Climate and vegetation water use efficiency at catchment scales

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- Hoshin Gupta – The University of Arizona

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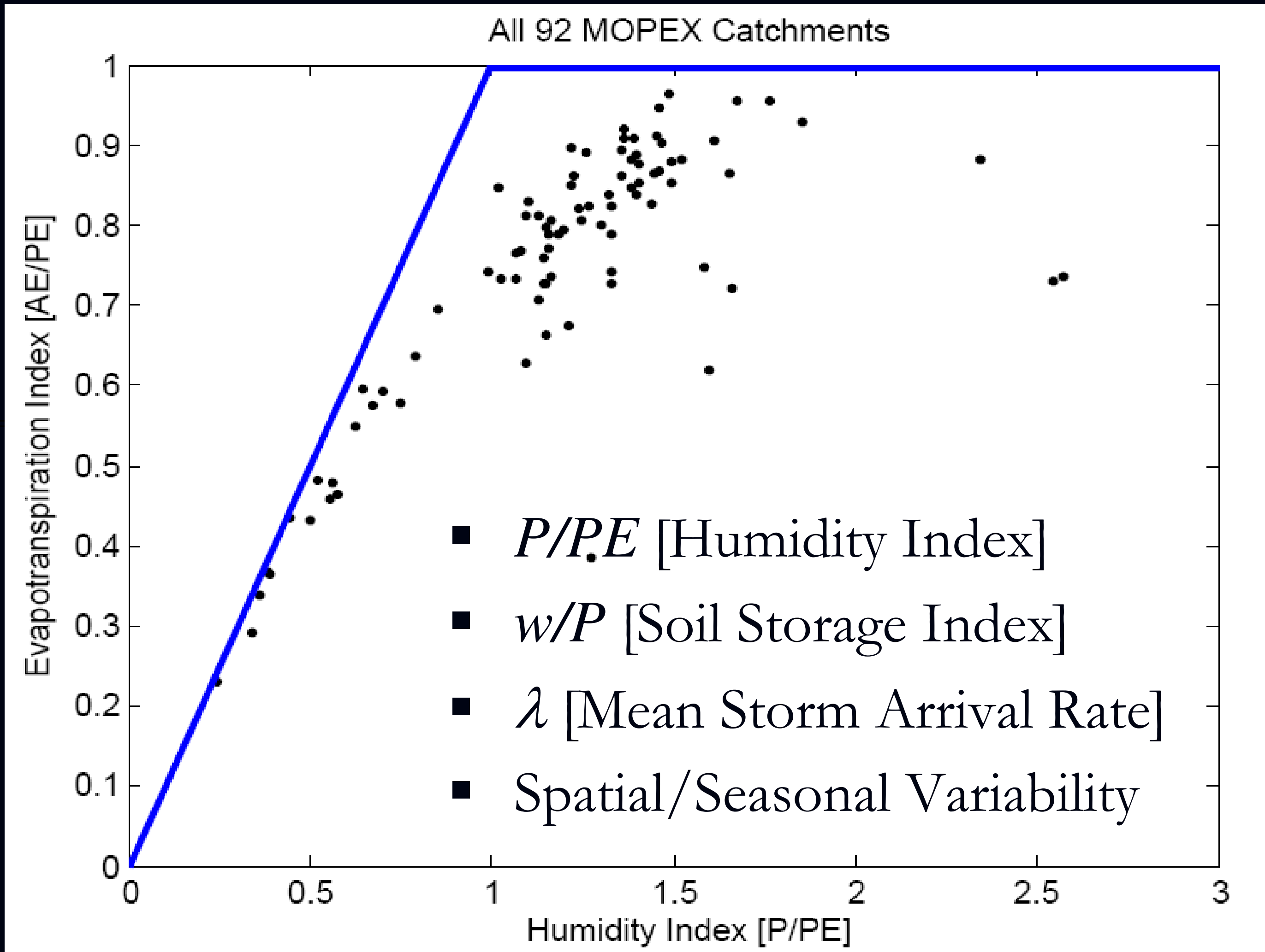
- NSF EAR-Hydrologic Sciences: Understanding the hydrologic implications of landscape structure and climate - Towards a unifying framework of watershed similarity (PIs: Thorsten Wagener, Murugesu Sivapalan, Peter Troch);
- NSF EAR-Hydrologic Sciences: Water cycle dynamics in a changing environment: Advancing hydrologic science through synthesis (PIs: Murugesu Sivapalan, Praveen Kumar, Bruce Roads, Don Wuebbles)

Outline

- Background and motivation
- Testing the Horton index
- Precipitation and vegetation productivity
- The annual water balance and L'vovich proportionality relations
- Testing the Ponce and Shetty model
- Conclusions

Budyko's hypothesis: $\frac{V}{PE} = \phi\left(\frac{P}{PE}\right)$

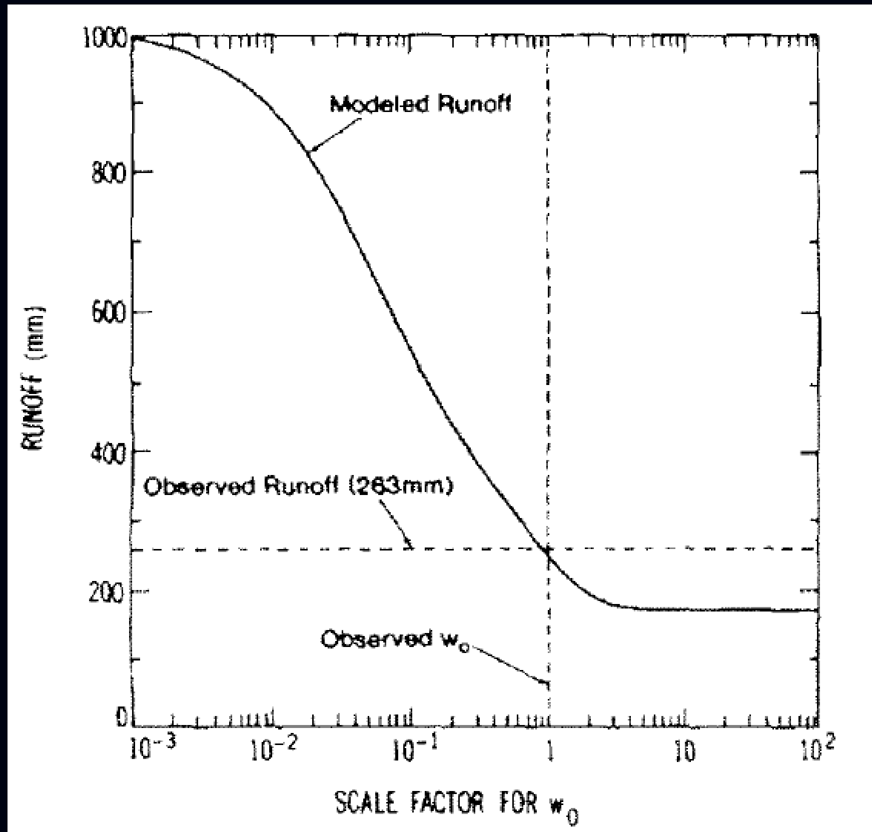


- *P/PE* [Humidity Index]
- *w/P* [Soil Storage Index]
- λ [Mean Storm Arrival Rate]
- Spatial/Seasonal Variability

Milly, 1994 (*WRR*)

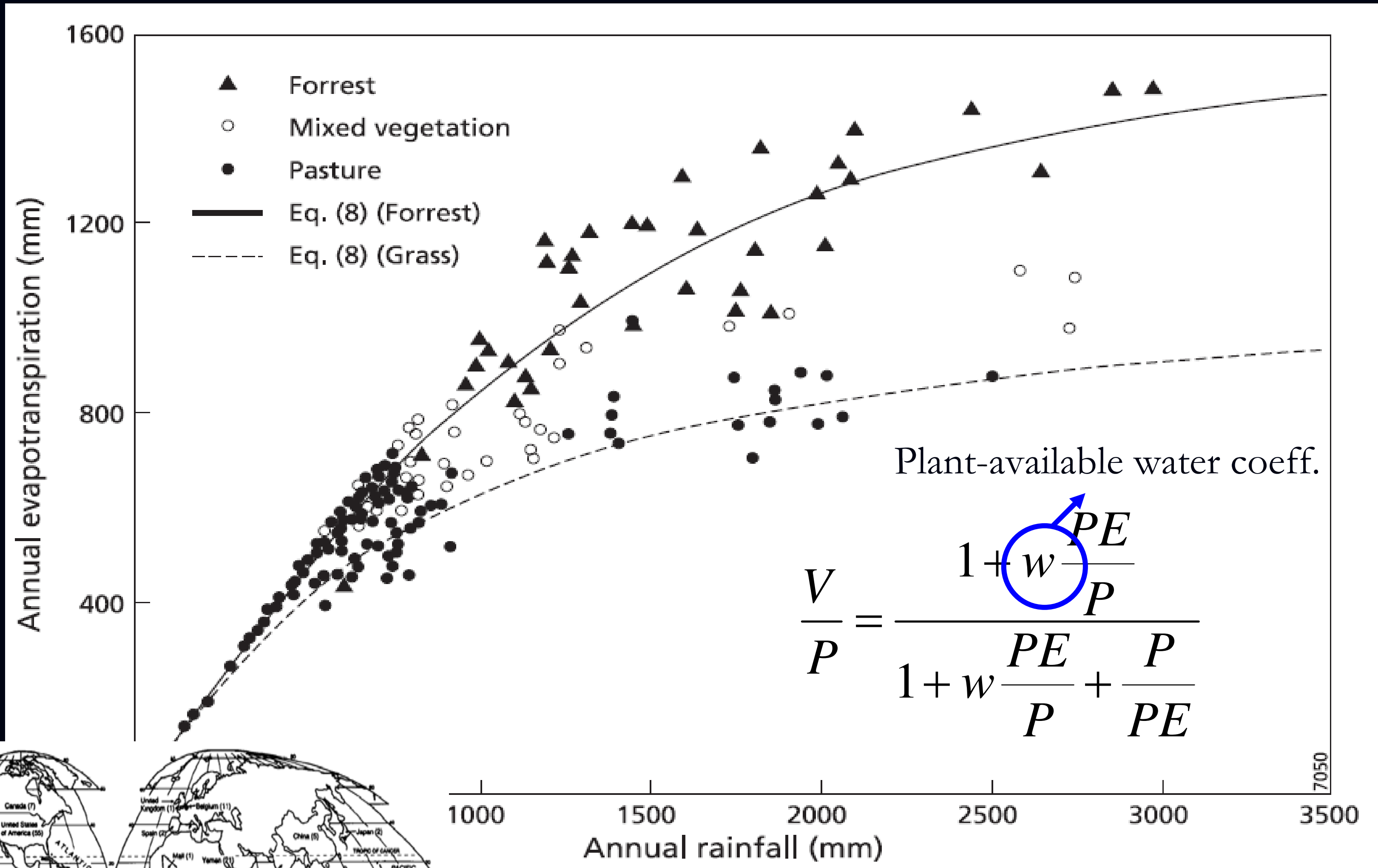
Sensitivity of water balance to water holding capacity

- Sensitivity diminishes at a scale factor on the order of 1;
- This implies that the actual values of capacity are almost large enough to maximize evapo-transpiration (minimize runoff);
- This could indicate that “the rooting depth of plants reflects ecologically optimized responses to the relative timing and magnitude of water and energy supplies”.



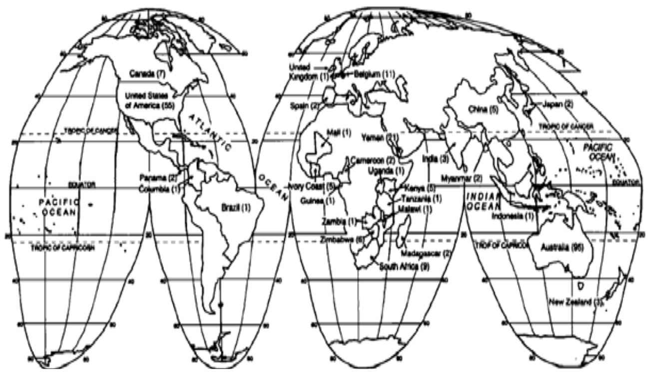
Milly, 1994 (*WRR*)

Plants are in control?



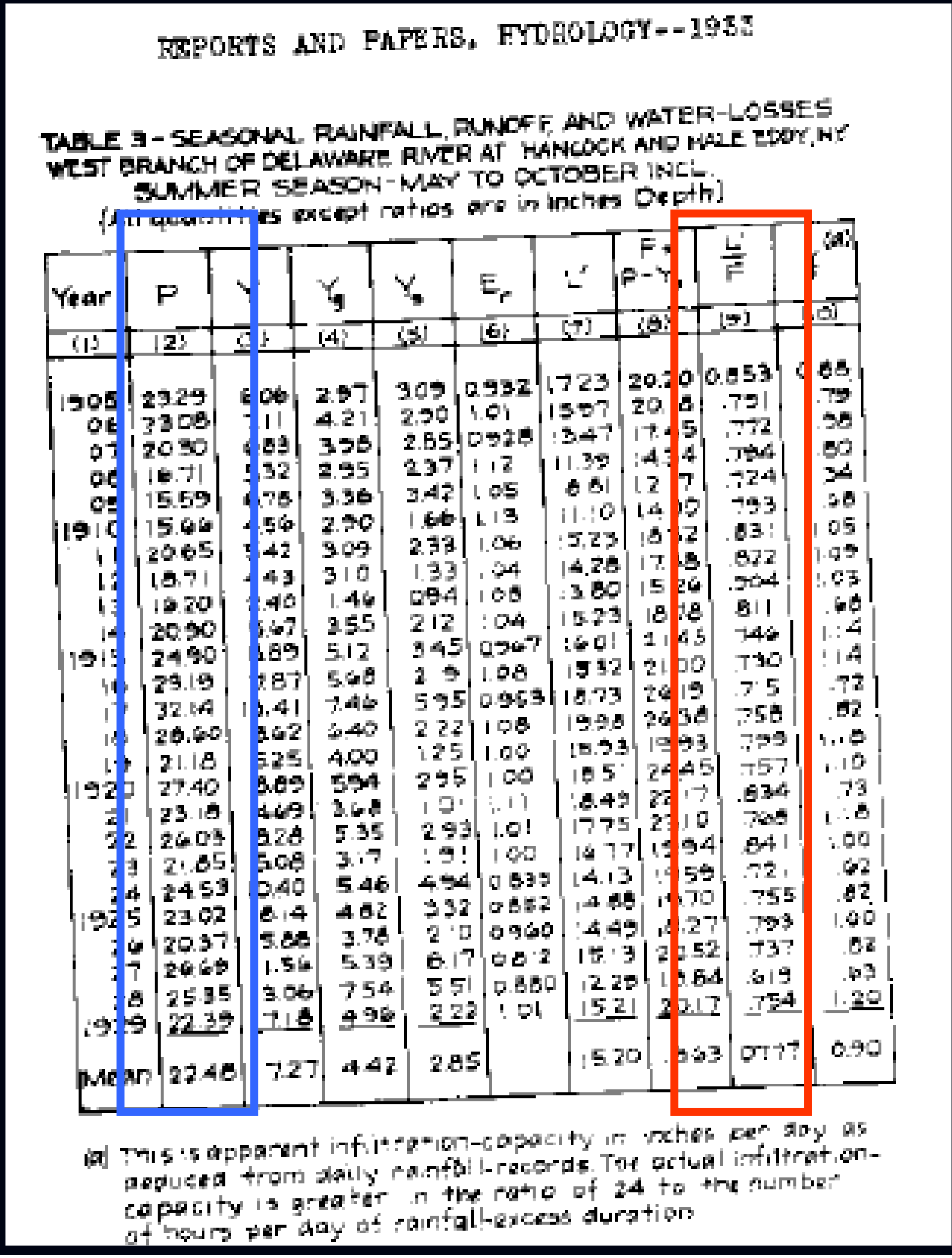
Plant-available water coeff.

$$\frac{V}{P} = \frac{1 + w\frac{PE}{P}}{1 + w\frac{PE}{P} + \frac{P}{PE}}$$



Zhang et al.., 2001 (*WRR*)

Motivation: another Horton index…



REPORTS AND PAPERS, HYDROLOGY--1933

TABLE 3 - SEASONAL RAINFALL, RUNOFF, AND WATER-LOSSES
WEST BRANCH OF DELAWARE RIVER AT HANCOCK AND HALE EDDY, NY
SUMMER SEASON - MAY TO OCTOBER INCL.
(All quantities except ratios are in inches Depth)

Year	P	Y	Y_g	Y_s	E_r	U	F = P-Y	U/F	f (a)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1905	23.29	6.06	2.97	3.09	0.932	17.23	20.20	0.853	0.88
06	23.08	7.11	4.21	2.90	1.01	15.97	20.[illegible]8	.751	.79
07	20.30	6.83	3.58	2.85	0.928	13.47	17.45	.772	.58
08	18.71	5.32	2.95	2.37	1.12	11.39	14.34	.794	.80
09	15.59	6.78	3.36	3.42	1.05	8.81	12.[illegible]7	.724	.34
1910	15.66	4.56	2.90	1.66	1.13	11.10	14.[illegible]0	.793	.98
11	20.65	5.42	3.09	2.33	1.06	15.23	18.[illegible]2	.831	1.05
12	18.71	4.43	3.10	1.33	.94	14.28	17.[illegible]8	.822	1.09
13	19.20	2.40	1.46	0.94	1.08	13.80	15.[illegible]6	.904	1.03
14	20.90	5.67	2.55	2.12	1.04	15.23	18.78	.811	.68
1915	24.90	6.89	5.12	3.45	0.967	16.01	[illegible]	.746	1.14
16	25.19	7.87	5.68	[illegible]	1.08	15.32	21.00	.730	1.14
17	32.64	[illegible].41	7.46	5.95	0.969	18.73	24.19	.715	.72
18	26.60	8.62	6.40	2.22	1.08	19.98	26.38	.758	.82
19	21.18	5.25	4.00	1.25	1.00	15.93	19.93	.799	1.18
1920	27.40	8.89	5.94	2.95	1.00	18.5[illegible]	24.45	.757	1.10
21	23.18	4.69	3.68	1.0[illegible]	1.11	18.49	22.17	.834	.73
22	26.03	8.28	5.35	2.93	1.01	17.75	21.10	.795	1.18
23	21.65	5.08	3.17	1.91	1.00	16.77	19.94	.841	1.00
24	24.53	10.40	5.46	4.94	0.839	14.13	19.59	.721	.92
1925	23.02	8.14	4.82	3.32	0.882	14.88	19.70	.755	.82
26	20.37	5.88	3.78	2.10	0.960	14.49	18.27	.793	1.00
27	26.69	1.56	5.39	6.17	0.8[illegible]2	15.13	20.52	.737	.82
28	25.35	13.06	7.54	5.51	0.880	12.29	19.84	.619	.93
1929	22.39	7.18	4.96	2.22	1.01	15.21	20.17	.754	1.20
Mean	22.48	7.27	4.42	2.85		15.20	[illegible]63	0.777	0.90

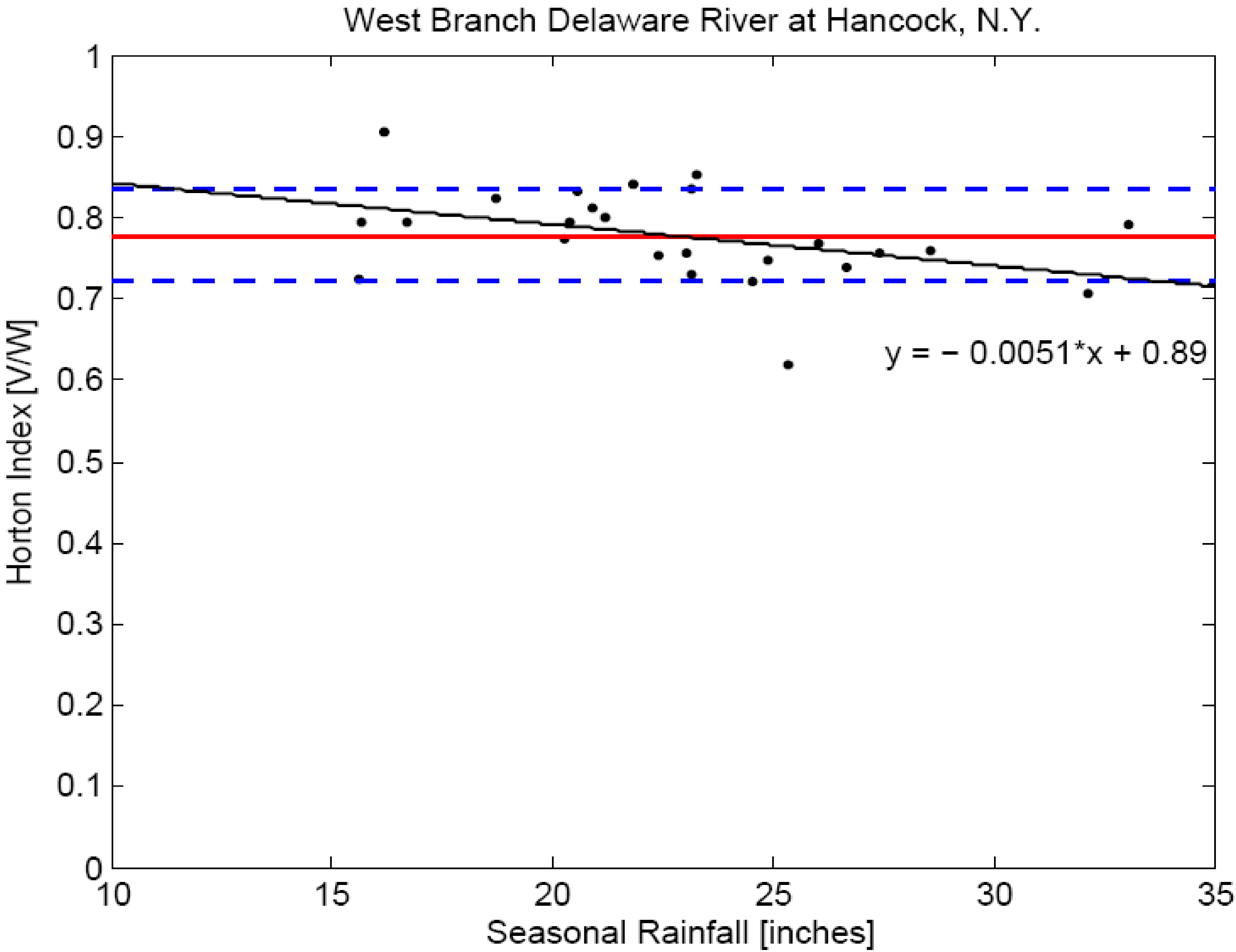
(a) This is apparent infiltration-capacity in inches per day as deduced from daily rainfall-records. The actual infiltration-capacity is greater in the ratio of 24 to the number of hours per day of rainfall-excess duration

$$H = \frac{V}{W} \cong \text{constant}$$

V : Growing-season vaporization (E+T)
W : Growing-season wetting (P-S)

"The natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil moisture supplied by infiltration" (Horton, 1933, p.455)

Horton, 1933 (*AGU*)


West Branch Delaware River at Hancock, N.Y.
y = − 0.0051*x + 0.89
Horton Index [V/W]
Seasonal Rainfall [inches]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
15
20
25
30
35

A closer look at the Horton index

$$\mathrm{H} = \frac{V}{W} \cong \frac{P - R}{P - S}$$

P : Growing-season rainfall
R : Growing-season total runoff (discharge)
S : Growing-season surface runoff (quick runoff)

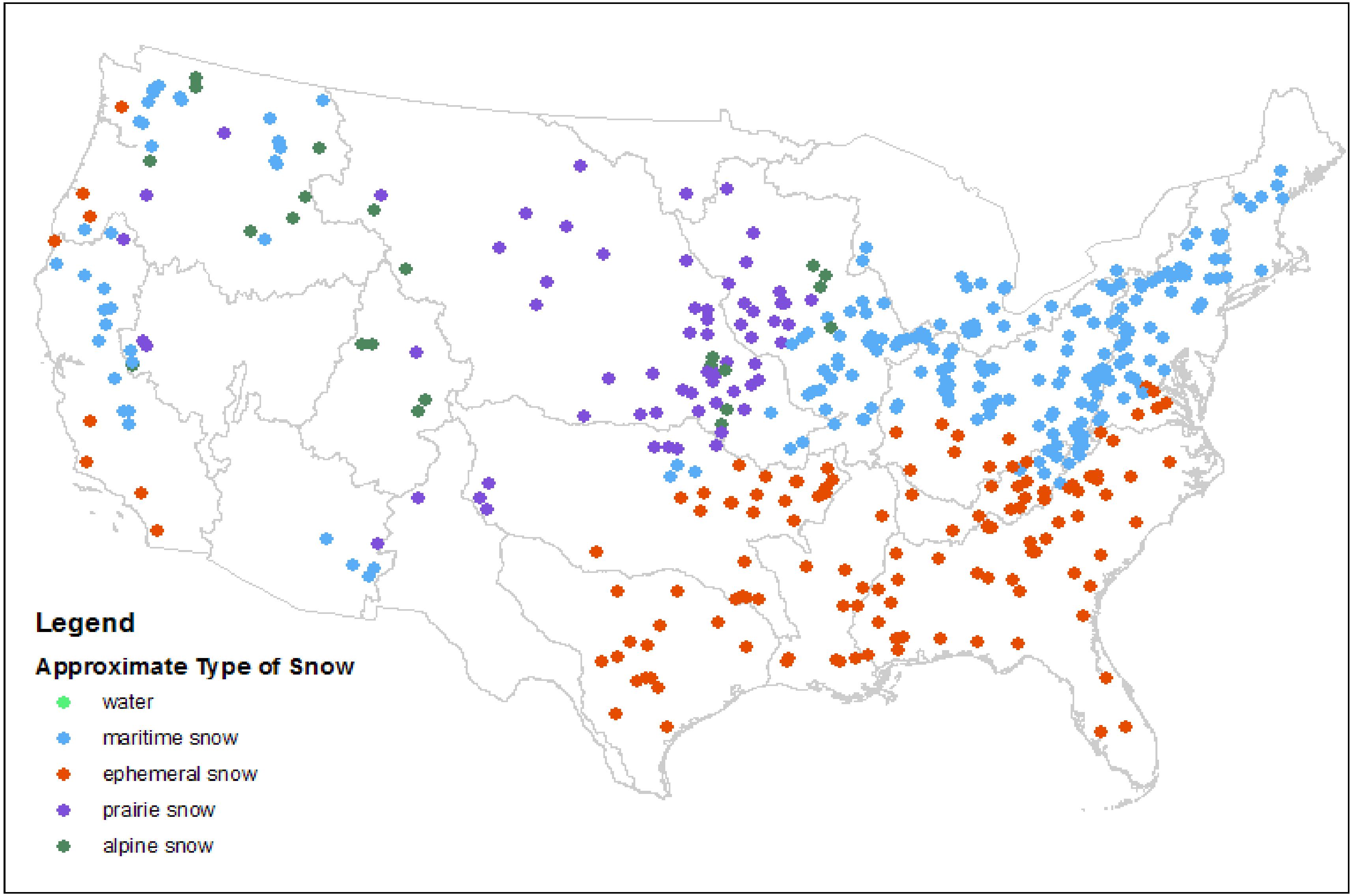
No energy: $P - R = V = 0 : H = 0$

No storage: $R = S = P : H = 0/0$

Humid: $R > S : H < 1$

Semi-arid: $R \cong S < P : H \cong 1$

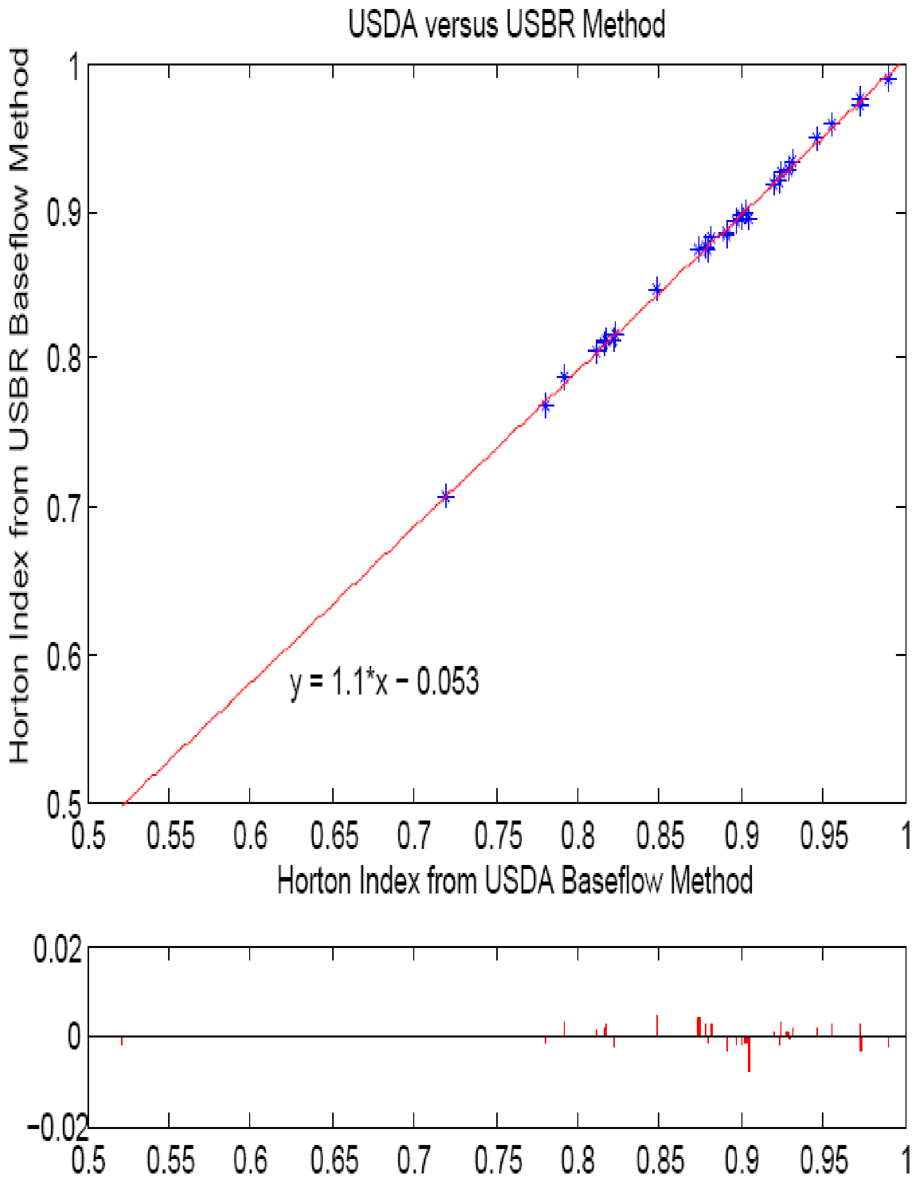
MOPEX watershed to test Horton Hypothesis



Three Baseflow Separation Methods

- USBR Method (*Wahl and Wahl*, 2006)
  - Based on IH method (recession slope test)
- USDA Method (*Arnold and Allen*, 1999)
  - Method adopted in SWAT model
- UG Method *(Huyck* et al., 2005)
  - Based on hydraulic groundwater theory
  - Accounts for catchment's geomorphology

Comparison of Results



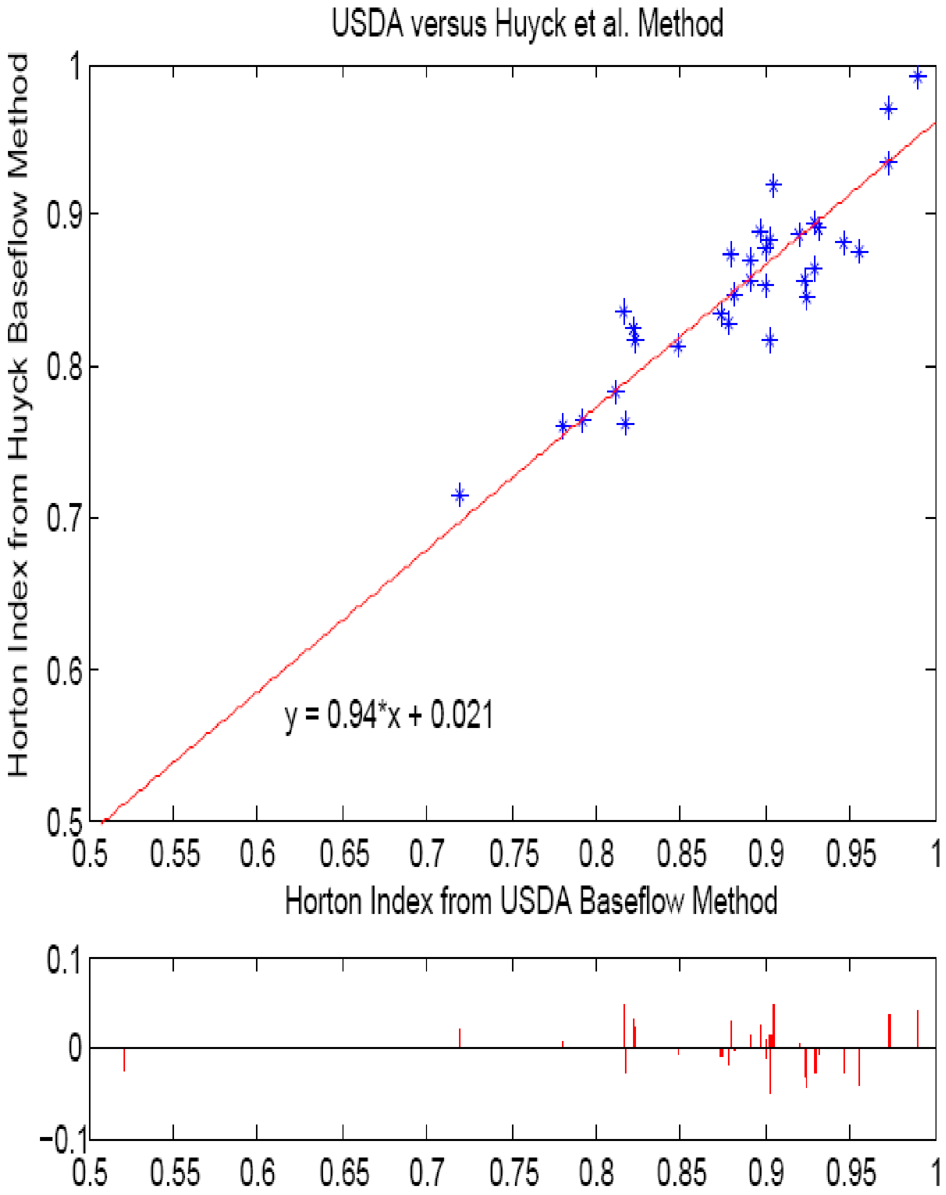
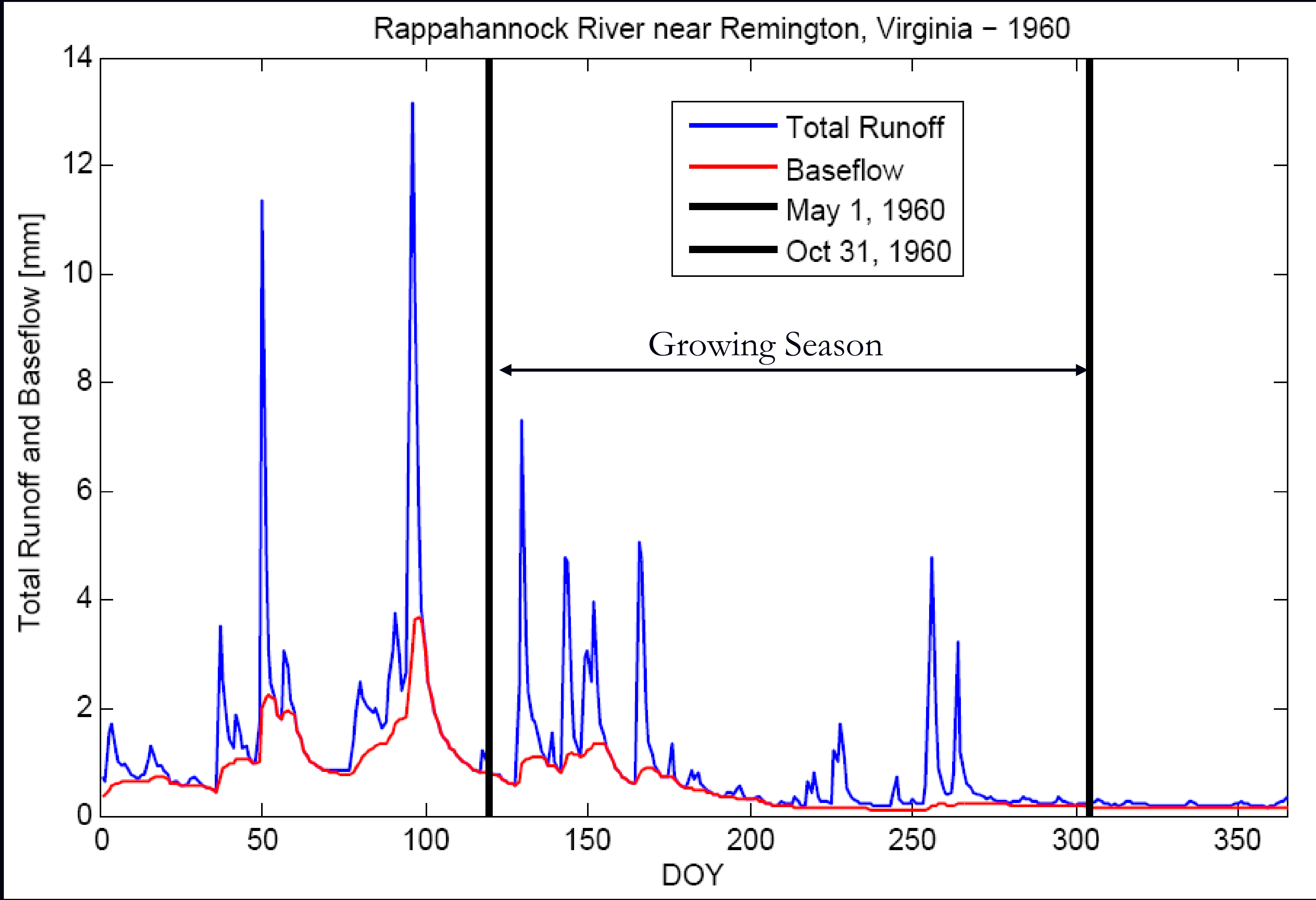
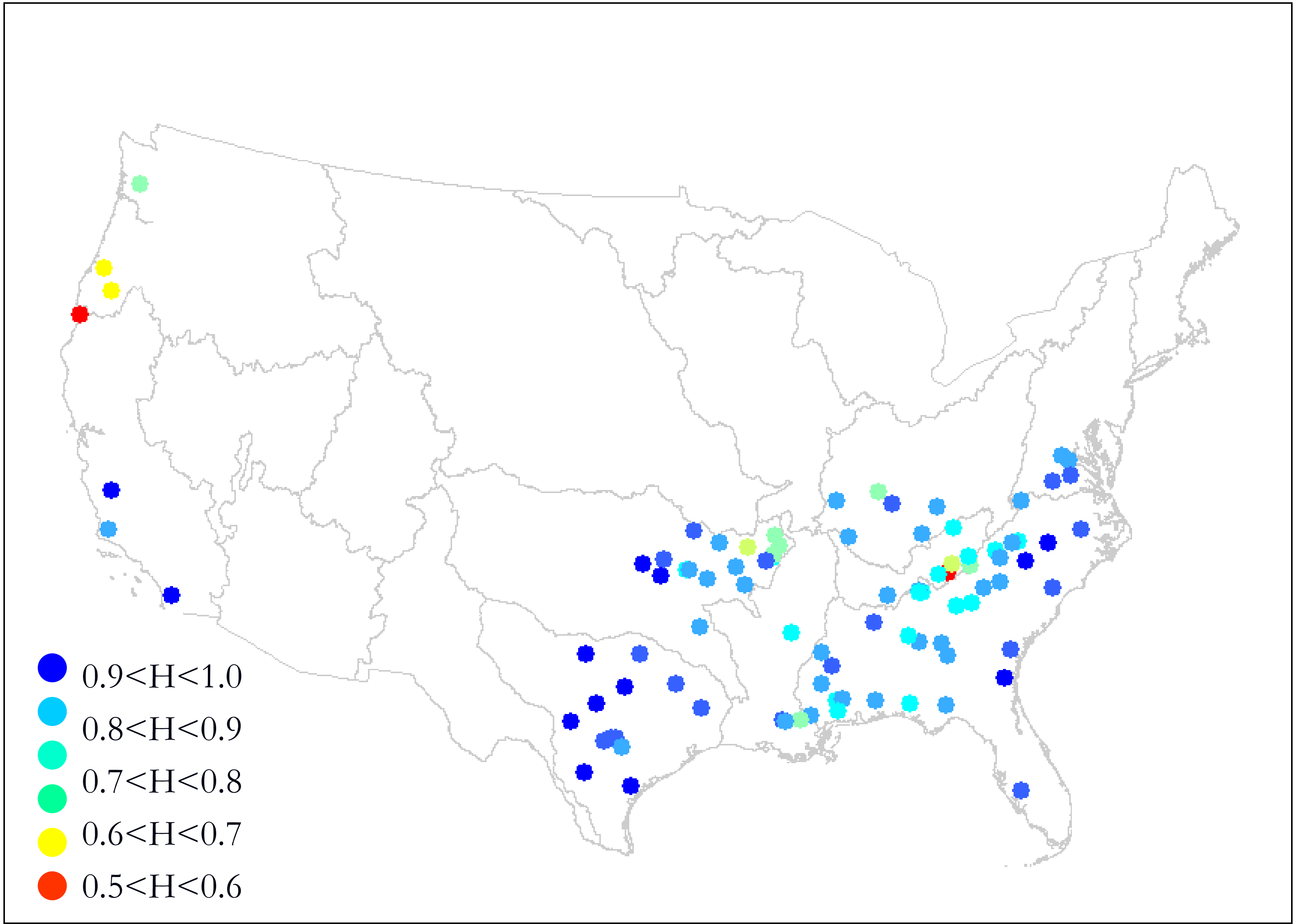


Illustration of *Huyck* et al. Method

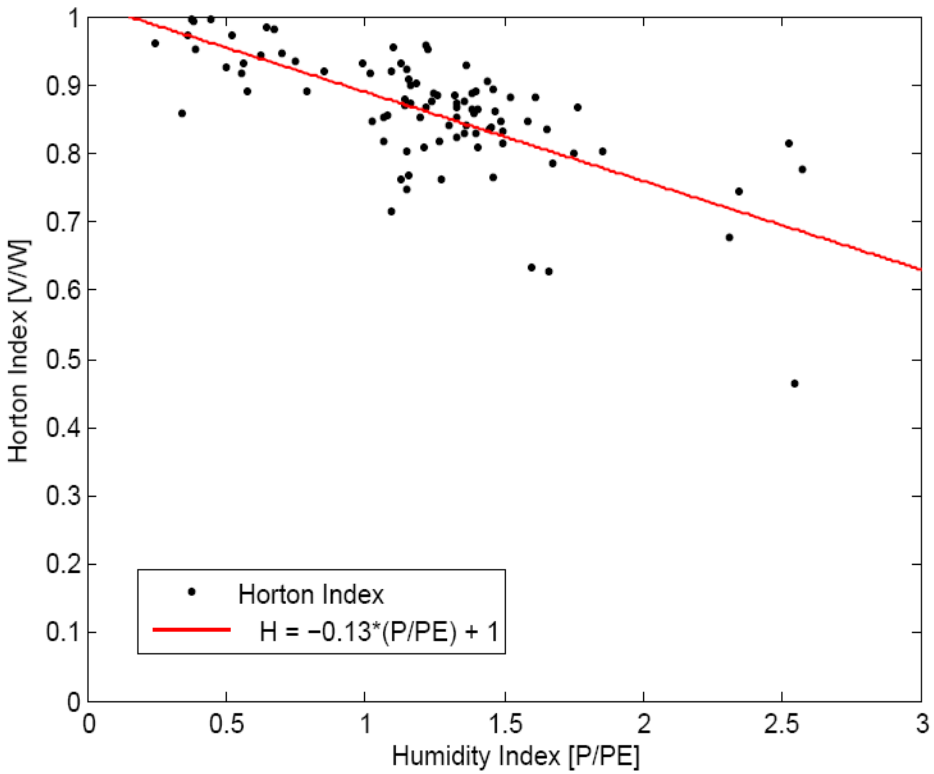


Spatial Variability of Horton Index

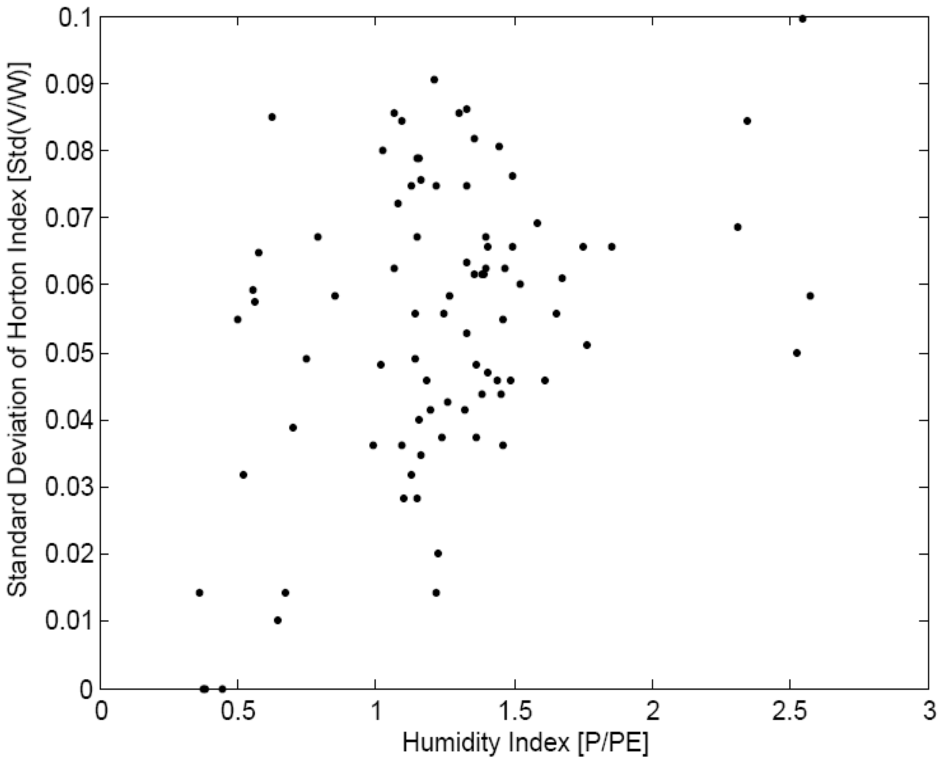


Horton Index vs. Humidity Index

Mean Horton Index

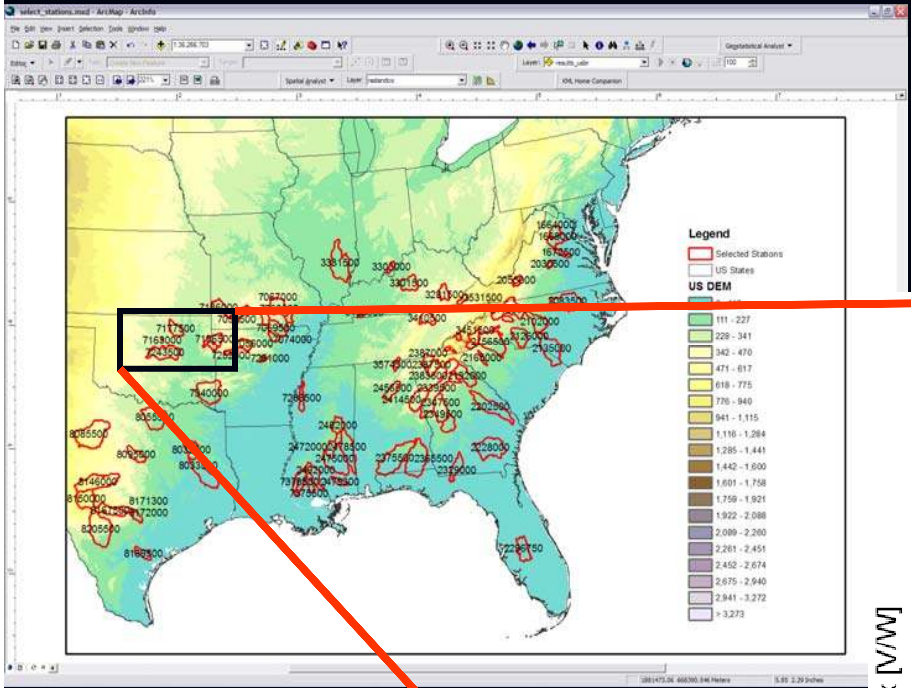


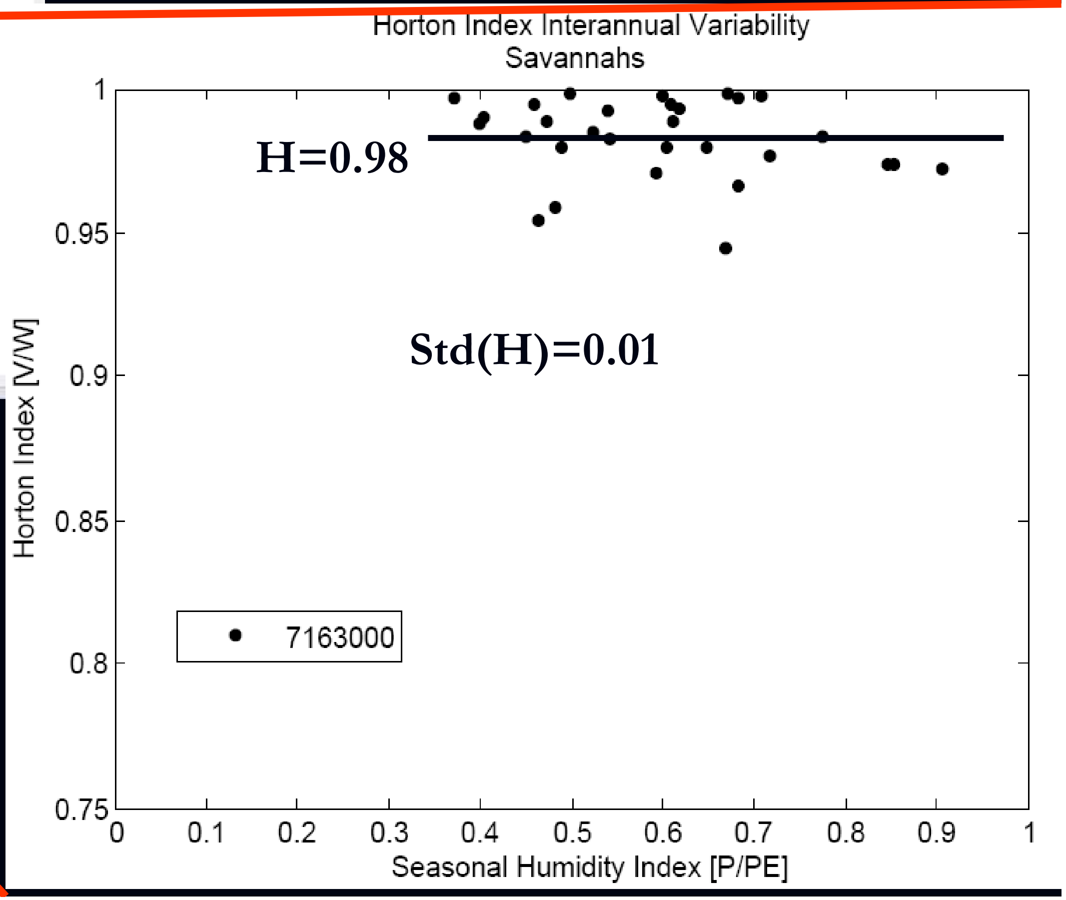
Std. Horton Index



53% with Std(H)<0.06
74% with Std(H)<0.07
83% with Std(H)<0.08
93% with Std(H)<0.10

Interannual Variability of Horton Index





Ecological controls to interannual variability in semi-arid regions

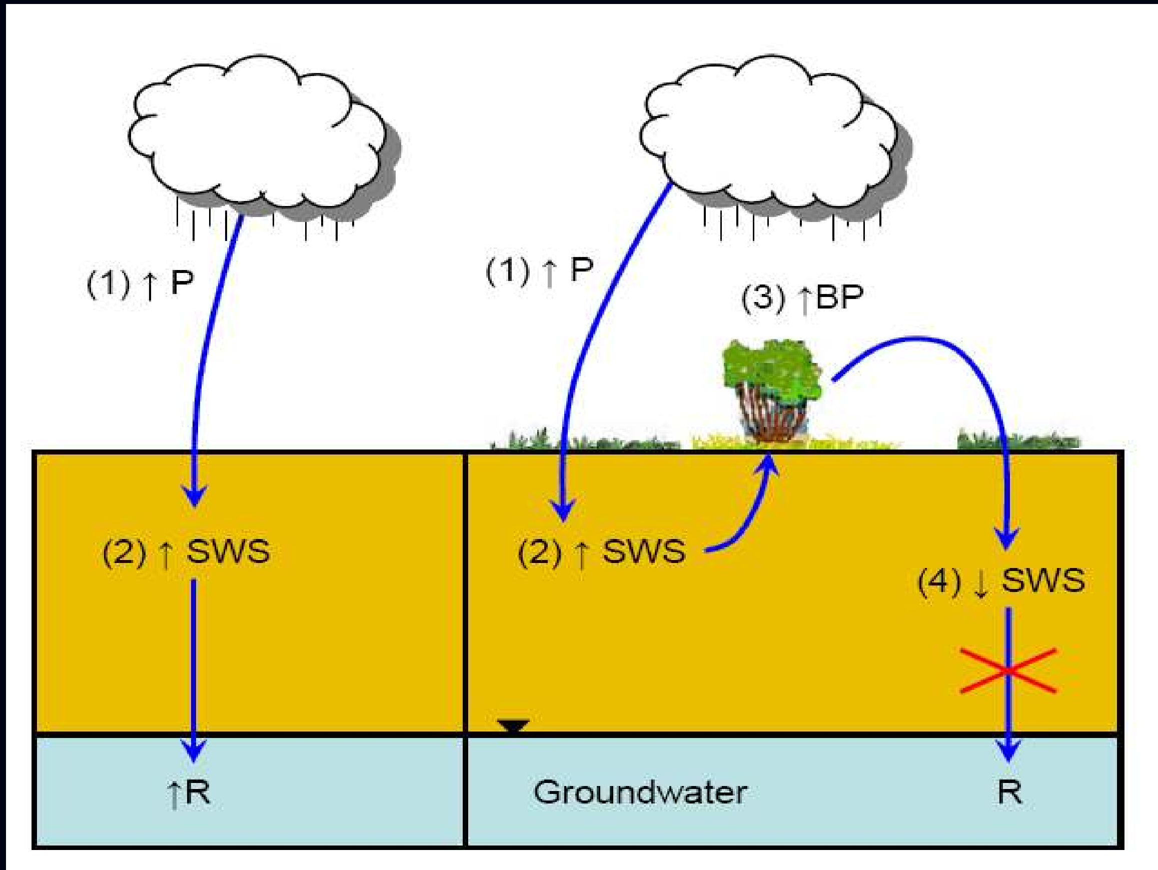
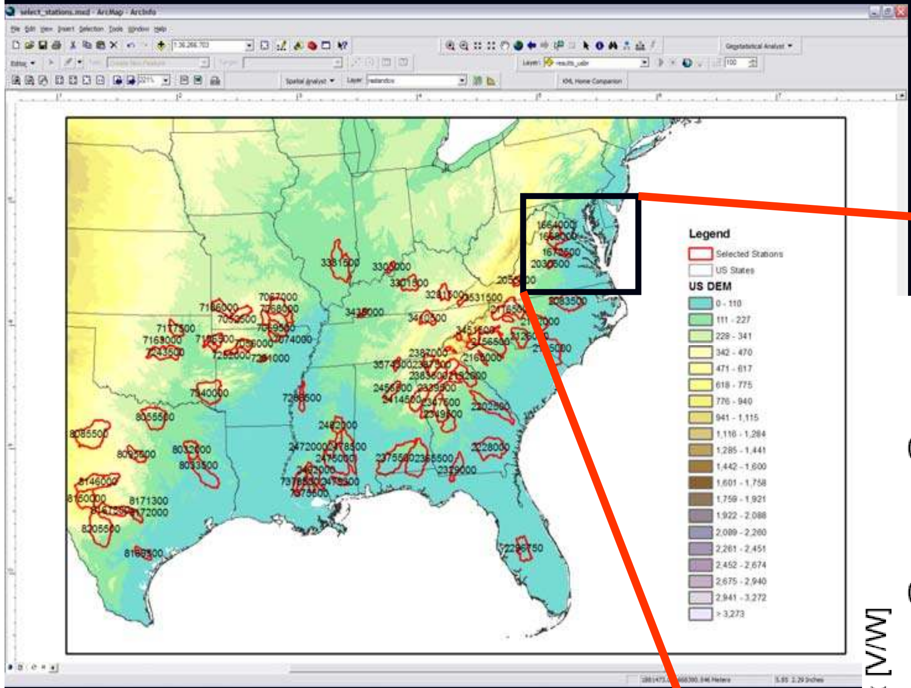
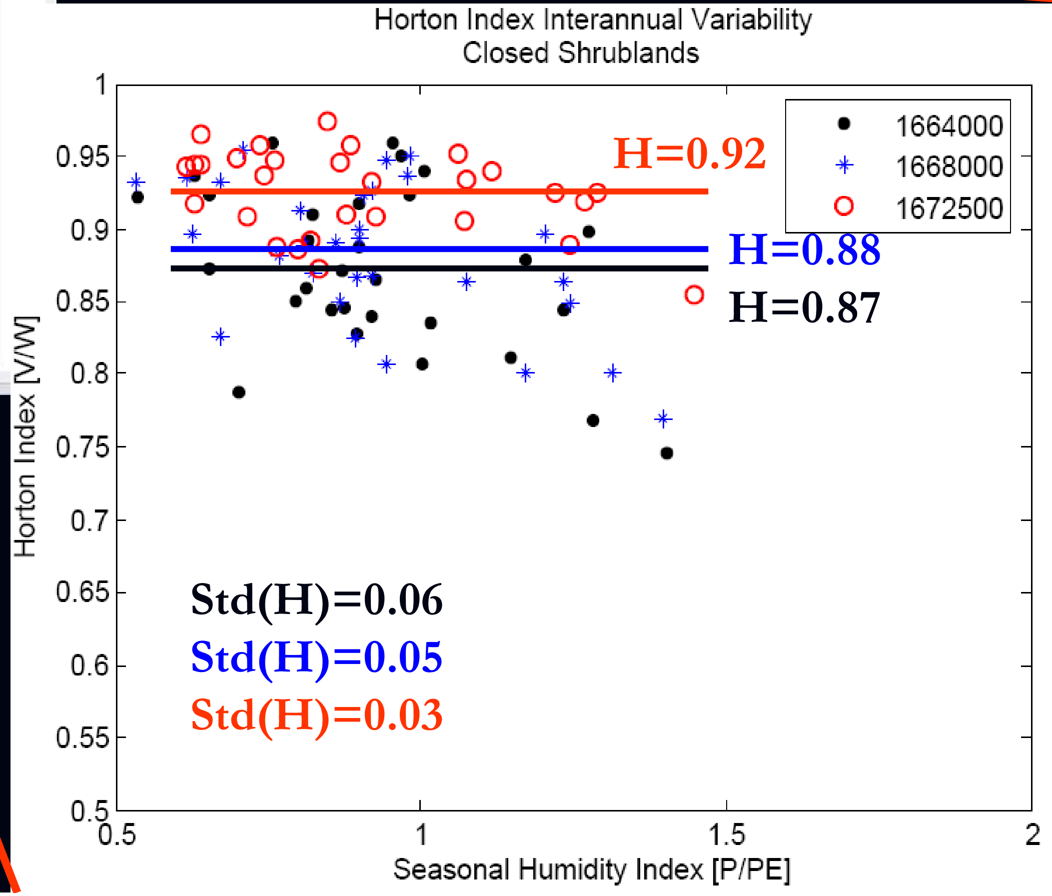


Figure 24: Schematic of non-vegetated and vegetated system responses to elevated precipitation. In non-vegetated systems (*Left*), elevated precipitation (*P*) results in increased soil-water storage (SWS) that drains resulting in groundwater recharge (*R*). In the vegetated systems (*Right*), elevated precipitation results in increased soil-water storage that enhances vegetation biomass production (BP), which feeds back to decrease soil-water storage and precludes recharge (Scanlon et al., 2005).

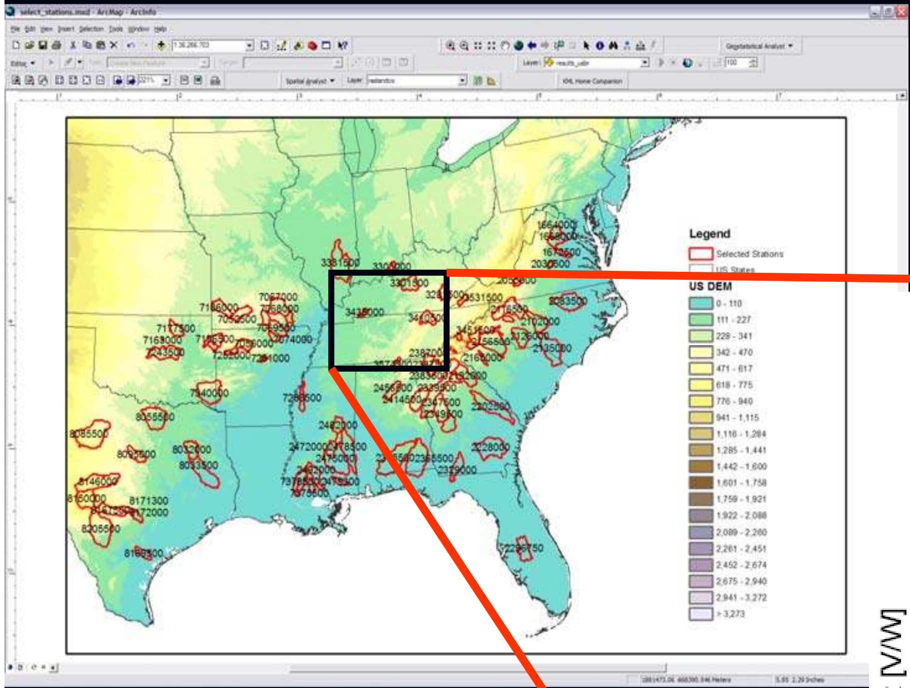
Scanlon et al., 2005 (*PNAS*)

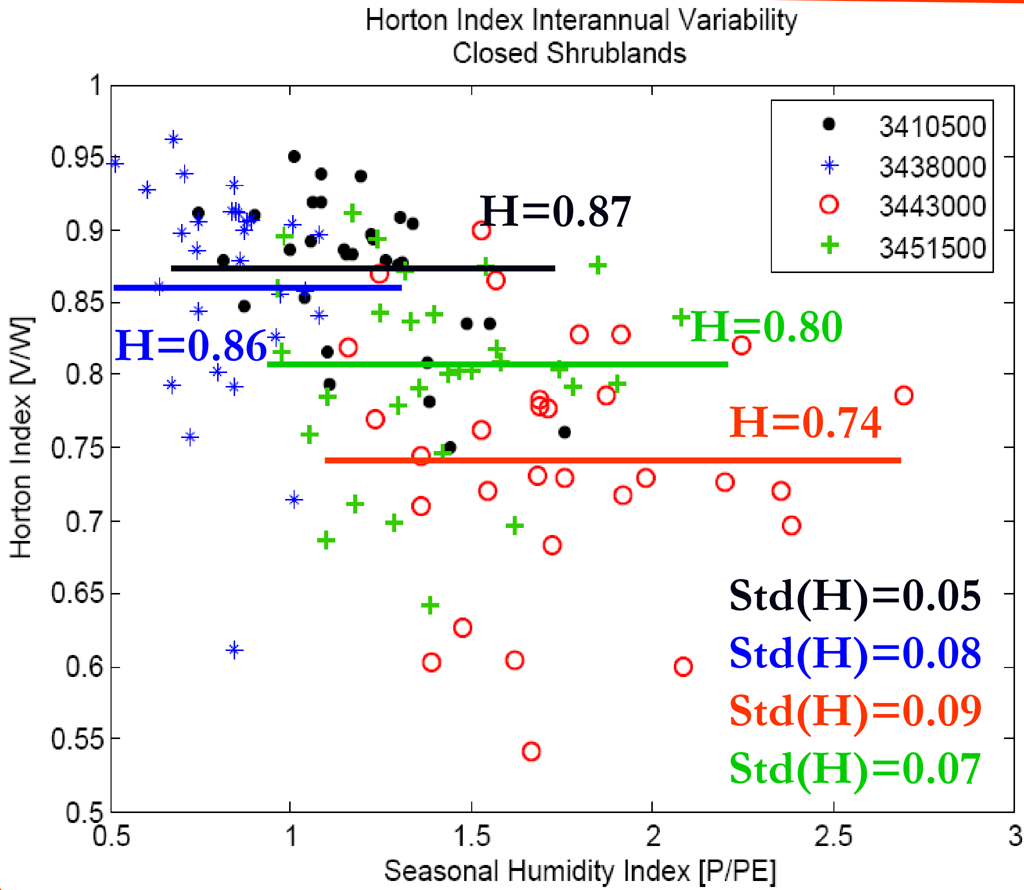
Interannual Variability of Horton Index



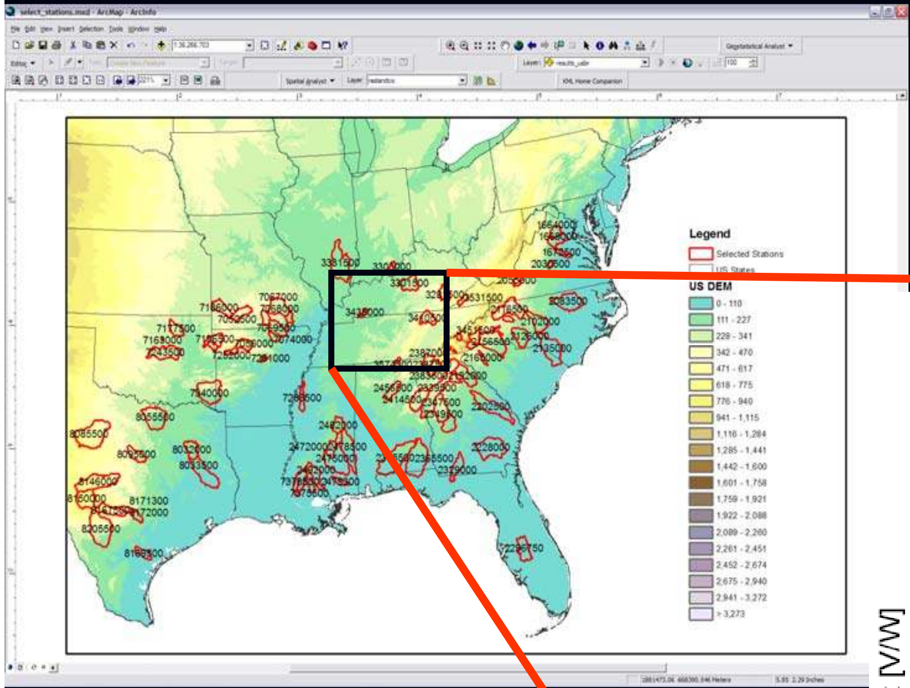


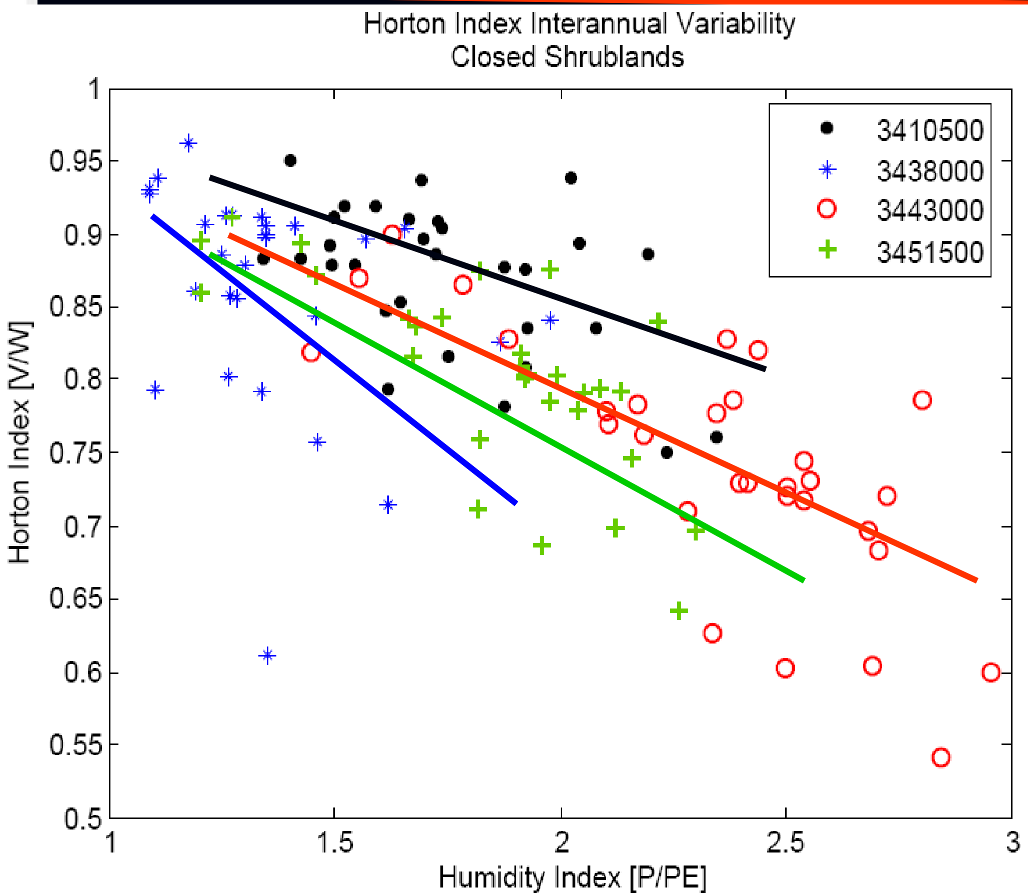
Interannual Variability of Horton Index



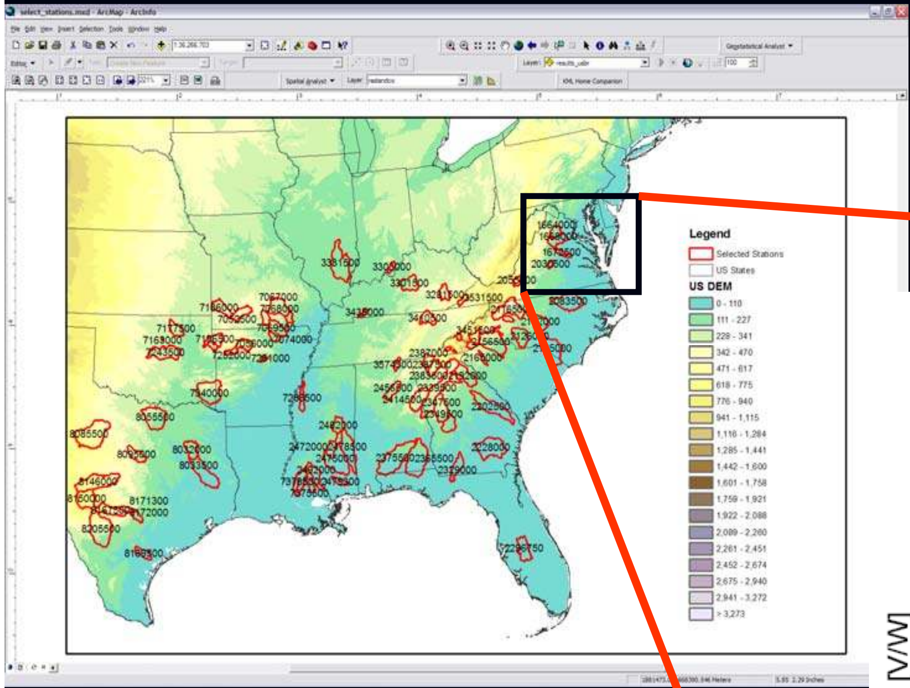


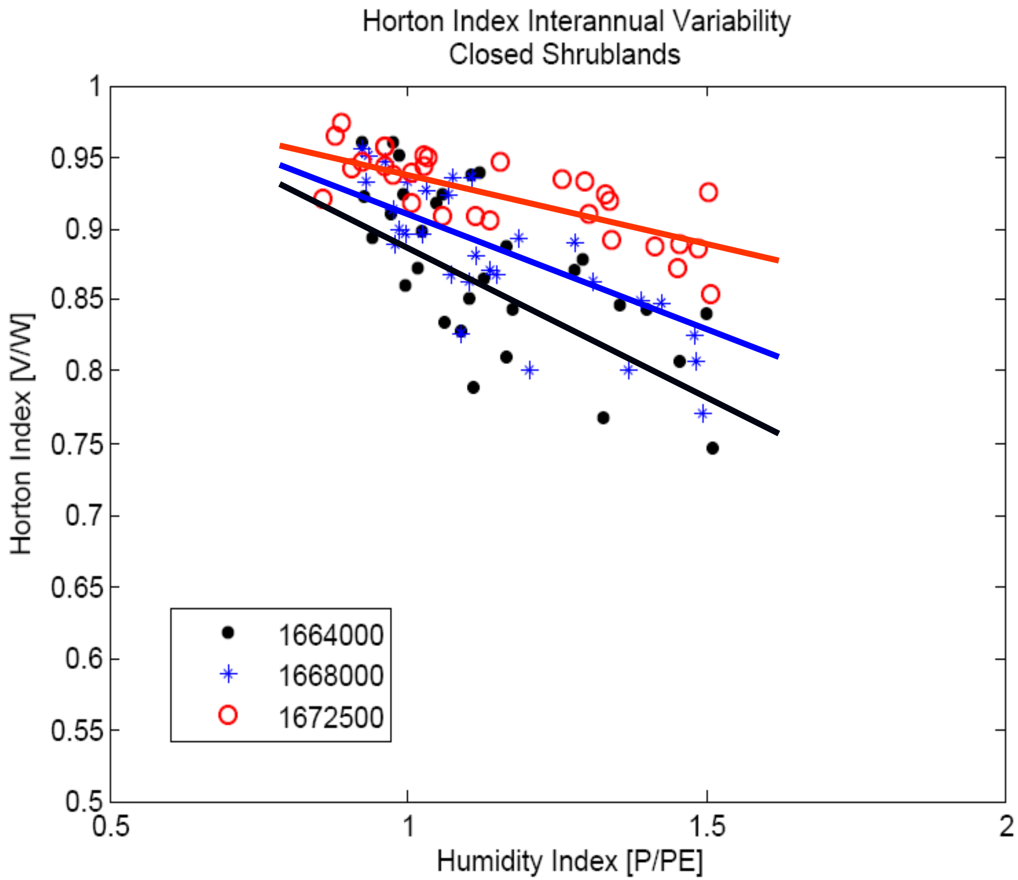
Interannual Variability of Horton Index





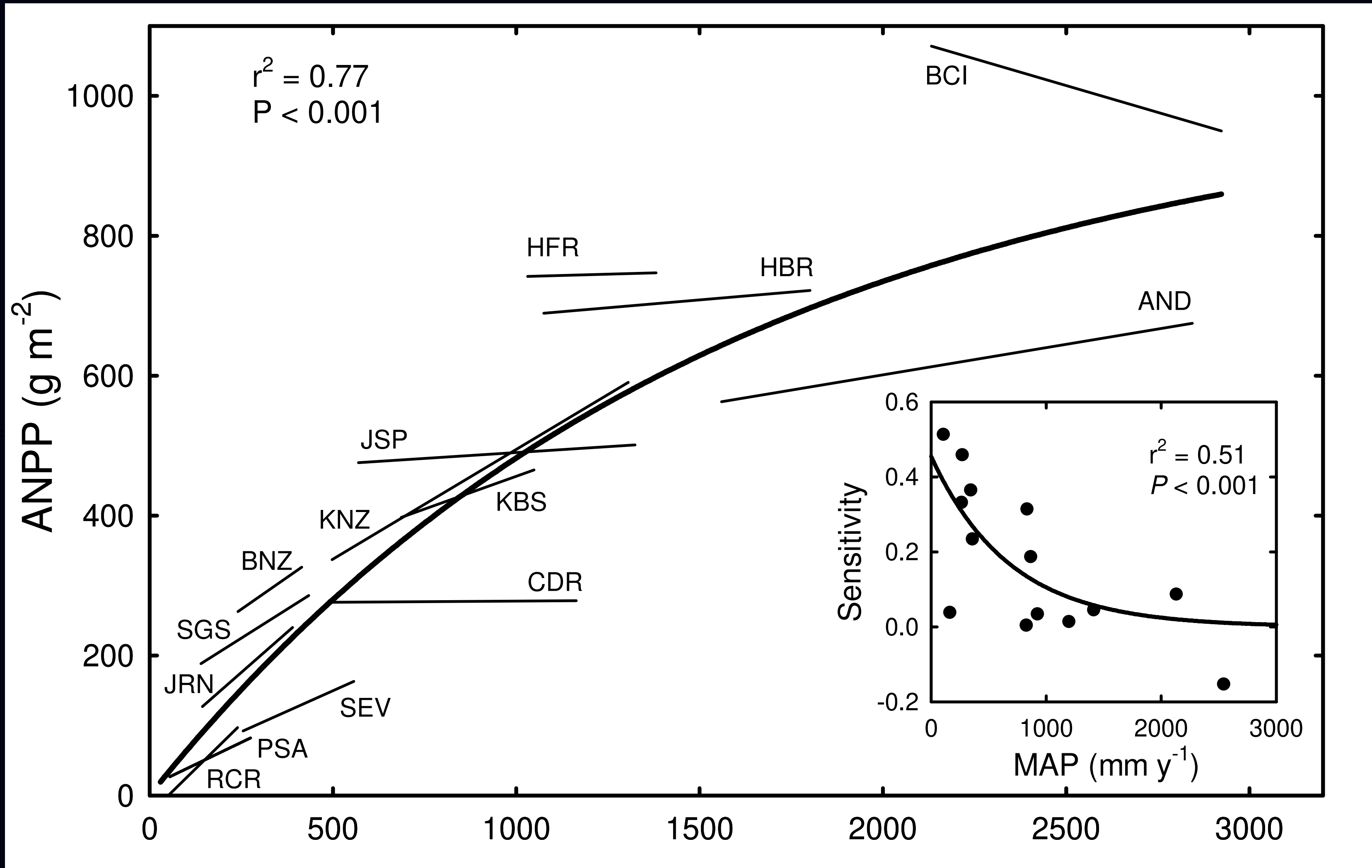
Interannual Variability of Horton Index





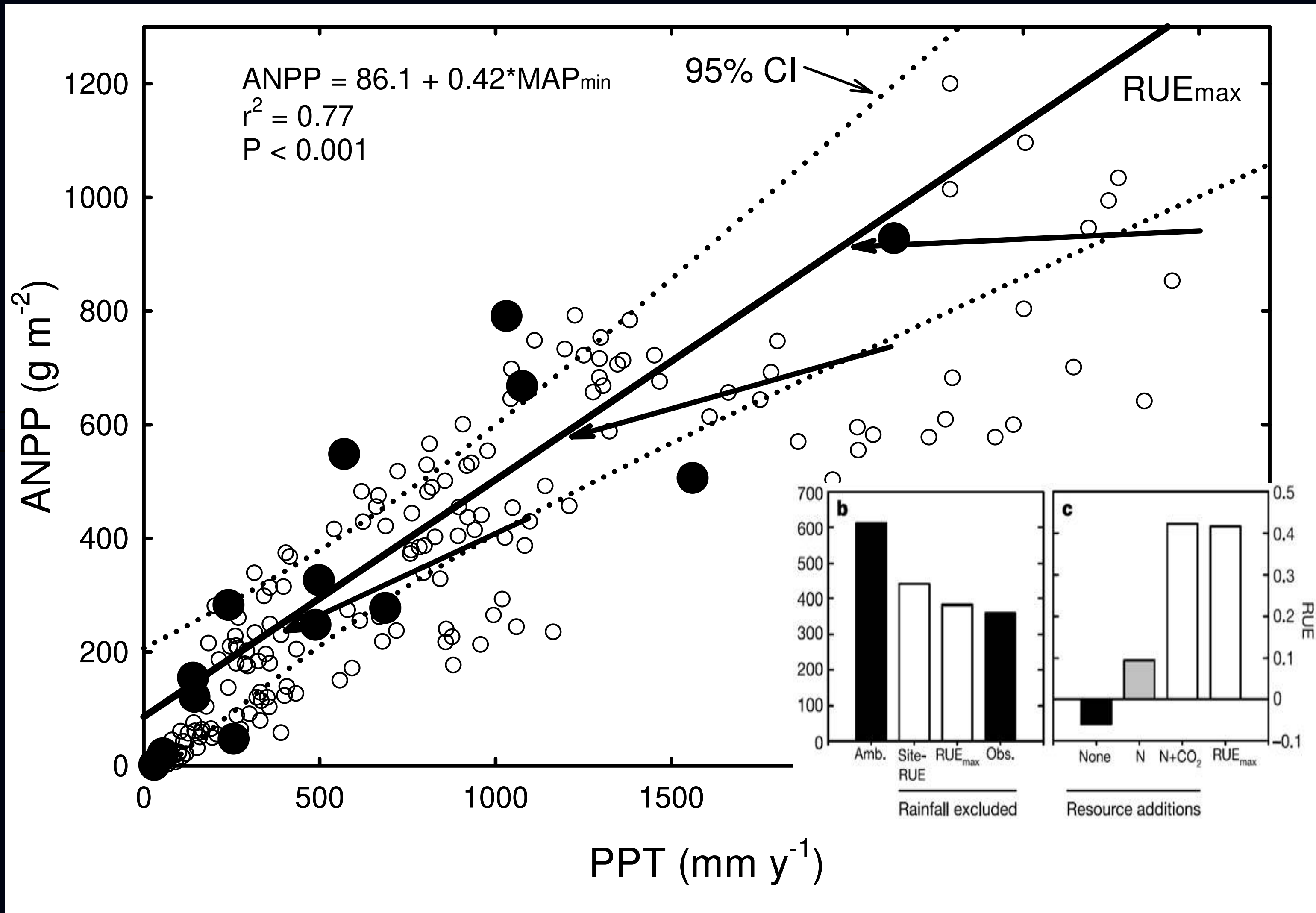
Precipitation and production

Biome rainwater use efficiency



Huxman, 2004 (*Nature*)

Convergence to a common RUE_{max}



Huxman, 2004 (*Nature*)

Water Use Efficiency and Actual ET

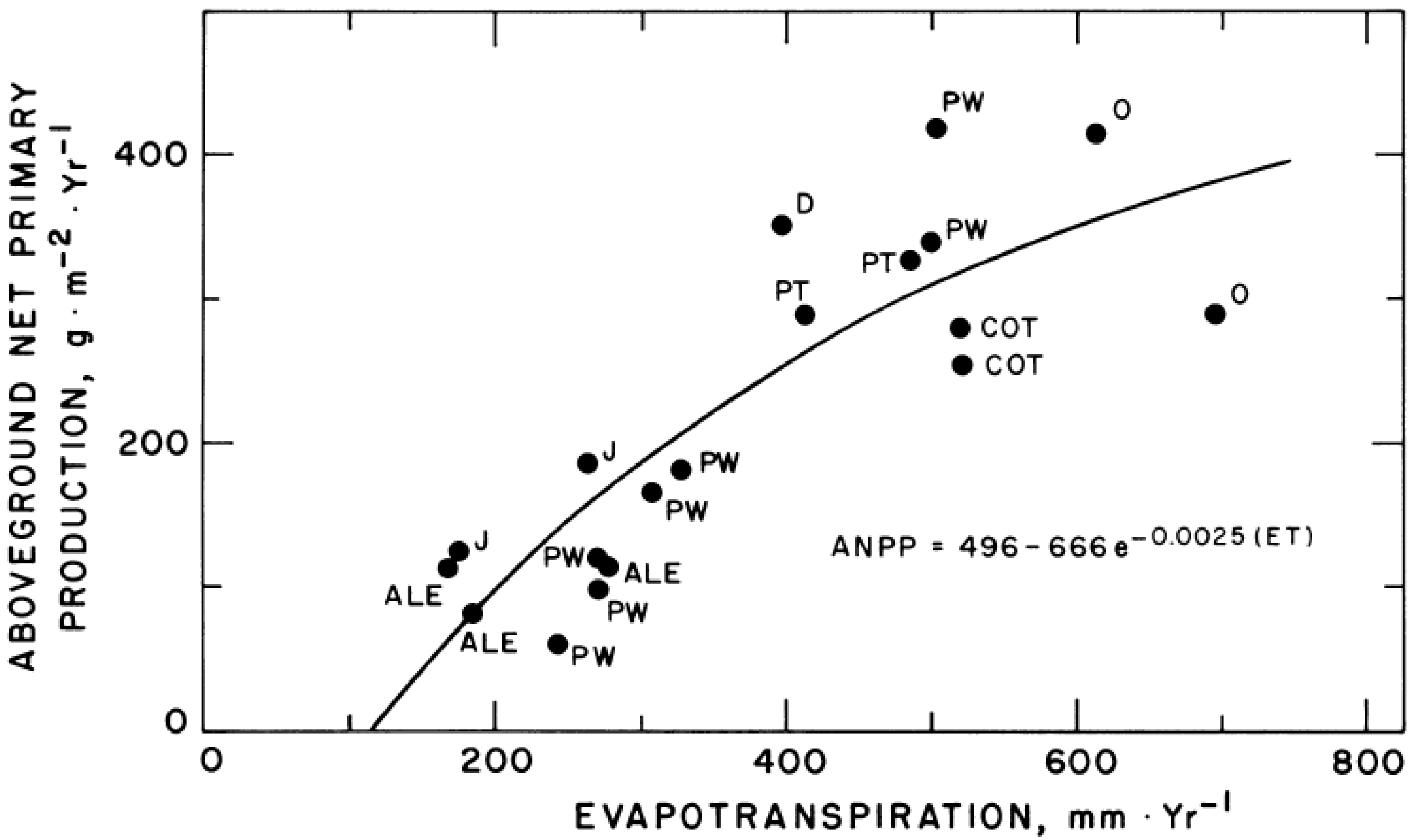
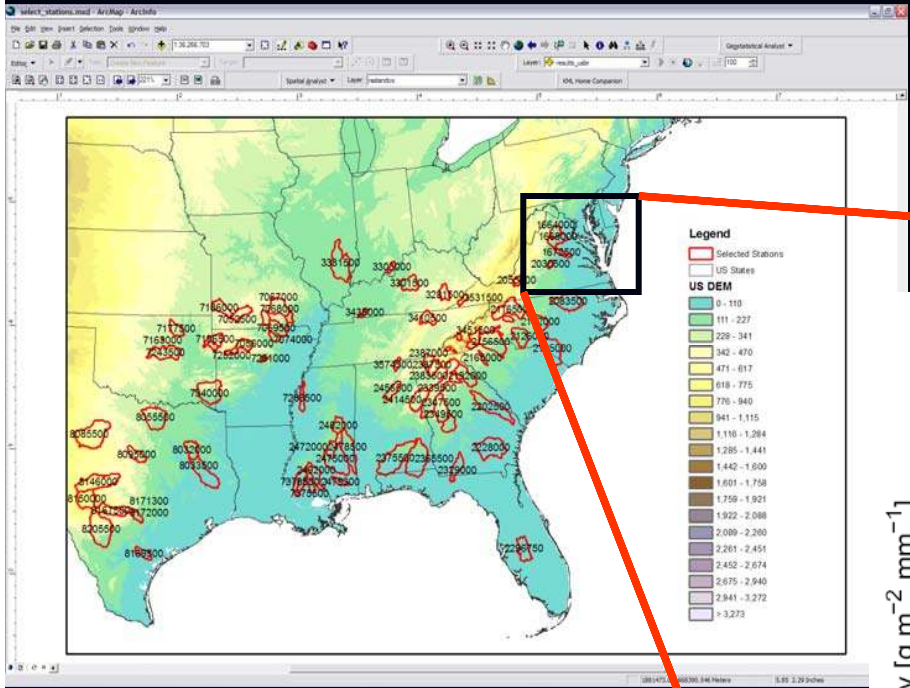
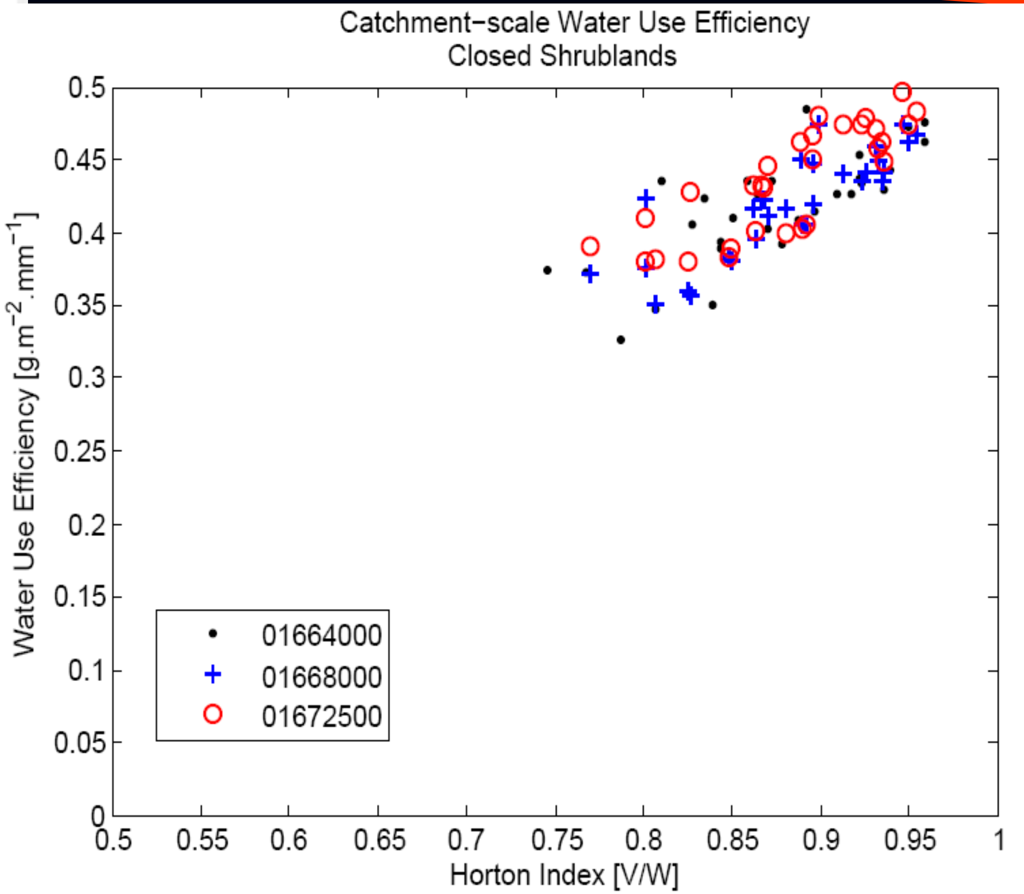


FIG. 2. Aboveground net primary production (ANPP) and actual evapotranspiration (AET) from several United States grasslands sites fully described by Sims et al. (1978). Location and dominant vegetation are listed in Table 1. Site abbreviations are ALE, Ale, Washington, USA; COT, Cottonwood, South Dakota, USA; D, Dickinson, South Dakota, USA; J, Jornada, New Mexico, USA; O, Osage, Oklahoma, USA; PW, Pawnee, Colorado, USA; and PT, Pantex, Texas, USA.

Webb et al, 1978 (*Ecology*)

Catchment-scale Water Use Efficiency

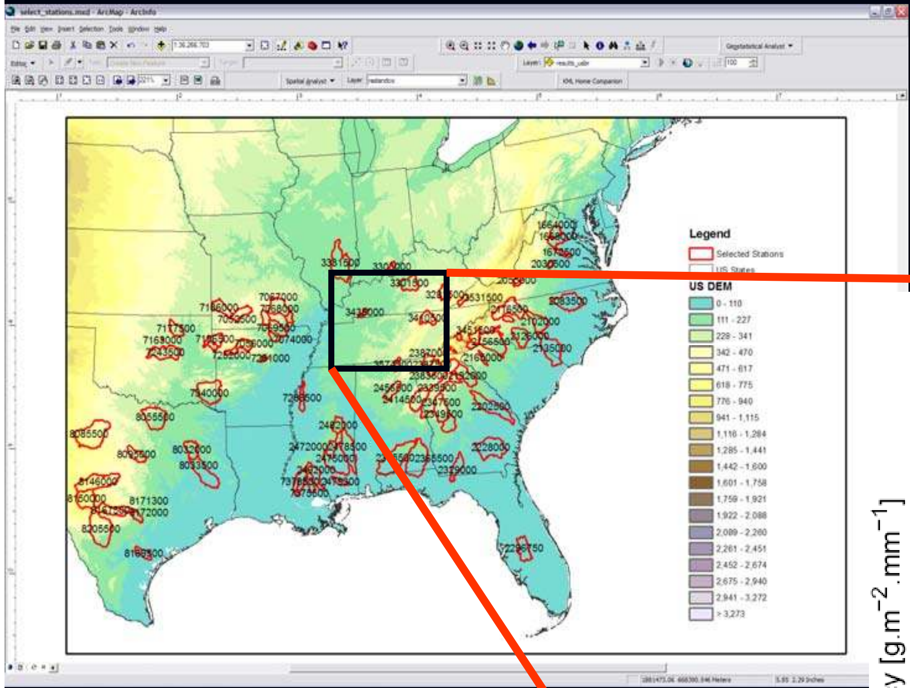


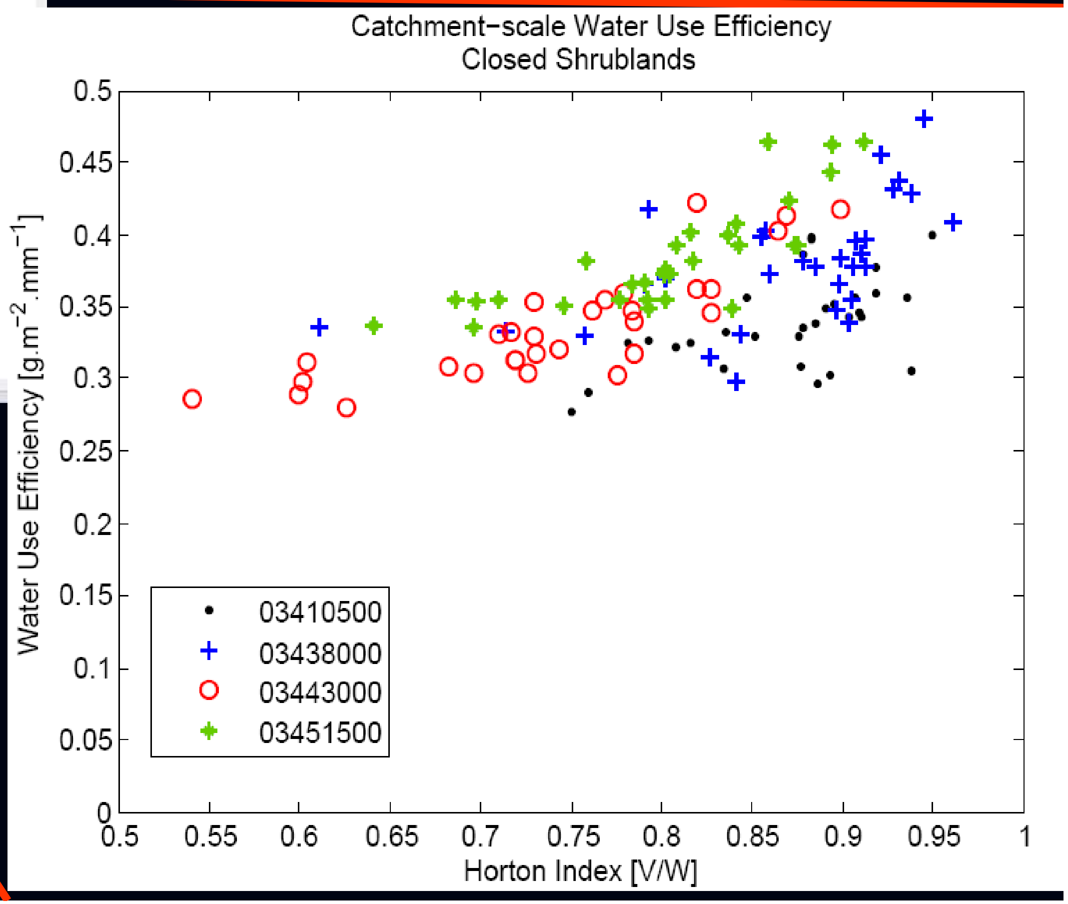


$$\text{ANPP} = f(V)$$

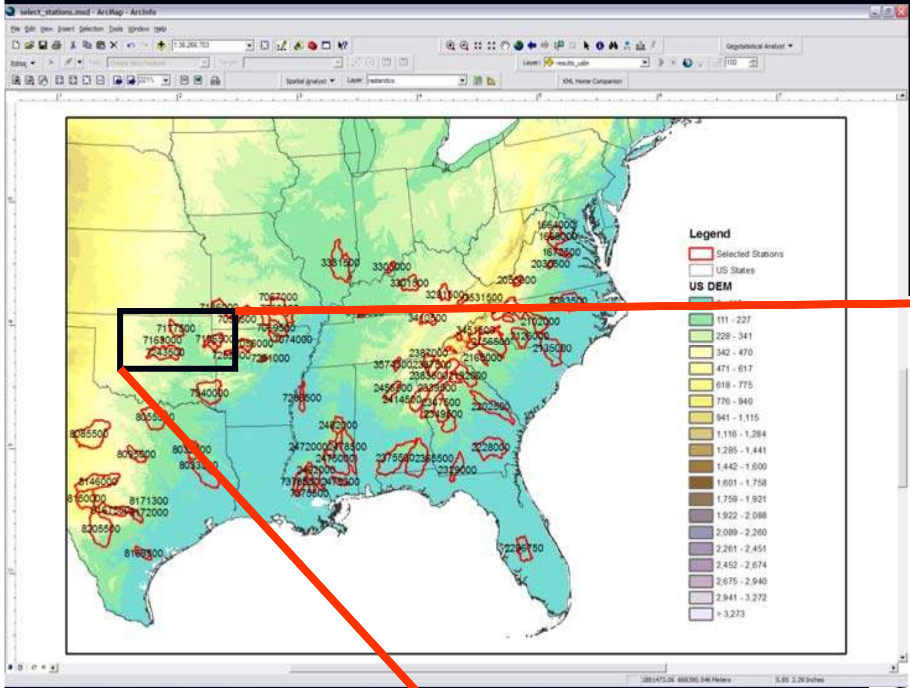
$$\text{WUE} = \frac{\text{ANPP}}{P - S}$$

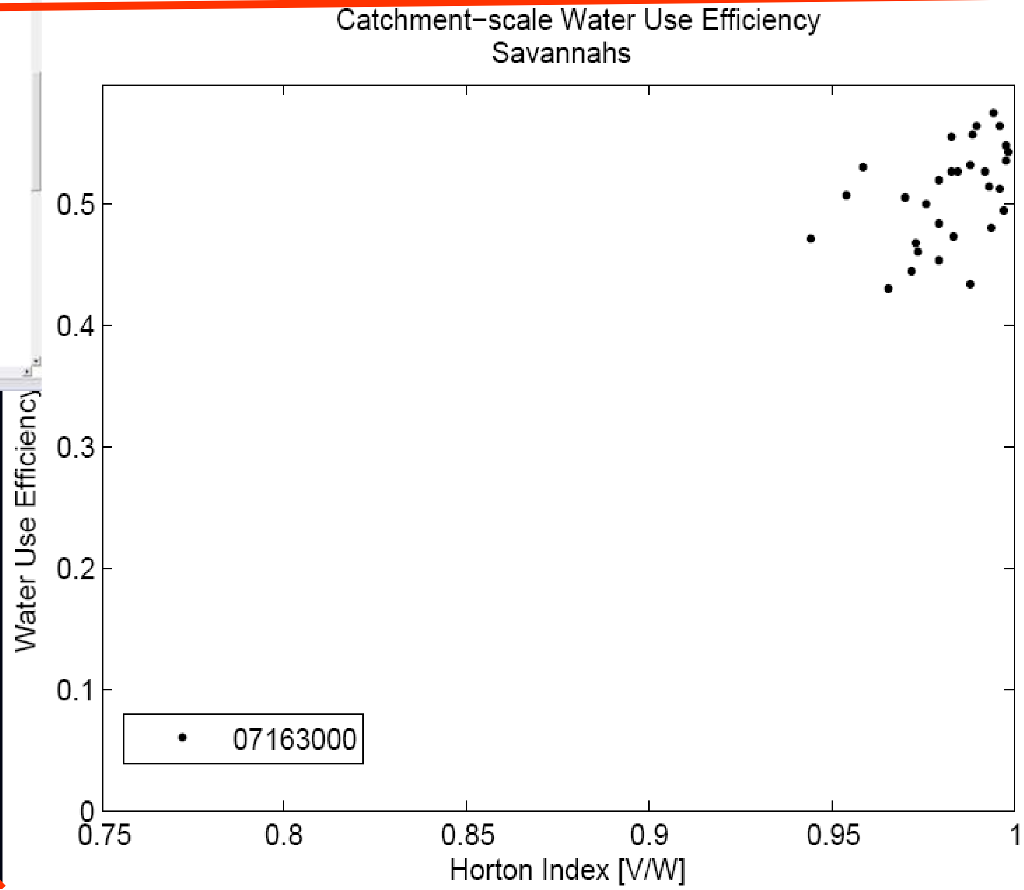
Catchment-scale Water Use Efficiency





Catchment-scale Water Use Efficiency





The annual water balance

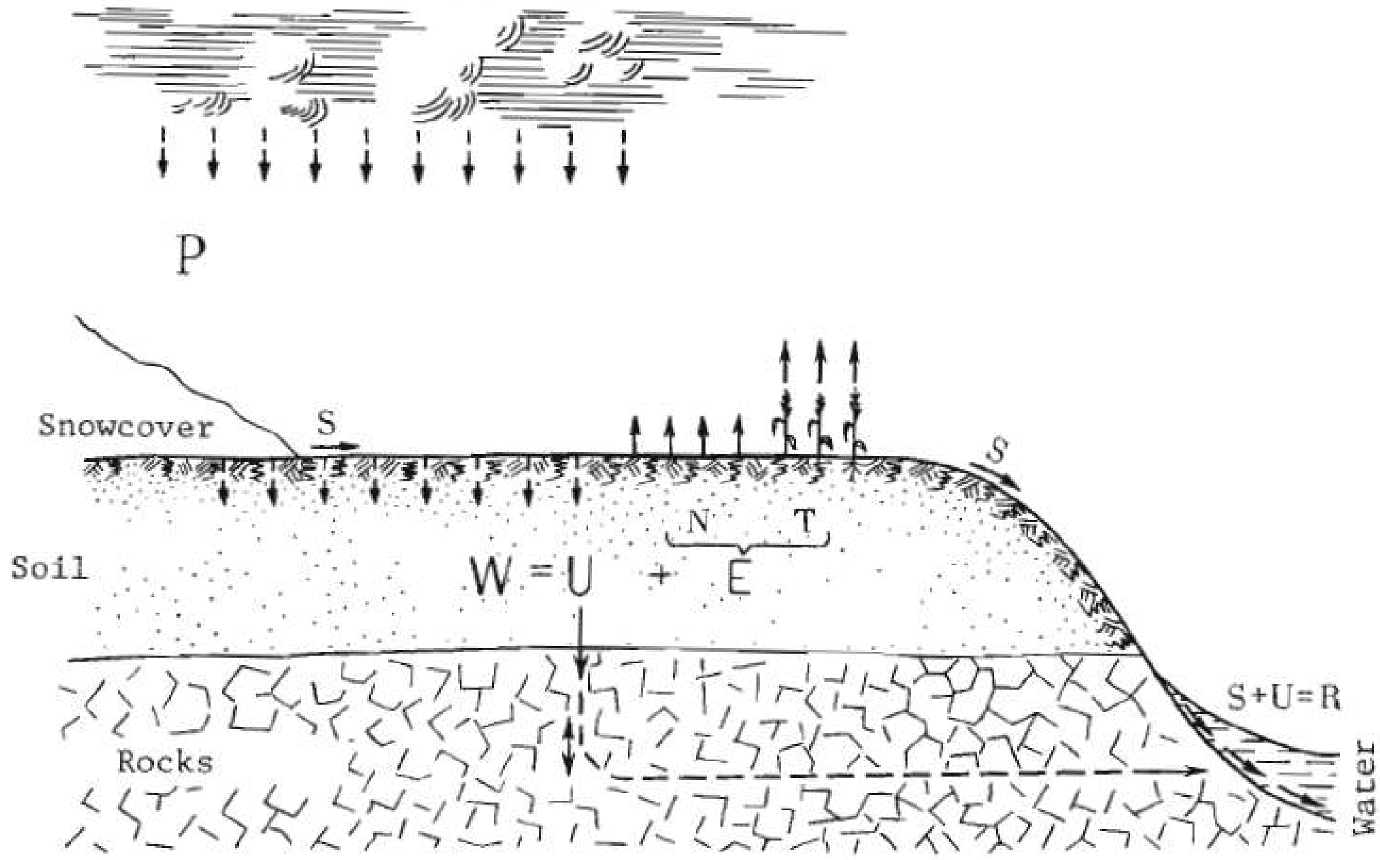


Fig. 3. Diagram of the water balance of land area. P--Precipitation; R--total runoff; U--groundwater runoff; S--surface runoff; W--total wetting of the area (annual infiltration) including surface retention; N--unproductive evaporation (evaporation proper); T--transpiration of plants; E--evapotranspiration.

L'vovich, 1979 (*AGU*)

The L'vovich Hypothesis

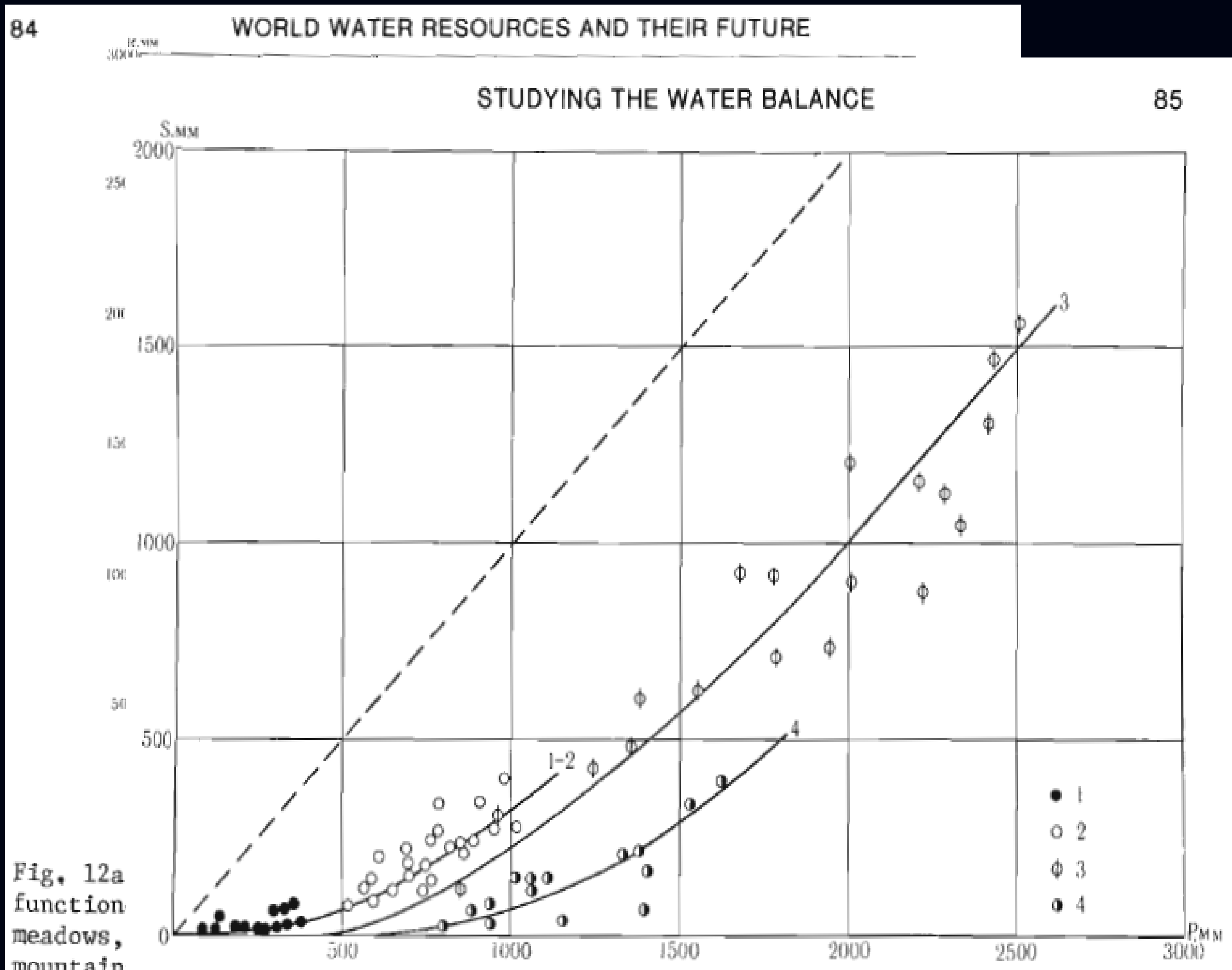


Fig. 12a function meadows, mountain

Fig. 12b. Plot of interpolation formula for surface runoff (S) as a function of rainfall (P) for South America. Notations same as in Fig. 12a.

$$P = R + V$$

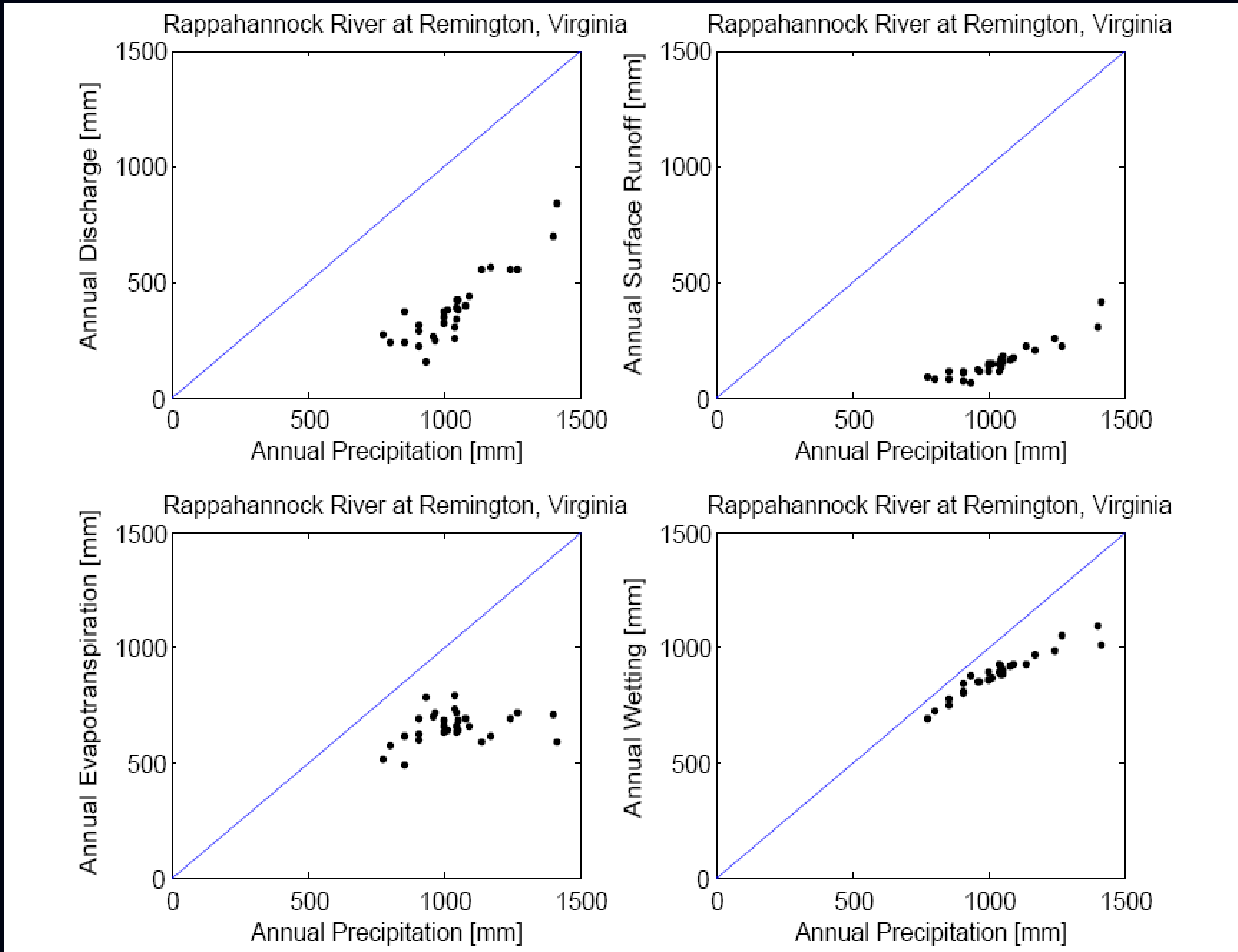
$$P = S + W$$

$$R = S + U$$

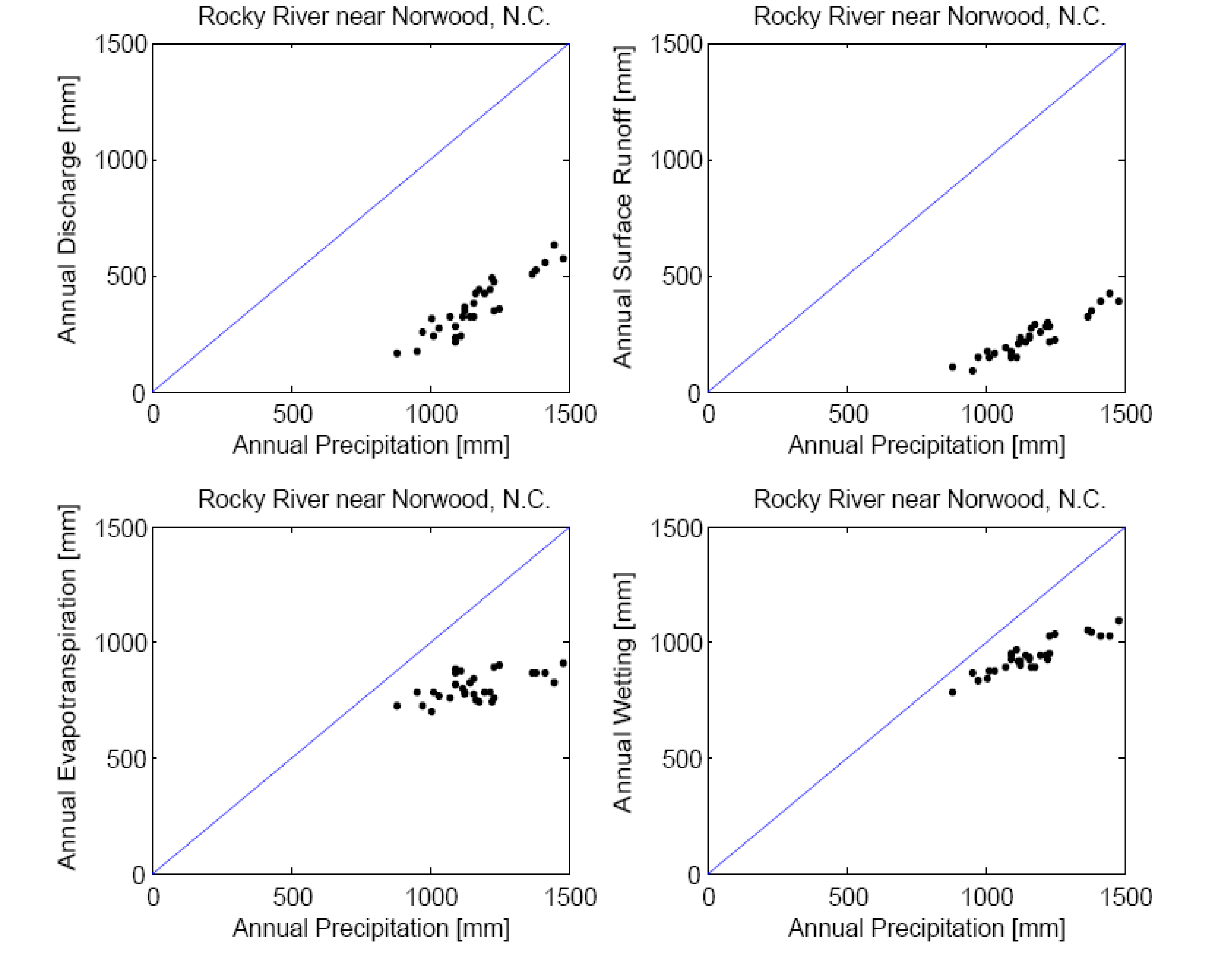
$$W = U + V$$

L'vovich, 1979 (*AGU*)

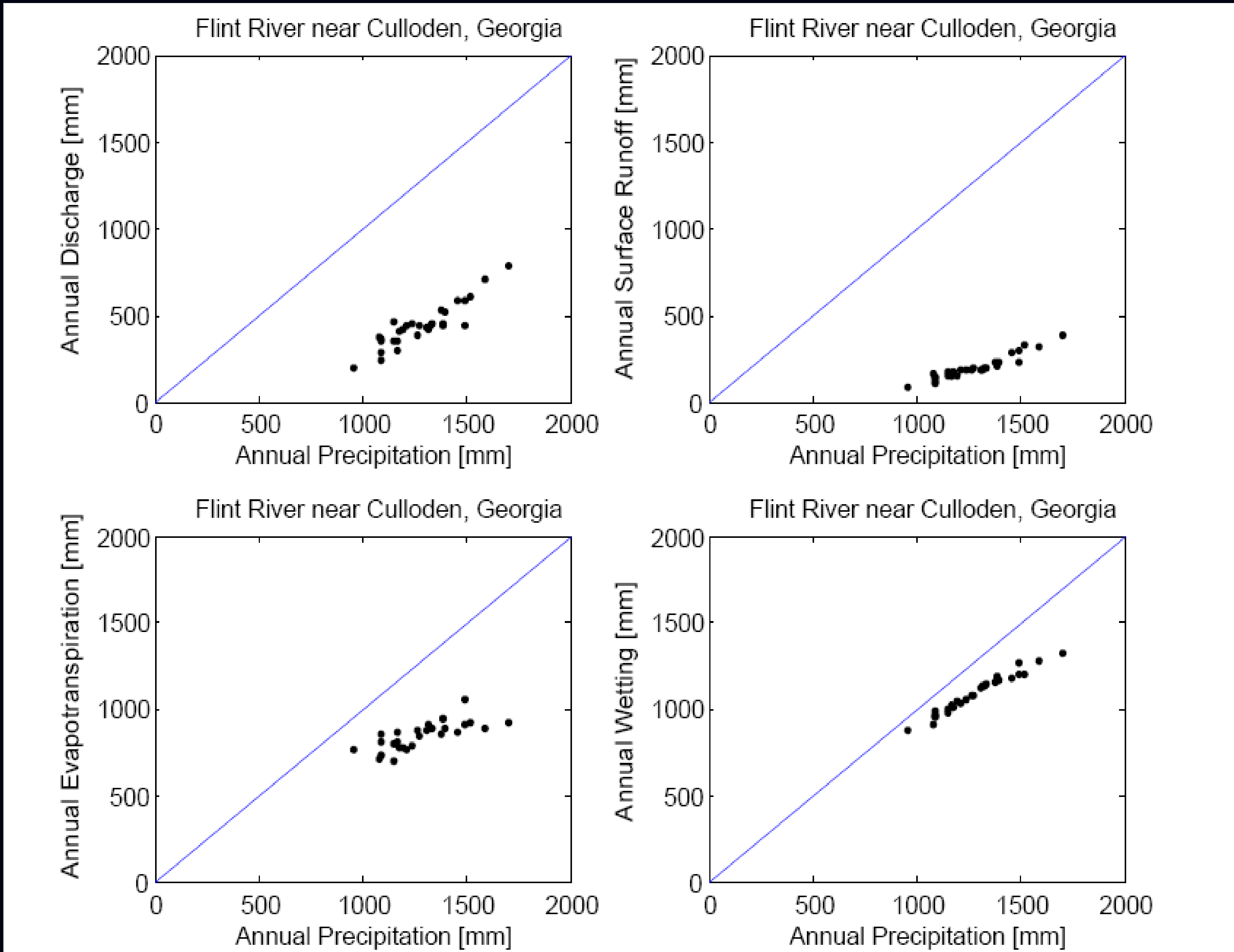
Rappahannock River, Virginia



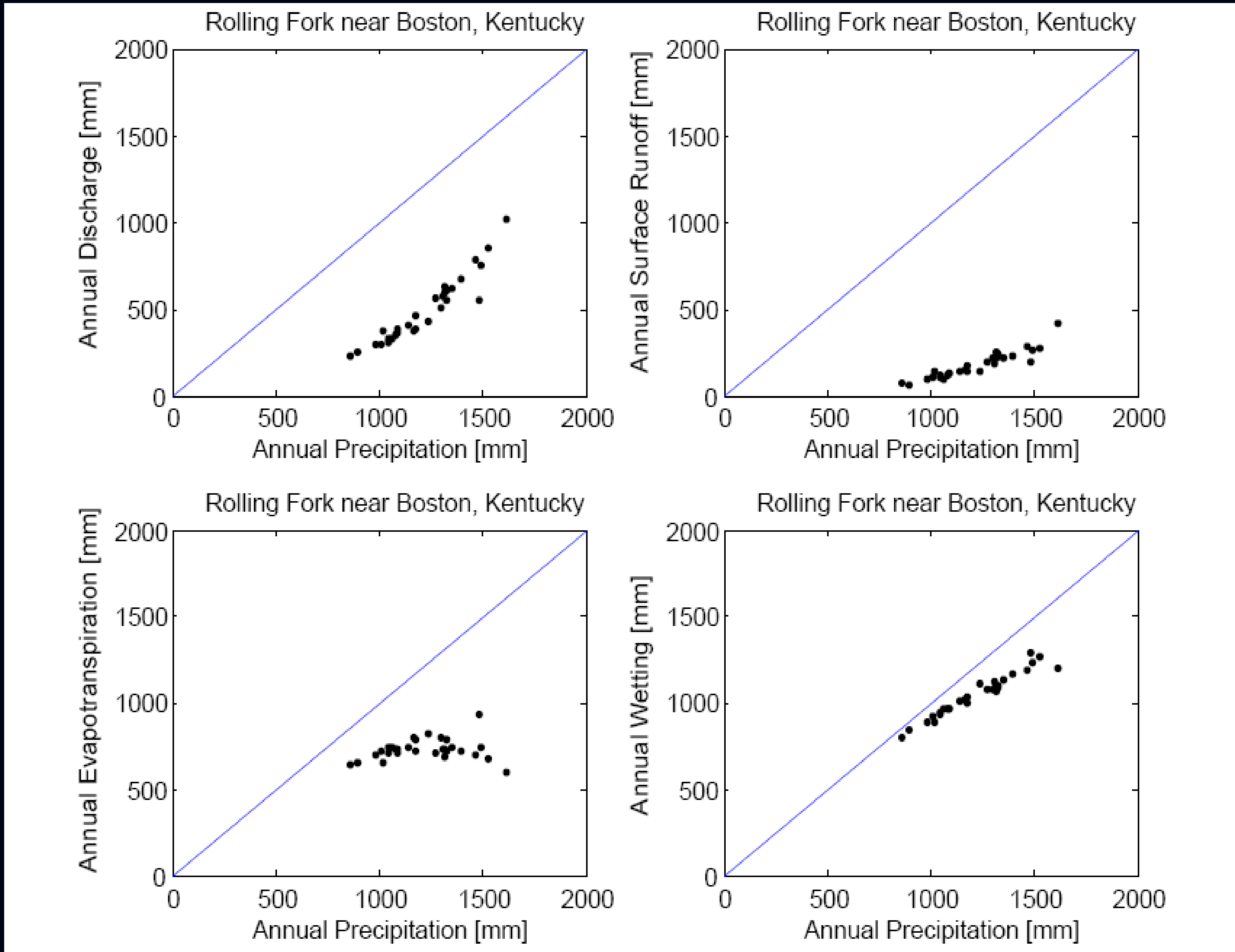
Rocky River, North Carolina



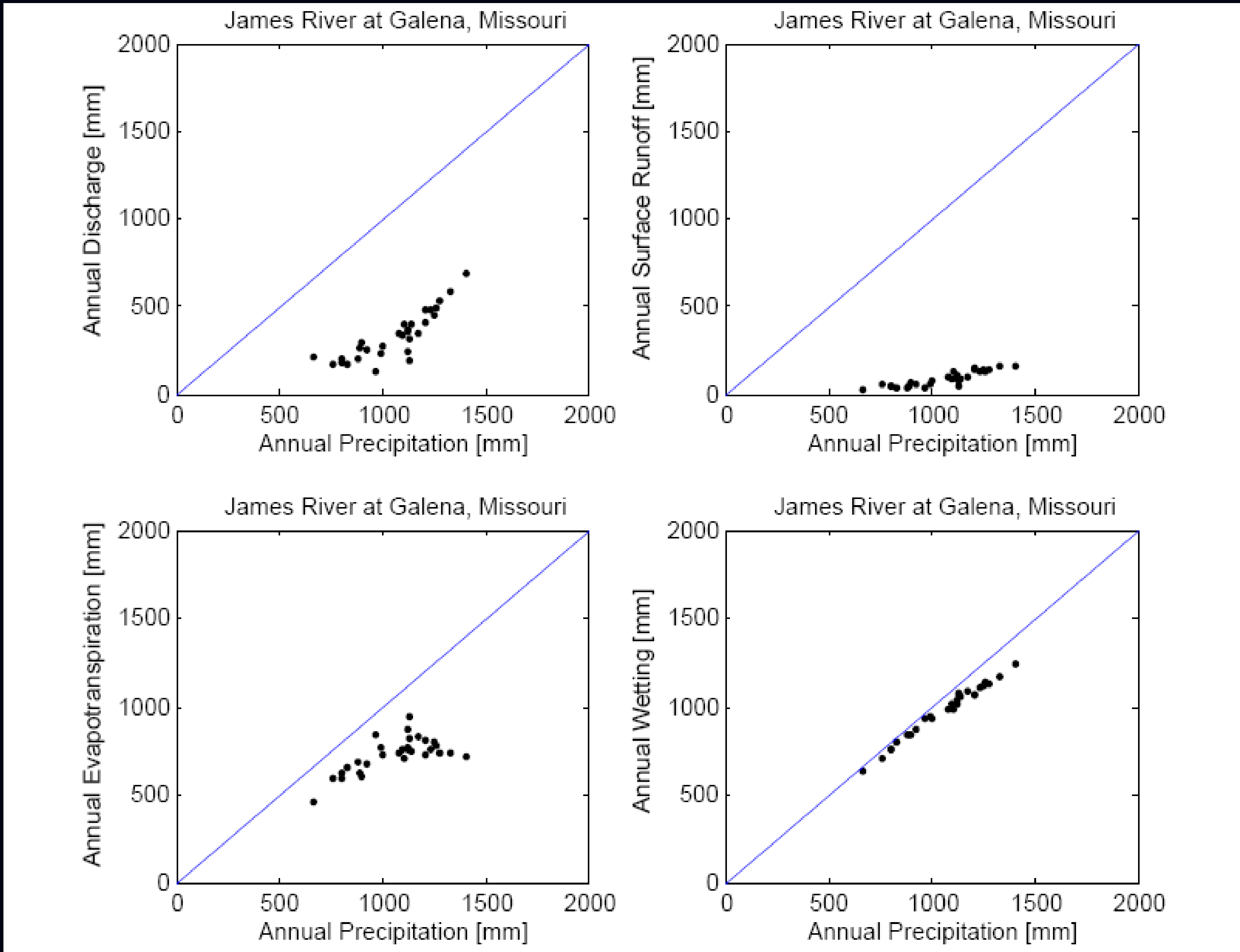
Flint River, Georgia



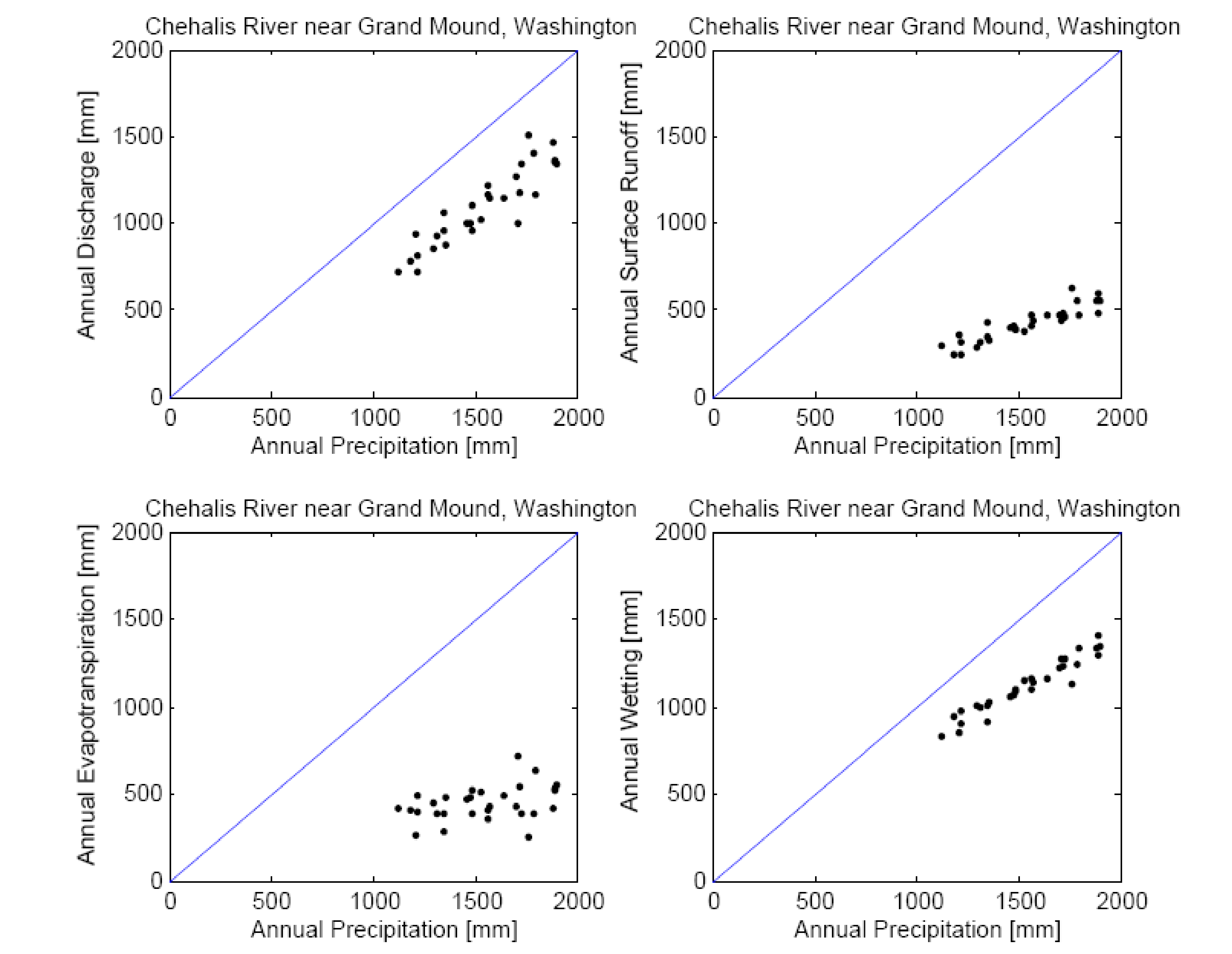
Rolling Fork River, Kentucky



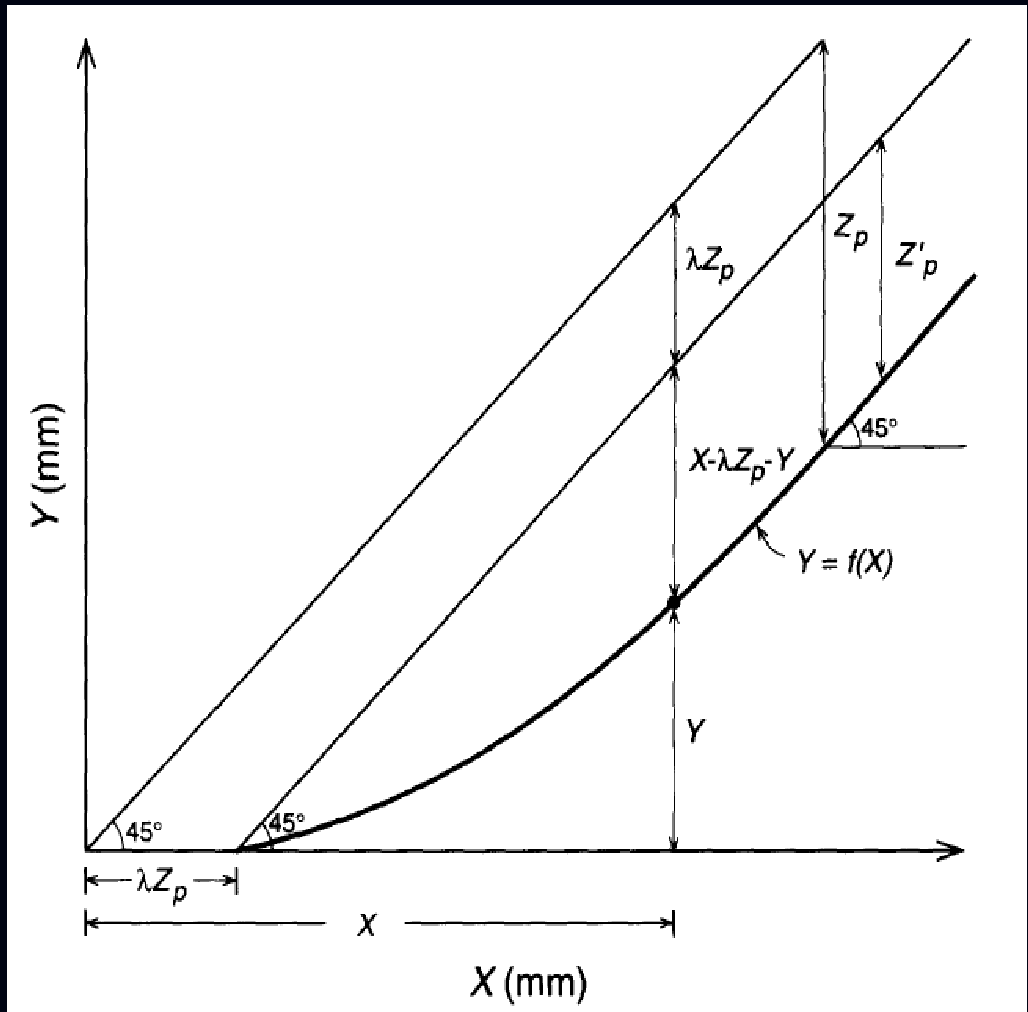
James River, Missouri



Chehalis River, Washington



Proportionality Relations



$$X = Y + Z$$

$$Z = X - Y$$

$$Z \to Z_p \Leftrightarrow X \to \infty; Y \to \infty$$

$$P = S + U + V = S + W$$

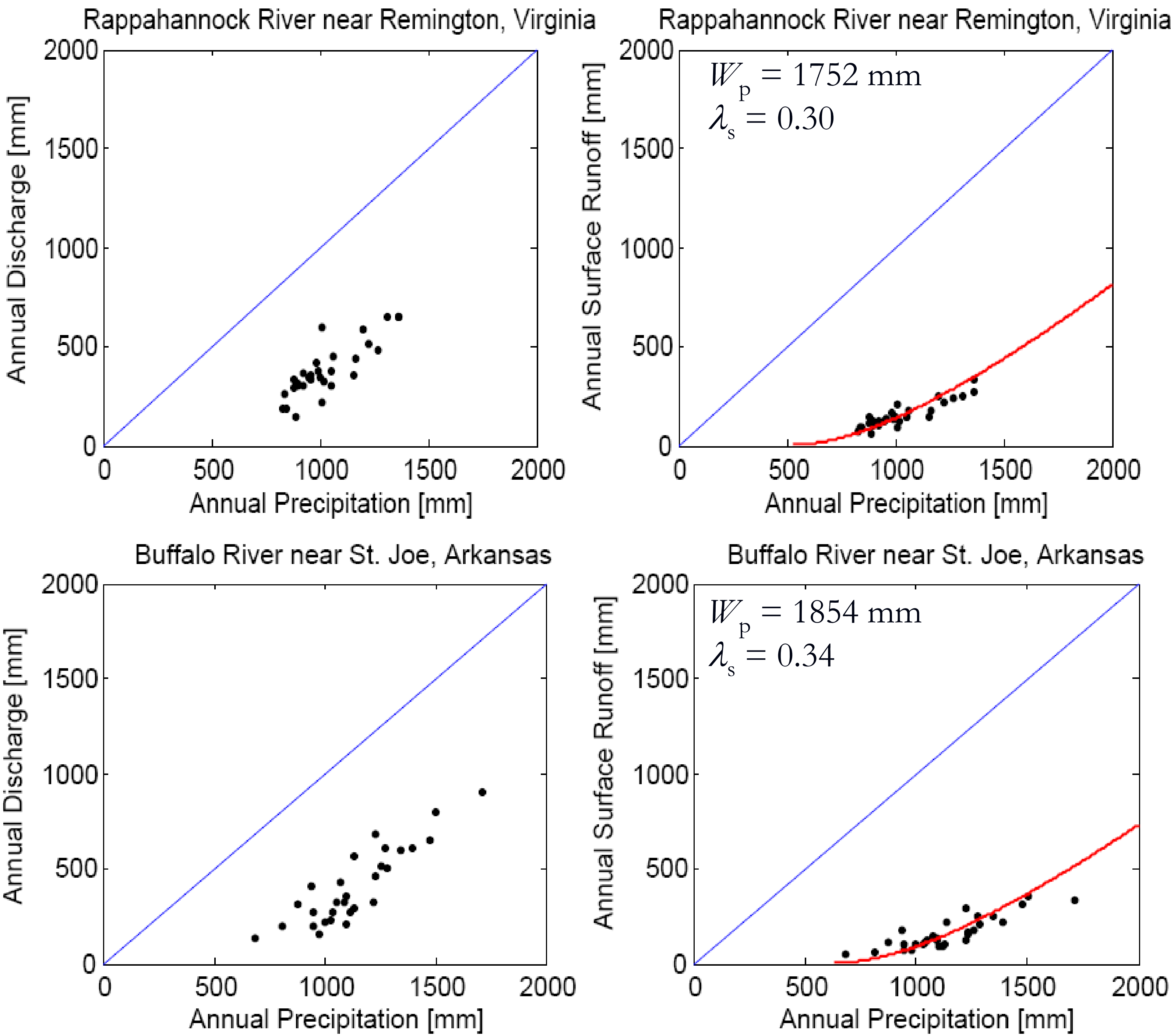
$$W = P - S$$

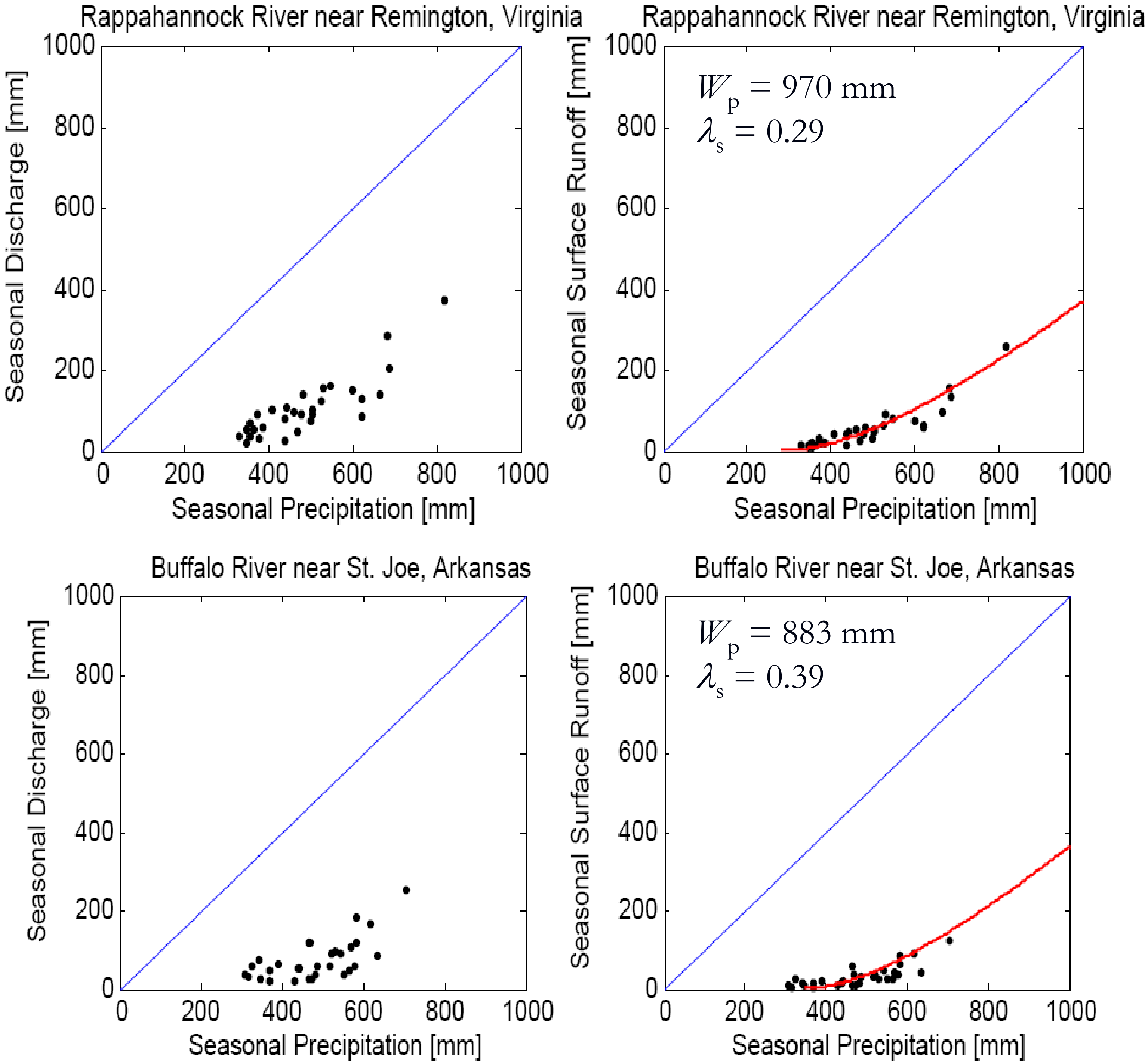
$$W \to W_p \Leftrightarrow P \to \infty; S \to \infty$$

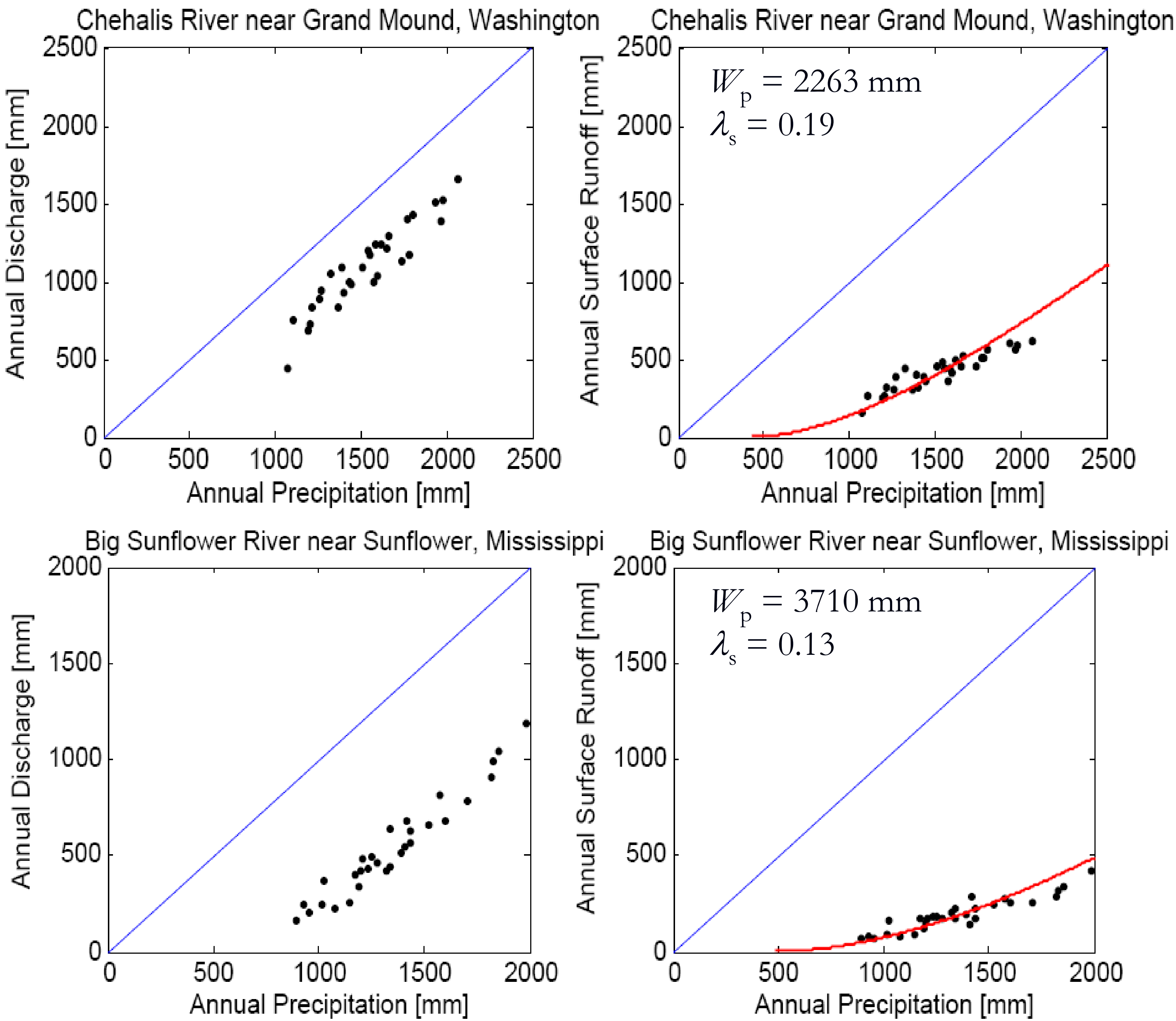
$$S = \frac{(P - \lambda_s W_p)^2}{P + (1 - 2\lambda_s) W_p}$$

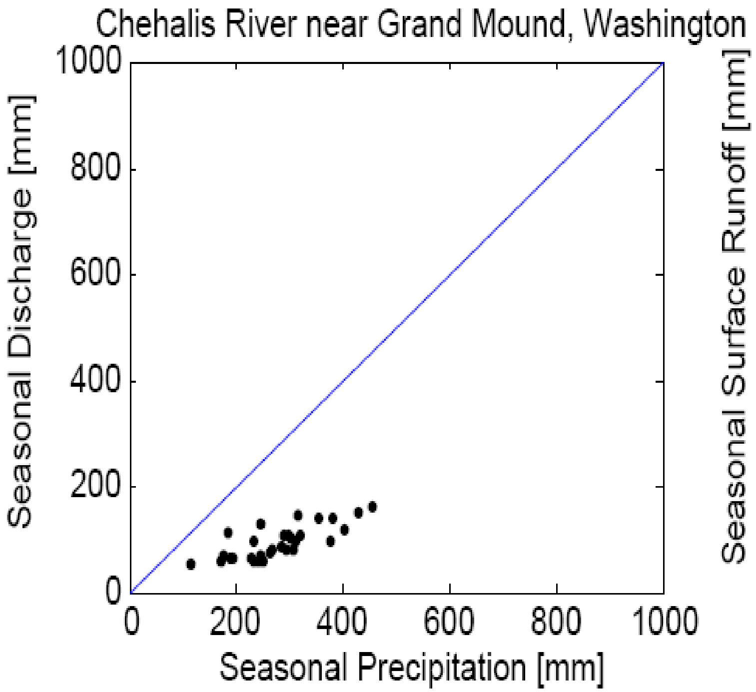
W_p : Wetting Potential (annual precipitation that can be retained by the catchment)
λ_s : Surface Runoff Abstration Coefficient

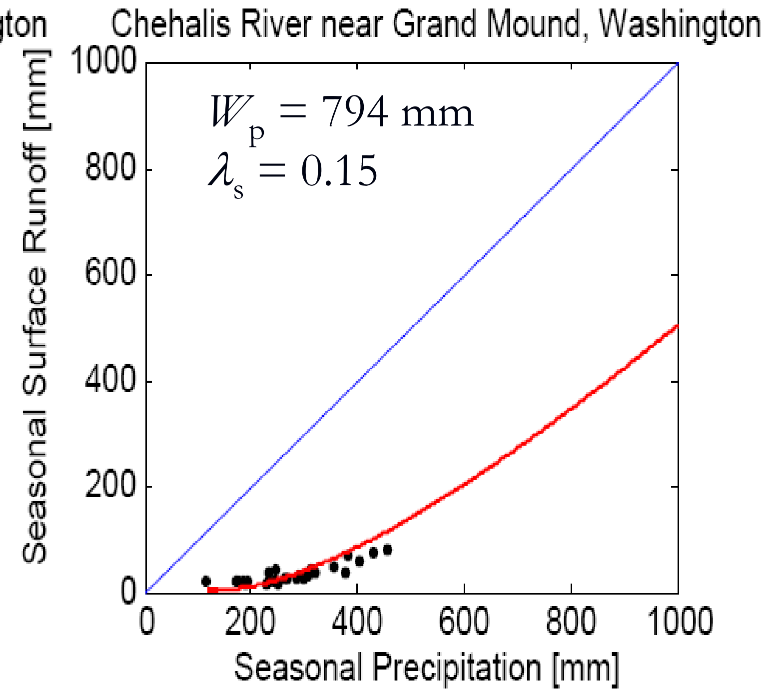
Ponce and Shetty, 1995 (*JoH*)

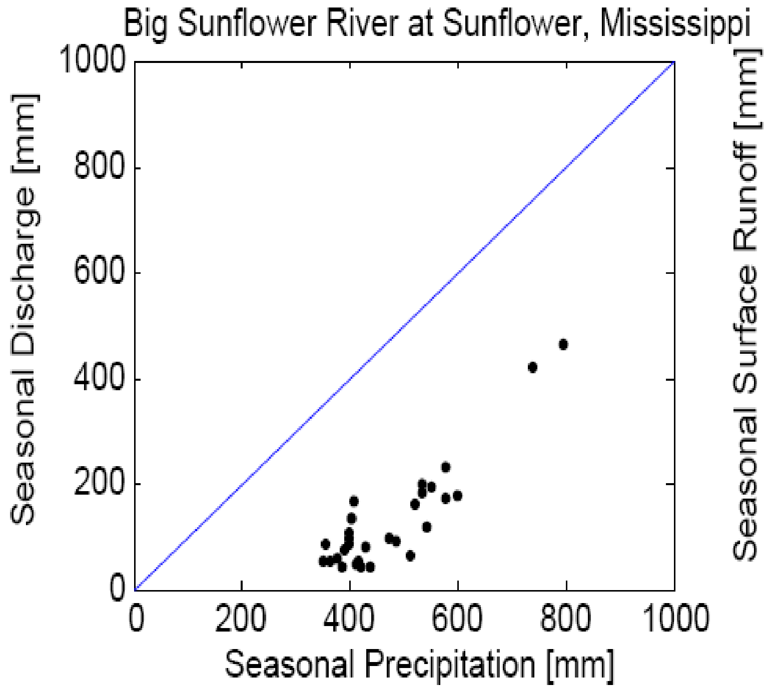

Rappahannock River near Remington, Virginia
Annual Discharge [mm]
Annual Precipitation [mm]
Rappahannock River near Remington, Virginia
W_p = 1752 mm
λ_s = 0.30
Annual Surface Runoff [mm]
Annual Precipitation [mm]
Buffalo River near St. Joe, Arkansas
Annual Discharge [mm]
Annual Precipitation [mm]
Buffalo River near St. Joe, Arkansas
W_p = 1854 mm
λ_s = 0.34
Annual Surface Runoff [mm]
Annual Precipitation [mm]

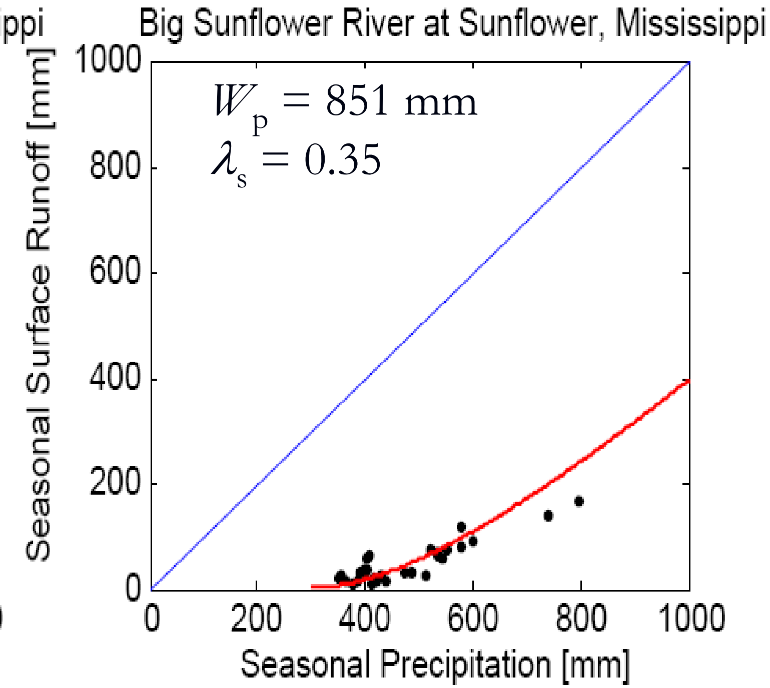

Rappahannock River near Remington, Virginia
Seasonal Discharge [mm]
Seasonal Precipitation [mm]
Rappahannock River near Remington, Virginia
Seasonal Surface Runoff [mm]
Seasonal Precipitation [mm]
W_p = 970 mm
λ_s = 0.29
Buffalo River near St. Joe, Arkansas
Seasonal Discharge [mm]
Seasonal Precipitation [mm]
Buffalo River near St. Joe, Arkansas
Seasonal Surface Runoff [mm]
Seasonal Precipitation [mm]
W_p = 883 mm
λ_s = 0.39
0
200
400
600
800
1000


Chehalis River near Grand Mound, Washington
Annual Discharge [mm]
Annual Precipitation [mm]
0
500
1000
1500
2000
2500
Chehalis River near Grand Mound, Washington
Annual Surface Runoff [mm]
Annual Precipitation [mm]
W_p = 2263 mm
λ_s = 0.19
Big Sunflower River near Sunflower, Mississippi
Annual Discharge [mm]
Annual Precipitation [mm]
0
500
1000
1500
2000
Big Sunflower River near Sunflower, Mississippi
Annual Surface Runoff [mm]
Annual Precipitation [mm]
W_p = 3710 mm
λ_s = 0.13

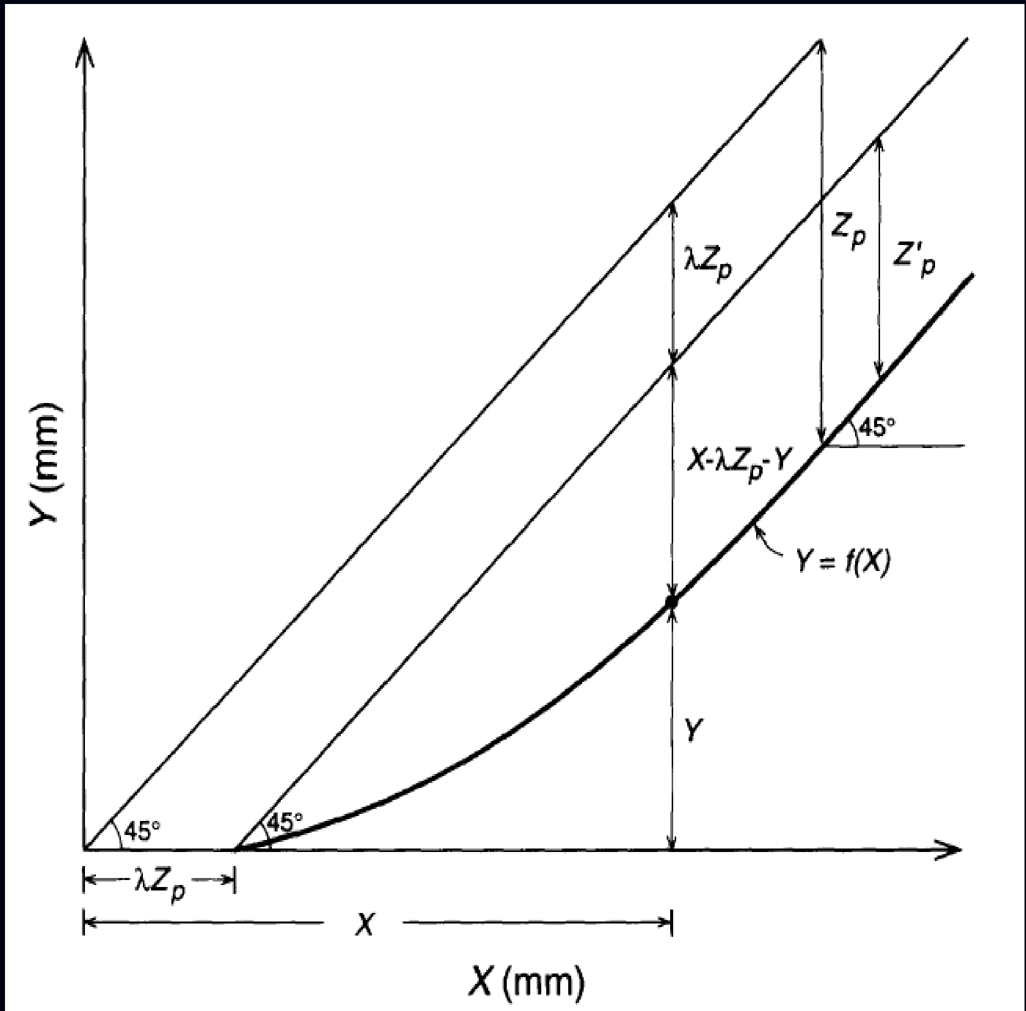

Chehalis River near Grand Mound, Washington
Seasonal Discharge [mm]
Seasonal Precipitation [mm]
0
200
400
600
800
1000


Chehalis River near Grand Mound, Washington
W_p = 794 mm
λ_s = 0.15
Seasonal Surface Runoff [mm]
Seasonal Precipitation [mm]
0
200
400
600
800
1000


Big Sunflower River at Sunflower, Mississippi
Seasonal Discharge [mm]
Seasonal Precipitation [mm]
0
200
400
600
800
1000


Big Sunflower River at Sunflower, Mississippi
W_p = 851 mm
λ_s = 0.35
Seasonal Surface Runoff [mm]
Seasonal Precipitation [mm]
0
200
400
600
800
1000

Proportionality Relations



$$X = Y + Z$$

$$Z = X - Y$$

$$Z \rightarrow Z_p \Leftrightarrow X \rightarrow \infty; Y \rightarrow \infty$$

$$W = U + V$$

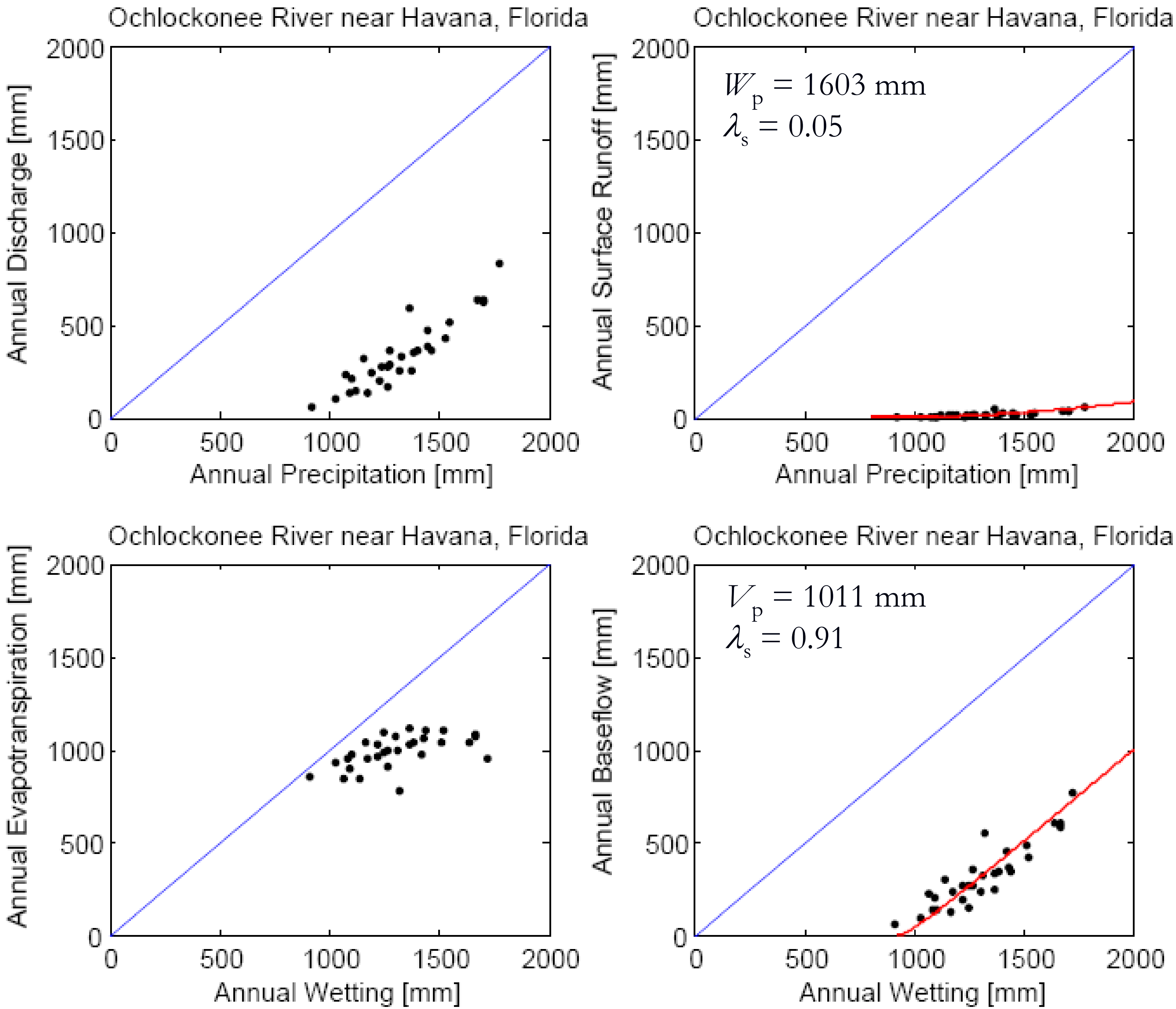
$$V = W - U$$

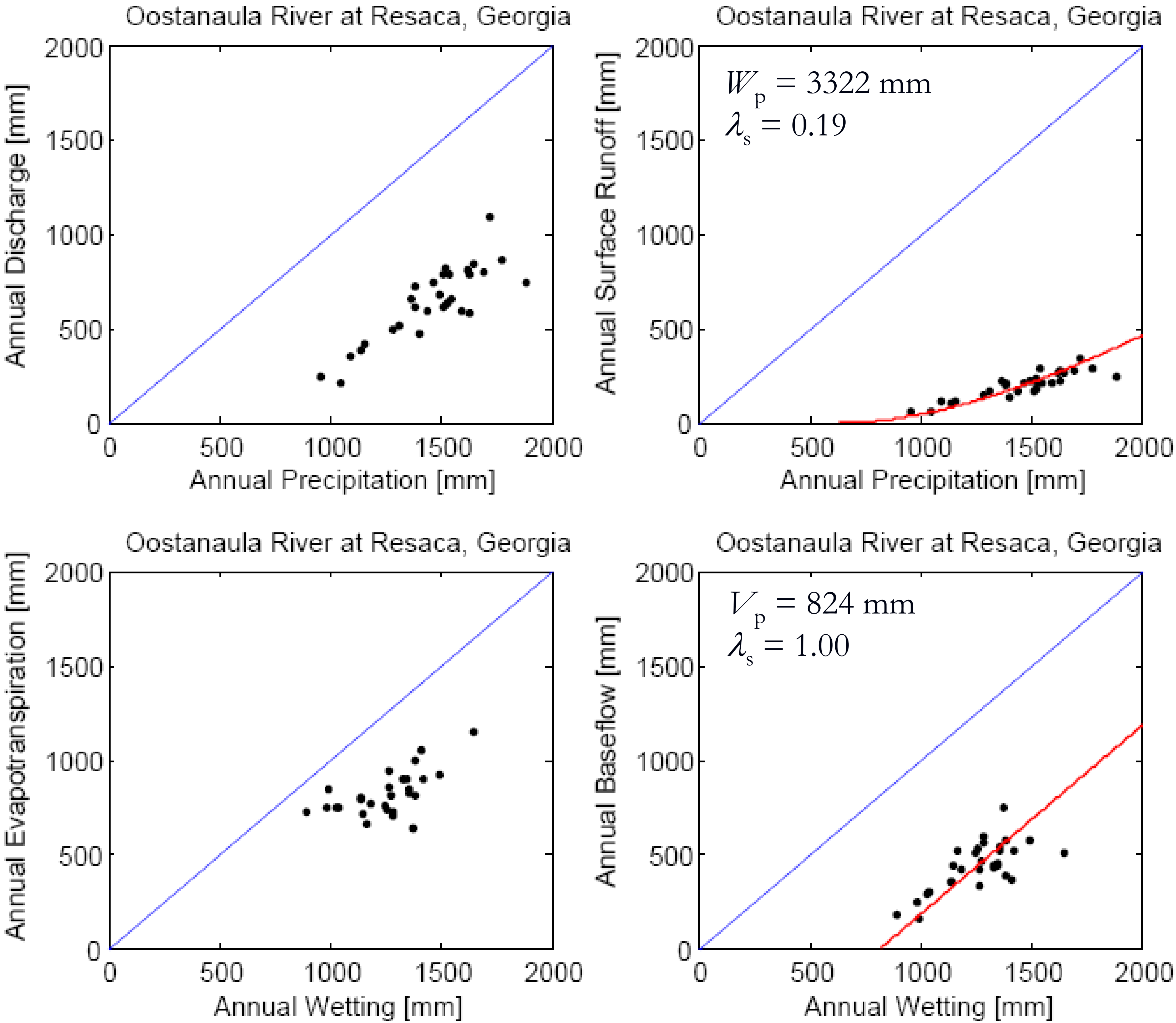
$$V \rightarrow V_p \Leftrightarrow W \rightarrow \infty; U \rightarrow \infty$$

$$U = \frac{(W - \lambda_u V_p)^2}{W + (1 - 2\lambda_u)V_p}$$

V_p : Vaporization Potential (annual wetting that can be evaporated)
λ_s : Baseflow Abstration Coefficient

Ponce and Shetty, 1995 (*JoH*)


Ochlockonee River near Havana, Florida
Annual Discharge [mm]
Annual Precipitation [mm]
Ochlockonee River near Havana, Florida
Annual Surface Runoff [mm]
Annual Precipitation [mm]
W_p = 1603 mm
λ_s = 0.05
Ochlockonee River near Havana, Florida
Annual Evapotranspiration [mm]
Annual Wetting [mm]
Ochlockonee River near Havana, Florida
Annual Baseflow [mm]
Annual Wetting [mm]
V_p = 1011 mm
λ_s = 0.91
0
500
1000
1500
2000



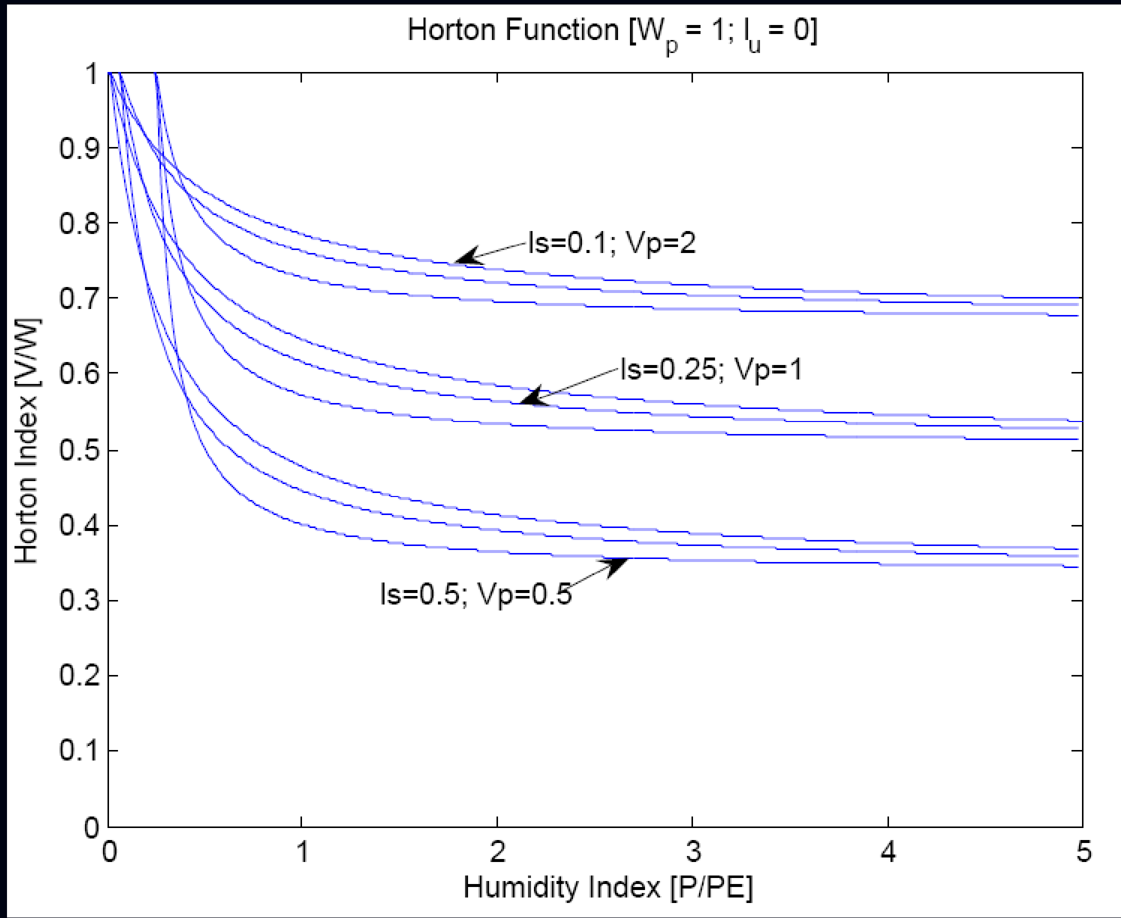
Oostanaula River at Resaca, Georgia
Annual Discharge [mm]
Annual Precipitation [mm]
Oostanaula River at Resaca, Georgia
W_p = 3322 mm
λ_s = 0.19
Annual Surface Runoff [mm]
Annual Precipitation [mm]
Oostanaula River at Resaca, Georgia
Annual Evapotranspiration [mm]
Annual Wetting [mm]
Oostanaula River at Resaca, Georgia
V_p = 824 mm
λ_s = 1.00
Annual Baseflow [mm]
Annual Wetting [mm]
0
500
1000
1500
2000

Back to the Horton Index

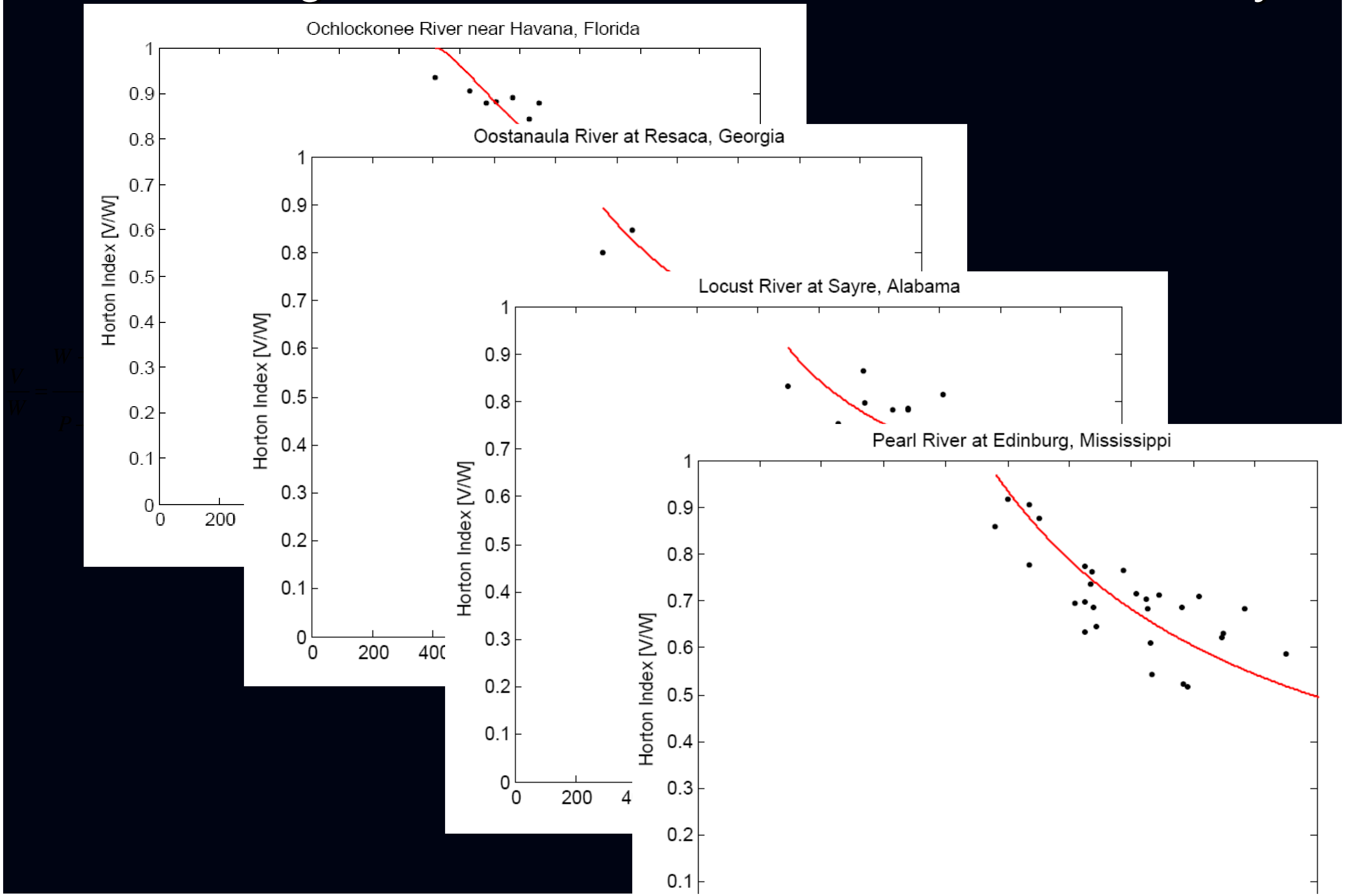
$$H = \frac{V}{W} = \frac{W - \dfrac{(W - \lambda_u V_p)^2}{W + (1 - 2\lambda_u) V_p}}{P - \dfrac{(P - \lambda_s W_p)^2}{P + (1 - 2\lambda_s) W_p}}$$

$$H = f(P, \theta)$$

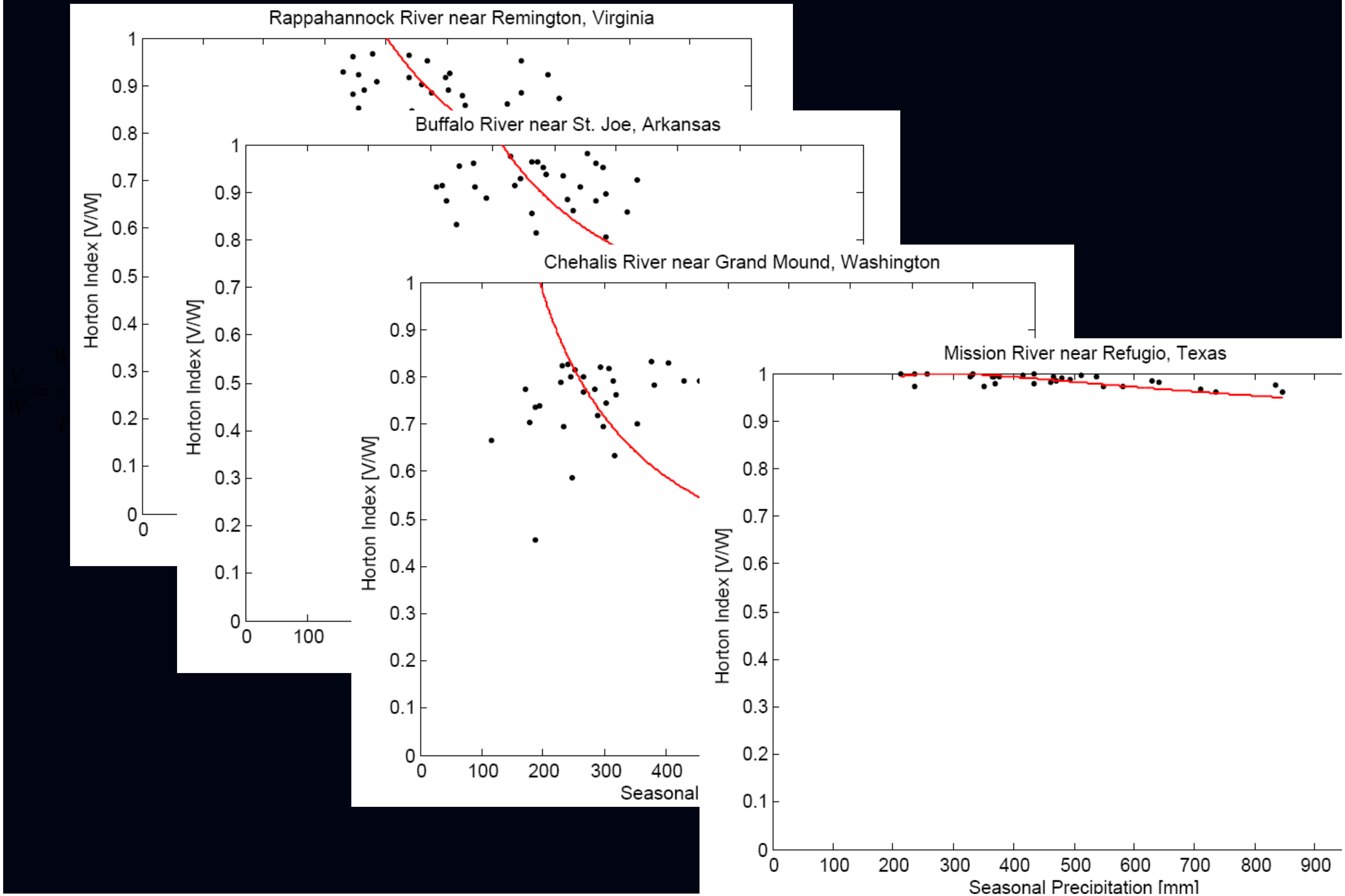
$$\theta = [V_p, W_p, \lambda_s, \lambda_u]$$



Predicting Horton Index interannual variability



Predicting Horton Index constancy



Conclusions (1)

- In semi-arid climates, the Horton index is very constant and close to 1 over the growing season, indicating that the biome WUE is constant and near maximum;
- In humid climate, the Horton index is fairly constant and its value below 1 depends on the available energy; the biome WUE depends on other factors, such as nutrients and radiation;

Conclusions (2)

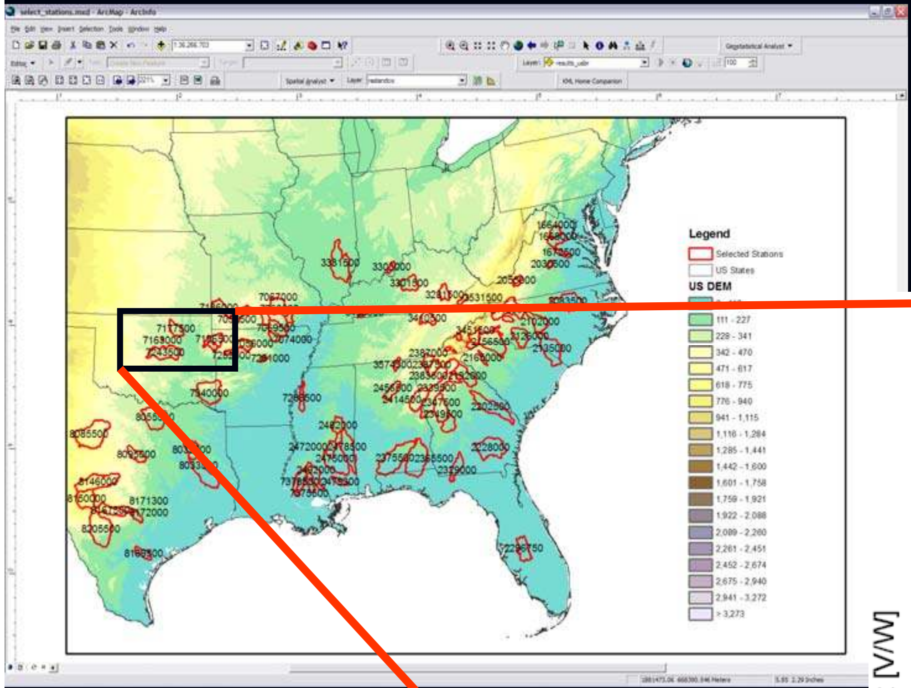
- When evaluated at annual time scales, the Horton index seems to converge to a common value, similar to those observed in semi-arid climates;
- This seems to indicate that the catchment WUE converges to a common maximum WUE, in line with previous observations at the biome level;

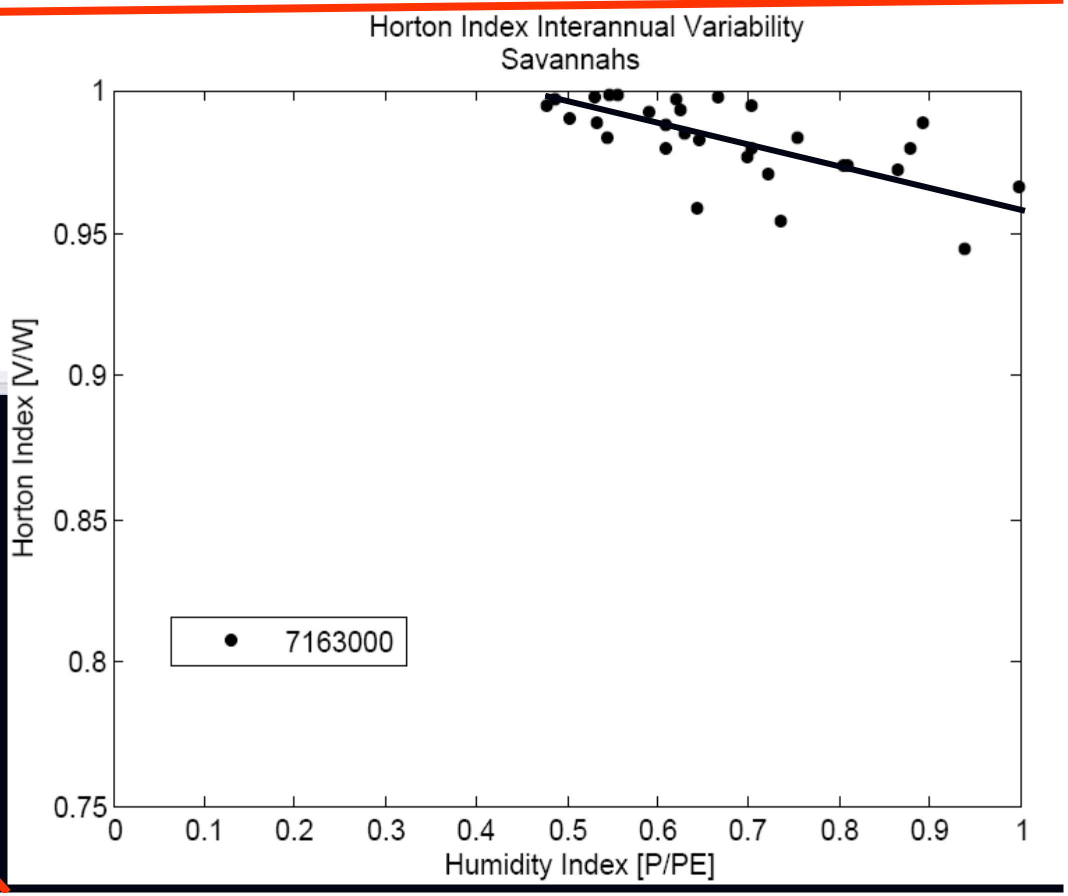
Conclusions (3)

- The interannual variability of the Horton index can be accurately reproduced using the proportionality relations of L'vovich;
- The parameters of the model indicate the catchment functioning in terms of competition between quick runoff and wetting, and between evapotranspiration and baseflow.

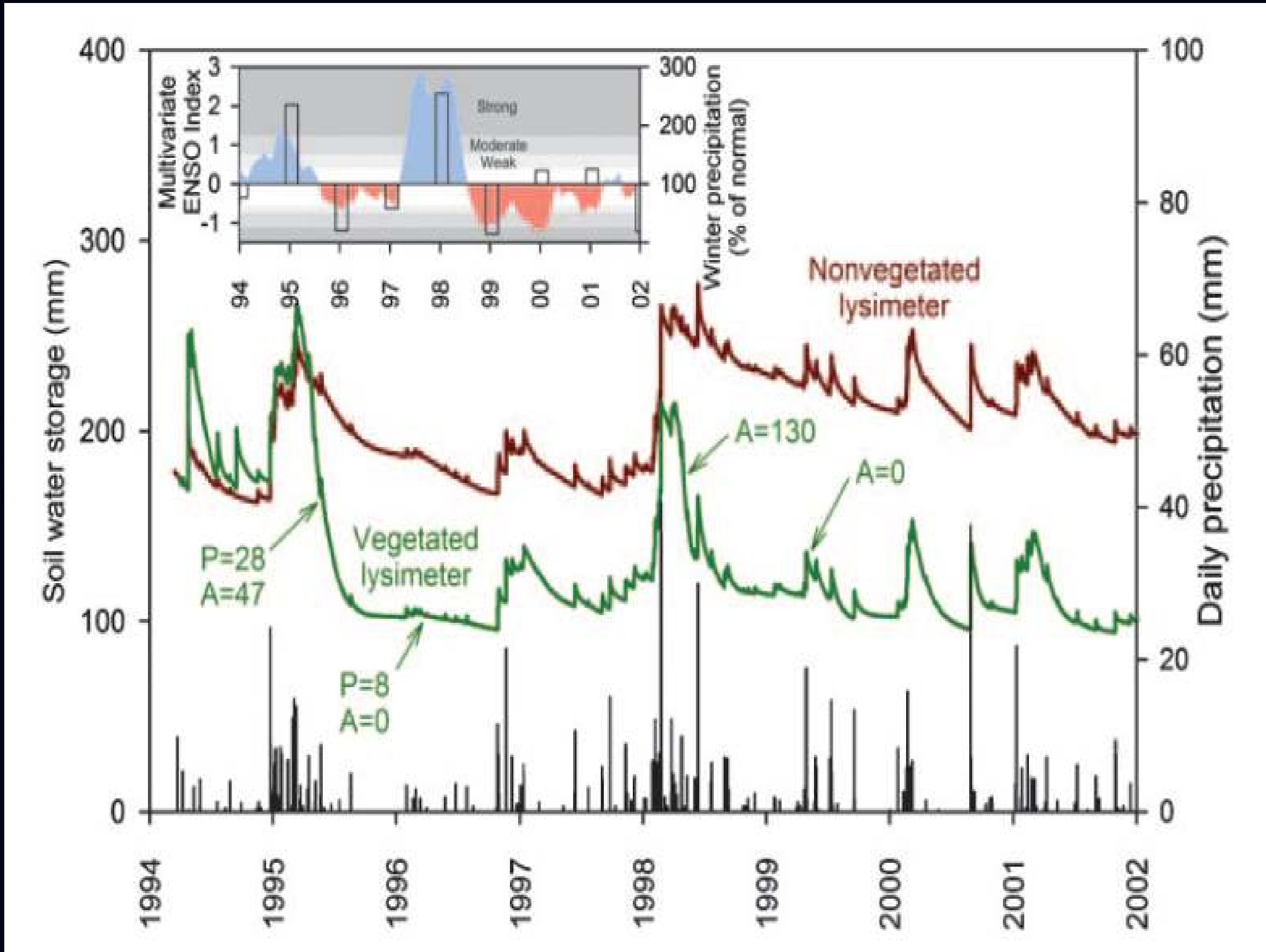
Questions?

Interannual Variability of Horton Index





Ecological controls to interannual variability



Scanlon et al., 2005 (*PNAS*)