

# Evaluating groundwater surface water interactions across the continental US using an integrated hydrologic model

Laura Condon & Reed Maxwell



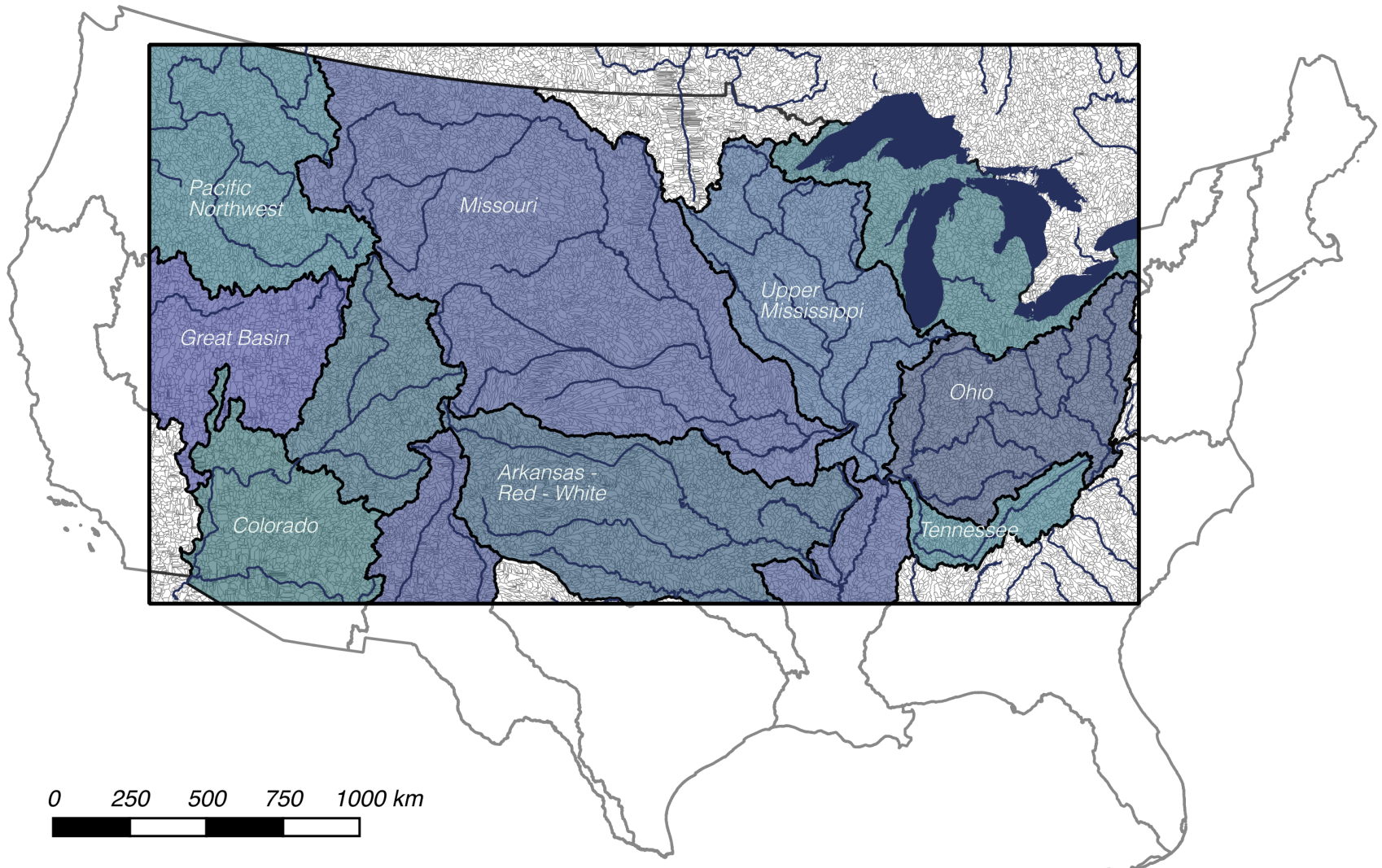
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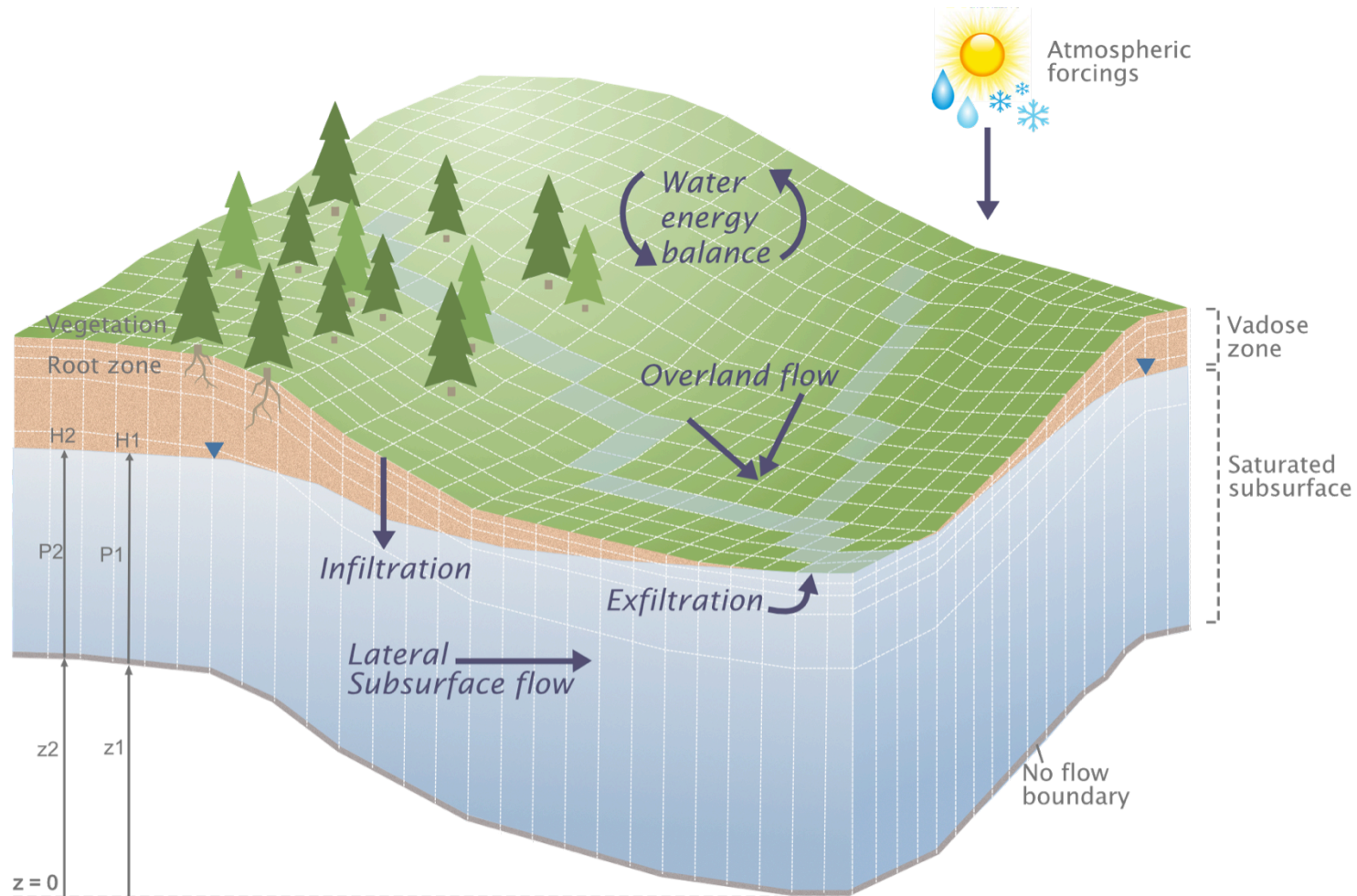
IDEAS  
productivity

- Connections between groundwater, surface water and land energy fluxes are well established  
*[Eltahir and Yeh, 1999; Konikow and Kendy, 2005; Koirala et al., 2014; Levine and Salvucci, 1999; Maxwell and Kollet, 2008; Shah et al., 2000; Sophocleous, 2002]*
- Open questions remain regarding nonlinear groundwater interactions and over large scales in different physical settings
- Understanding groundwater's role in watershed dynamics is a key missing link to better predicting hydrologic change  
*[Clark et al, 2015; Fan, 2015]*

# Numerical model of 6.3M km<sup>2</sup> of the Continental US at 1km lateral resolution



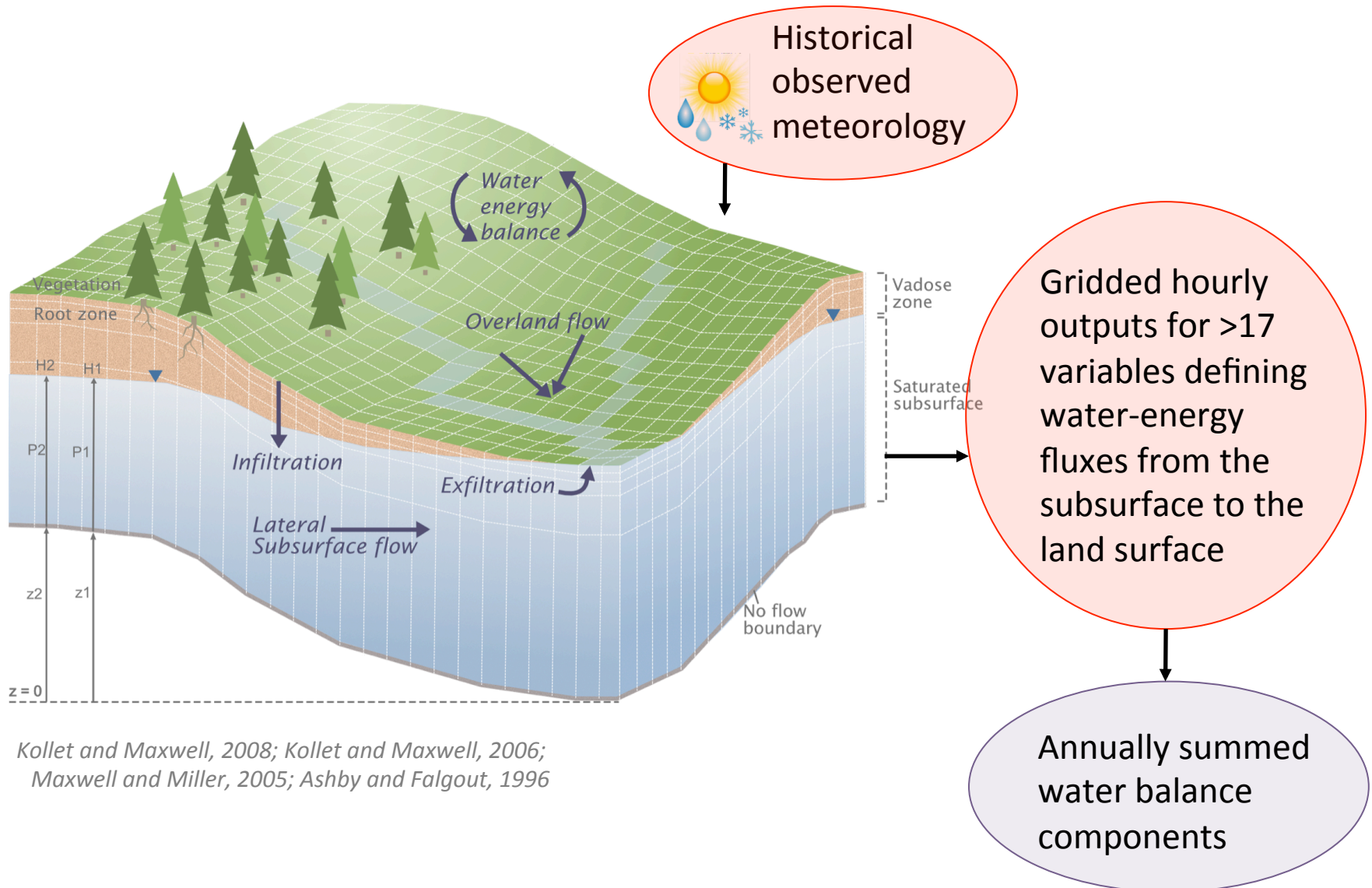
# Solving fully integrated groundwater surface water system with ParFlow



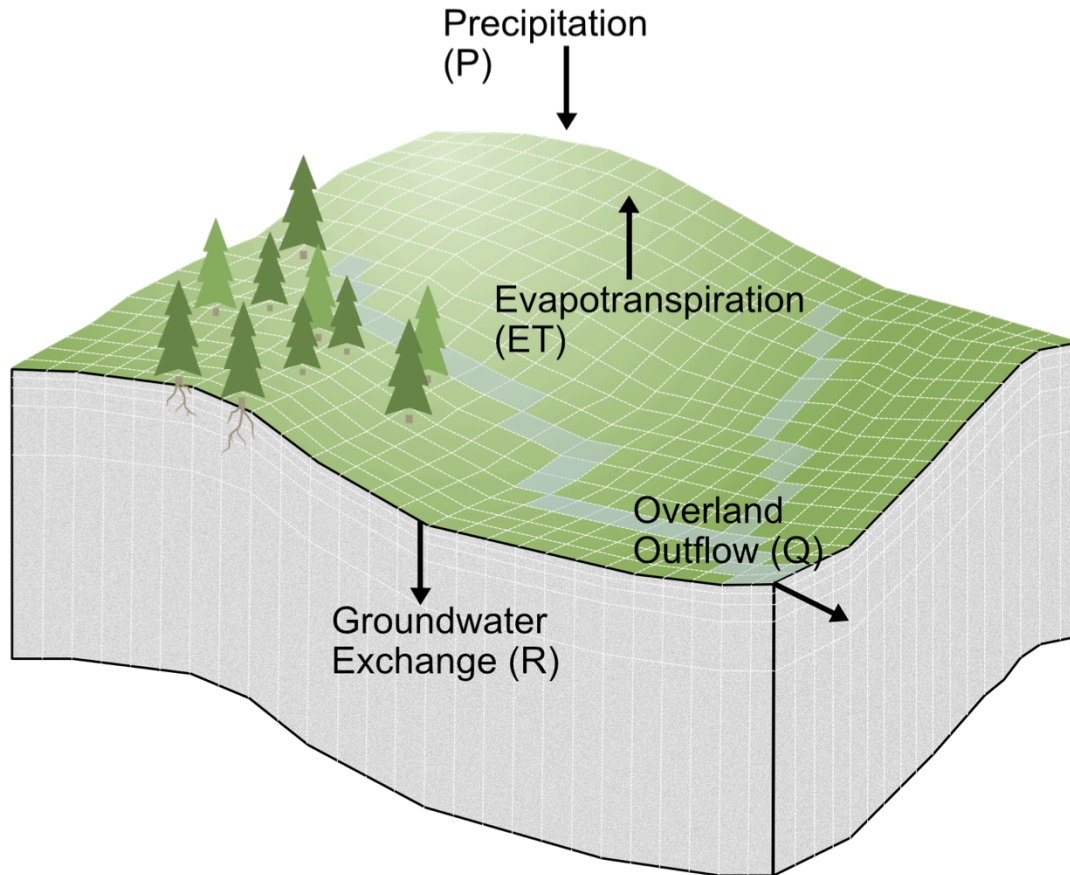
Kollet and Maxwell, 2008; Kollet and Maxwell, 2006;  
Maxwell and Miller, 2005; Ashby and Falgout, 1996



# Transient simulation of water year 1985



# Explicit modeled outputs allow us to calculate a fully defined water balance



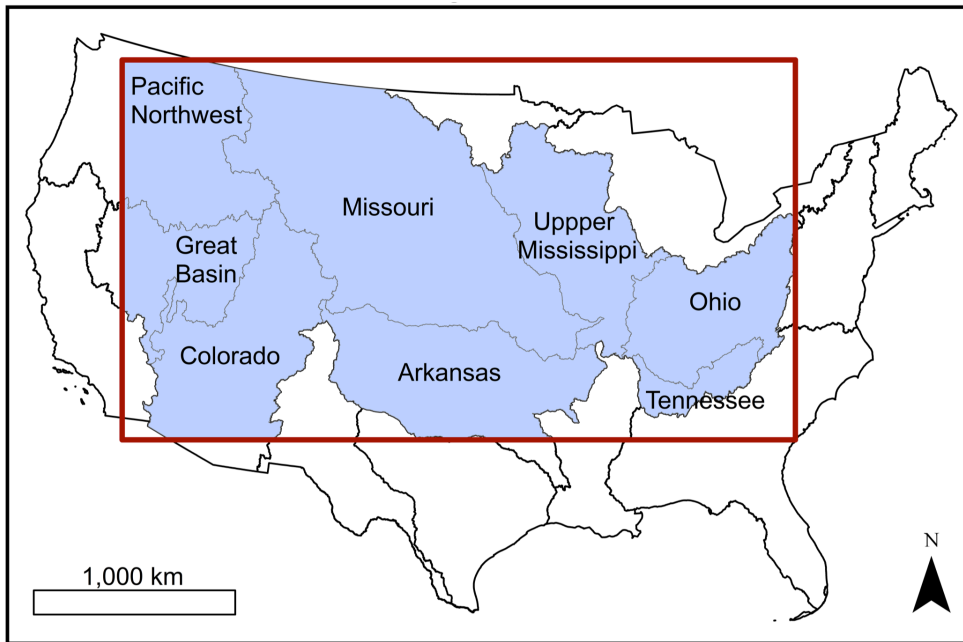
Surface water balance  
for a watershed:

$$ET + Q + R = P$$

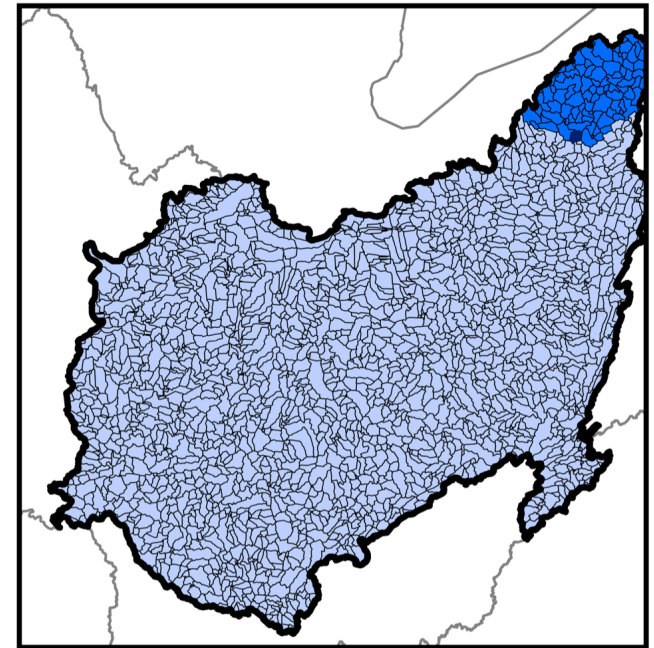
$$ET/P + Q/P + R/P = 1$$

Using this approach can we improve our understanding of groundwater surface water interactions across spatial scales?

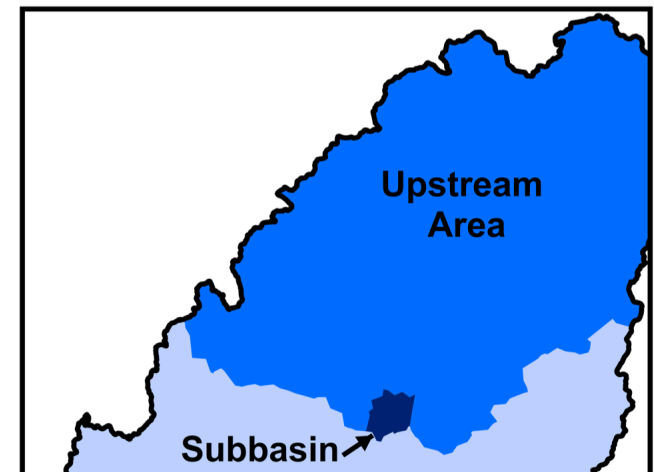
8 major river basins with drainage areas exceeding 2 million km<sup>2</sup>



33,454 subbasins  
(~100 km<sup>2</sup>)

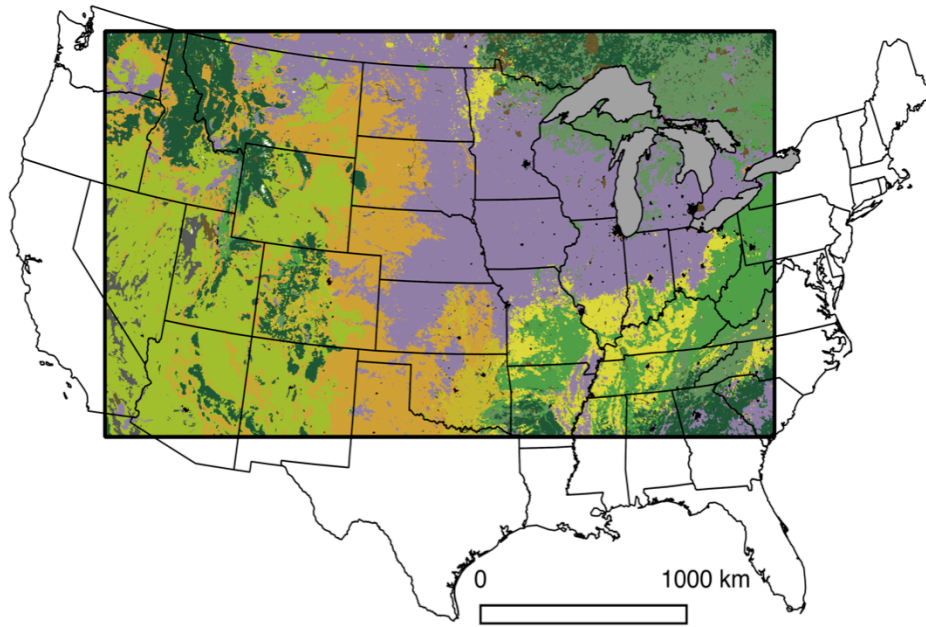


Every subbasin is aggregated to include its entire upstream area creating a system of 33,454 nested watersheds

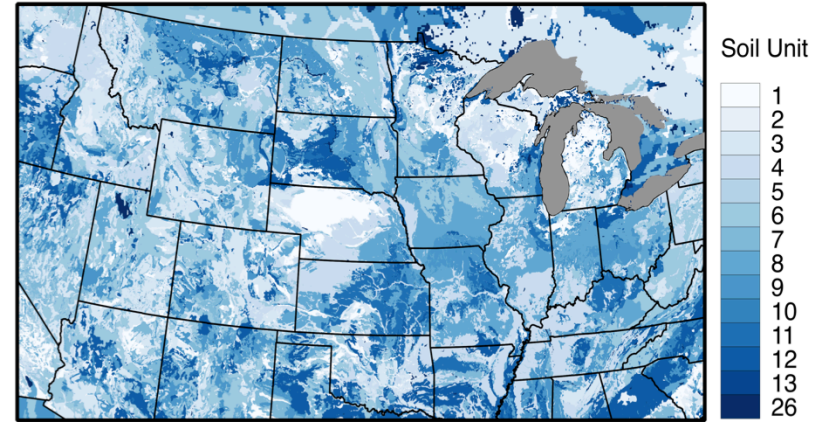




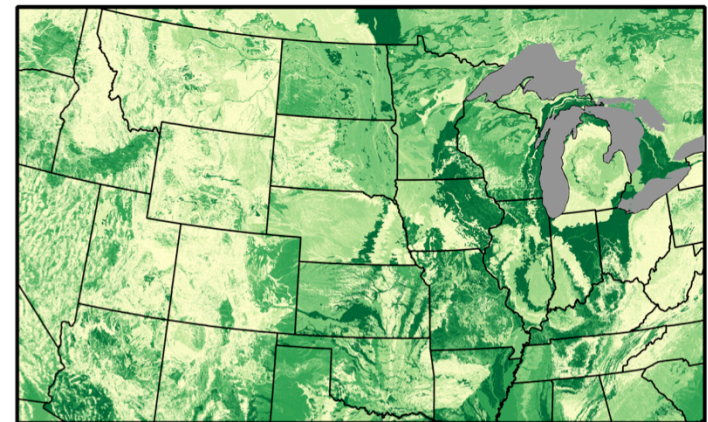
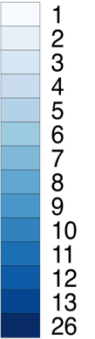
# Covering a broad range of physical settings



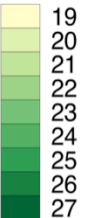
Land Cover Type



Soil Unit



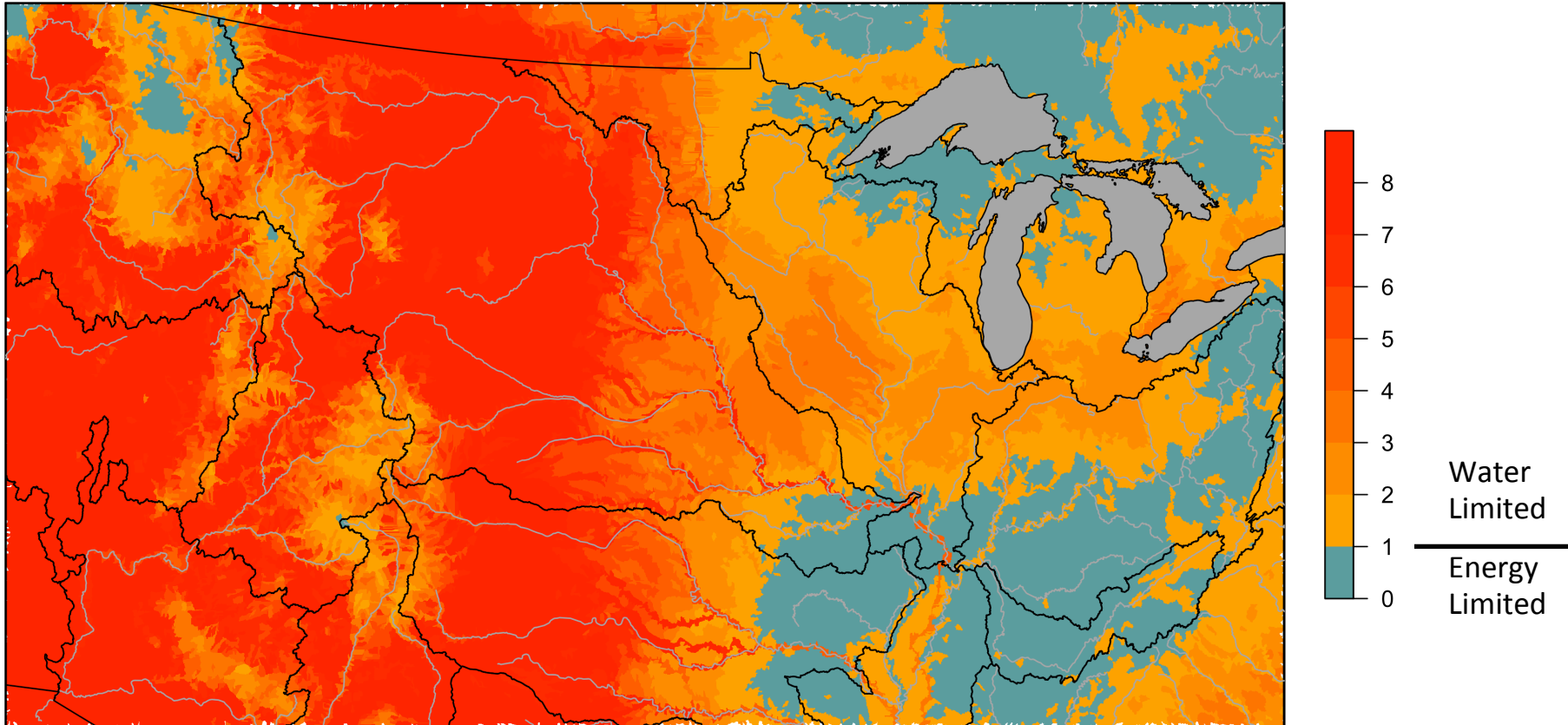
Geologic Unit





# Covering a broad range of physical settings and climates

Aridity Index (PE/P)

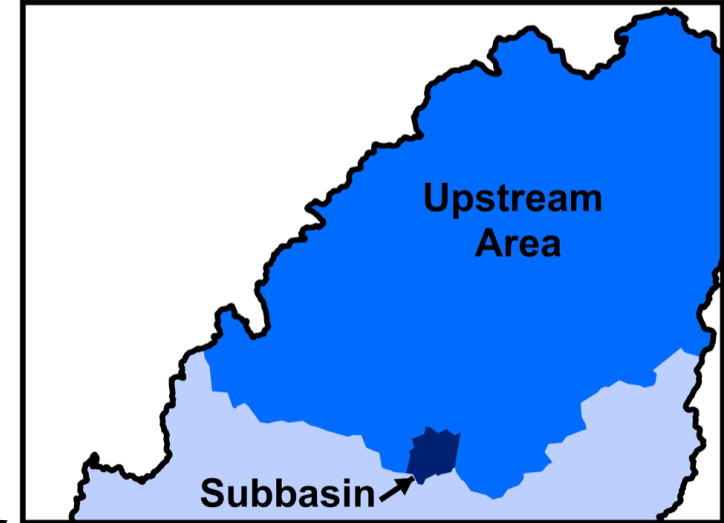
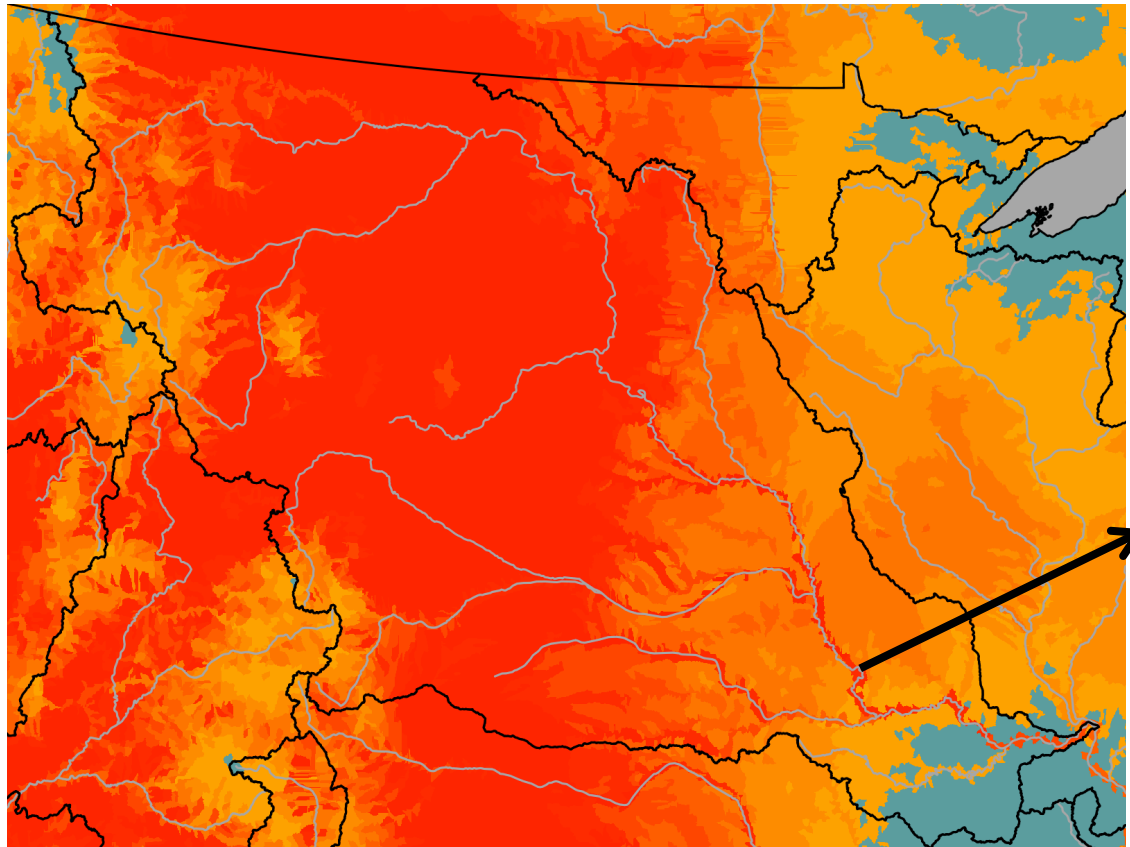


PE = Potential evaporation

Calculated using similarity approach based on:

- 1) Climate forcings: pressure, temperature, wind, specific humidity
- 2) Simulated ground temperature

Covering a broad range of spatial scales,  
physical settings and **climates**

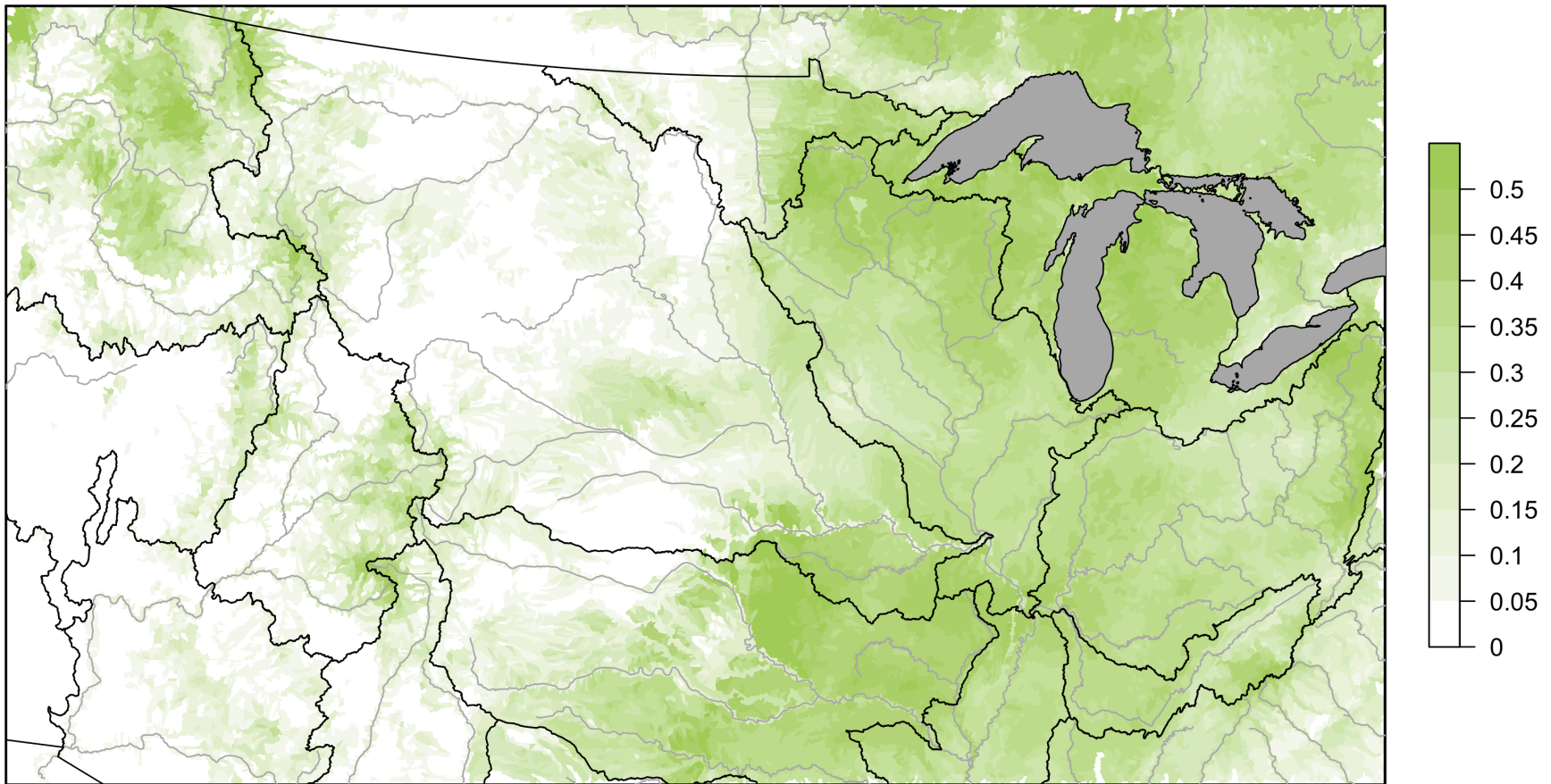


How do groundwater surface water exchanges influence surface water partitioning?

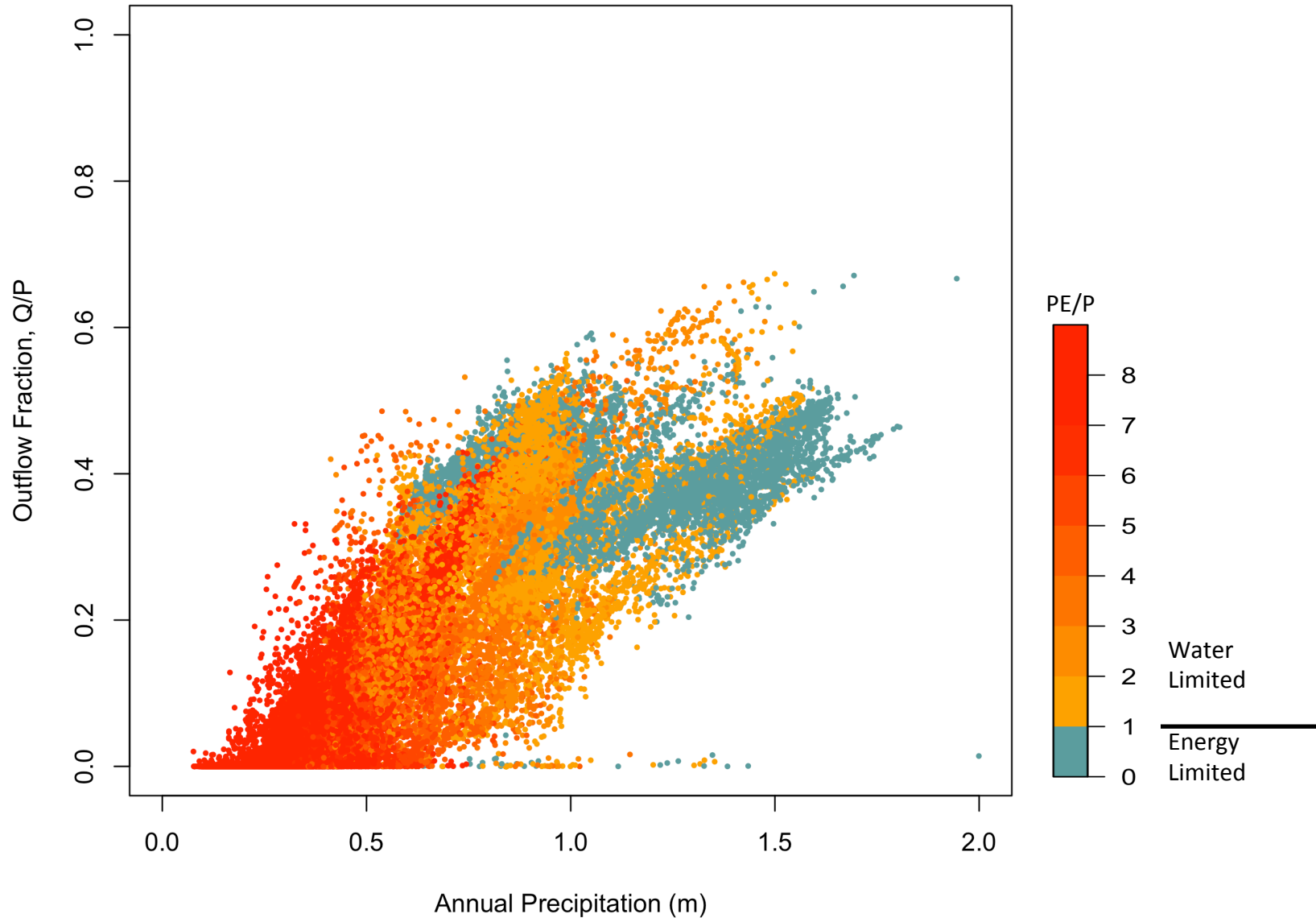
# Using model result to evaluate water and energy balance

Overland Flow Fraction (Q/P)

$$ET/P + Q/P + R/P = 1$$



# Outflow fractions vary with precipitation

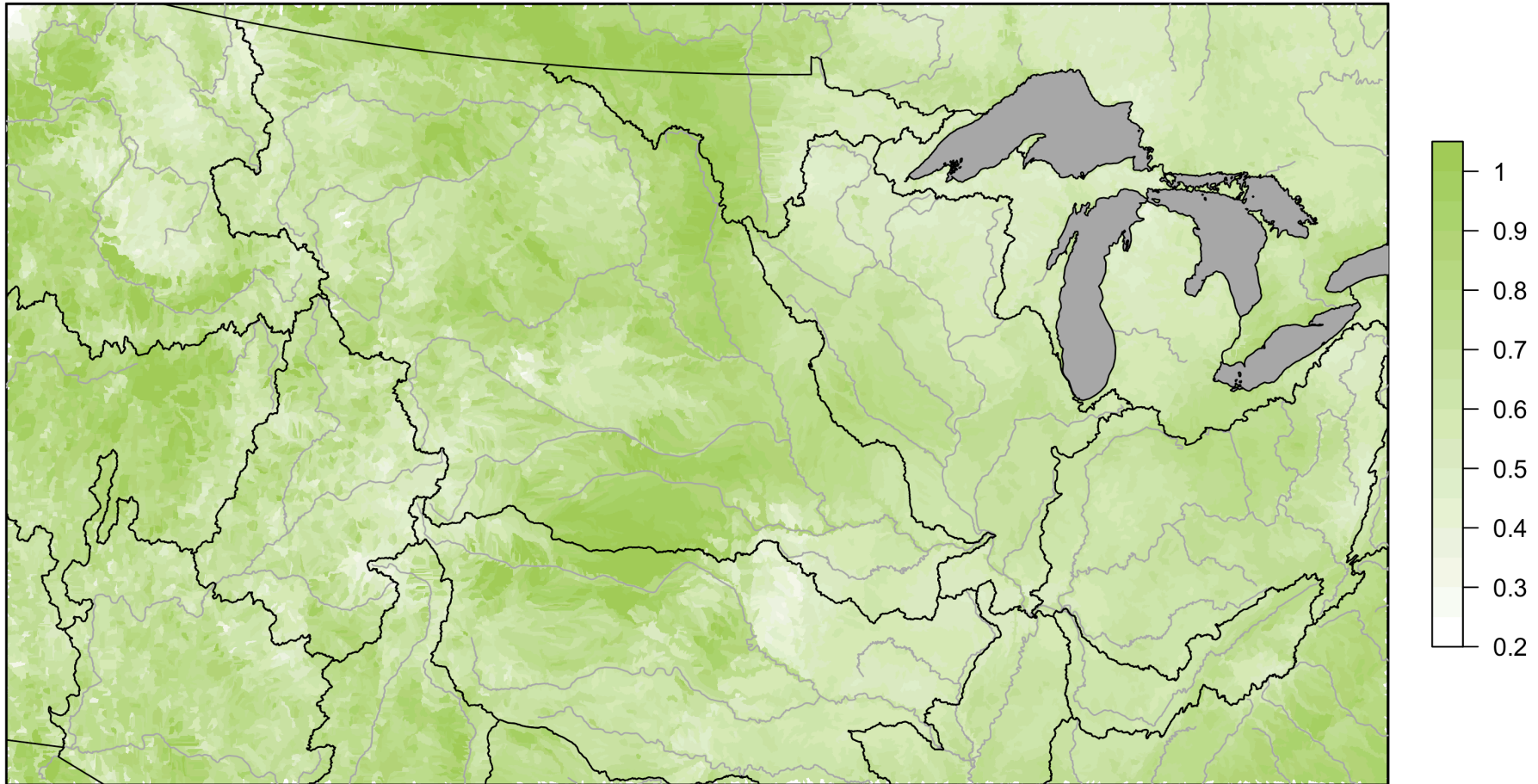




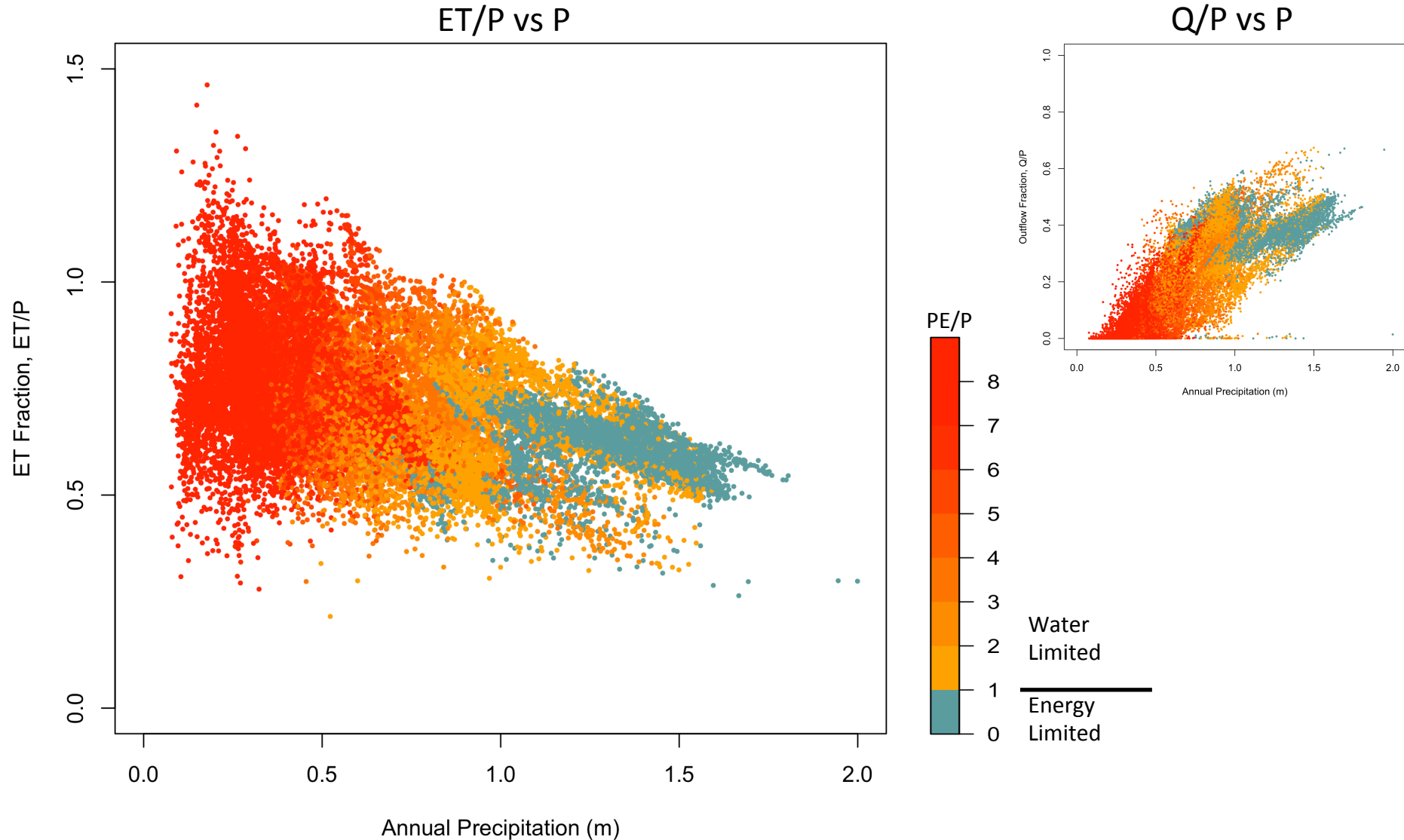
# ET is a significant component of the water balance

**Evapotranspiration Fraction (ET/P)**

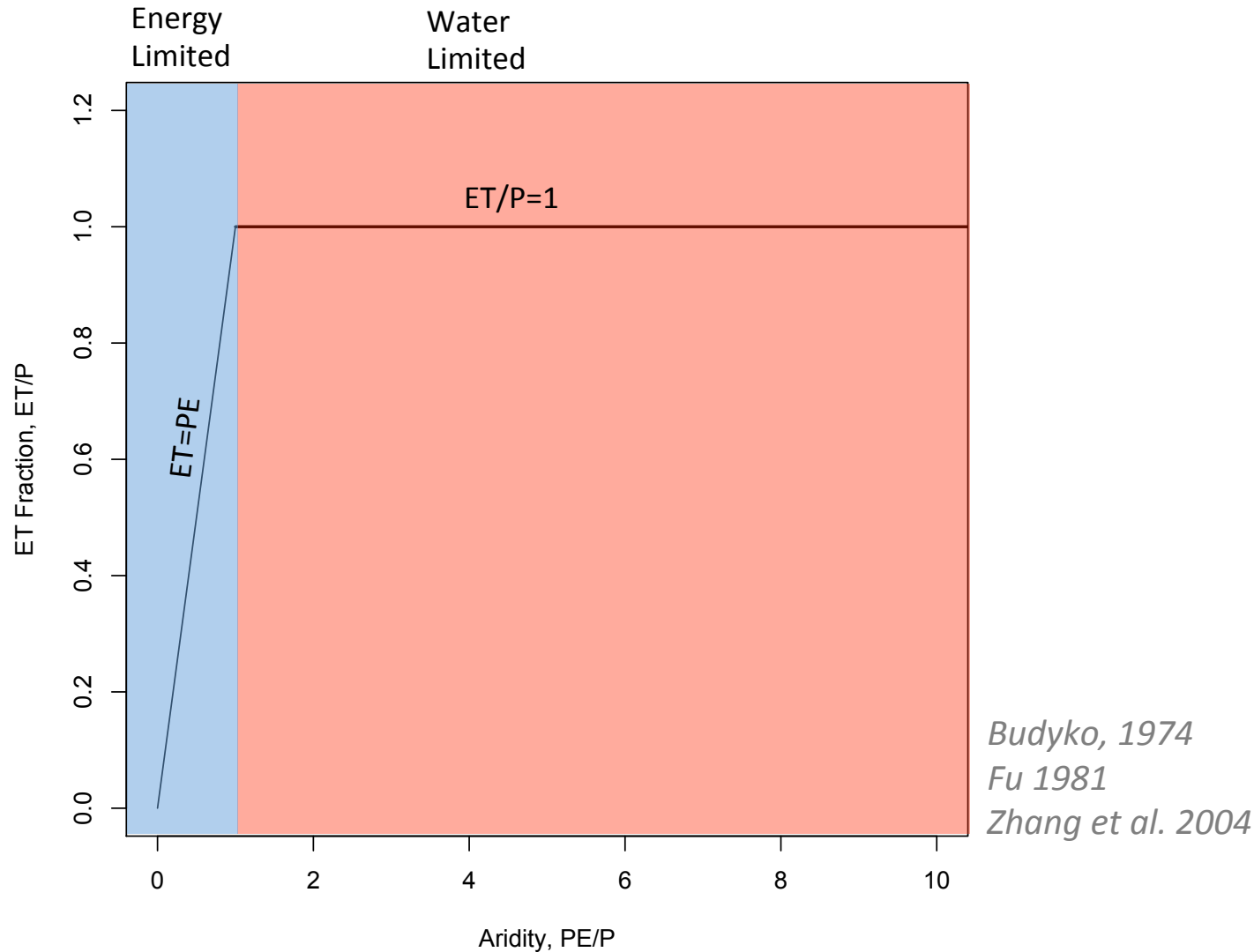
$$ET/P + Q/P + R/P = 1$$



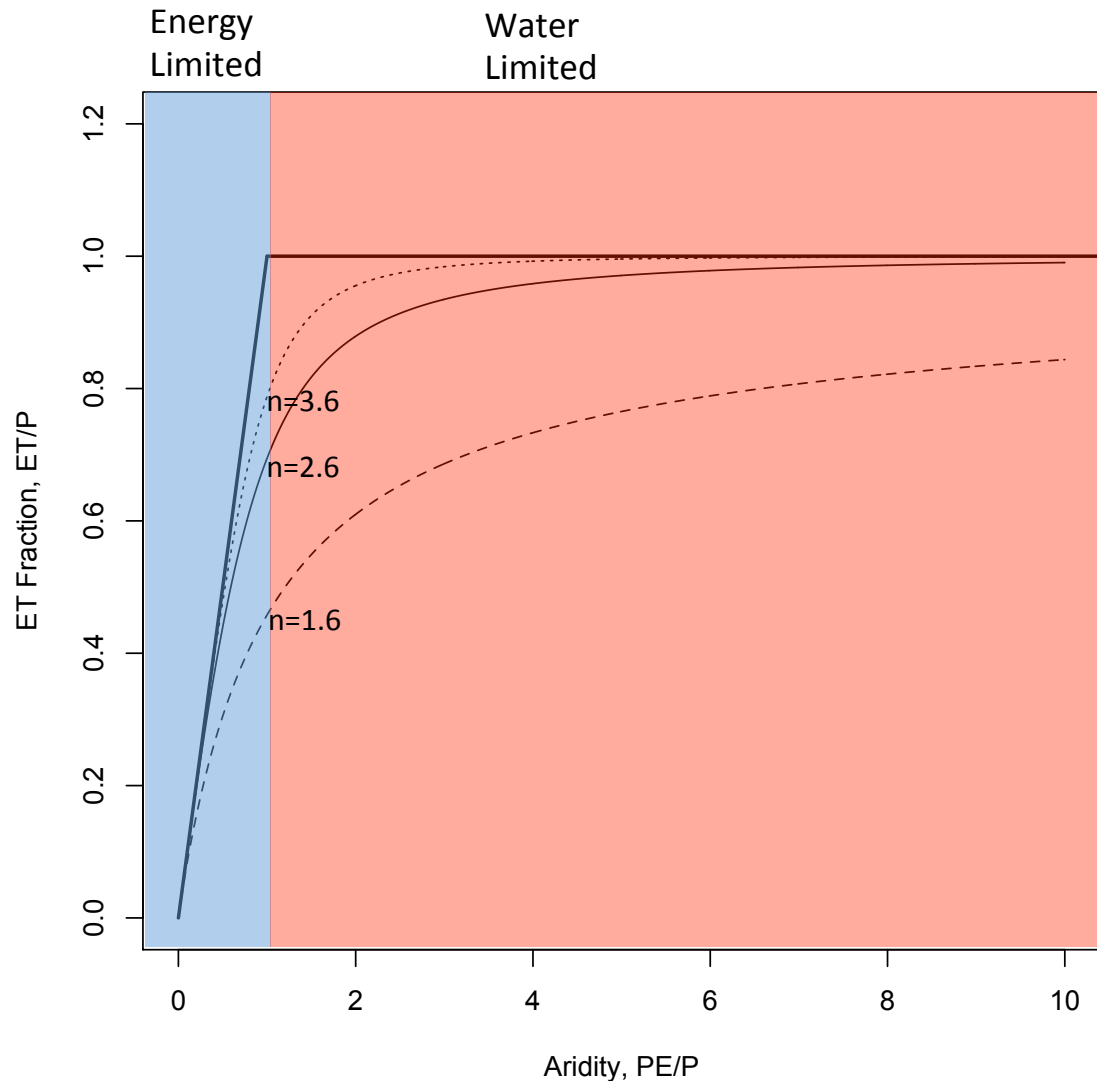
# ET is not related as strongly to precipitation as streamflow



# Budyko hypothesis relates ET fraction to both water and energy supply



# Budyko Hypothesis relates ET fraction to both water and energy supply



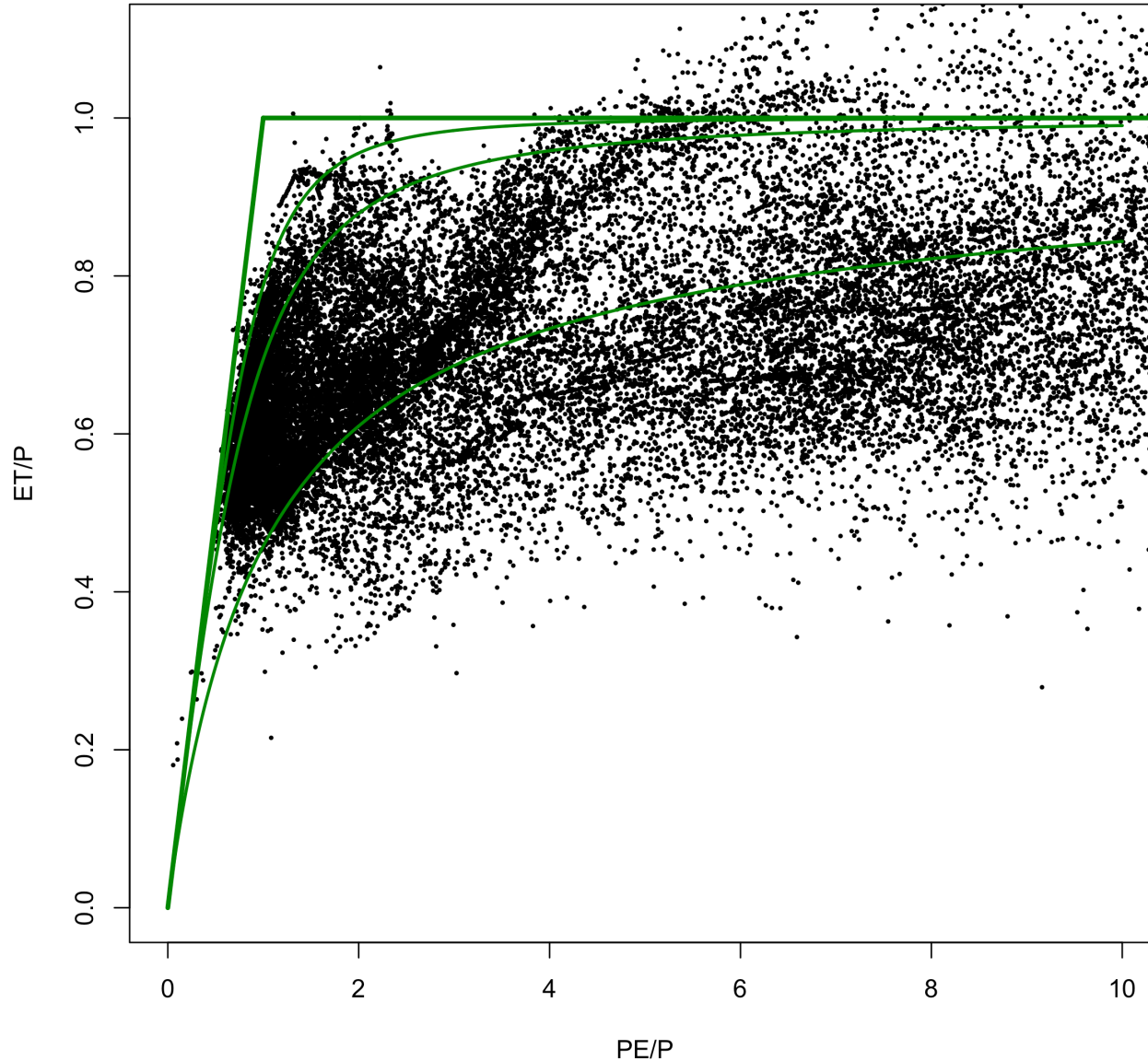
$$\frac{ET}{P} = 1 + \frac{PE}{P} - \left( 1 - \left( \frac{PE}{P} \right)^n \right)^{1/n}$$

*Budyko, 1974*

*Fu 1981*

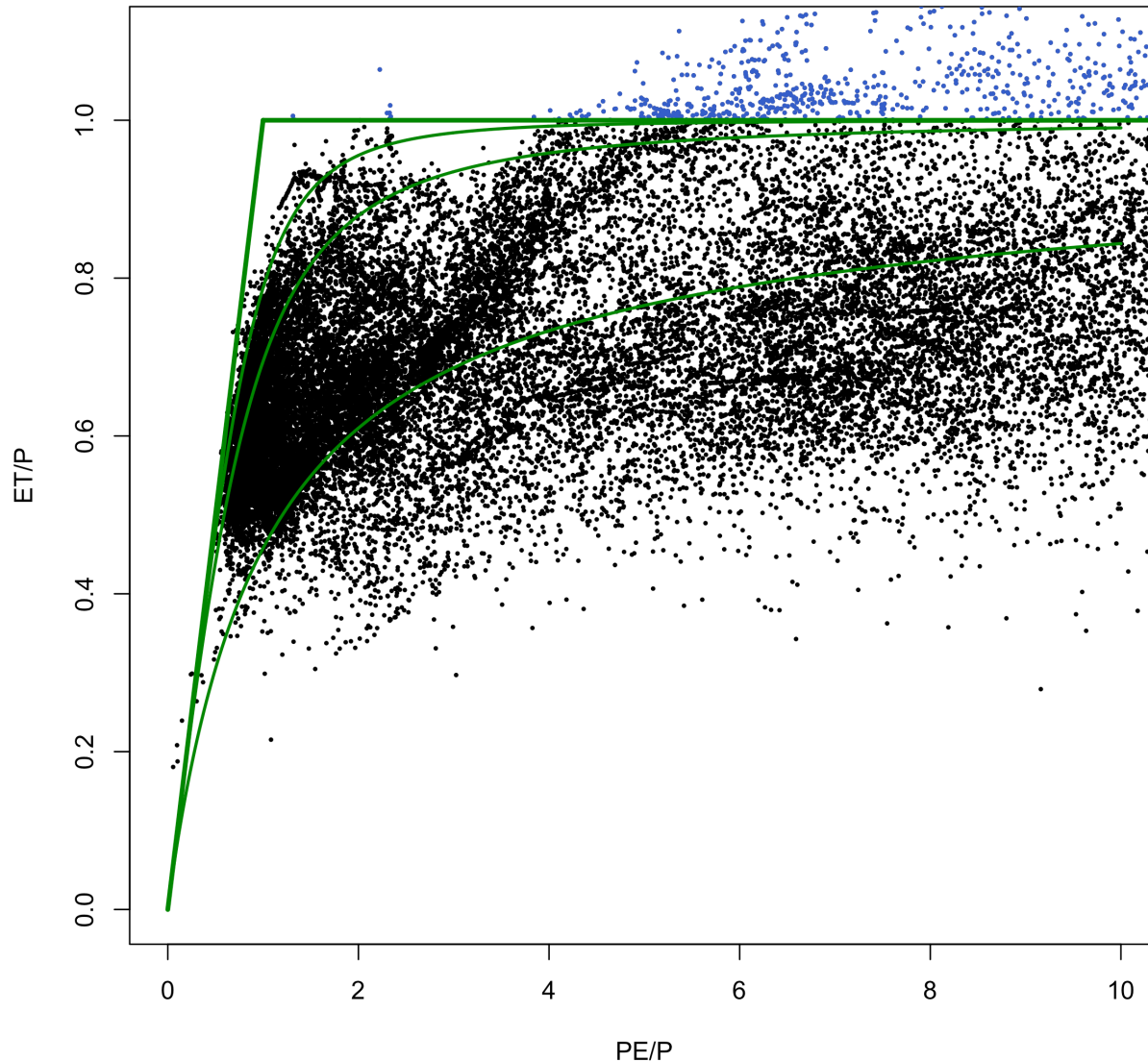
*Zhang et al. 2004*

# Simulated results follow Budyko curves





# Groundwater surface water exchanges violate BH assumptions

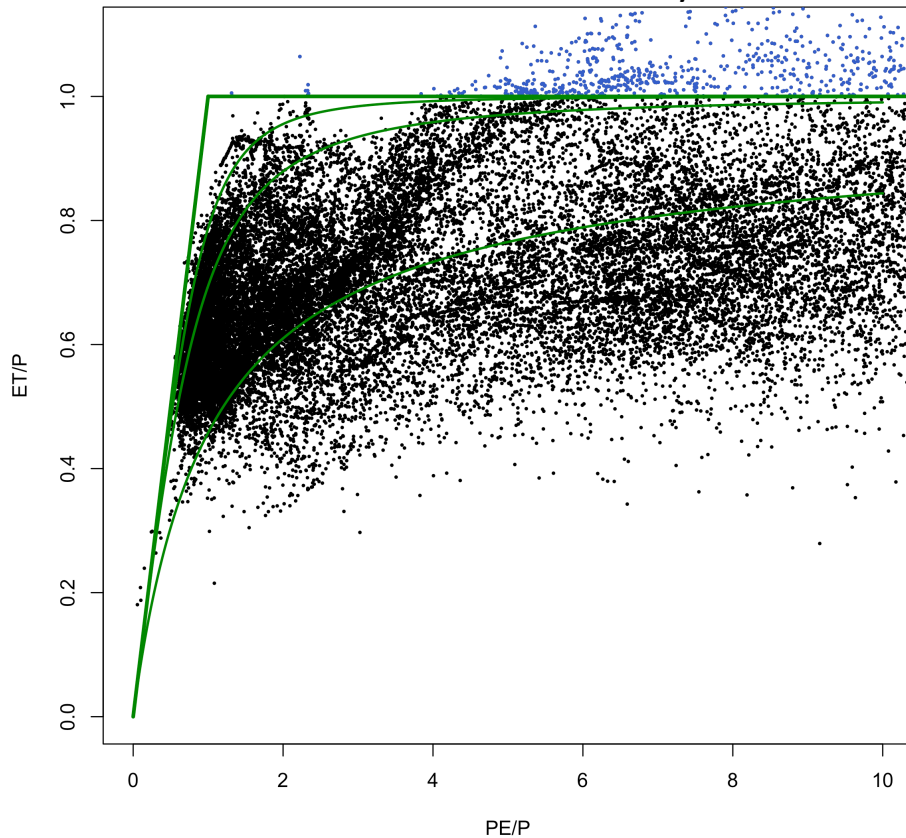


ET/P > 1 values can occur when lateral groundwater flow supports ET

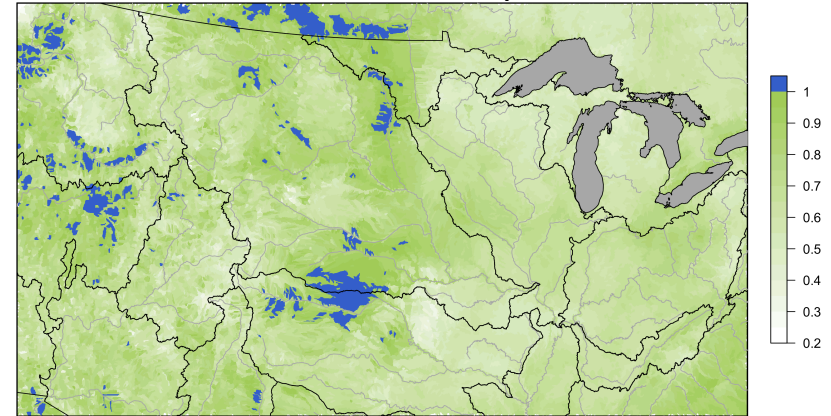
BH assumes no storage changes and groundwater surface water exchanges:  
 $ET + Q = P$

# ET fractions greater than one can occur in arid locations

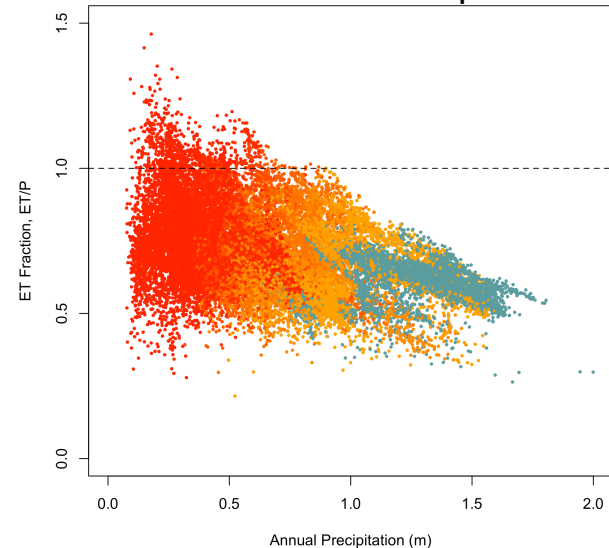
ET Fraction vs. Aridity



ET Fraction Map



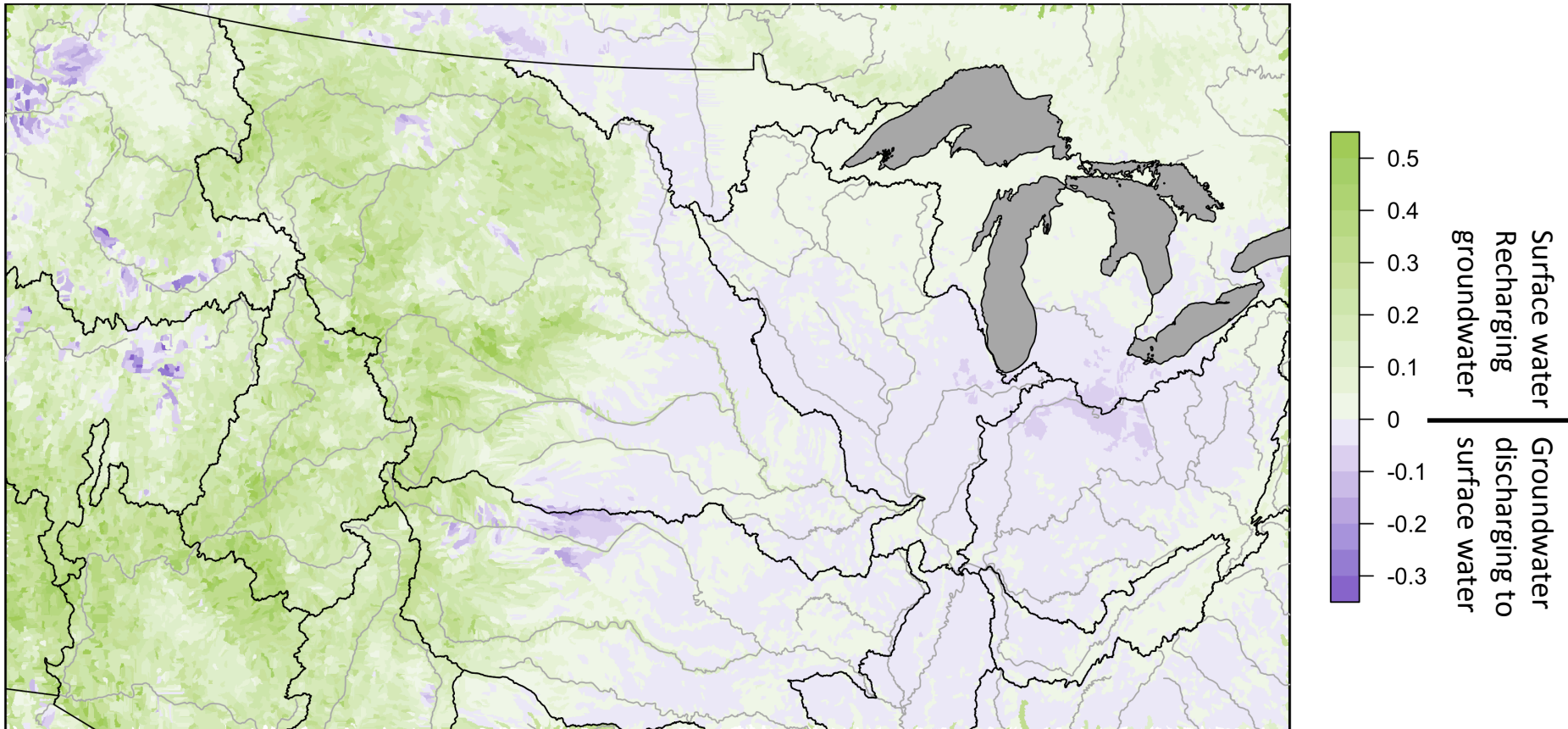
ET Fraction vs. Precipitation



# Groundwater surface water exchanges are prevalent

Recharge Fraction (R/P)

$$ET/P + Q/P + R/P = 1$$

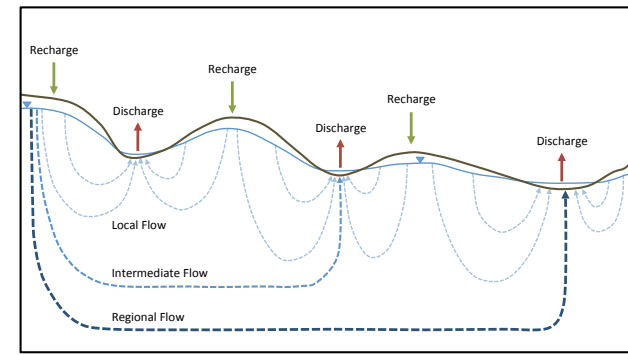




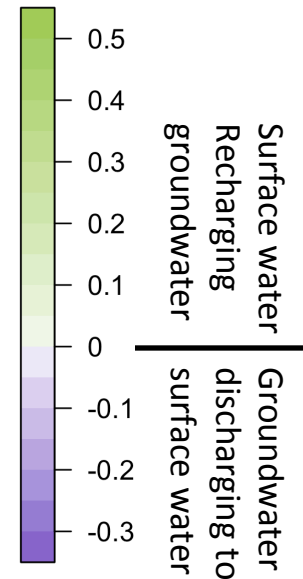
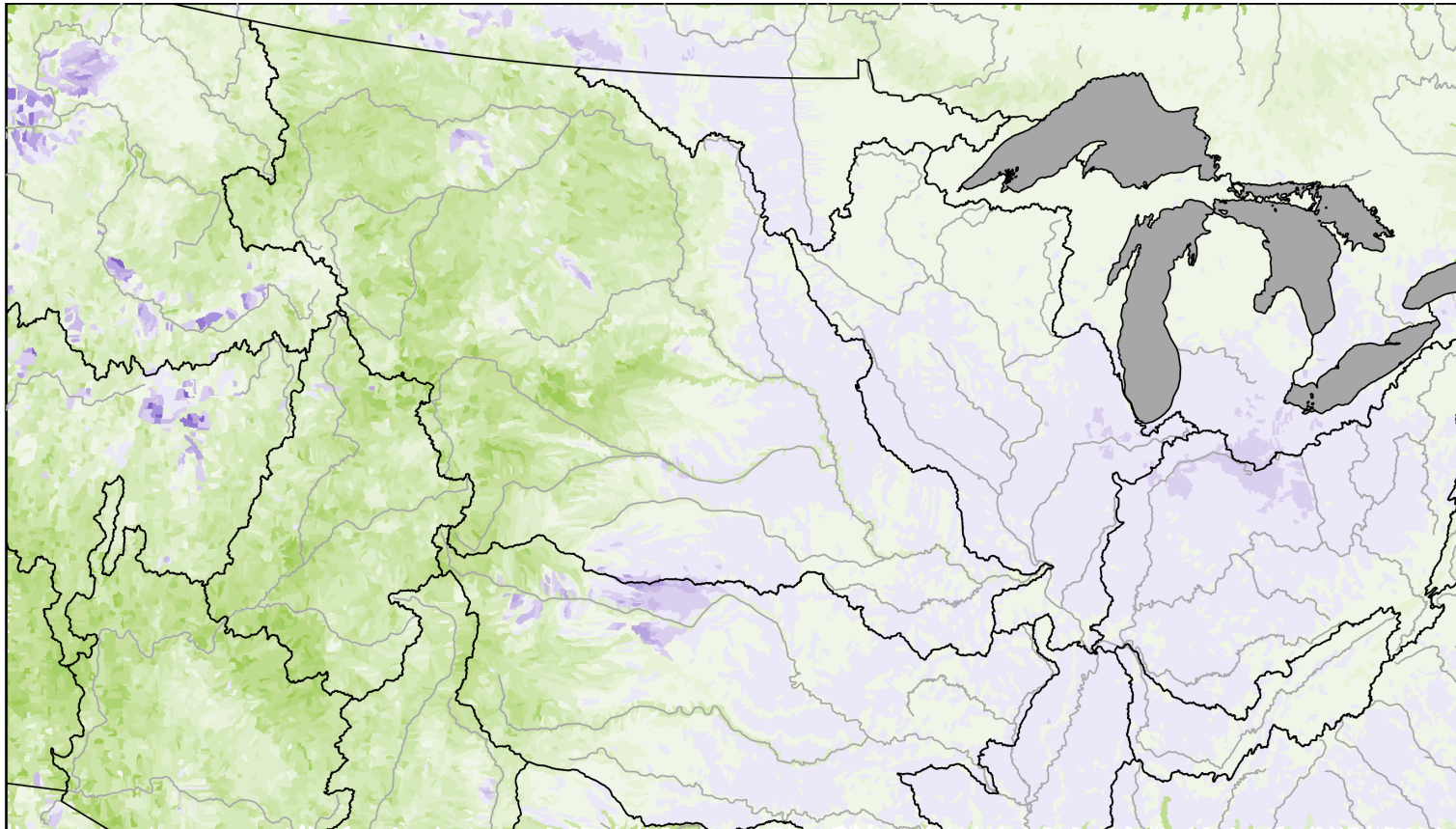
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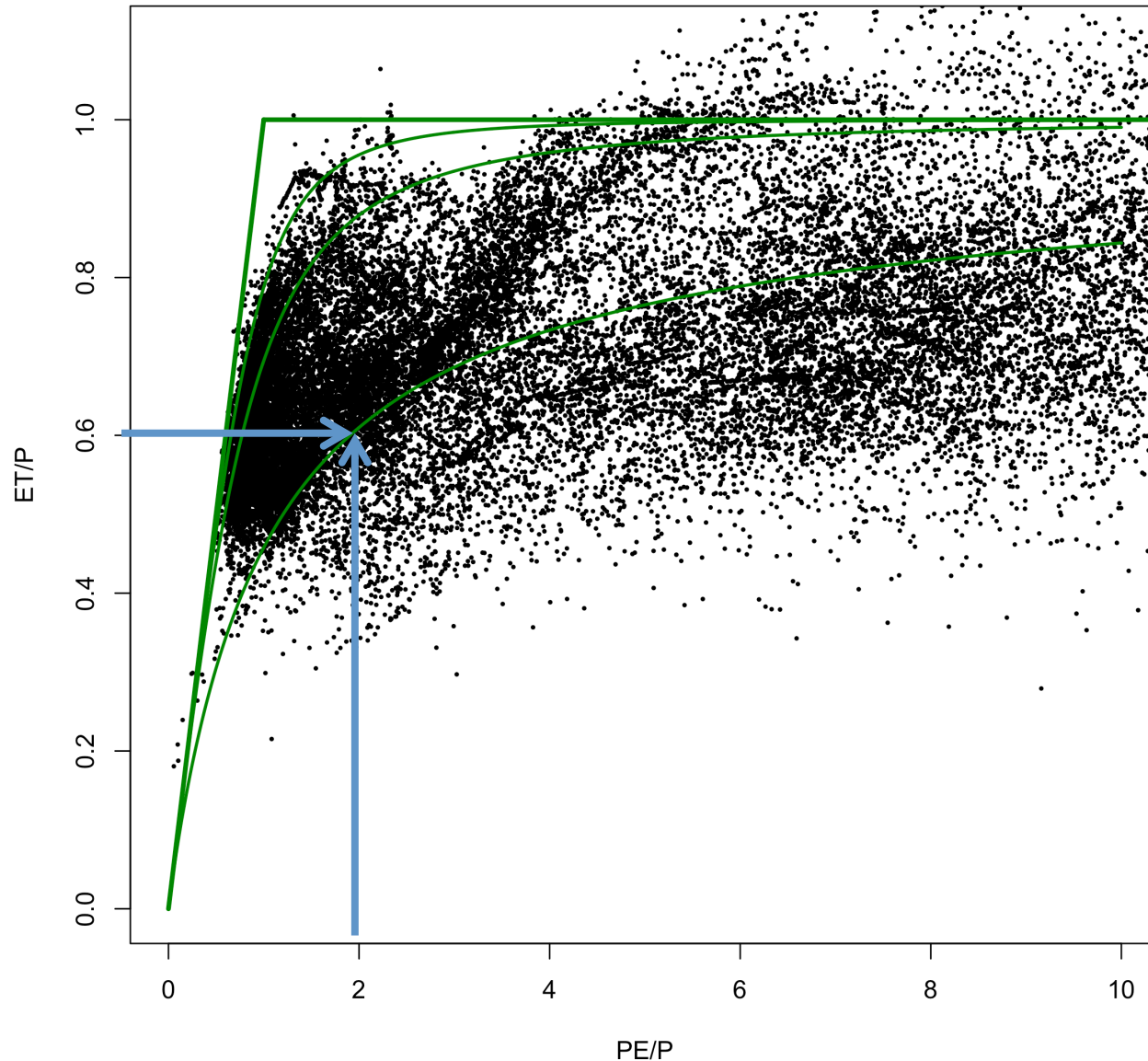
$$ET/P + Q/P + R/P = 1$$



e.g. Hubert, 1940; Toth, 1963

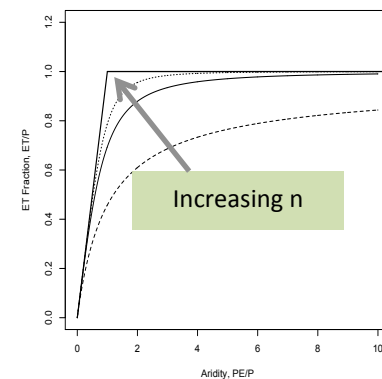
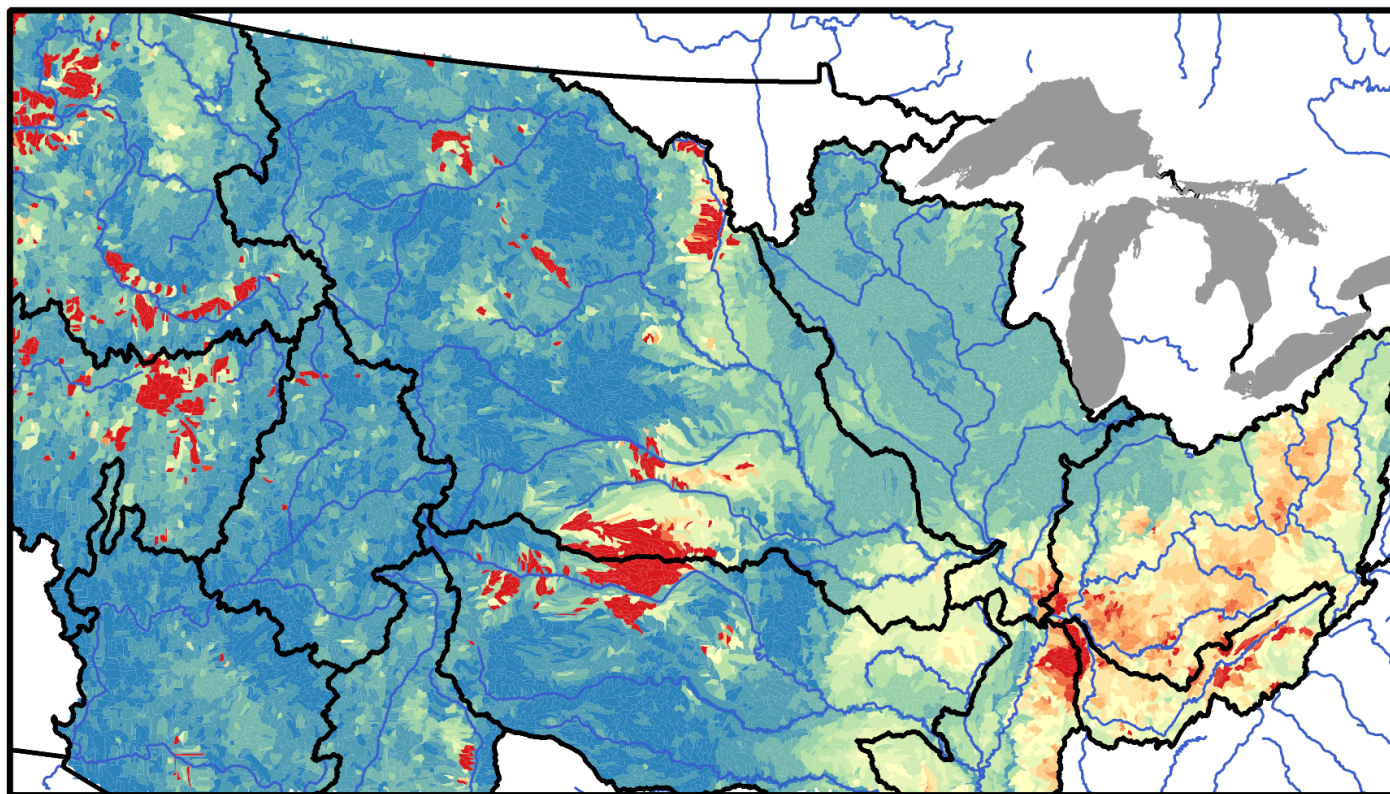


# A unique shape parameter can be calculated for every point

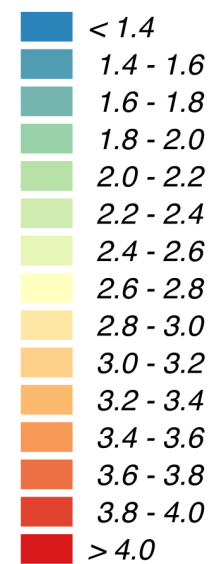


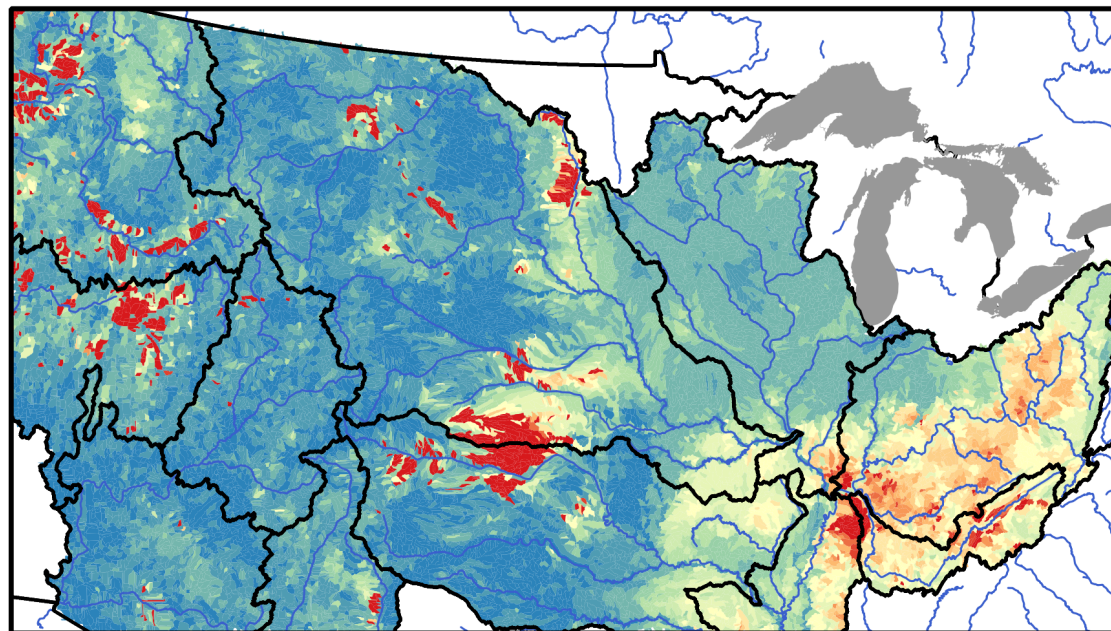
$$\frac{ET}{P} = 1 + \frac{PE}{P} - \left( 1 - \left( \frac{PE}{P} \right)^n \right)^{1/n}$$



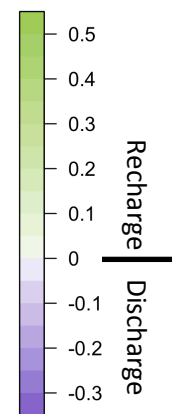
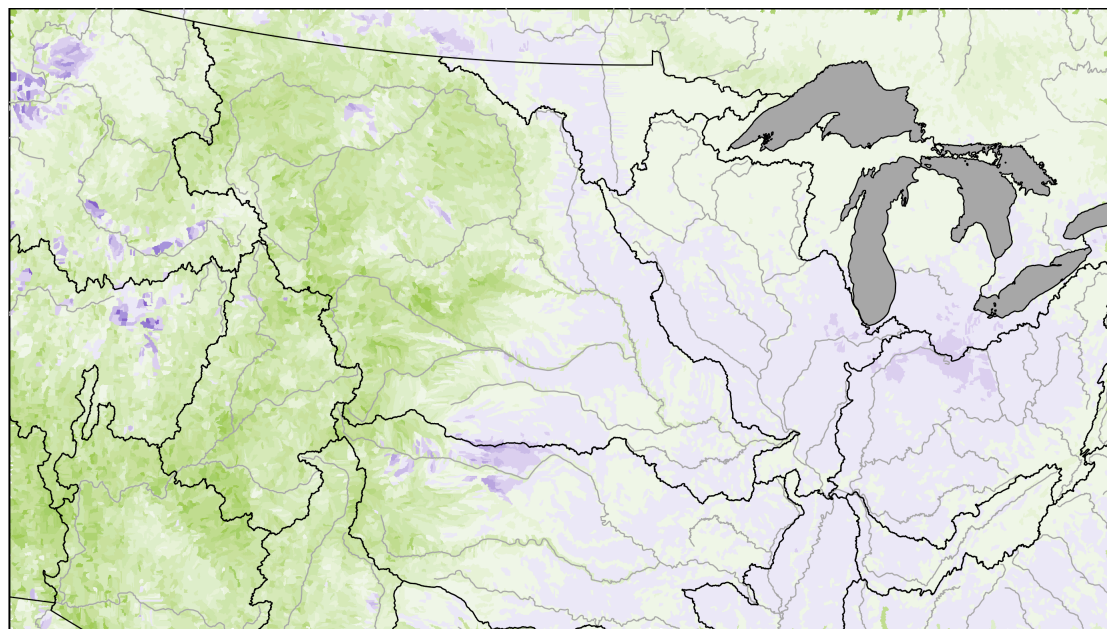
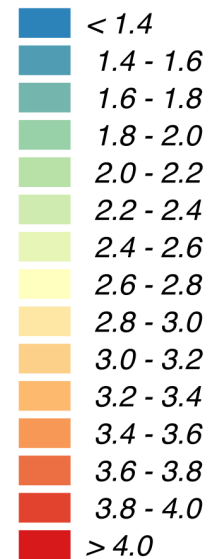


#### Shape Parameter

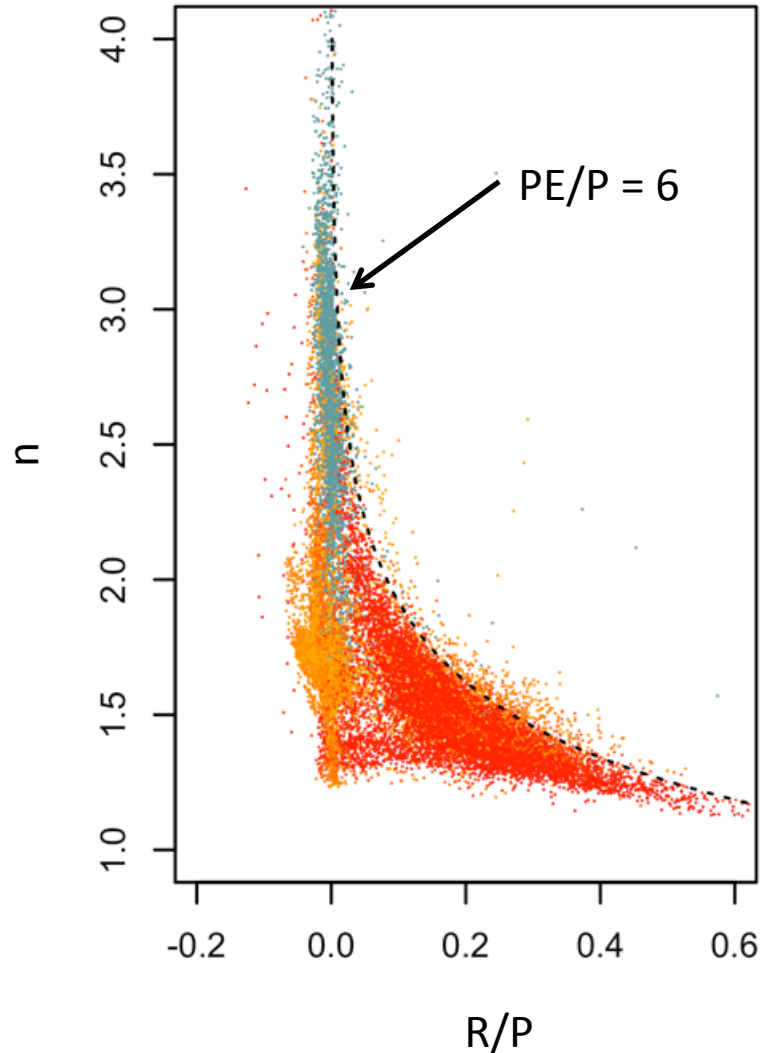




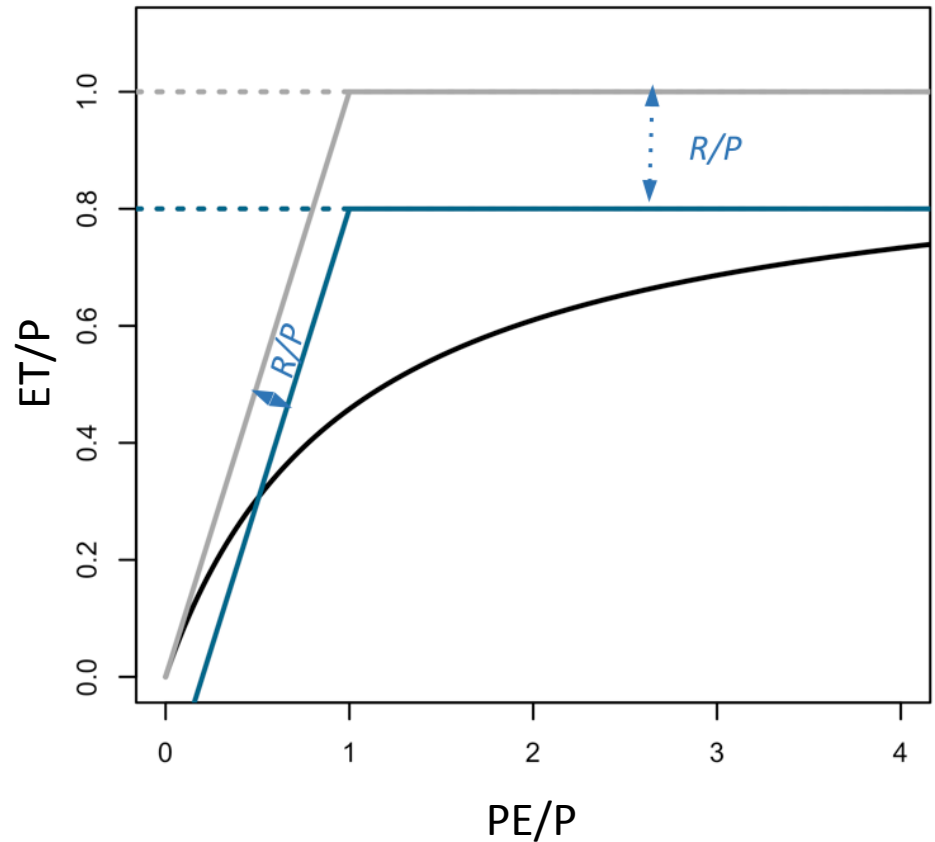
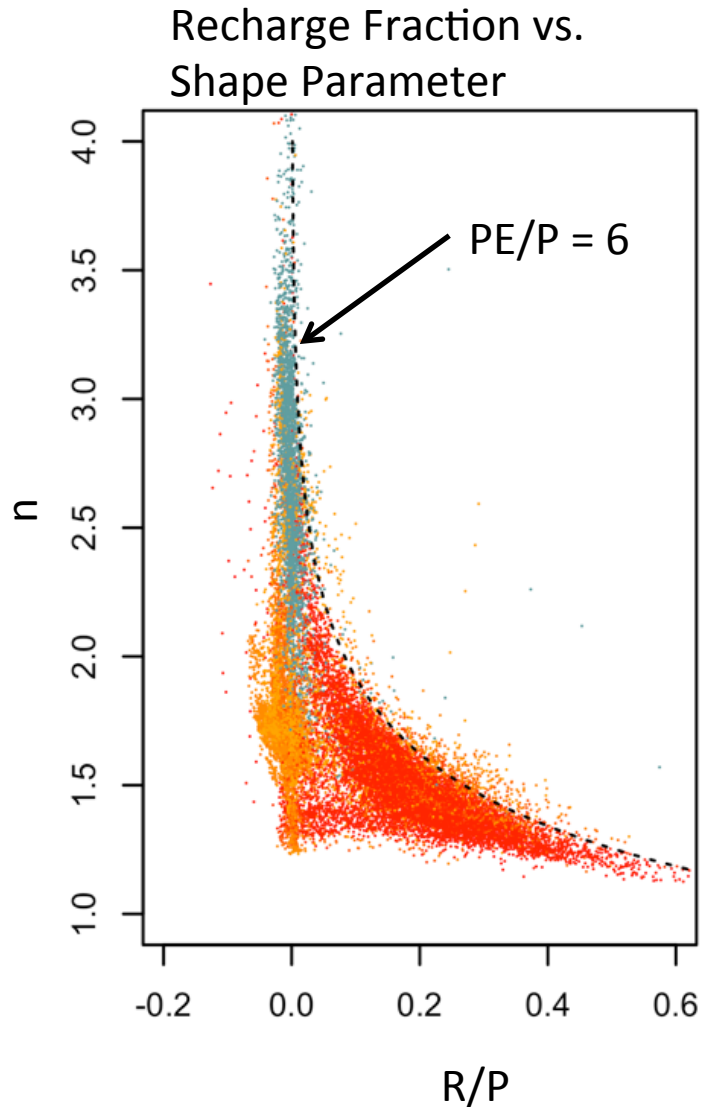
Shape Parameter



# Recharge biases the shape parameters in systematic ways



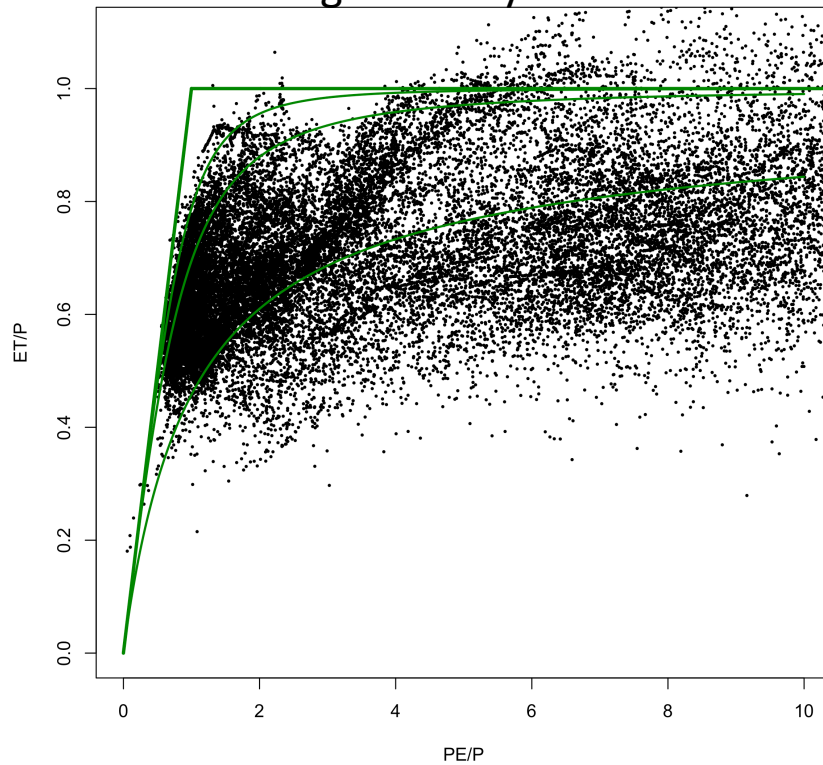
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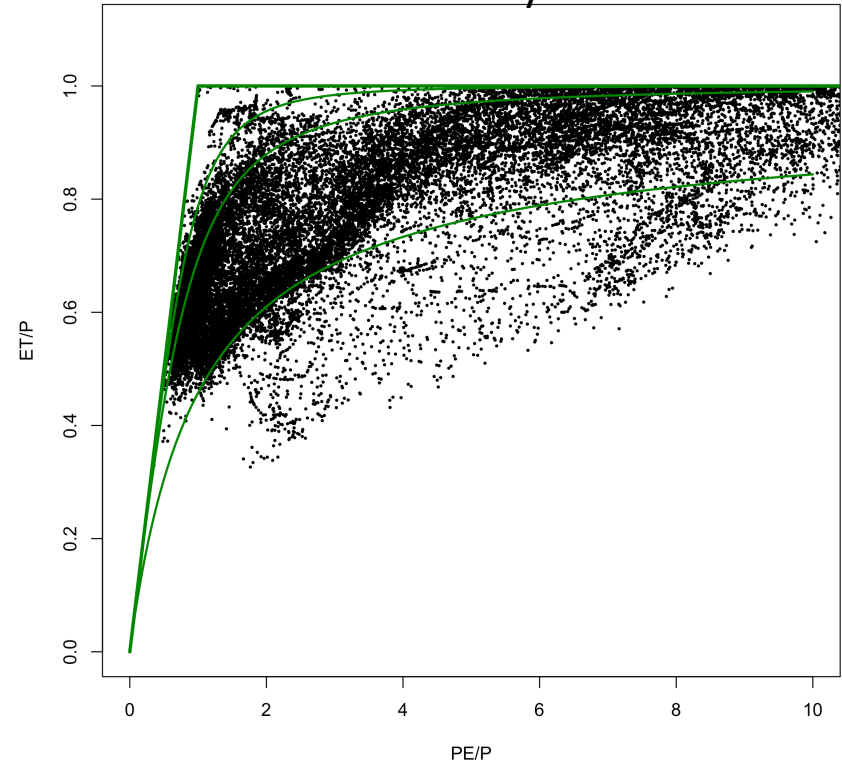


# Adjusting for recharge improves fit with Budyko curves

Original Budyko Plot



Modified Budyko Plot

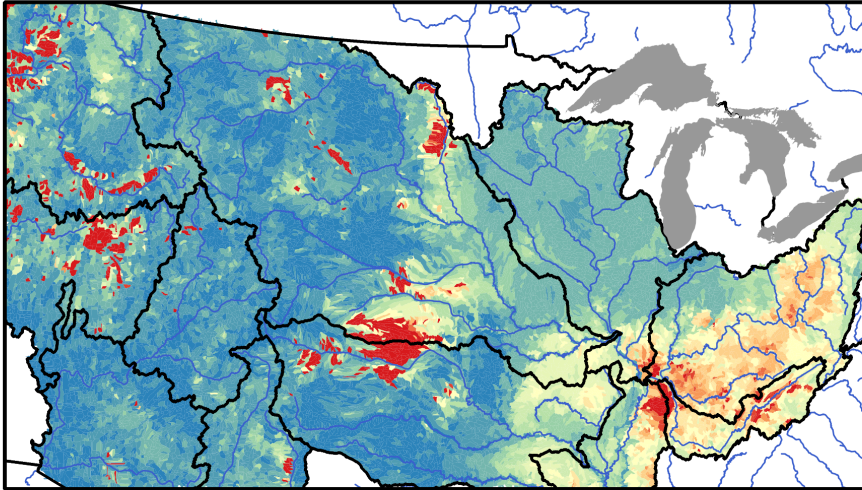


Differences highlight the importance of lateral flow

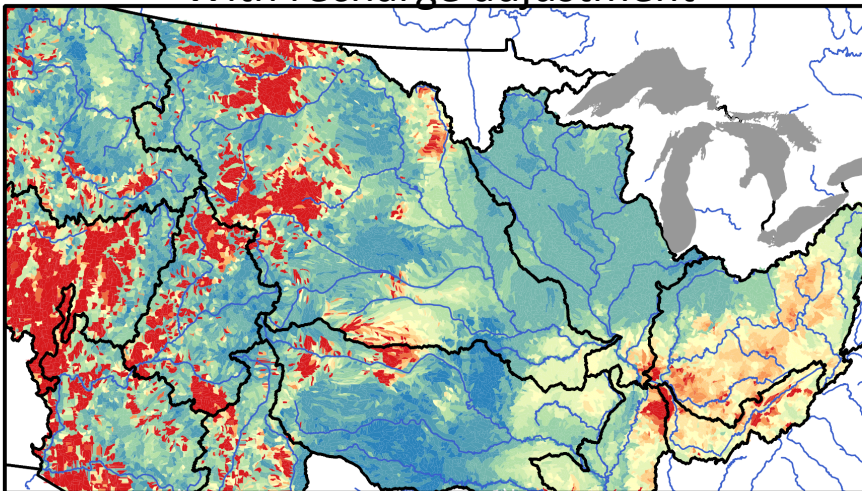


# Adjusting for recharge changes spatial patterns in shape parameters

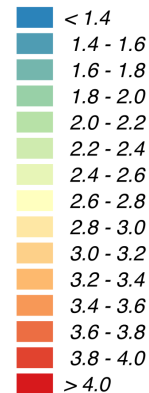
Without recharge adjustment



With recharge adjustment

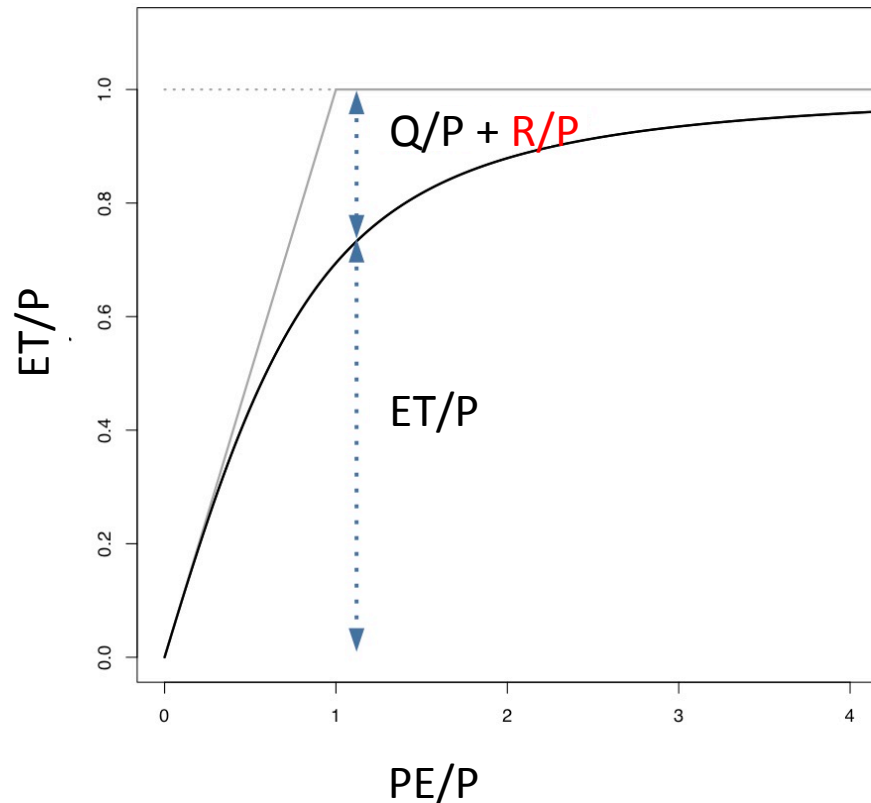


Shape Parameter



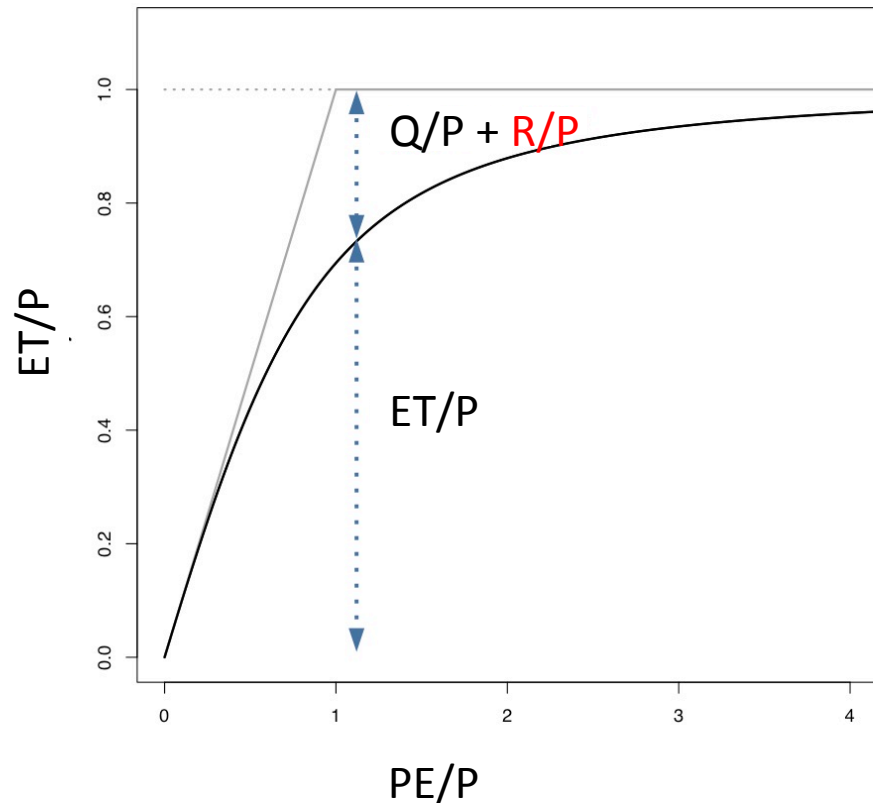
# This impact of groundwater surface water exchanges will vary with methodology

Directly calculating ET but  
assuming no recharge

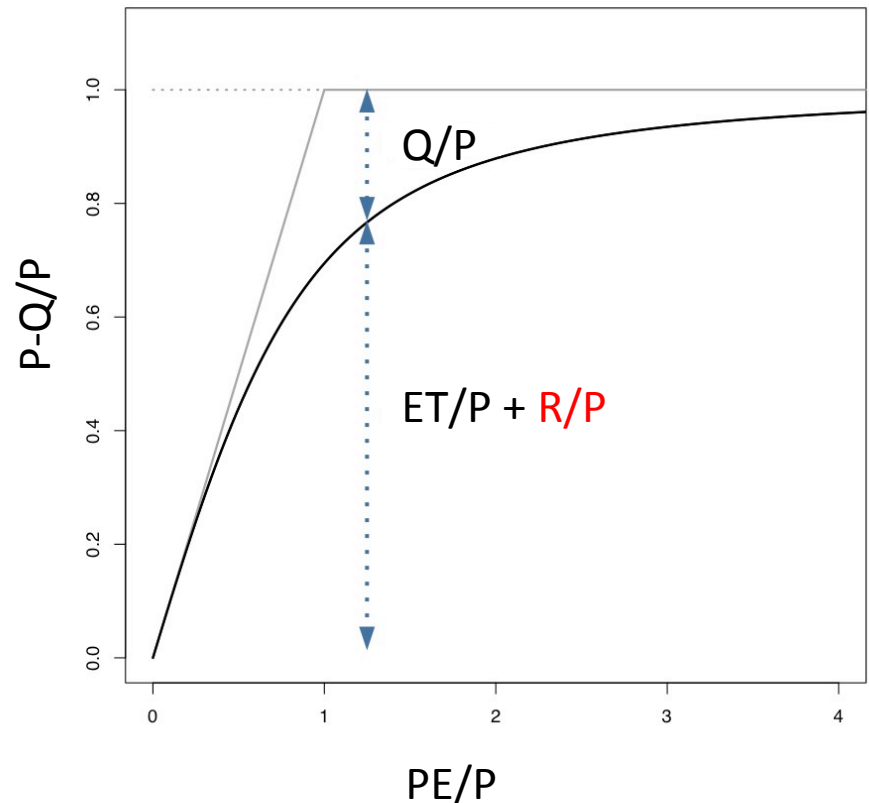


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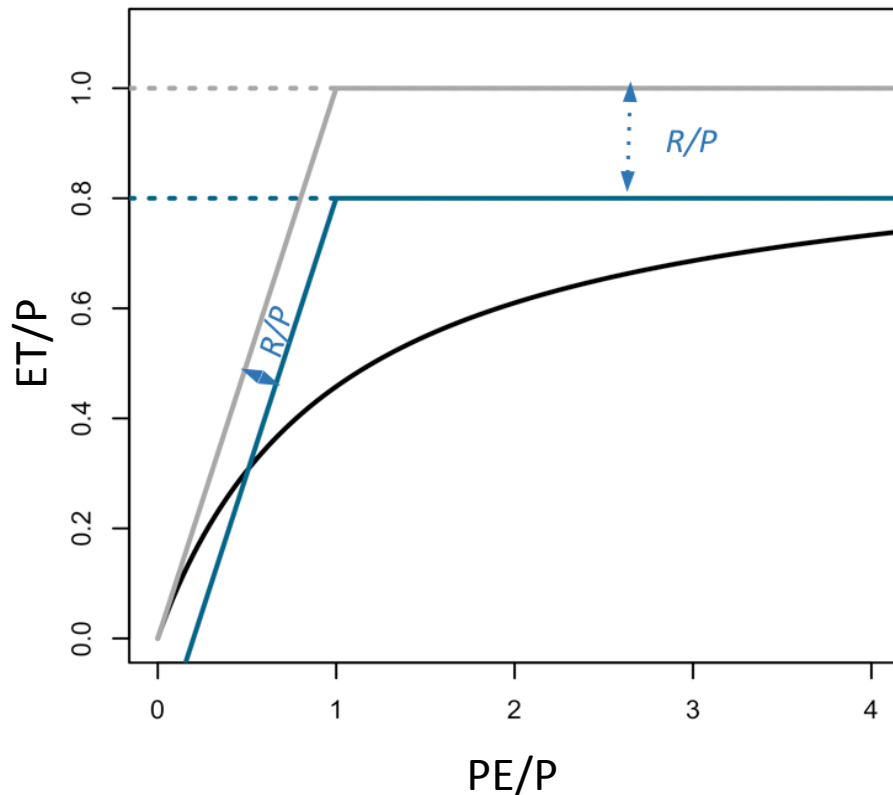


Inferring ET from precipitation and outflow

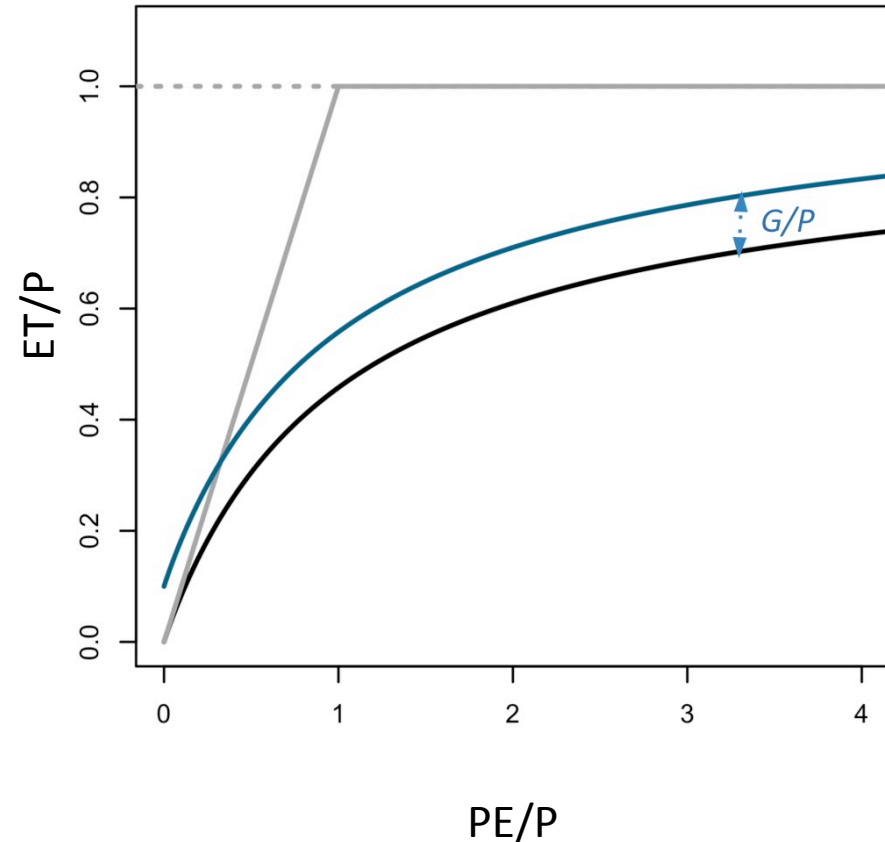


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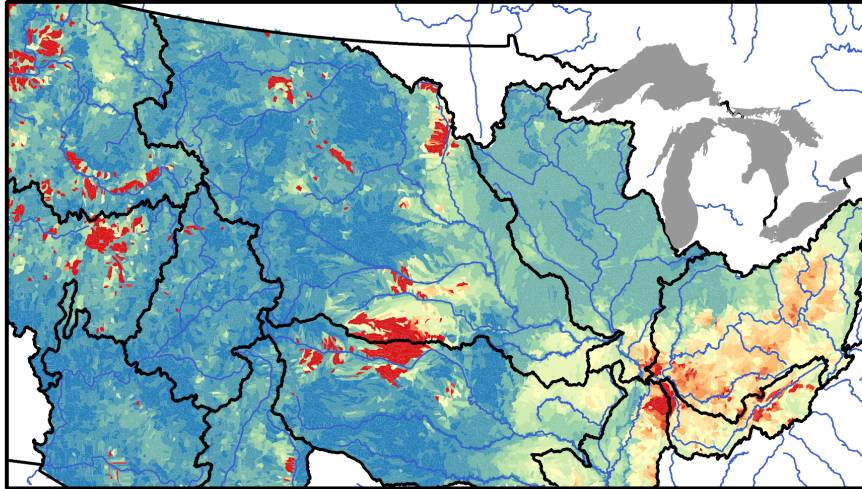


Inferring ET from precipitation and outflow

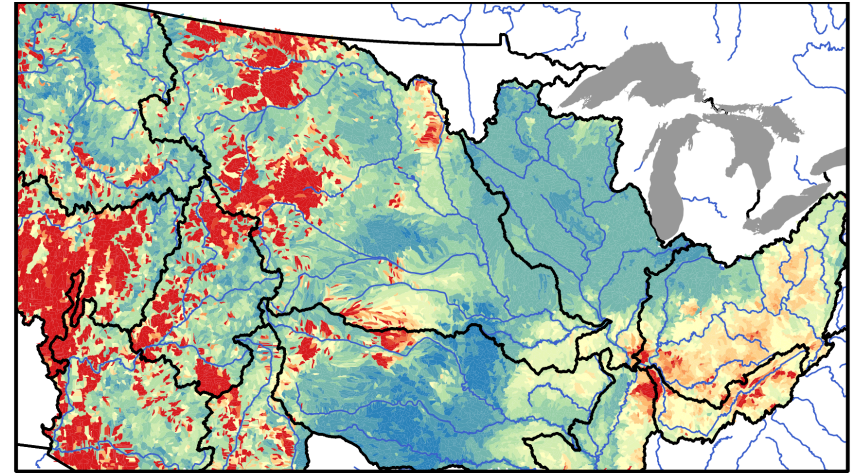




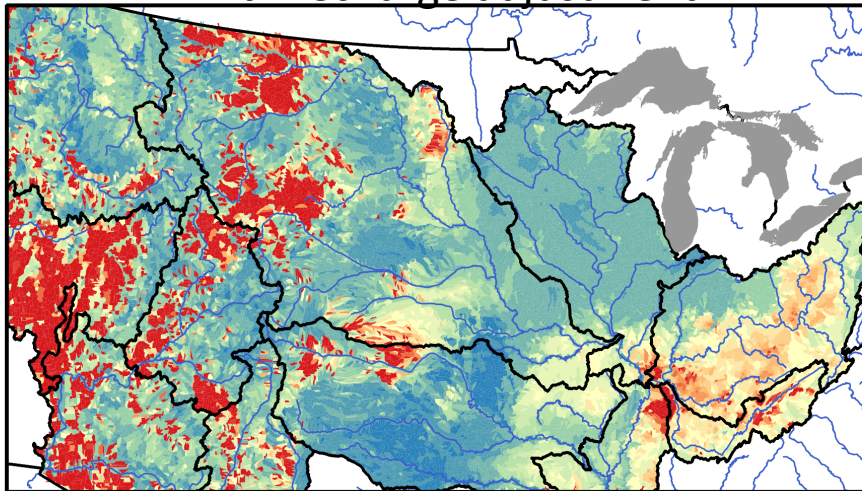
Without recharge adjustment: Directly  
Calculating ET



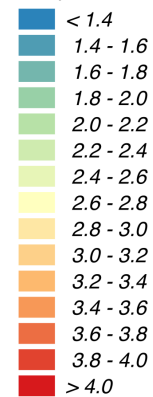
Without recharge adjustment: Inferring  
ET from precipitation and outflow



With recharge adjustment

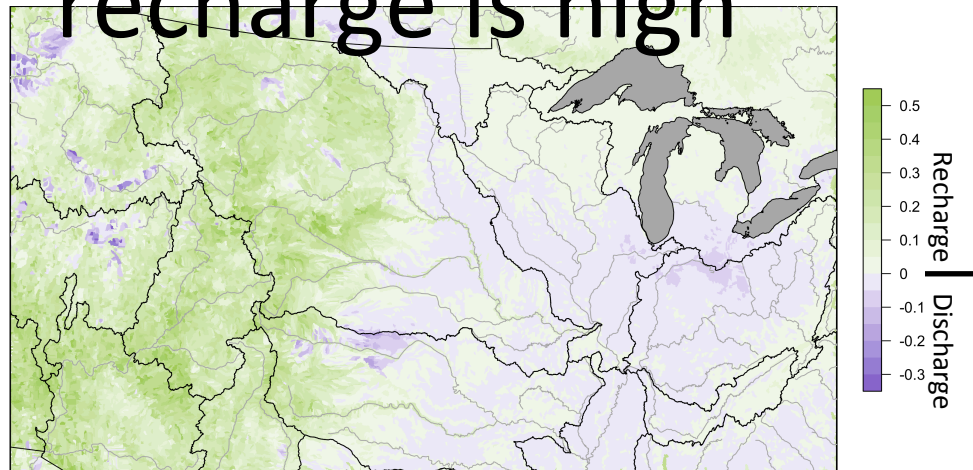
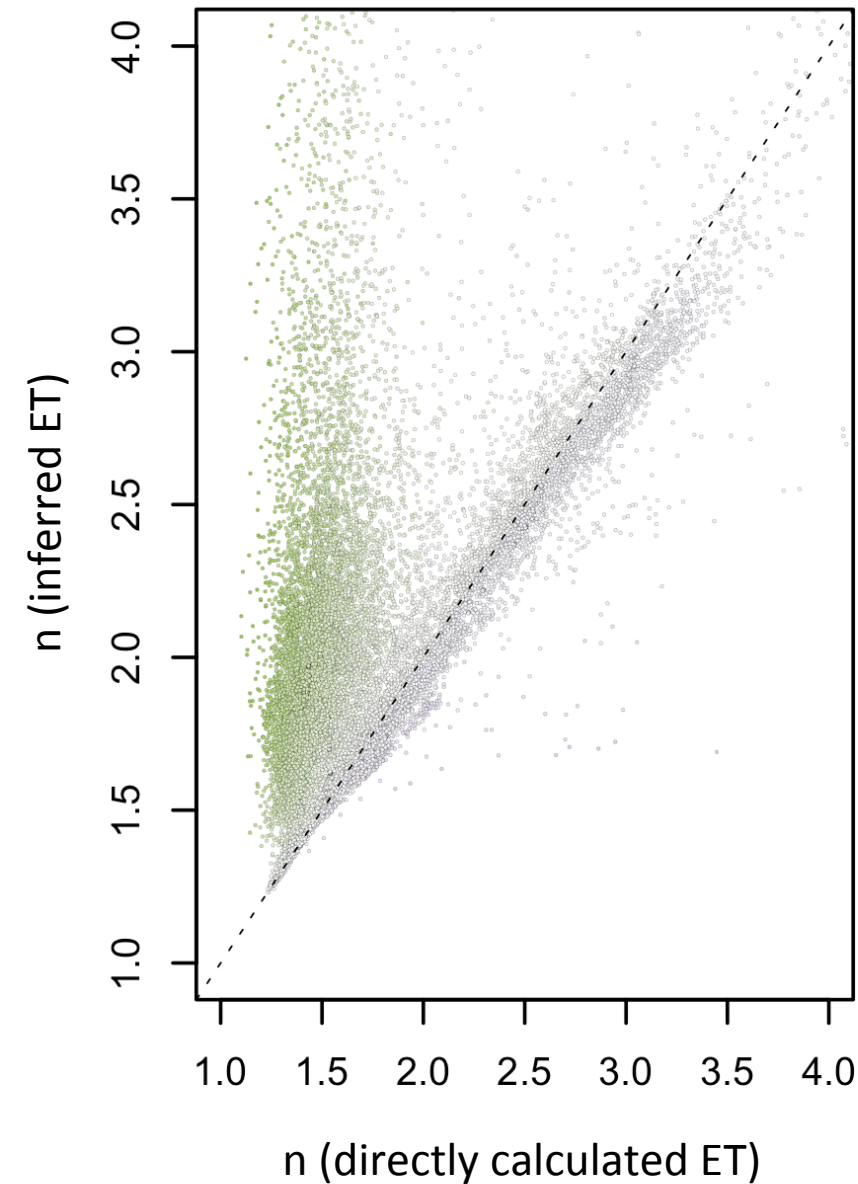


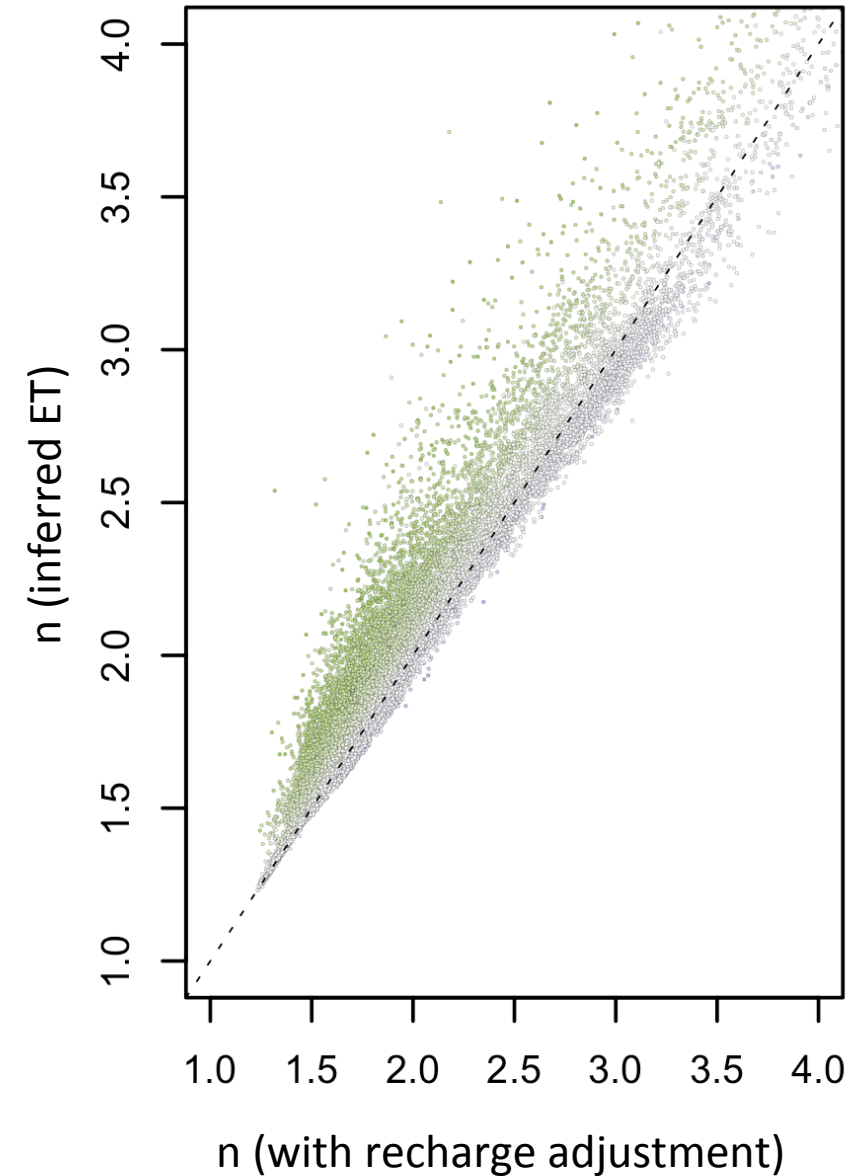
Shape Parameter



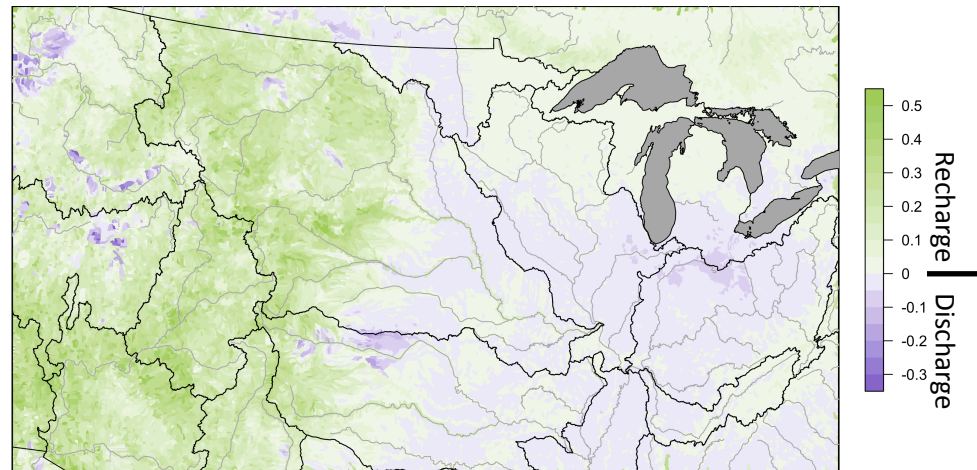


There are  
systematic  
differences between  
the inferred and  
direct ET  
approaches when  
recharge is high





The inferred ET approach agrees much more closely with the recharge adjusted results



# Conclusions

- We recreate Budyko behavior over drainage areas spanning 100 - 2,000,000 km<sup>2</sup>
- Lateral groundwater flow can significantly influence surface water partitioning and must be accounted for
- The way that groundwater surface water interactions are incorporated into Budyko analysis systematically impacts the results

# Questions?

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