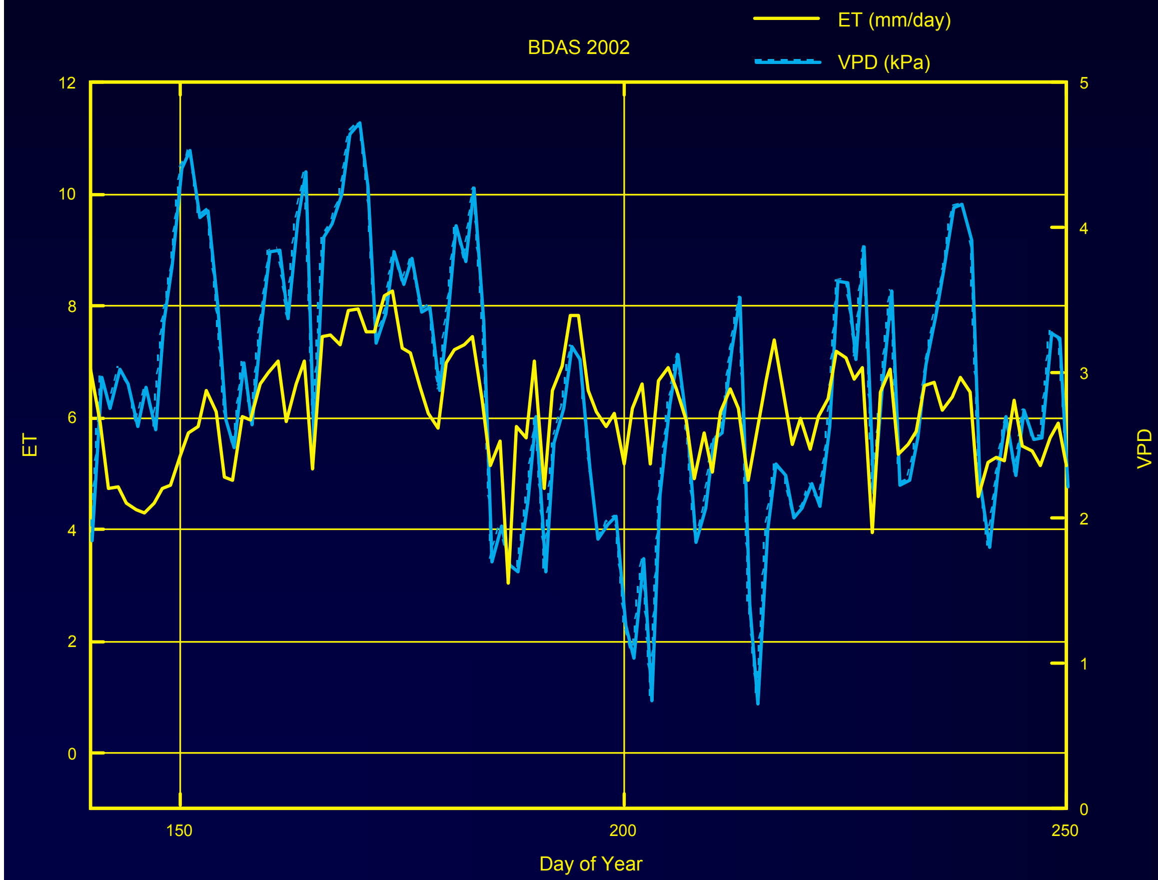
Topography

Site	Temp □C	Valley width m	Angle □	Distance km	Nearest Arroyo
Albuquerque	20.3 (11.7, 27.7)	2 600 Š 5 100	0.0 Š 2.3	16.5	60□, 4 000 m, upstream, E
Belen Ń R io Communities	20.5 (11.0, 28.6)	3 300 Š 4 000	1.0 Š 1.6	20.0 (37.0)[b]	30□, 24 000 m, downstream, W[c]
Sevilleta NWR	20.7 (8.5, 30.3)	4 00 Š 4 000 (6 500)[a]	2.0 Š 13.2	27.2	90 Š 180□ onsite, W[d]
Bosque del Apache NWR	20.1 (7.8, 30.6)	3 000 Š 5 000	2.0 Š 8.7	39.2	80□, 23 600 m, downstream, W[e]



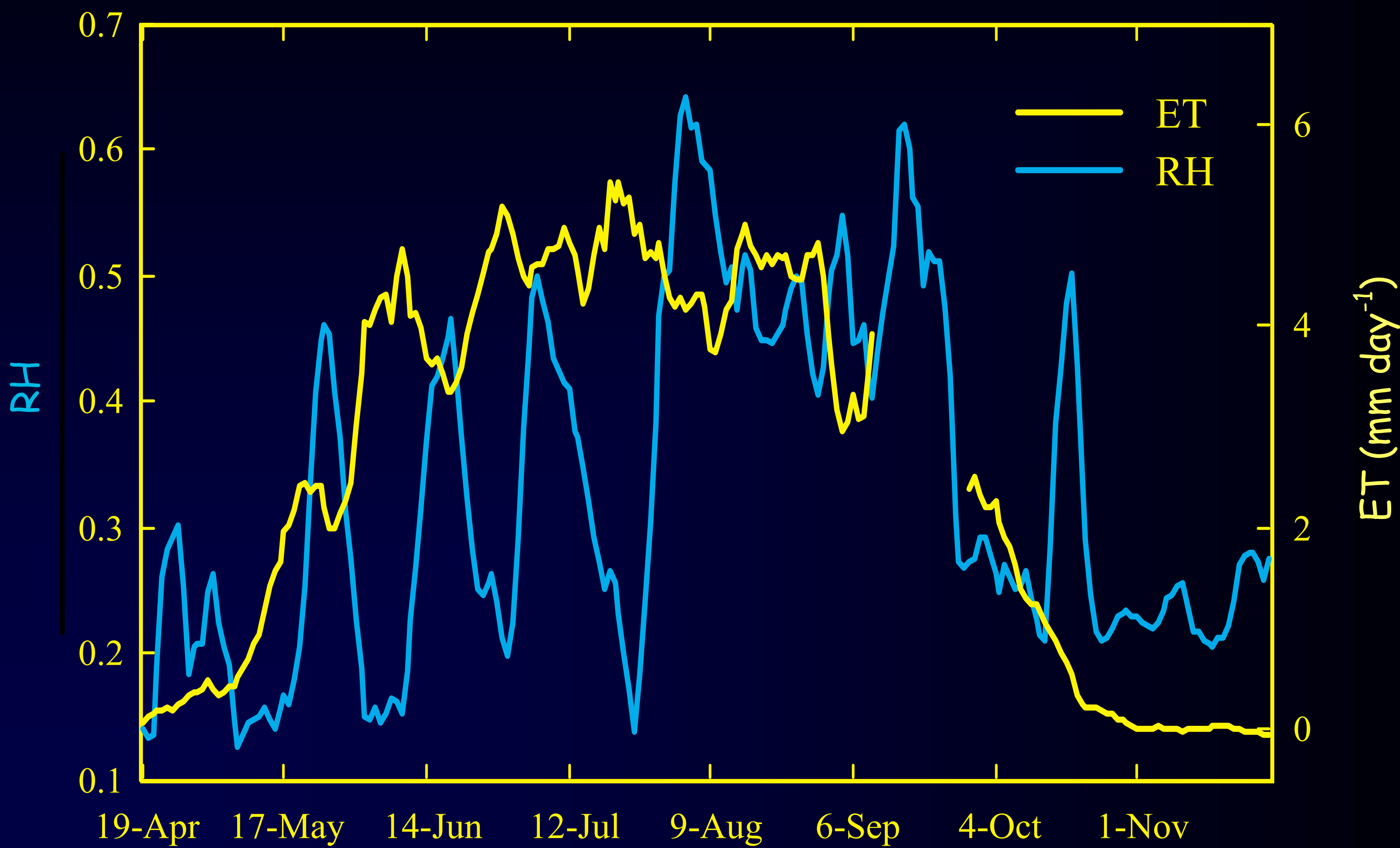
Vapor Pressure Deficit

$$VPD = e_{air} - e_{leaf\text{-}saturated}$$



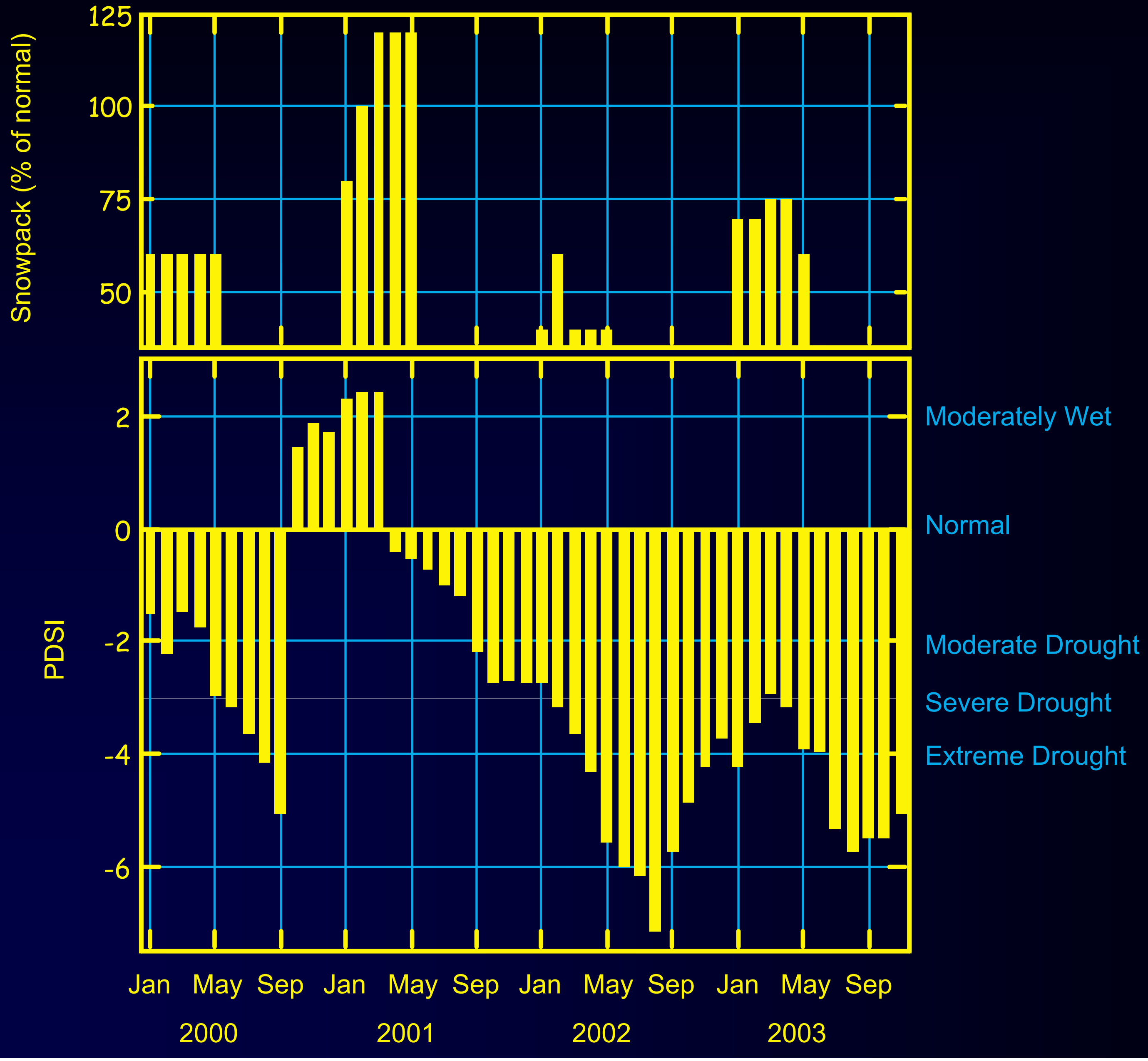
Factor	Coefficient ± se	F	p
Albuquerque and Belen ŃŹRio Communities, *Populus deltoides*			
Model:	**0.54**	**110.8**	**< 0.0001**
Energy Balance:			
H	-0.008 ± 0.002	19.2	< 0.0001
R_n	0.02 ± 0.0008	388.1	< 0.0001
Aerodynamics:			
v	-0.1 ± 0.06	5.8	0.02
v X u	-0.09 ± 0.02	16.2	< 0.0001
Sevilleta and Bosque del Apache NWRs, *Tamarix chinensis*			
Model:	**0.66**	**77.7**	**< 0.0001**
Energy Balance:			
R_n	0.005 ± 0.0005	83.7	< 0.0001
Aerodynamics:			
u	0.08 ± 0.03	7.5	0.007
u_*	1.2 ± 0.3	12.9	0.0004
q_*	-4.2 ± 0.6	50.2	< 0.0001
u_* X q_*	11.8 ± 4.3	7.4	0.007
Surface Scalars and Interaction Effects:			
VPD	0.5 ± 0.07	43.0	< 0.0001
T_{max} X T_{min}	-0.01 ± 0.003	9.8	0.002
PPT X H	-0.003 ± 0.0005	24.3	< 0.0001
R_n X PPT	0.001 ± 0.0003	18.4	< 0.0001

Atmospheric Humidity



(Cleverly et al, In Review)

Drought in the Rio Grande Basin



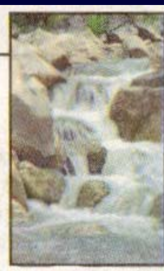
Water Controversies

Overdrawn at the Riverbank

Drought compounds problems along Rio Grande as water users demand more and more

Running low

First in a five-part series



The Rio Grande is being stretched to the limit by growing demands for its water

How Do You Stretch a River?

Rio Grande Domesticated for Human Needs

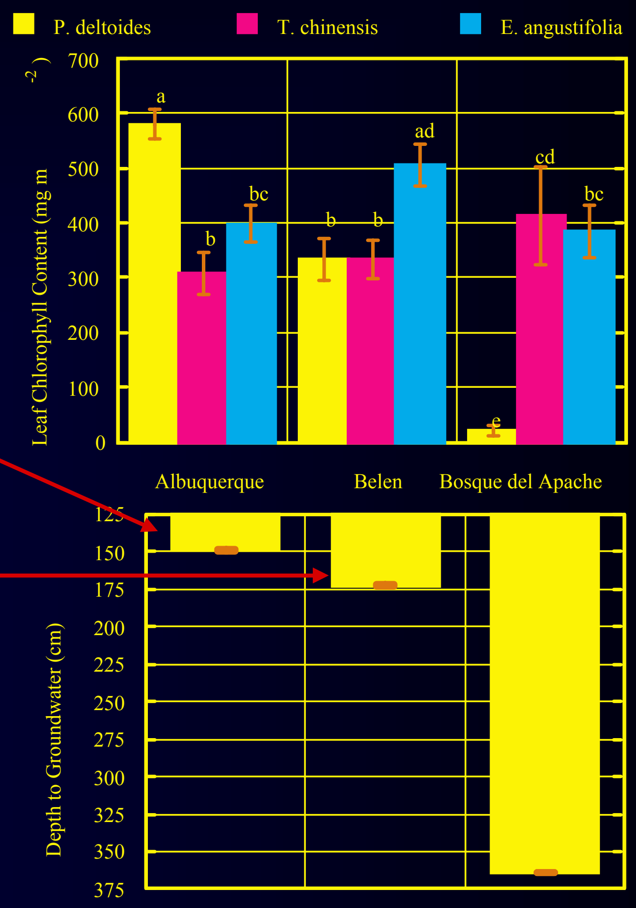
Cottonwoods Take Back Bosque From Cedars

Crown dieback

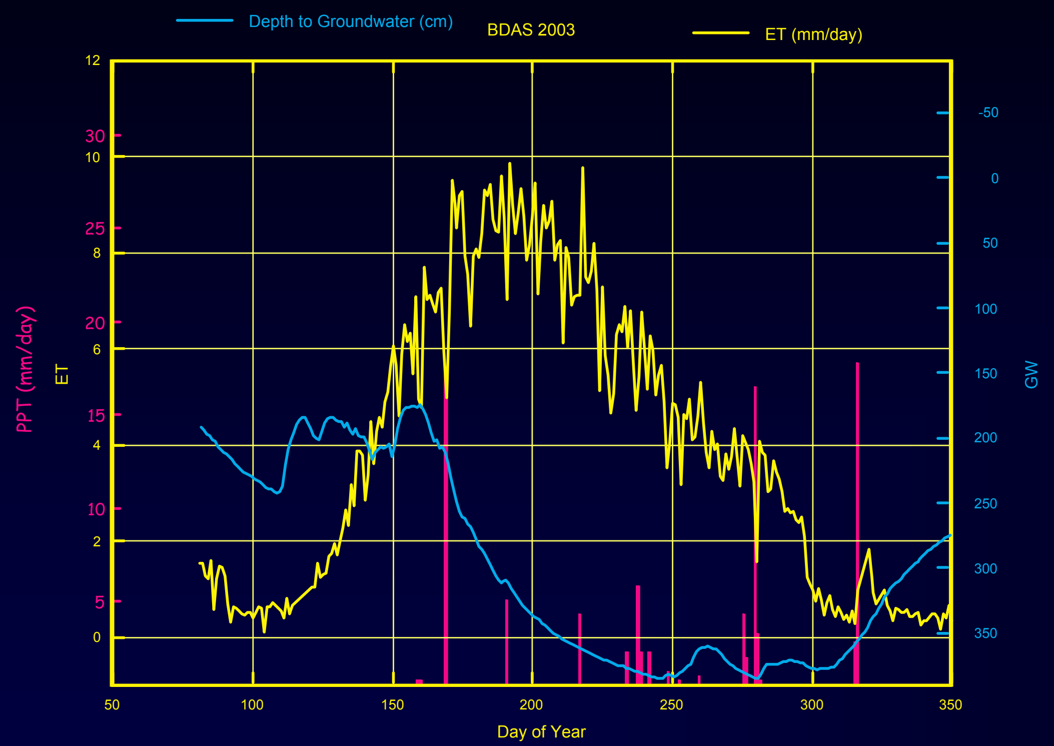
Water table maintained by:

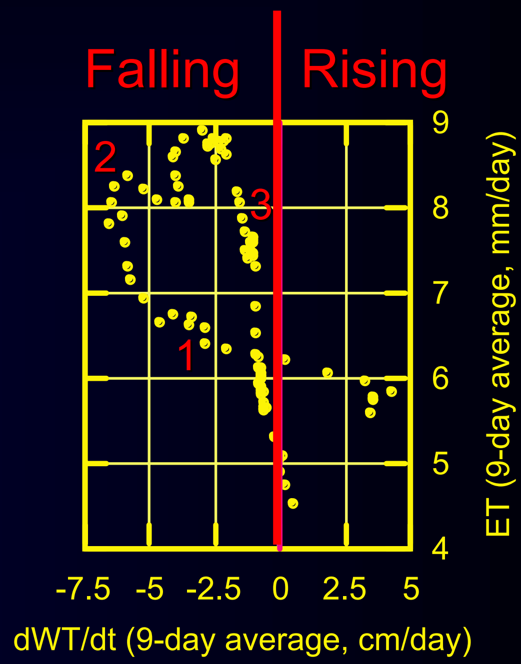
Wastewater treatment

Irrigation return



Groundwater recession





1 Draining begins, soil too saturated for taproot elongation, uptake continues at original capillary fringe

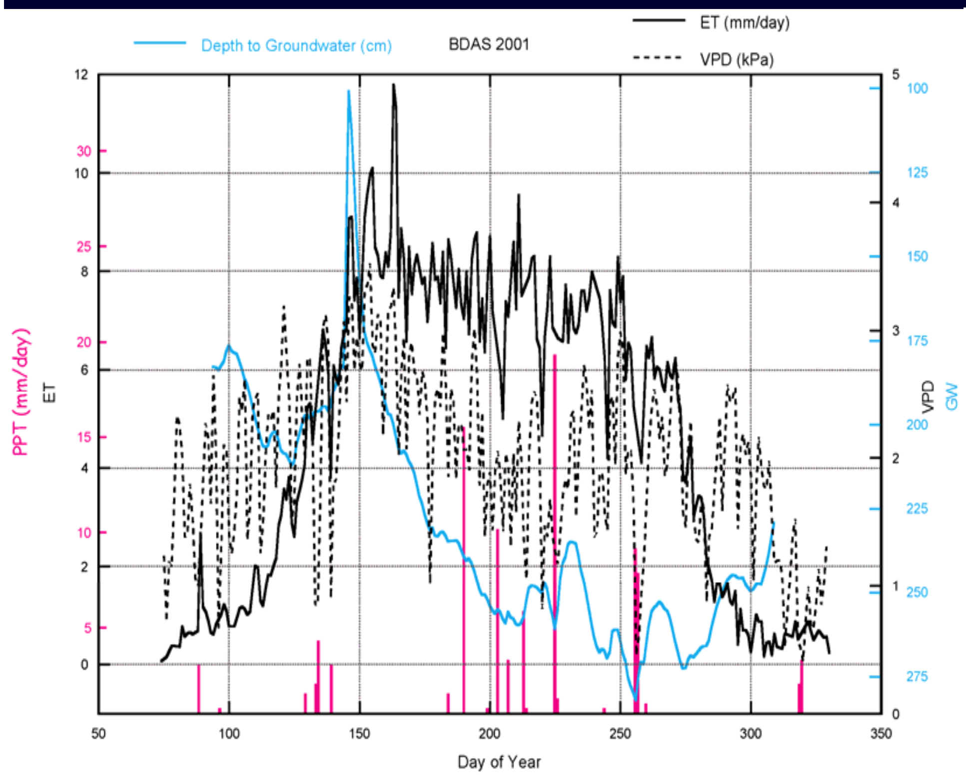
2 Taproot growth exploits deeper water table, uptake continues at or near original capillary fringe

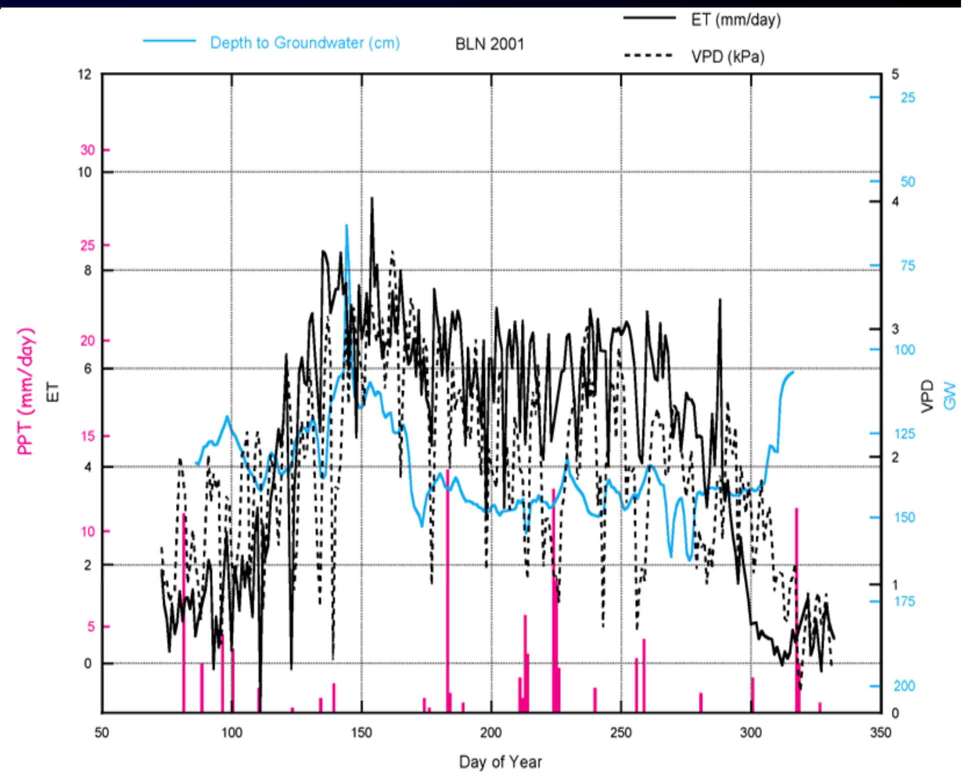
3 Uptake continues at deeper water table, uptake at original water table curtailed by soil drying

Flooding 2001
(1-day inundation initiated by US ACoE)

Dense saltcedar
Clay soil (R. Puerco)
Perched floodwater

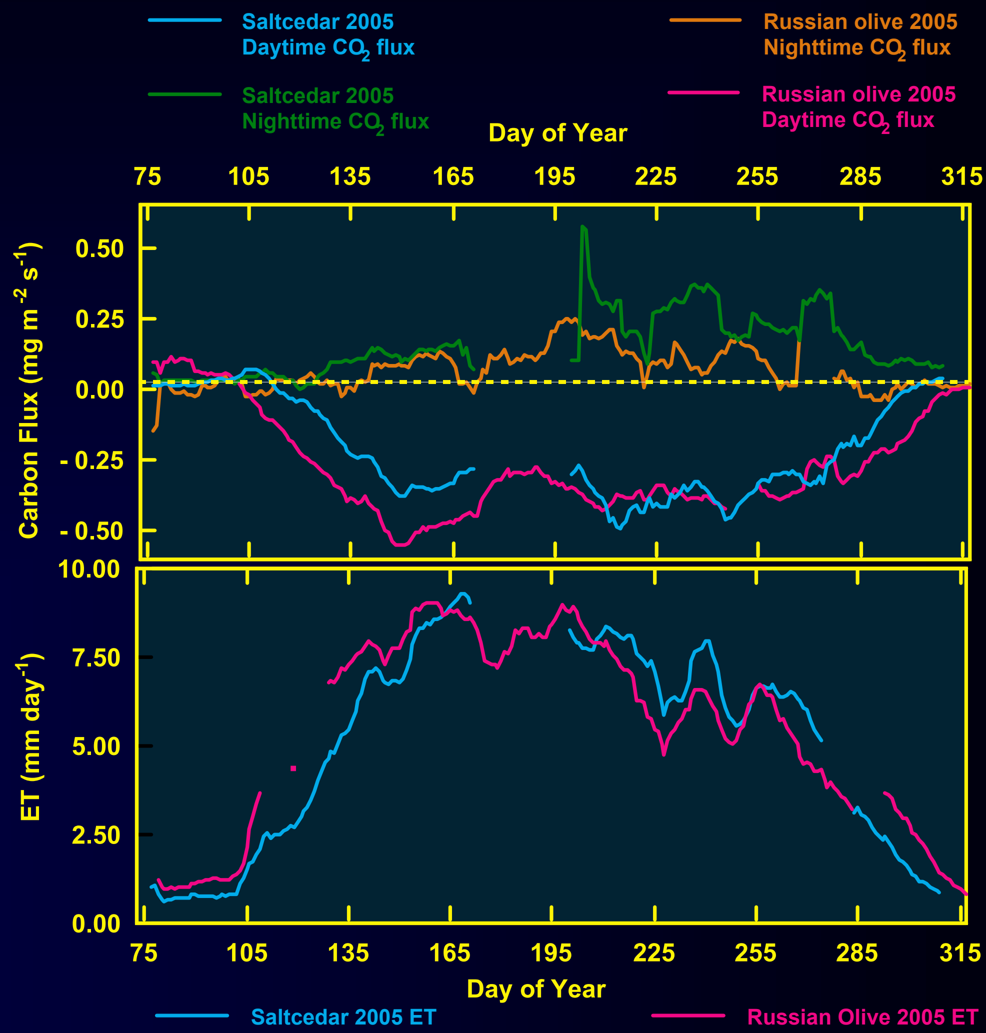
Cottonwood
+ (mostly) native understory
Loamy-sand soil
Partially inundated site
(microtopography)





Flooding


'05 6 21


Saltcedar 2005
Daytime CO2 flux
Saltcedar 2005
Nighttime CO2 flux
Russian olive 2005
Nighttime CO2 flux
Russian olive 2005
Daytime CO2 flux
Day of Year
75
105
135
165
195
225
255
285
315
Carbon Flux (mg m -2 s-1)
0.50
0.25
0.00
- 0.25
- 0.50
10.00
7.50
5.00
2.50
0.00
ET (mm day-1)
Day of Year
Saltcedar 2005 ET
Russian Olive 2005 ET

Factors Influencing ET

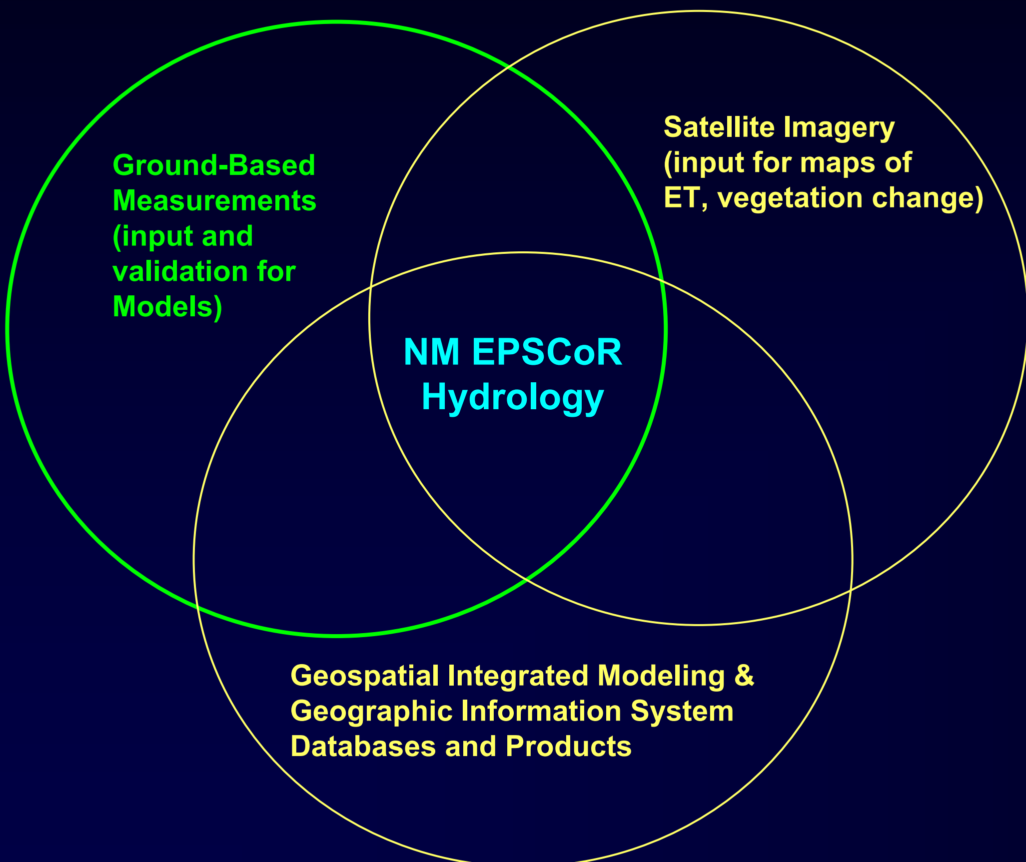
- Leaf Area Index
    - Chloride, Nitrate, Water Table depth
- Drought & Groundwater Decline/Dynamics
- Flooding
- Topography
    - Cold air drainage (Katabatic winds)
        - Temperature, Season Length, & Sensible heat advection
- Vapor Pressure Deficit
- Precipitation
- Energy balance
- Turbulence

New Mexico EPSCoR: a Statewide Ecohydrology and Flux Network Within a Semi-arid Region

James Cleverly*, *Robert Bowman, Clifford Dahm, Julie Allred Coonrod, Zohrab Samani, James Thibault, and James Gosz*

***UNM Hydrogeoecology, http://sevilleta.unm.edu/~cleverly**

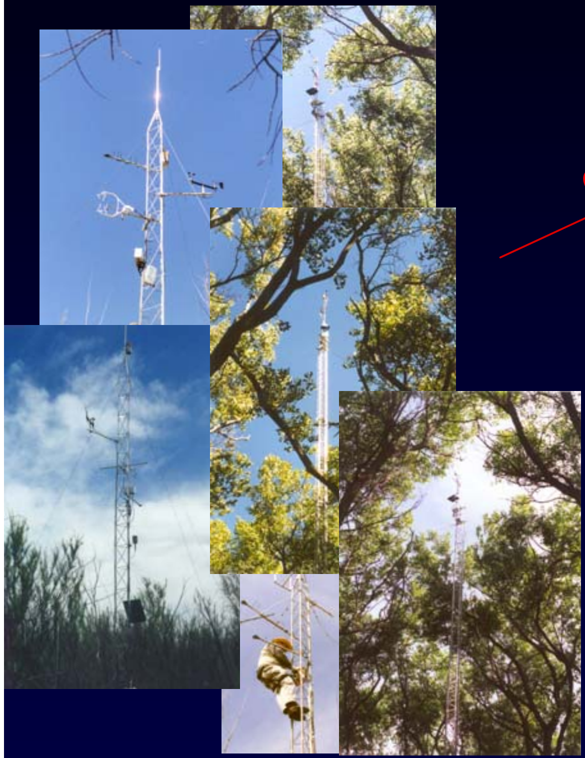
EPSCoR: Experimental Program to Stimulate Competitive Research



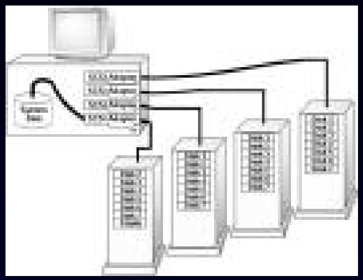
- Ground-based measurements: Fluxnet+ NM
- Remote sensing: scaling, statewide ET maps, and model input
- Geospatial integrated modeling: distributed hydrological processes, computation, and data products

EPSCoR New Mexico

NM EPSCoR



daily



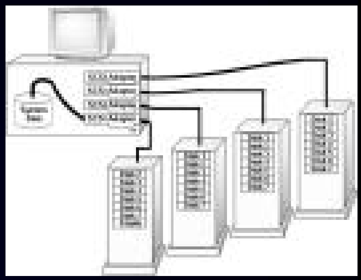
UNM GigaPOP

Flux corrections

RS Imagery

Data Distribution

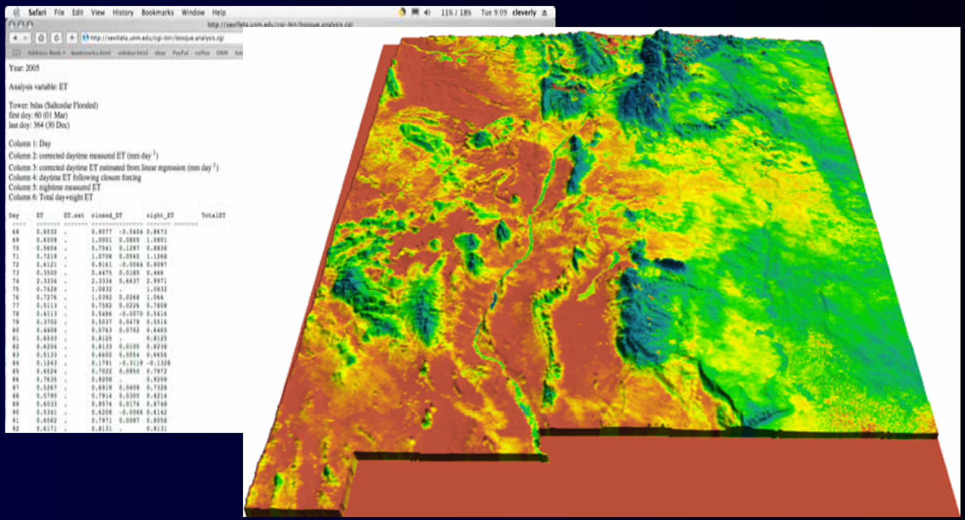
LambdaRail



NMT GigaPOP

Hydrologic Model

Data Archive



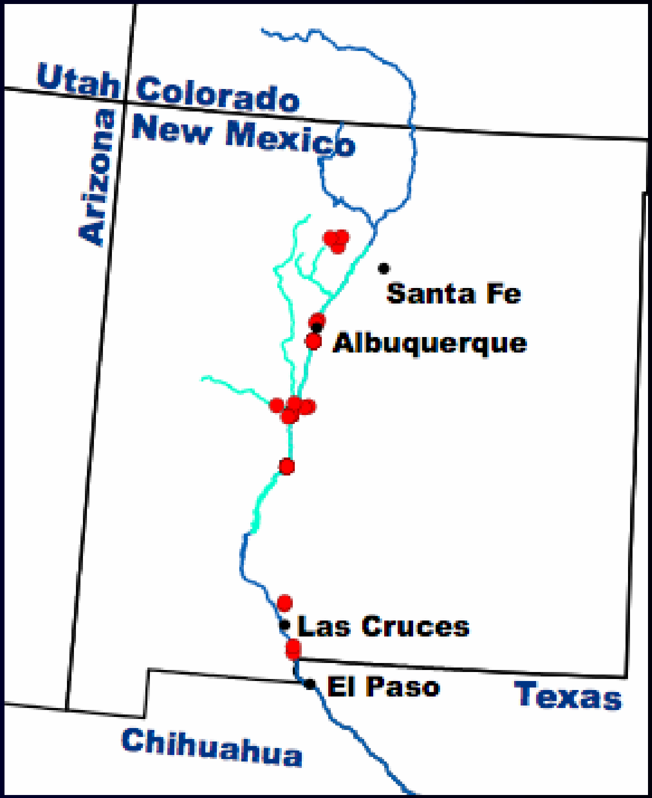
NM-EPSCoR FluxNet

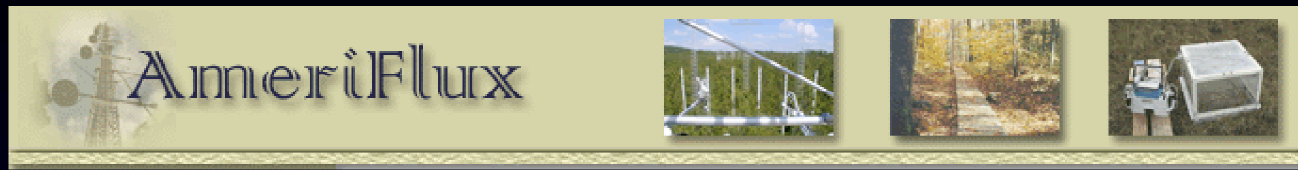
Founding Nodes

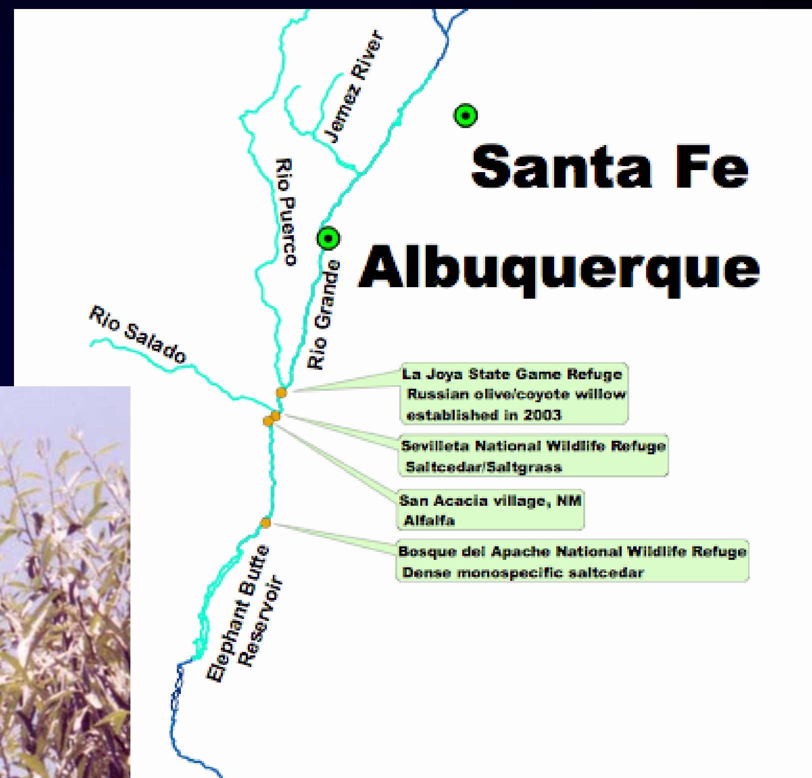
- Riparian and Middle valley – UNM
- Arid upland – UNM-Litvak
- Mesilla valley – NMSU-Bawazir

Extended network

- Albuquerque – NMT-Kleissl
- Arid lowland – USDA/ARS-Rango
- High elevation conifer – UA-Brooks

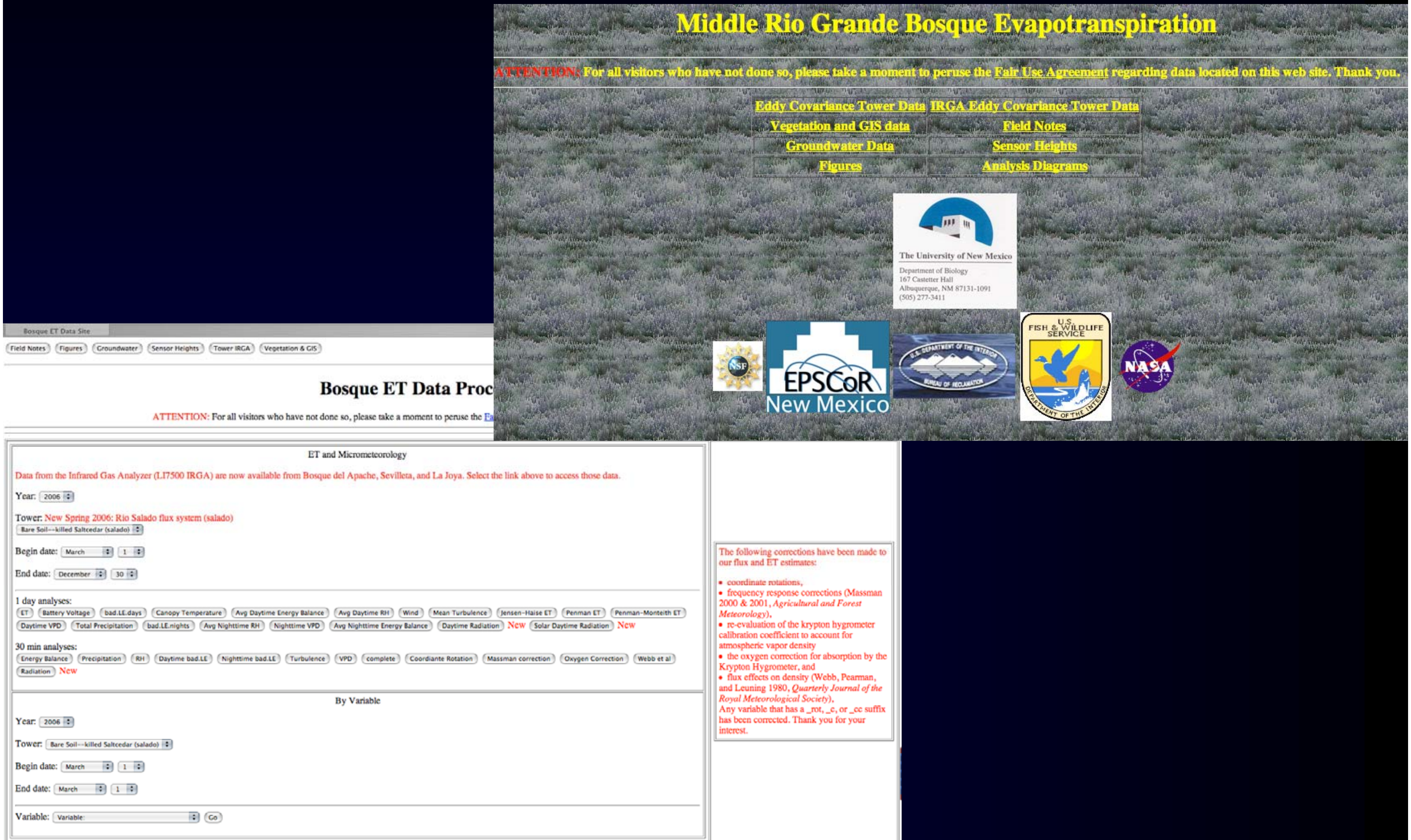






http://public.ornl.gov/ameriflux/

UNM Bosque ET web



http://bosque.unm.edu/~cleverly/bosque/index.html