A Budyko analysis of LTER sites

Evidence for resistance vs. resilience of water yield responses to climate variability

Irena Creed, Julia Jones and ….

A consortium of catchment scientists, including:

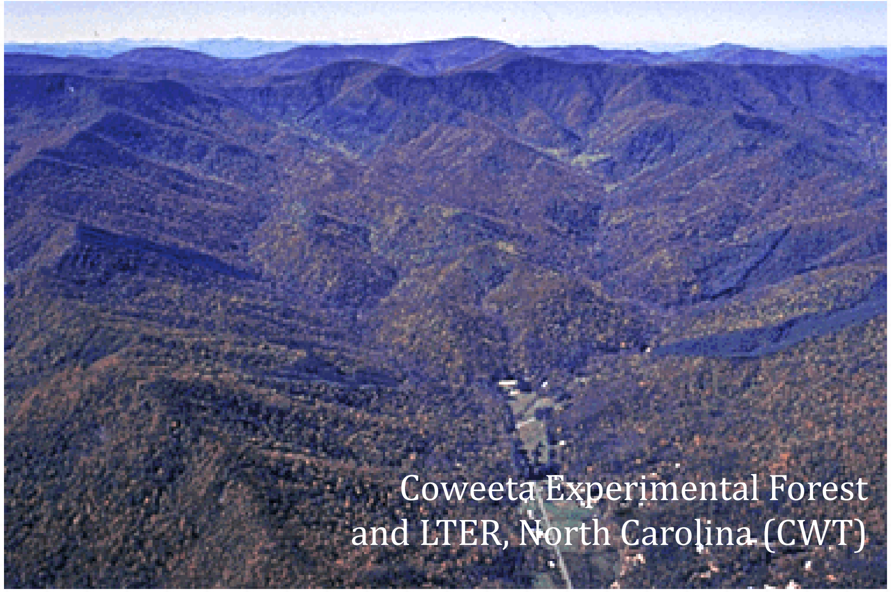
Adam Spargo

USA
Mary Beth Adams (FER)
John Campbell (HBR)
Alan Covich (LUQ)
David Clow (LVW)
Clifford Dahm (SEV)
Kelly Elder (FRA)
Nancy Grimm (CAP)
Julia Jones (AND)
Stephen Sebestyen (MAR)
James Vose (CWT)
Mark Williams (NWT)

Canada
Fred Beall (TLW)
Tom Clair (KEJ)
John Pomeroy (MRM)
Patricia Ramlal (ELA)
Rita Winkler (UPC)
Huaxia Yao (DOR)

Rationale

- These watershed studies are unique.
- Represent longest existing paired records of climate and hydrology.
- Provide opportunity to explore effects of climate on water yields in headwaters of the US and Canada.
- Collective potential of these studies is only beginning to be realized.


Coweeta Experimental Forest and LTER, North Carolina (CWT)

Motivation

Why are we interested in the Budyko curve?

- The Budyko Curve provides a reference condition for the water balance.
- *If* we assume it depicts the expected partitioning of P into Q, *then* we can begin to account for the reasons why sites vary from the curve.

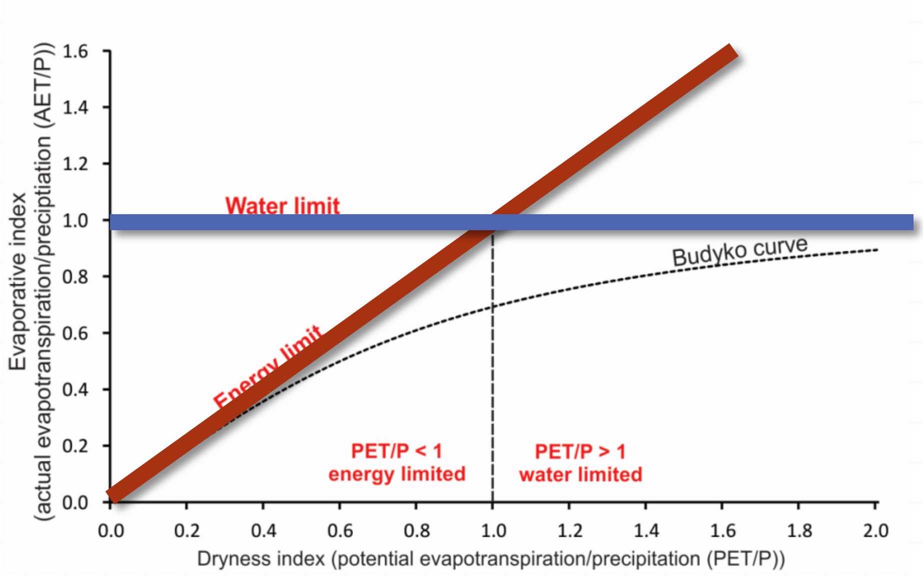
Russian climatologist
1920 –2001

Jones et al. 2011. *Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites* . Bioscience Under Review

Breaking down the Budyko Curve

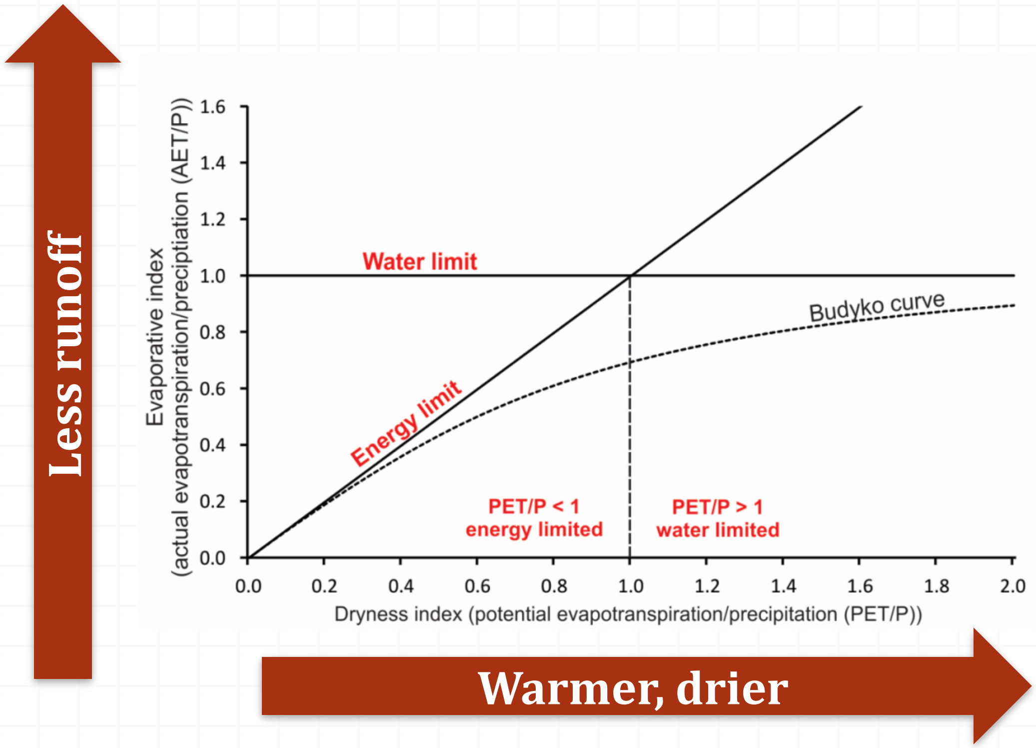
Water limit: AET = P.
A site cannot plot above the **blue line** unless there is an additional input of water beyond precipitation.

Energy limit: AET = PET.
A site cannot plot above the **red line** unless precipitation is being lost (e.g., water lost to groundwater system).



What do deviations from the Budyko curve mean?

VERTICAL deviations change in partitioning between ET and Q



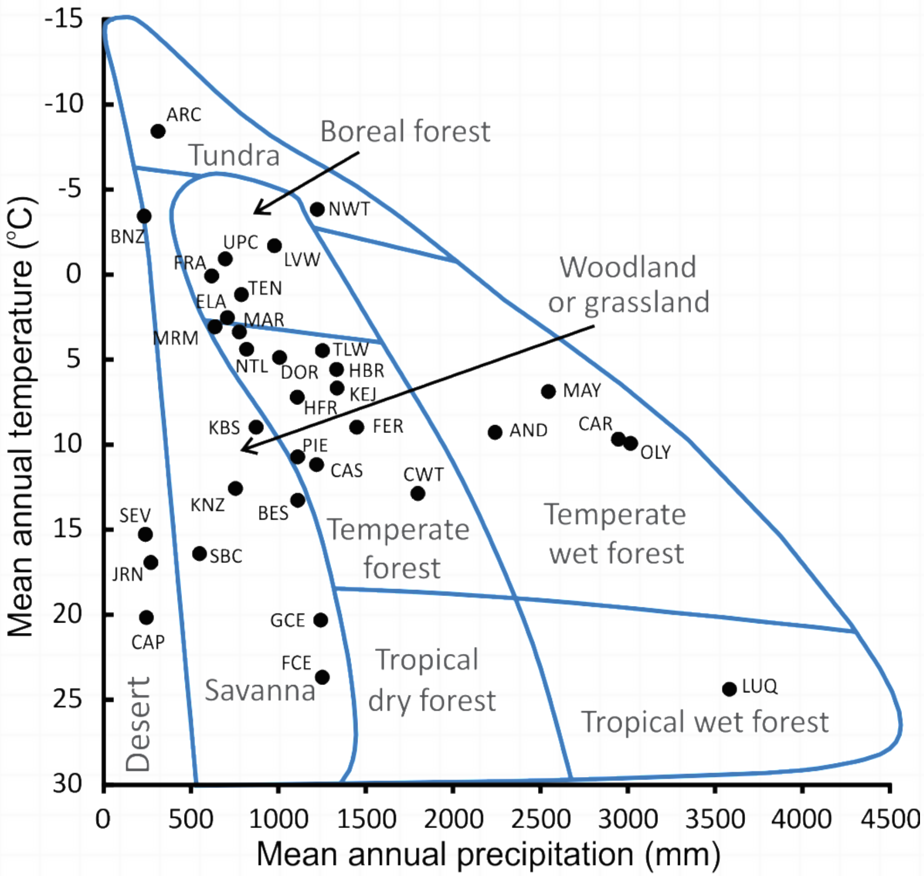
HORIZONTAL deviations change in the climatic conditions

Question 1

Do average annual values for <u>reference</u> catchments fall on the Budyko curve?

"LTER" Sites

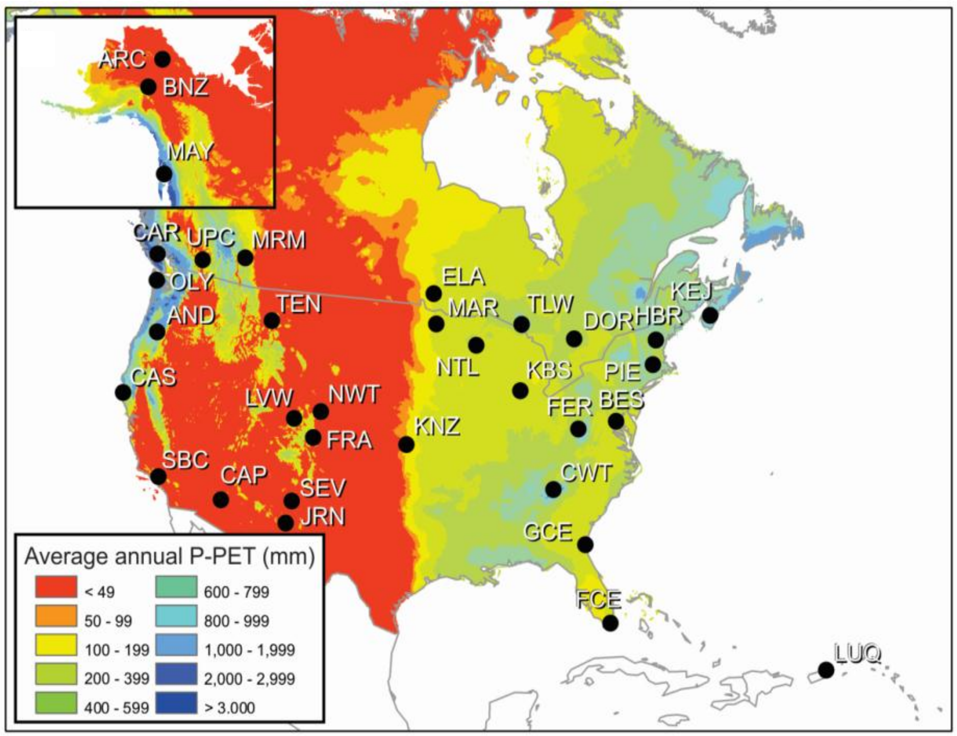
(including US LTER, USGS, USFS and Cdn sites)



- 30 sites across North America selected based on
  - Reference catchments
  - Coverage of major biomes
  - Coverage of major climate regions

"LTER" Sites

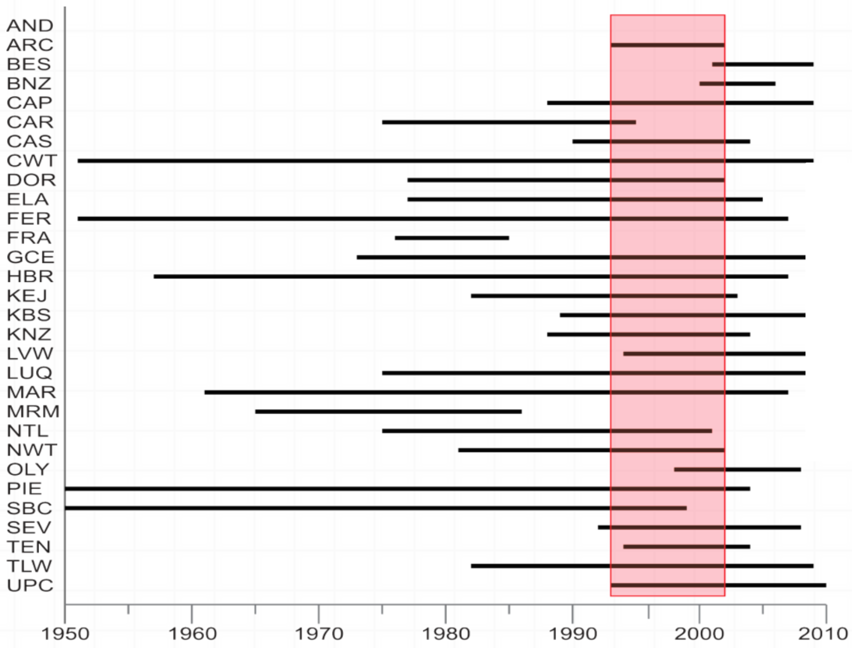
(including US LTER, USGS, USFS and Cdn sites)

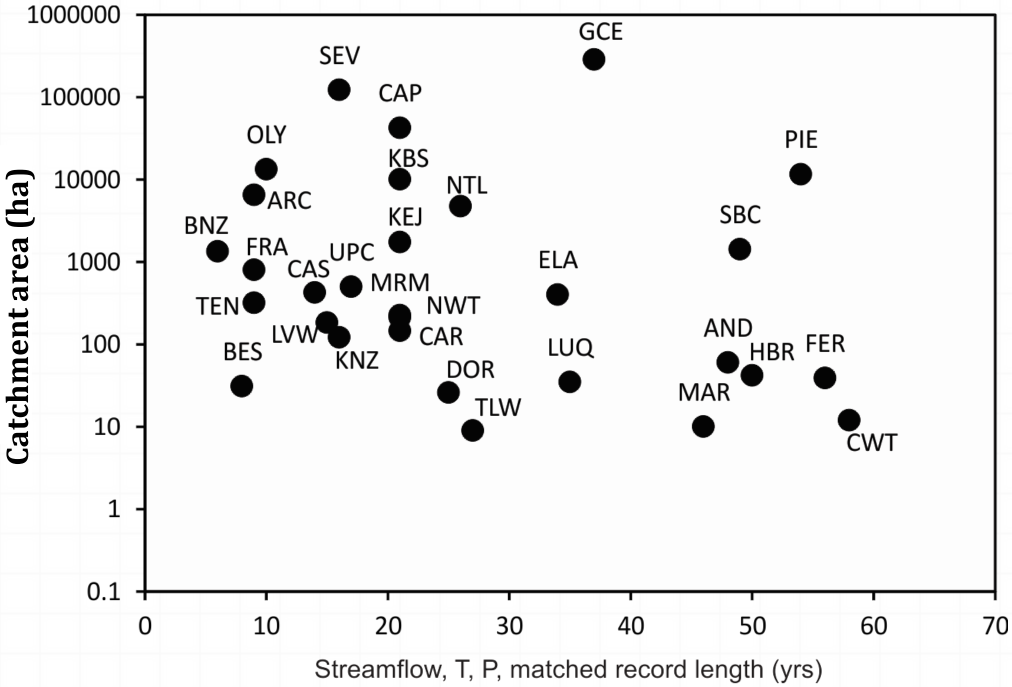


- 30 sites across North America selected based on
  - Reference catchments
  - Coverage of major biomes
  - Coverage of major climate regions

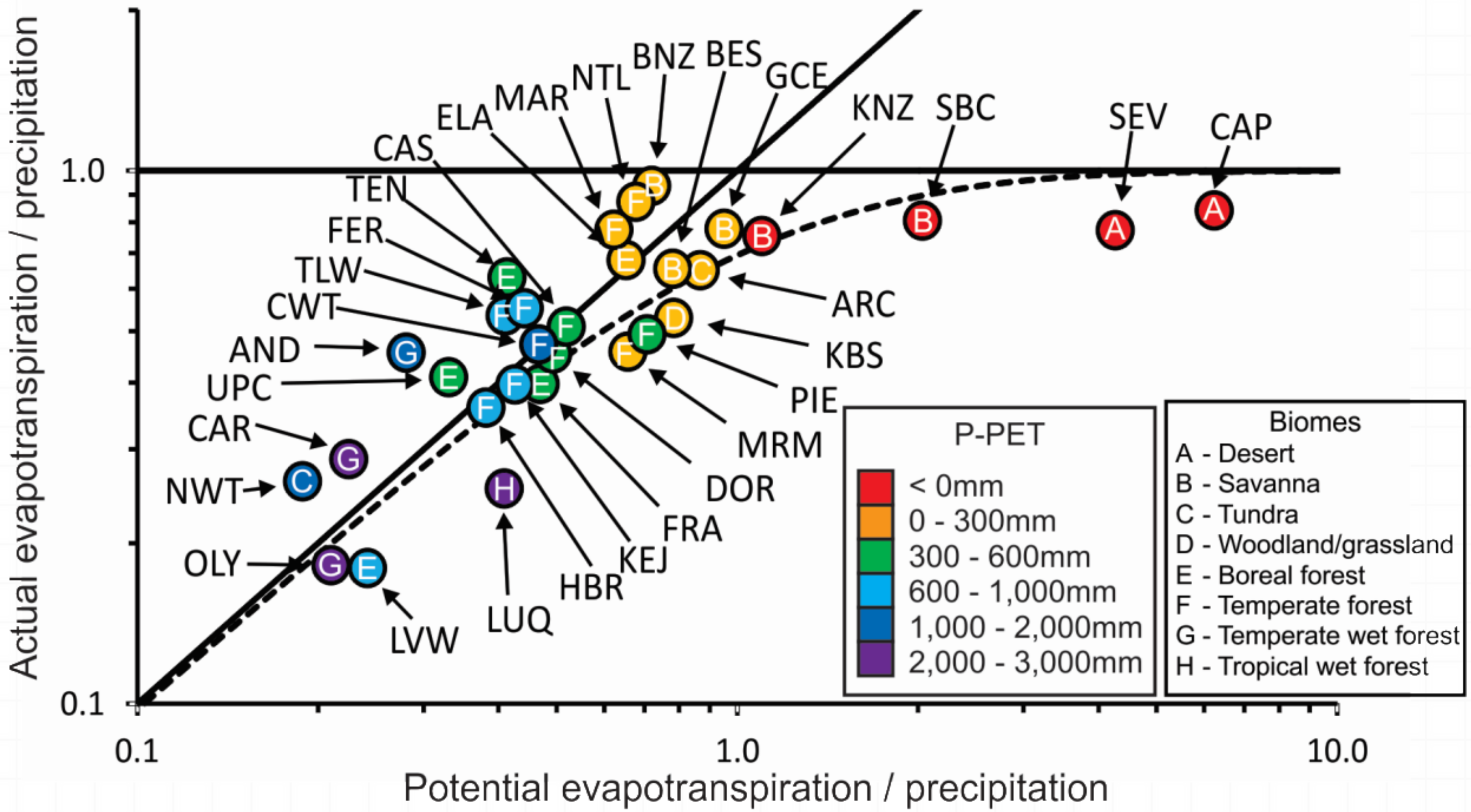
Record length - matched P, T, Q

Long-term **matching** climate and flow records from
US clim/hydroDB website (http://www.fsl.orst.edu/climhy/)
Cdn HELP website (http://www.canforhydro.org/)

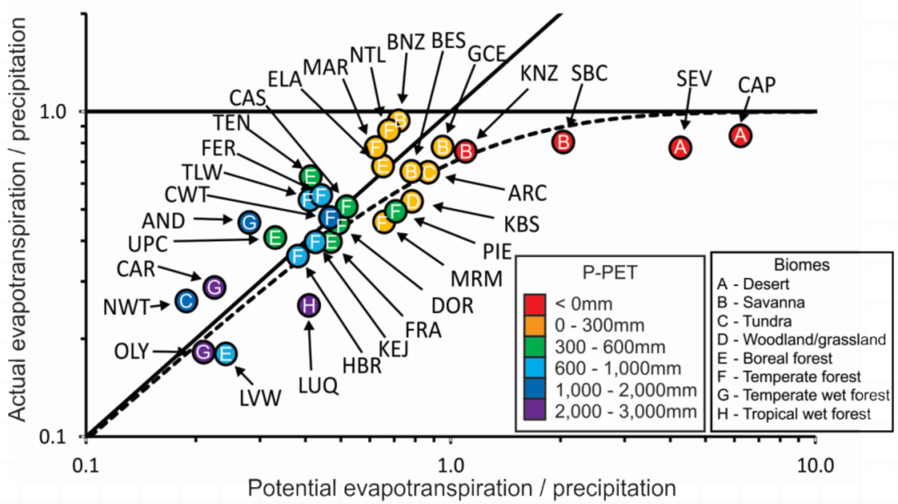


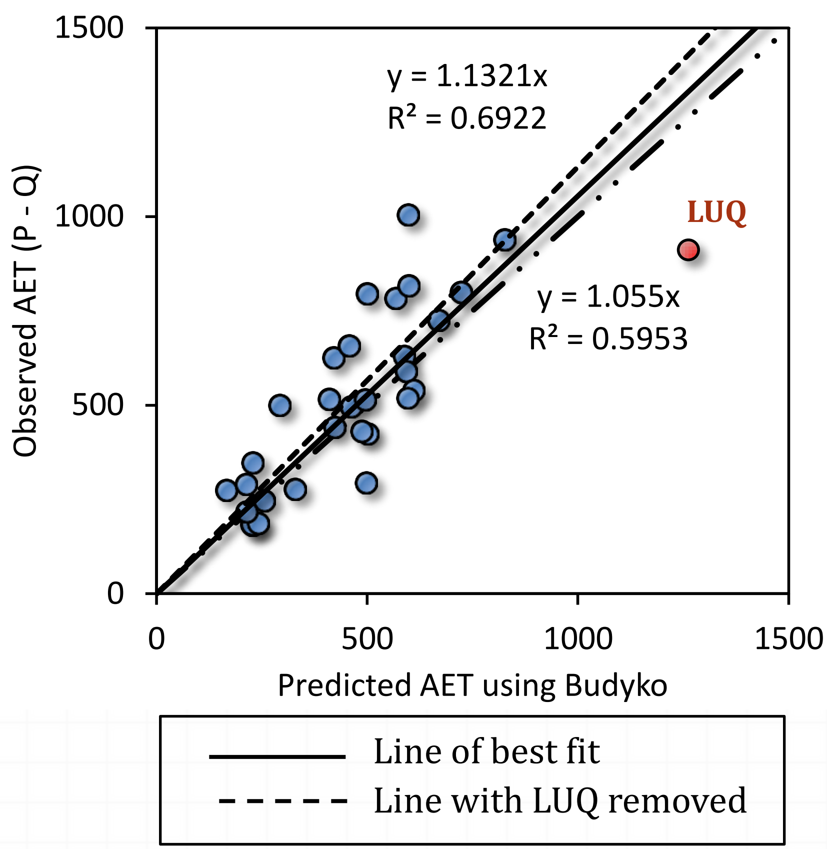


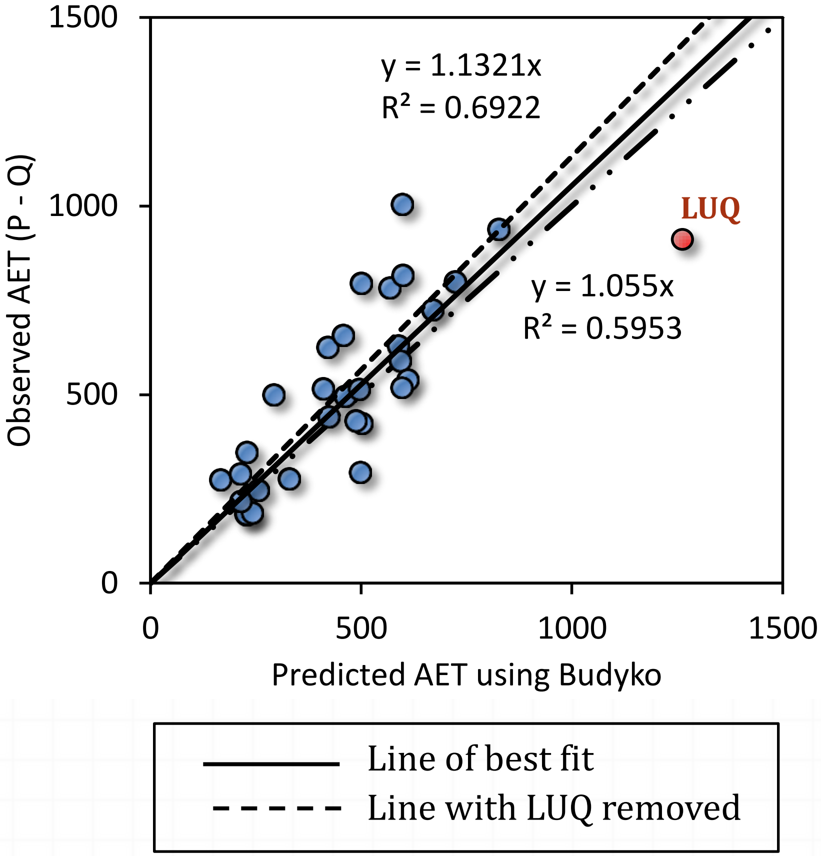
Theoretical vs. observed distribution of study sites relative to the Budyko Curve



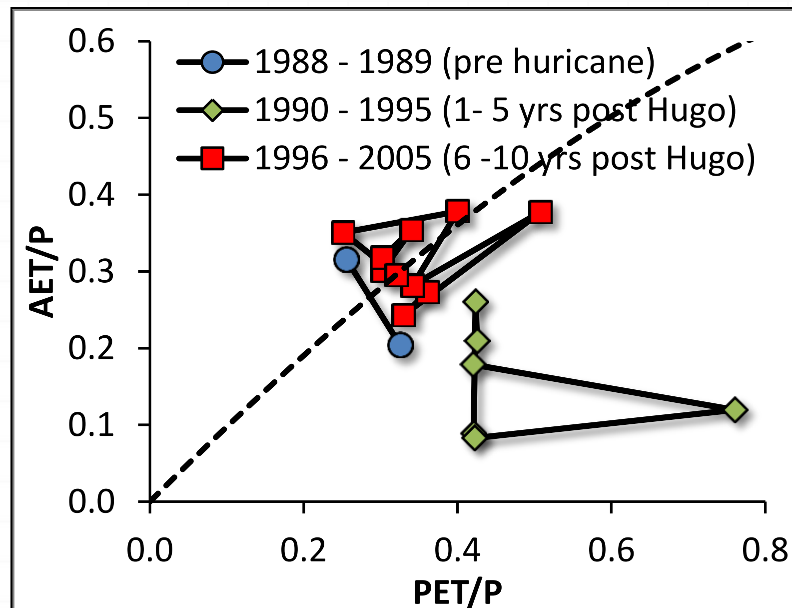
Accuracy of Budyko in predicting long-term (10-yr) average discharge





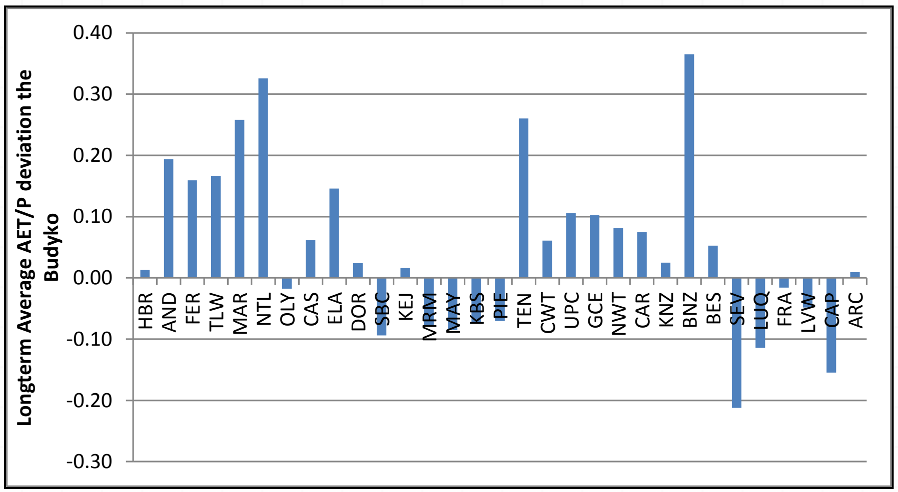


Hurricane Hugo hit the site in September 1989 reducing above ground biomass by 50%.



Whilst the Evaporative Index for the 30 sites generally follows the Budyko curve there remains a lot of deviation.

Why does this occur?

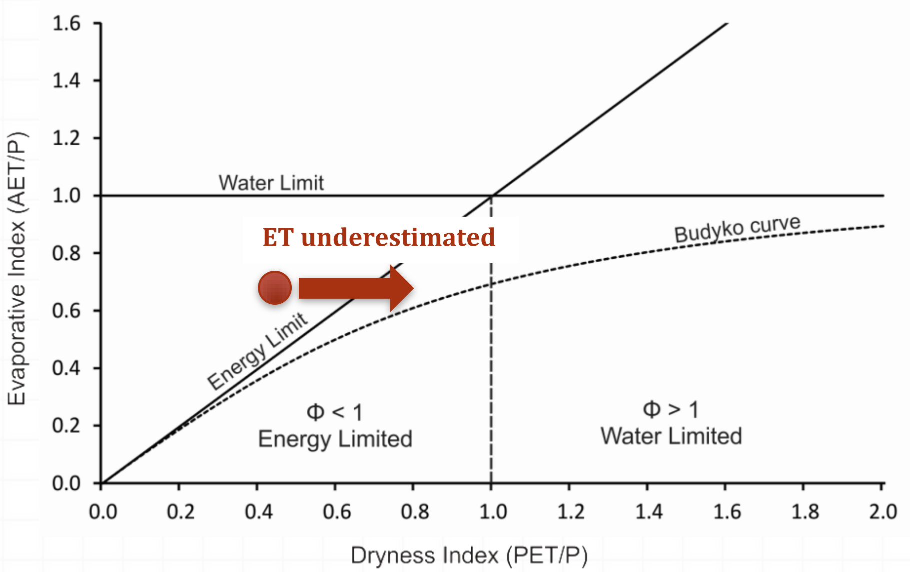


Maximum deviation of the longterm average Evaporative index from the Budyko Curve for each of the 30 study sites

- ARTIFACT?
  - ET=P-Q
  - Timing of P vs. ET over the year
  - Inadequate measures of P, ET, Q
  - Missing measures of other components of the water balance (i.e., groundwater gains or losses?)
- REAL?
  - Natural disturbance legacy effects
  - Vegetation, topography, and soils may modify water balance
  - Ecosystem may acclimate/adapt to climate change

Whilst the Evaporative Index for the 30 sites generally follows the Budyko curve there remains a lot of deviation.

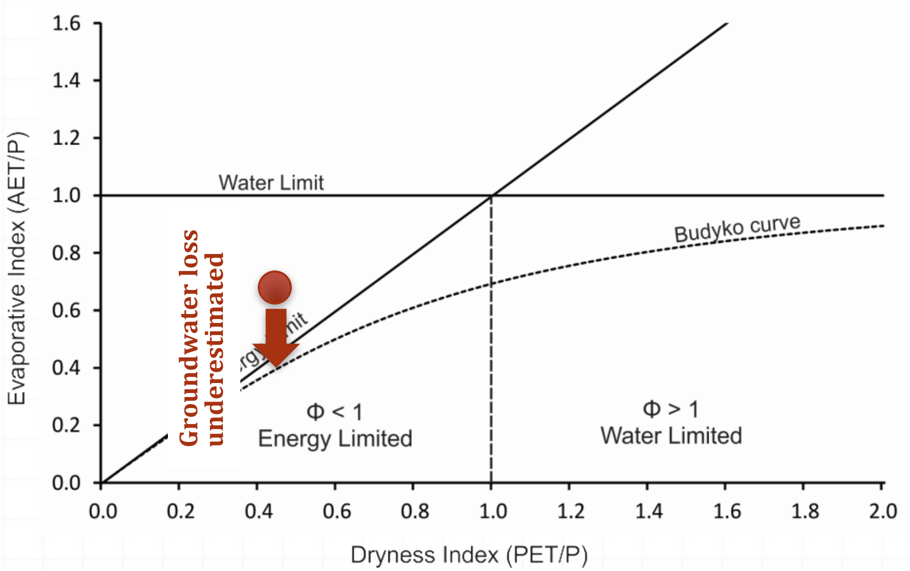
Why does this occur?



- ARTIFACT?
  - ET=P-Q
  - Timing of P vs. ET over the year
  - **Inadequate measures of P, ET, Q**
  - Missing measures of other components of the water balance (i.e., groundwater gains or losses?)
- REAL?
  - Vegetation, topography, and soils may modify water balance
  - Ecosystem may acclimate/adapt to climate change

Whilst the Evaporative Index for the 30 sites generally follows the Budyko curve there remains a lot of deviation.

Why does this occur?



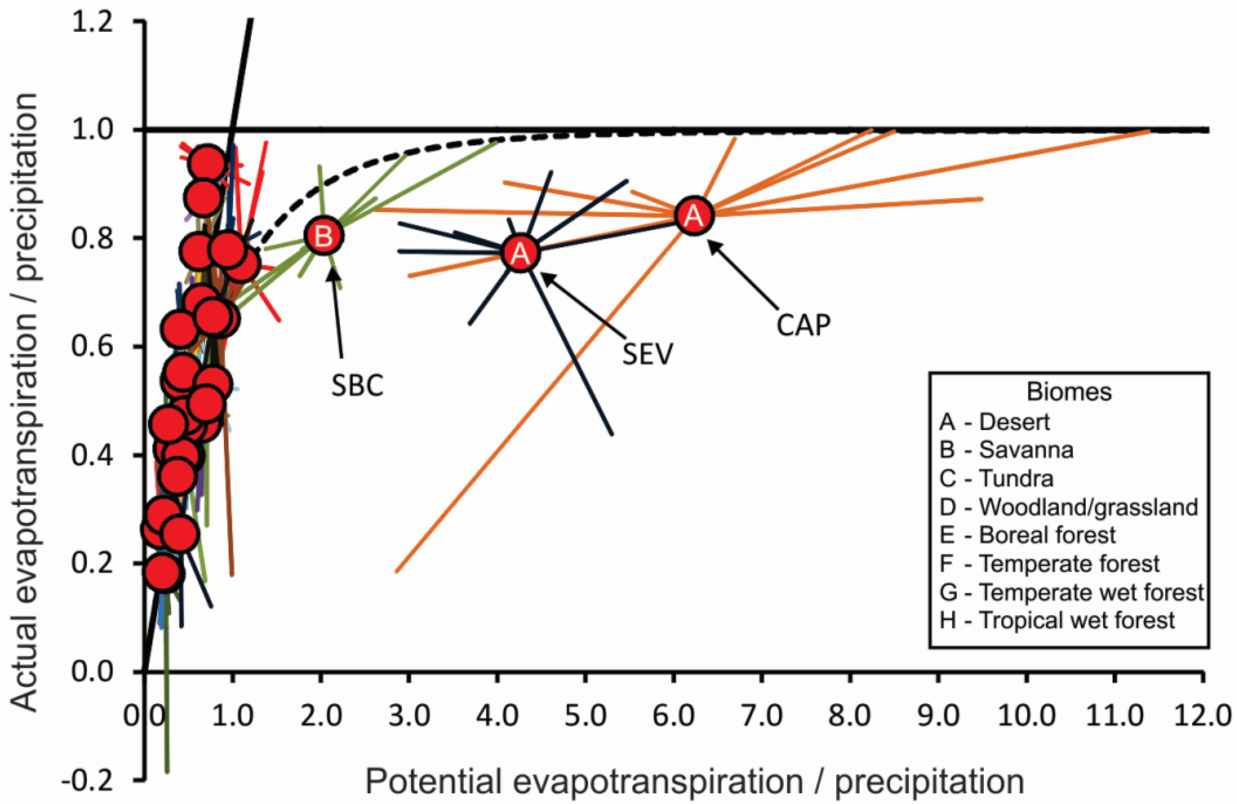
- ARTIFACT?
  - ET=P-Q
  - Timing of P vs. ET over the year
  - Inadequate measures of P, ET, Q
  - **Missing measures of other components of the water balance** (i.e., groundwater gains or losses?)
- REAL?
  - Vegetation, topography, and soils may modify water balance
  - Ecosystem may acclimate/adapt to climate change

Can we use the Budyko curve to identify where we have confidence in closing the water budget?
What are our gaps in knowledge?

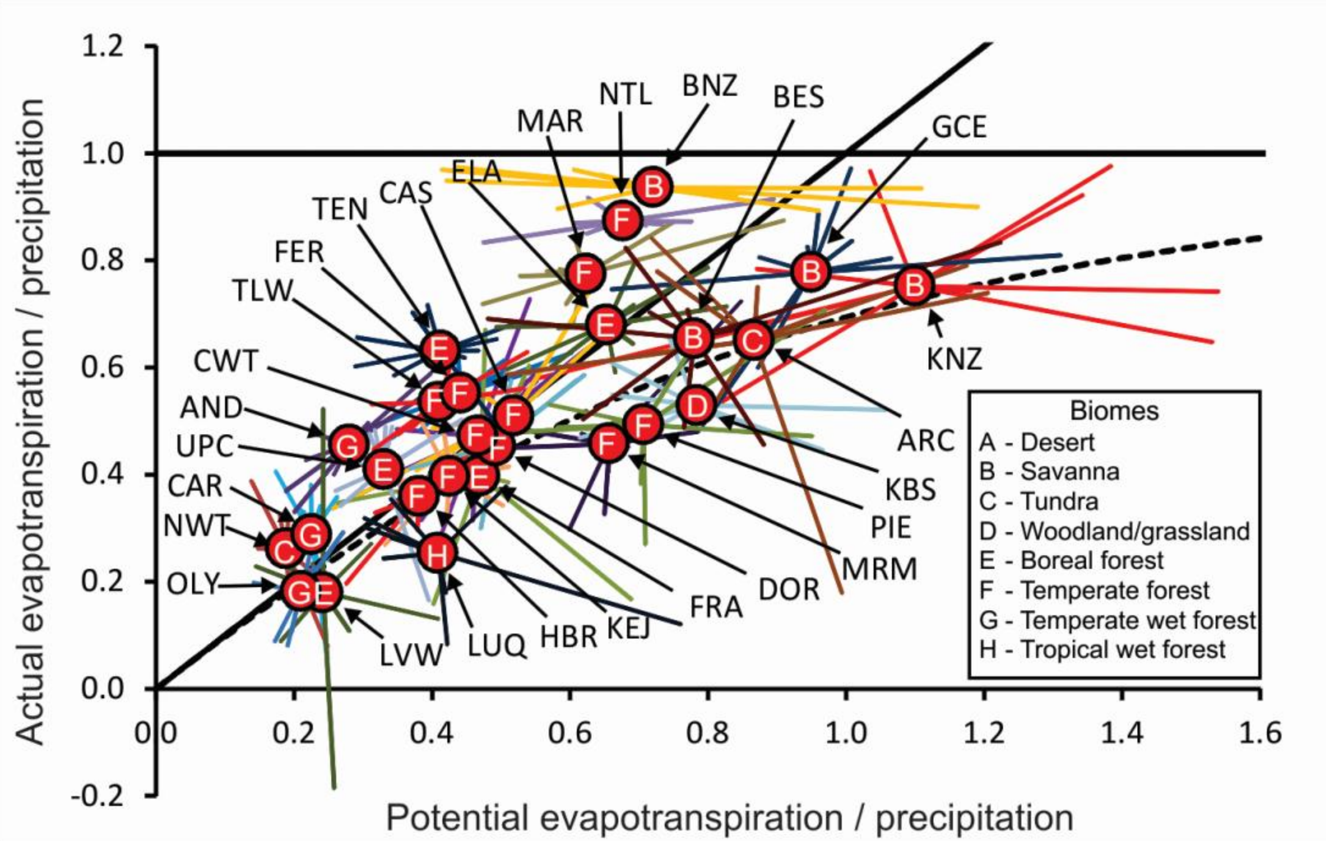
Question 2

Do year-to-year deviations in the evaporative index provide insight into the responsivity (resistance) and elasticity (resilience) of catchment water yields to changing climatic conditions?

Spider plots showing year-to-year deviations from long term average

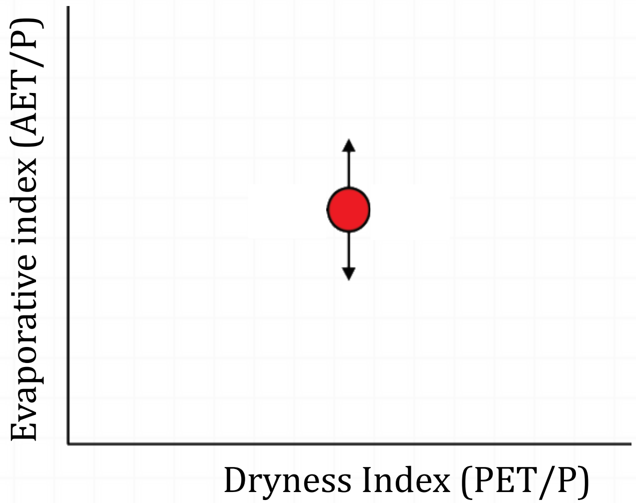


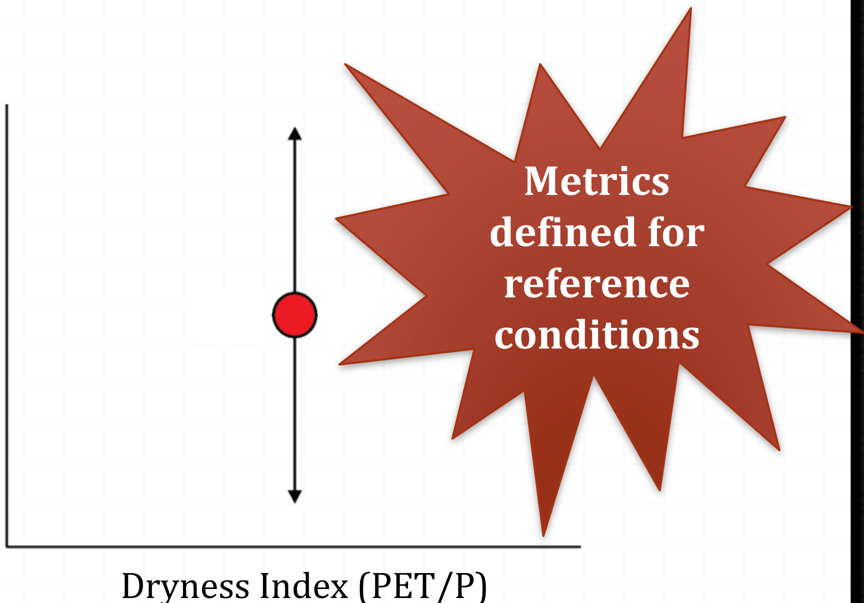
Spider plots showing year-to-year deviations from long term average



Water Yield Metrics

RESPONSIVITY is the degree to which runoff (Q) is synchronized with precipitation (P), and is measured from the deviation in the Evaporative Index (i.e., Δy-axis).



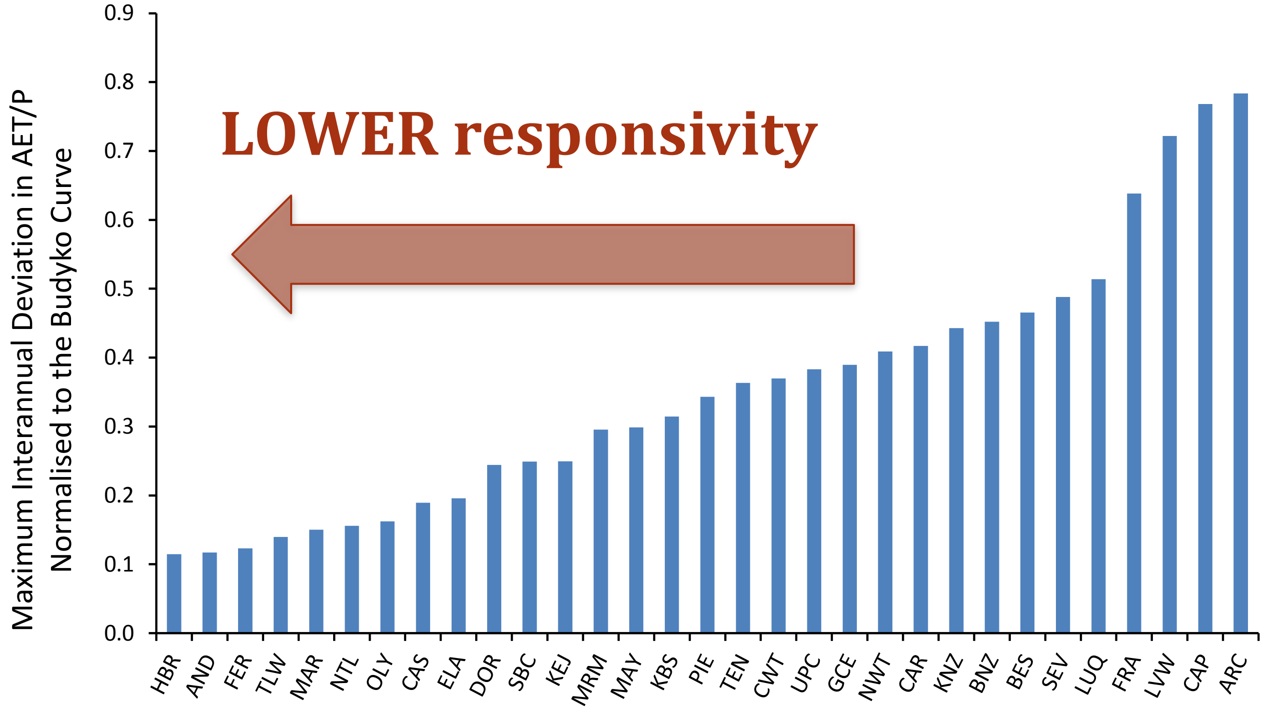


HIGH responsivity (or resistance); water yields are expected as P is transferred to Q (synchronous)

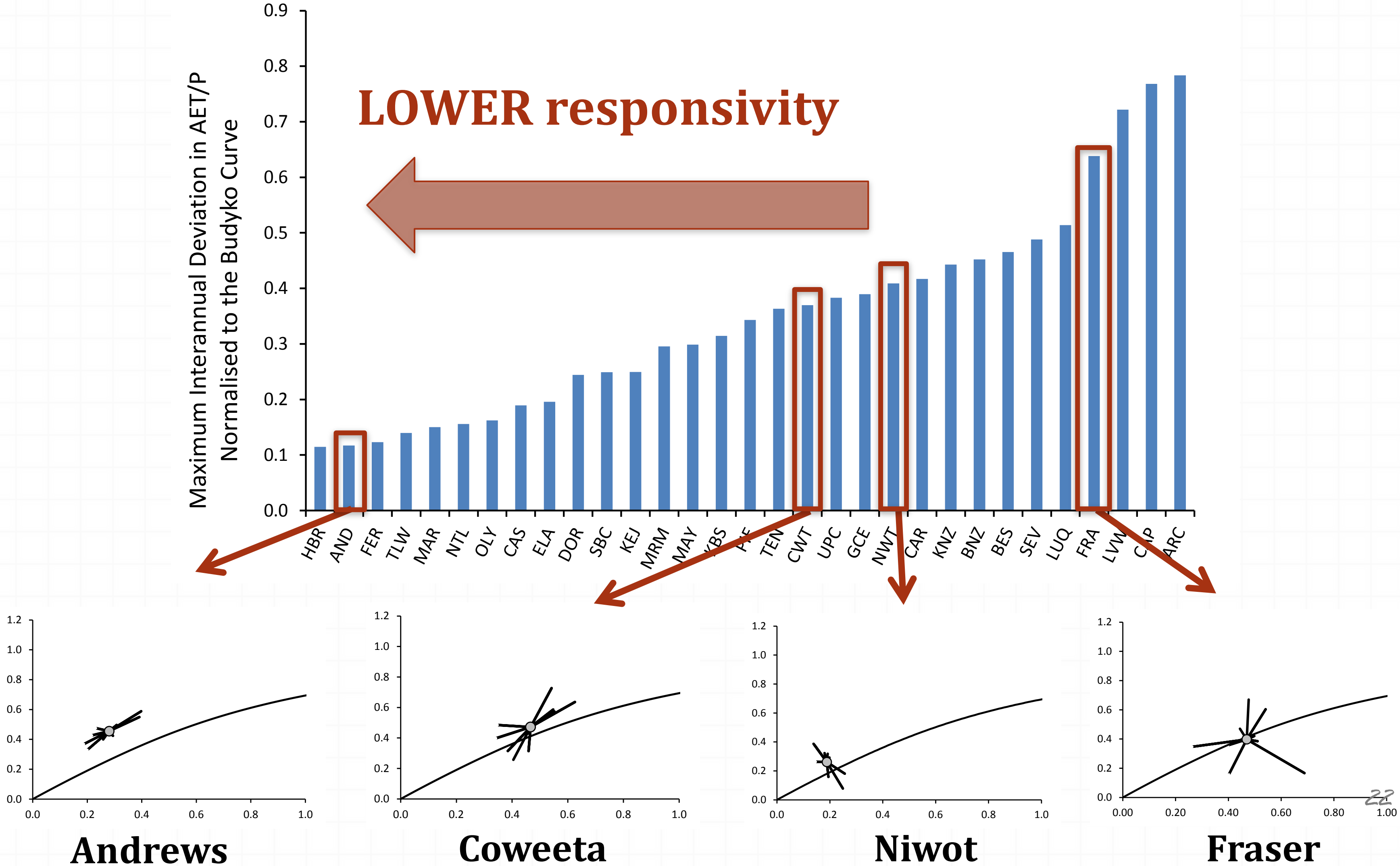
LOW responsivity (or resistance); water yields are higher or lower than expected (not synchronous)

Carey et al. 2010. *Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience.* Hydrol. Process. (2010)

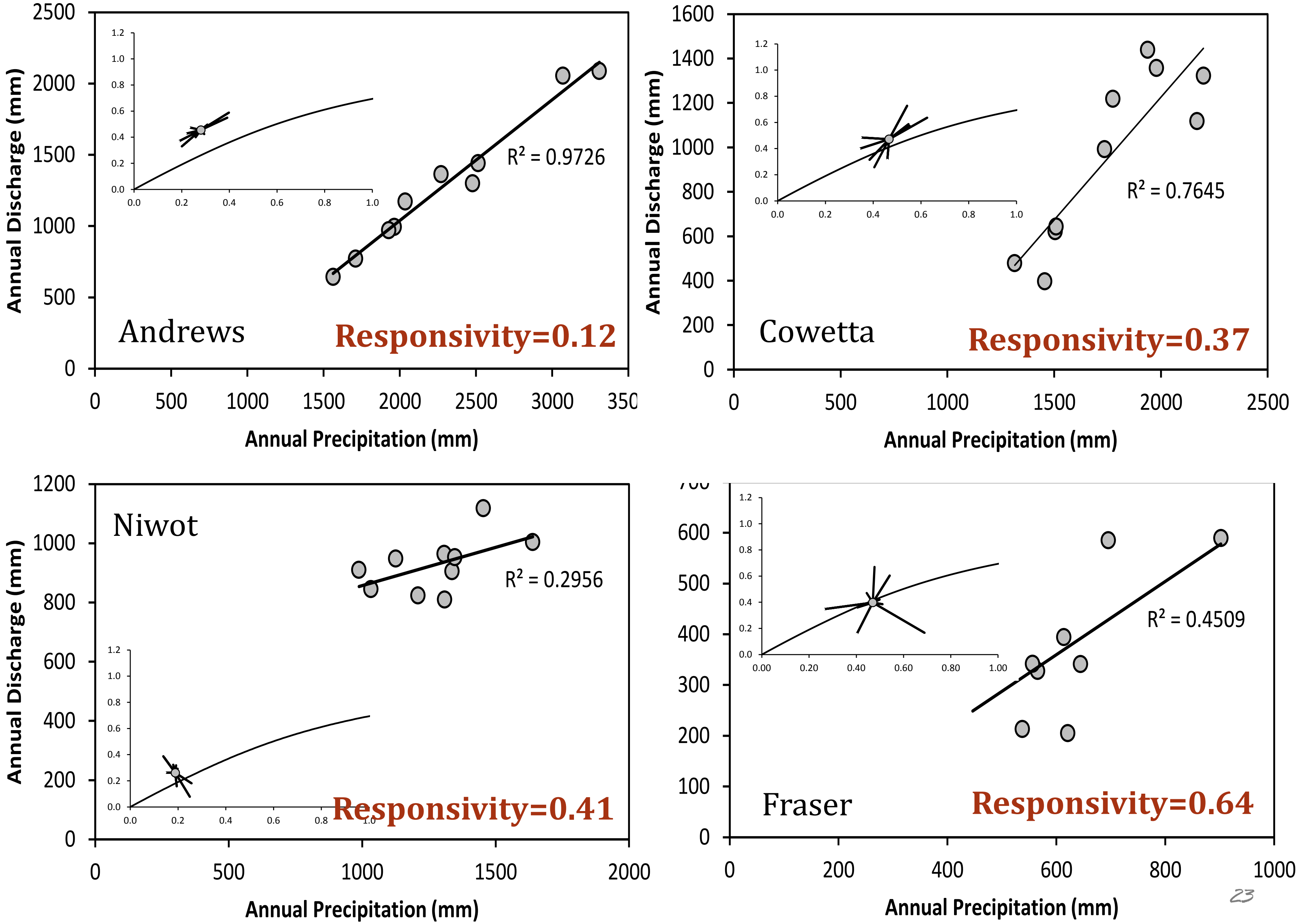
Rank ordering of amplitude of year-to-year deviation in Evaporative index (normalized to the Budyko Curve)



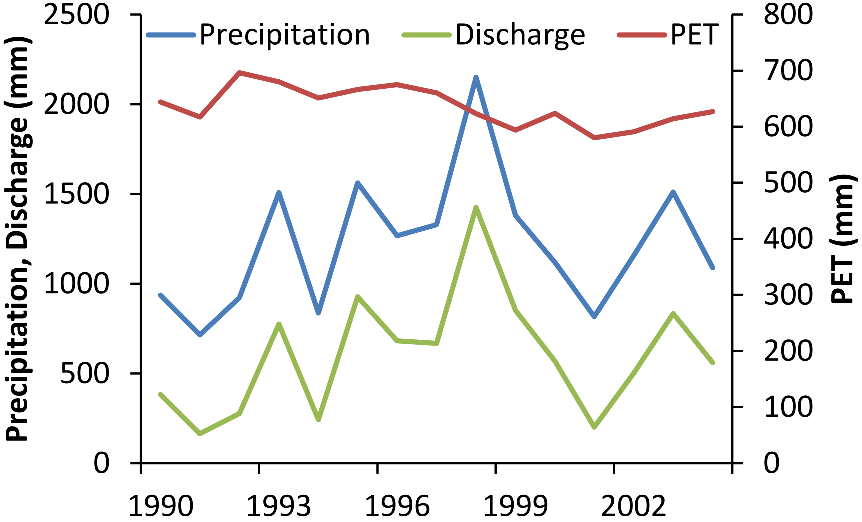
Rank ordering of amplitude of year-to-year deviation in Evaporative index (normalized to the Budyko Curve)



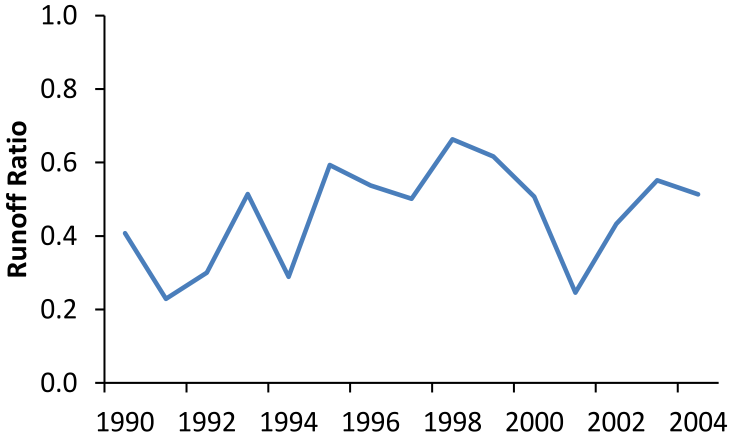
Associations between year-to-year deviations (inset) and P vs. Q coupling)

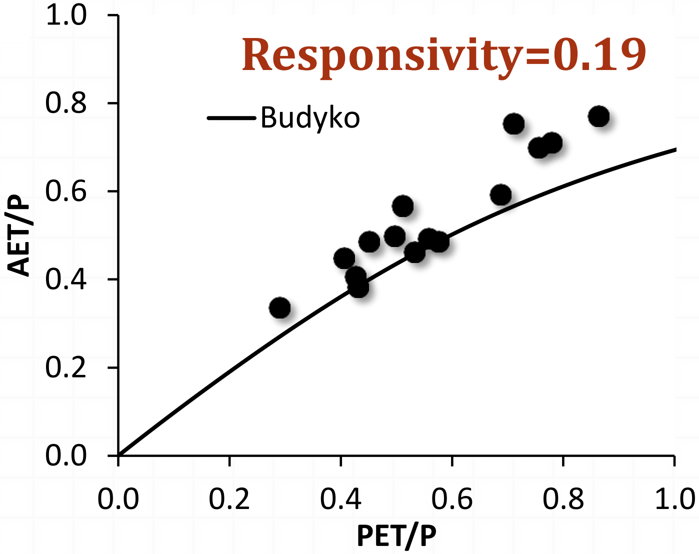


Can we identify sites where ecosystems are undergoing fundamental changes in response to climatic conditions?

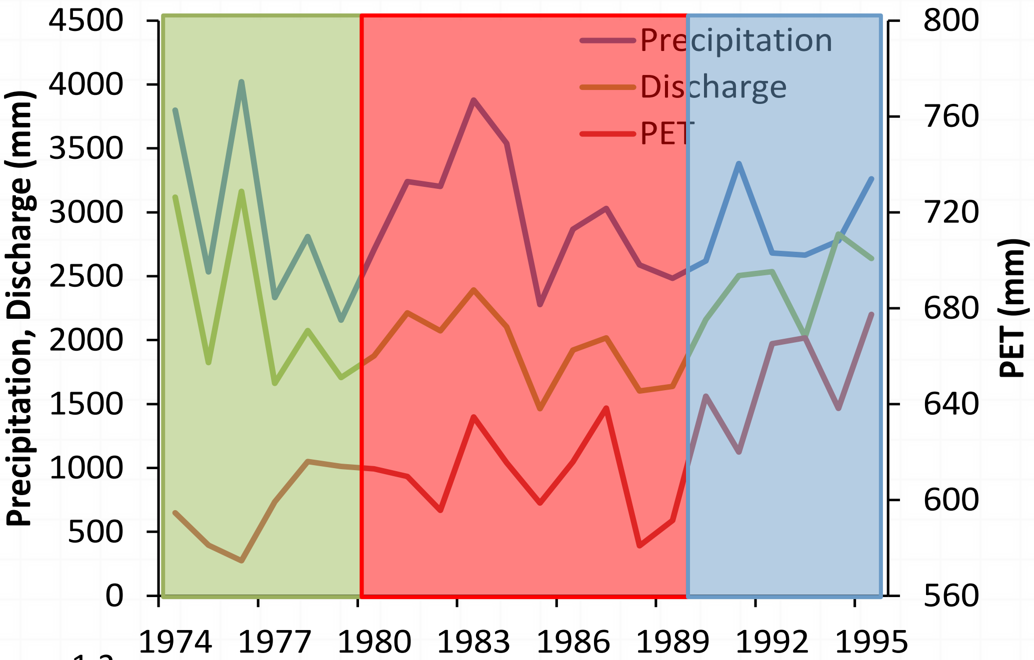


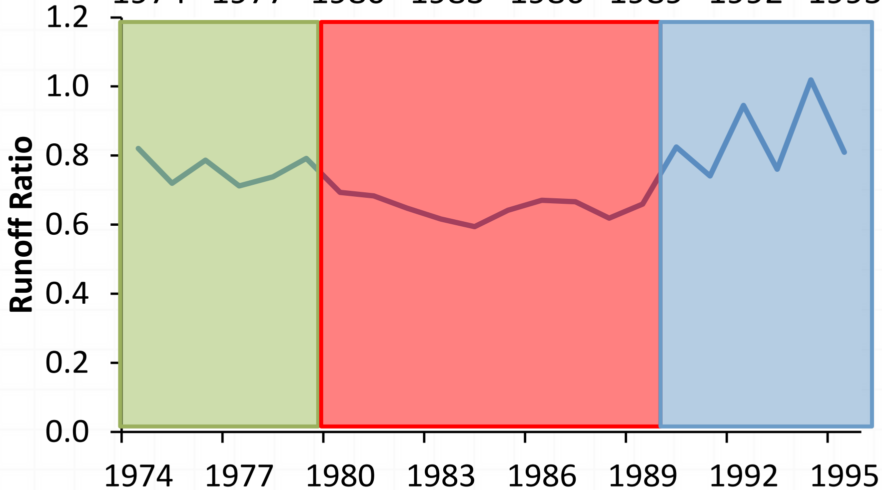
Caspar (California, USA)



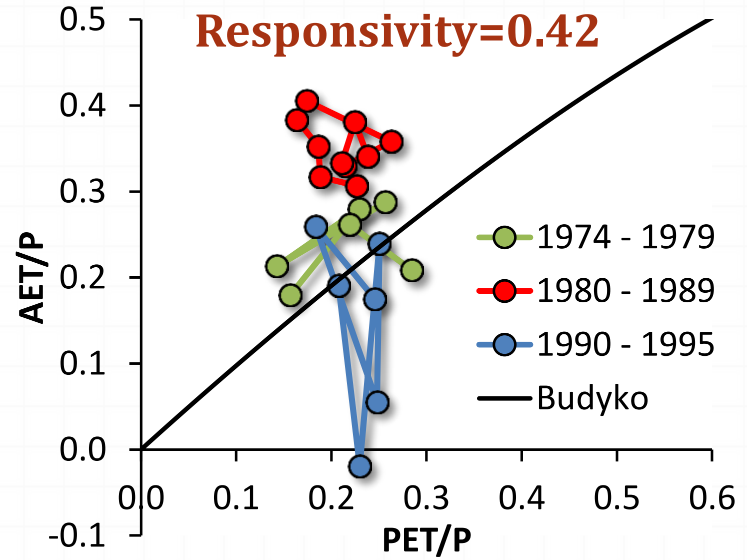


Can we identify sites where ecosystems are undergoing fundamental changes in response to climatic conditions?



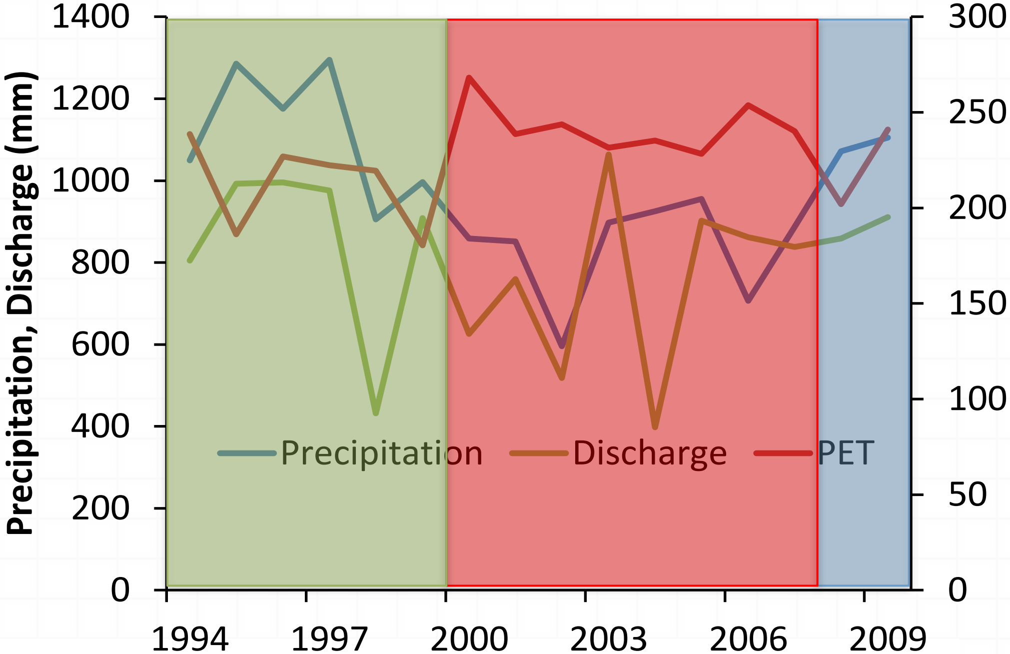


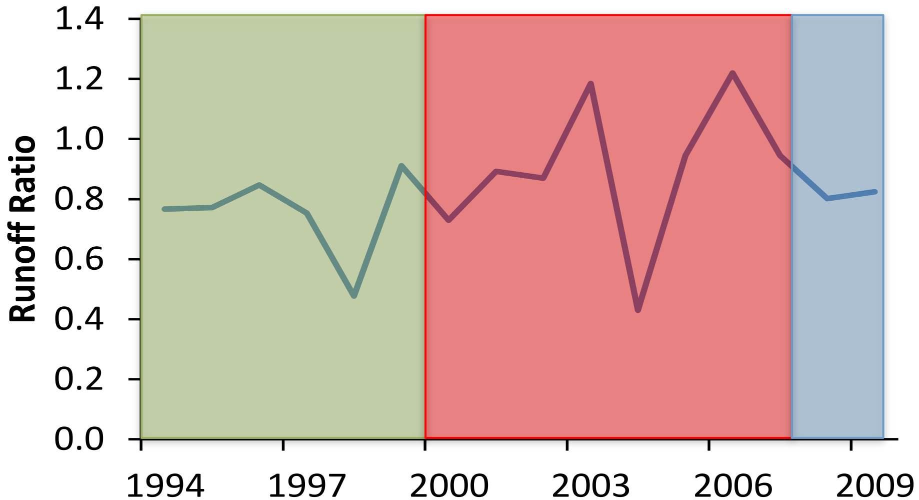
Carnation Creek (British Columbia, Canada)

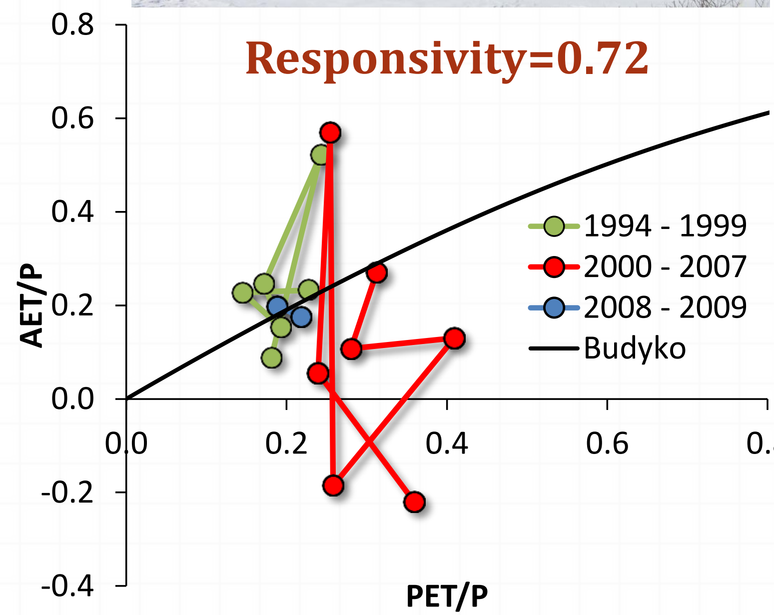


Can we identify sites where ecosystems are undergoing fundamental changes in response to climatic conditions?

Loch Vale (Colorado, USA)





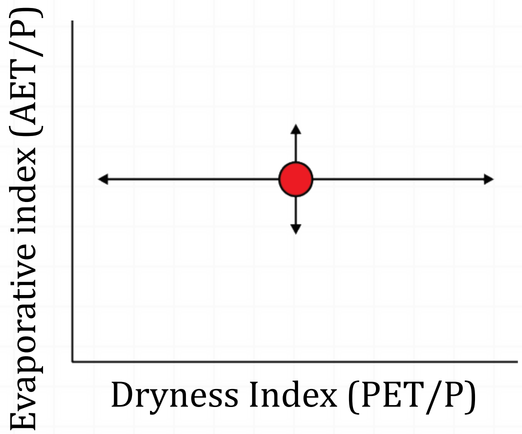


Question 3

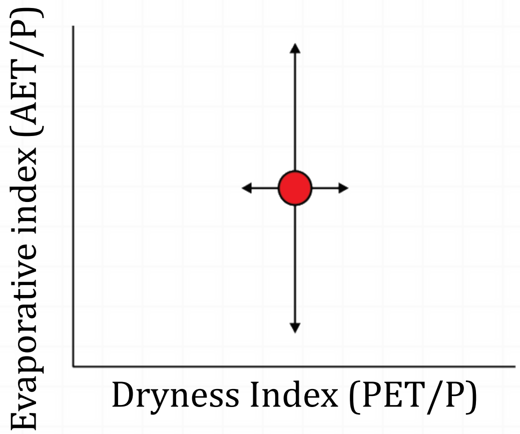
Does elasticity lead to shorter recovery times (return to pre-disturbance water yield) following disturbance?

Water Yield Metrics

ELASTICITY is the degree to which a catchment can return to normal functioning following perturbations, and is measured as the ratio of deviations in dryness index to evaporative index (i.e., Δx-axis/Δy-axis).



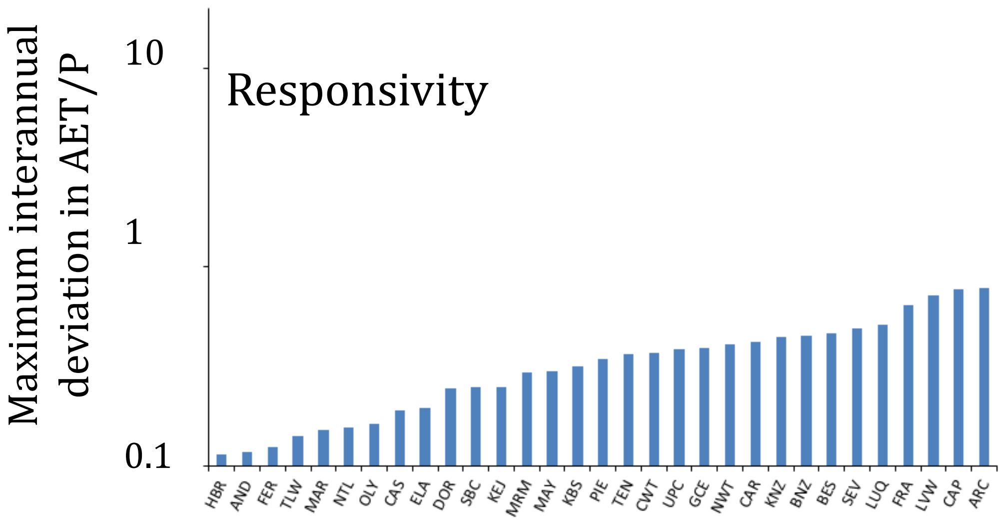
HIGH elasticity (>1) is the result of large horizontal range relative to vertical range

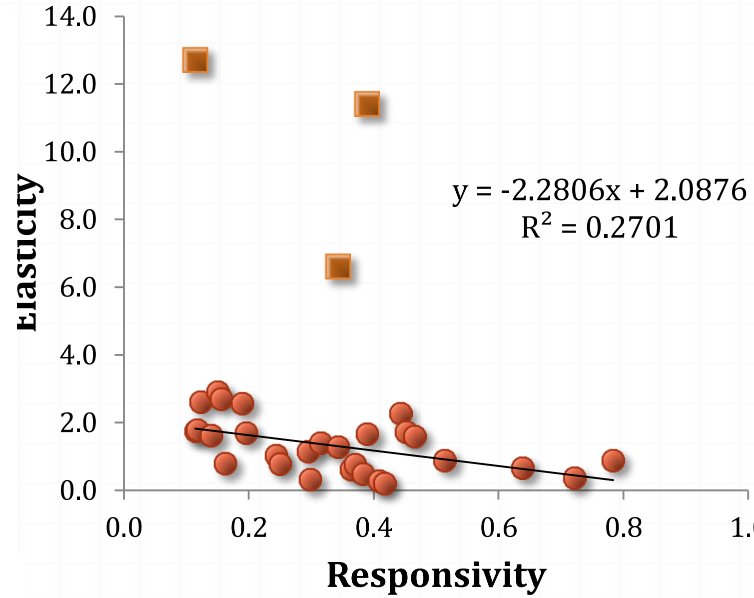


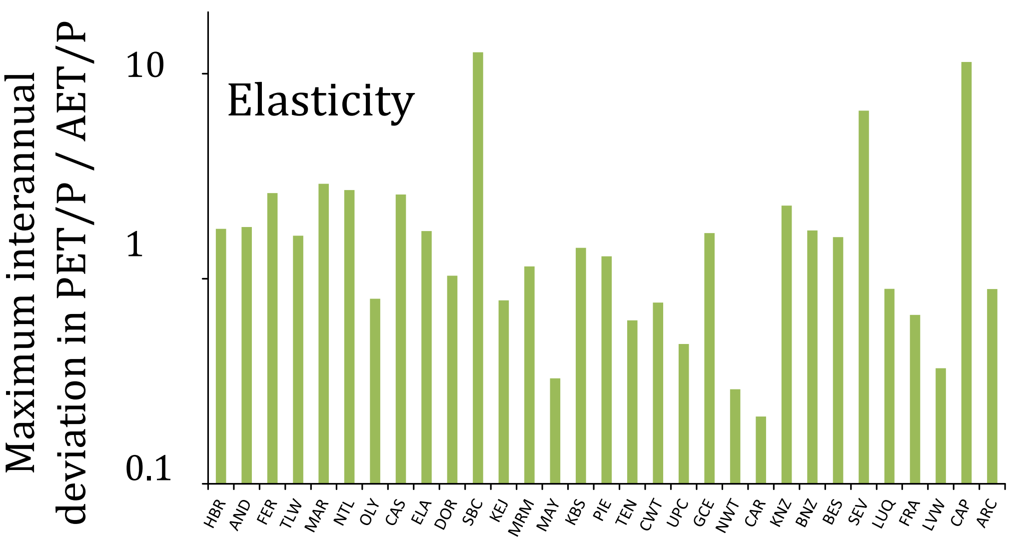
LOW elasticity (<1) is the result of small horizontal range relative to vertical range

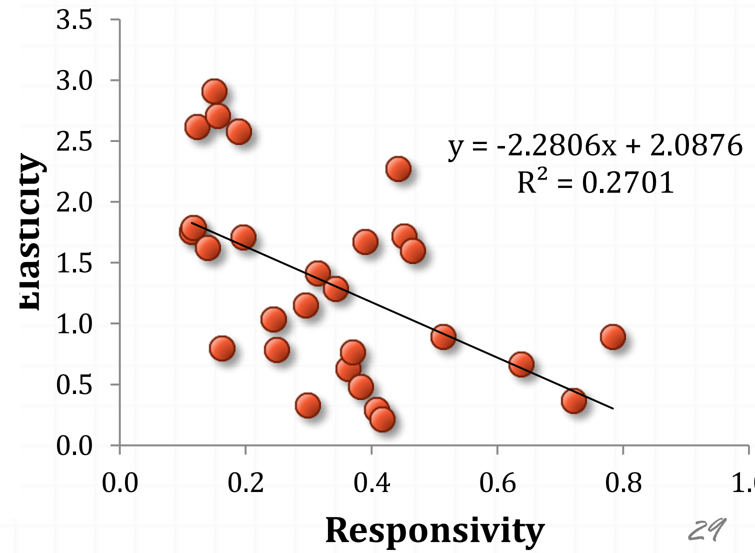
Carey et al. 2010. *Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience.* Hydrol. Process. (2010)

Responsivity does not imply elasticity





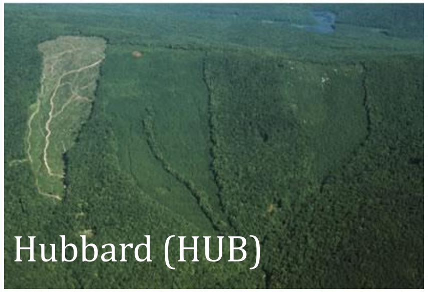




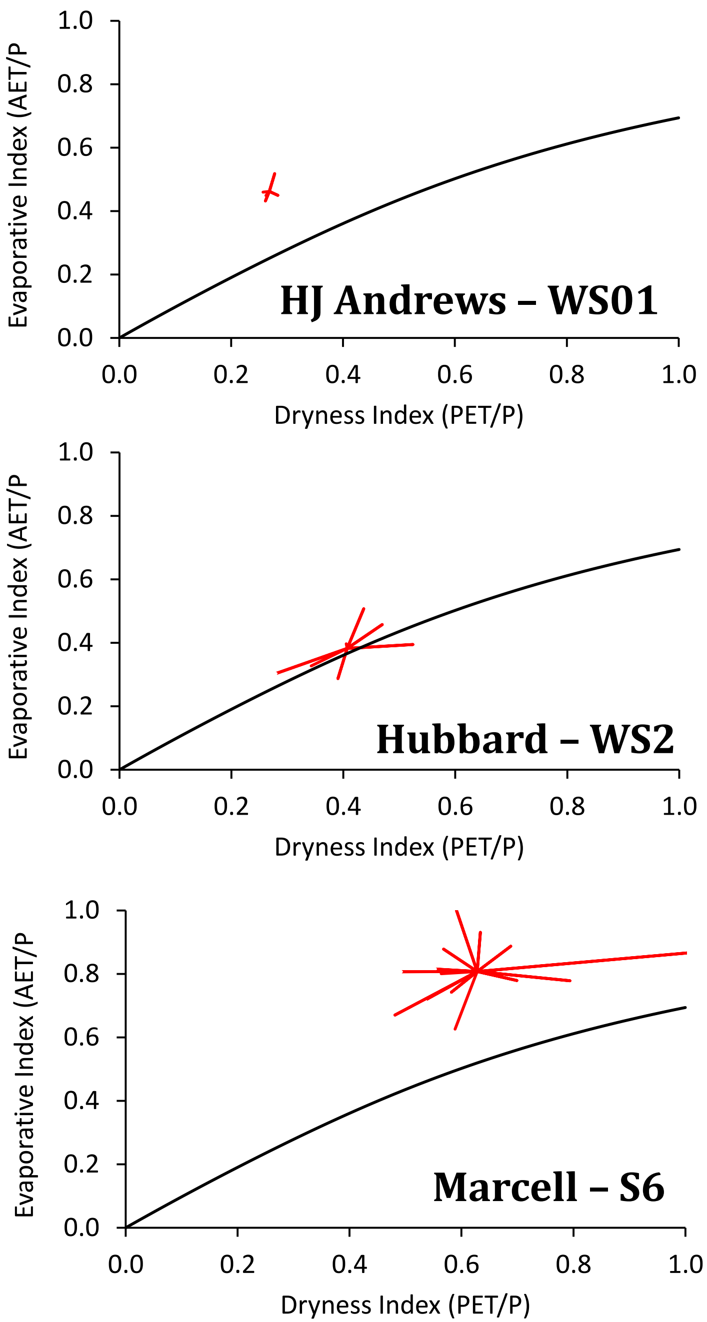
Demonstration of elasticity vs. recovery following disturbance using paired catchment studies

<u>Site selection criteria:</u>

1. **Pre and post disturbance data available**
2. **Similar disturbance (100% cut)**

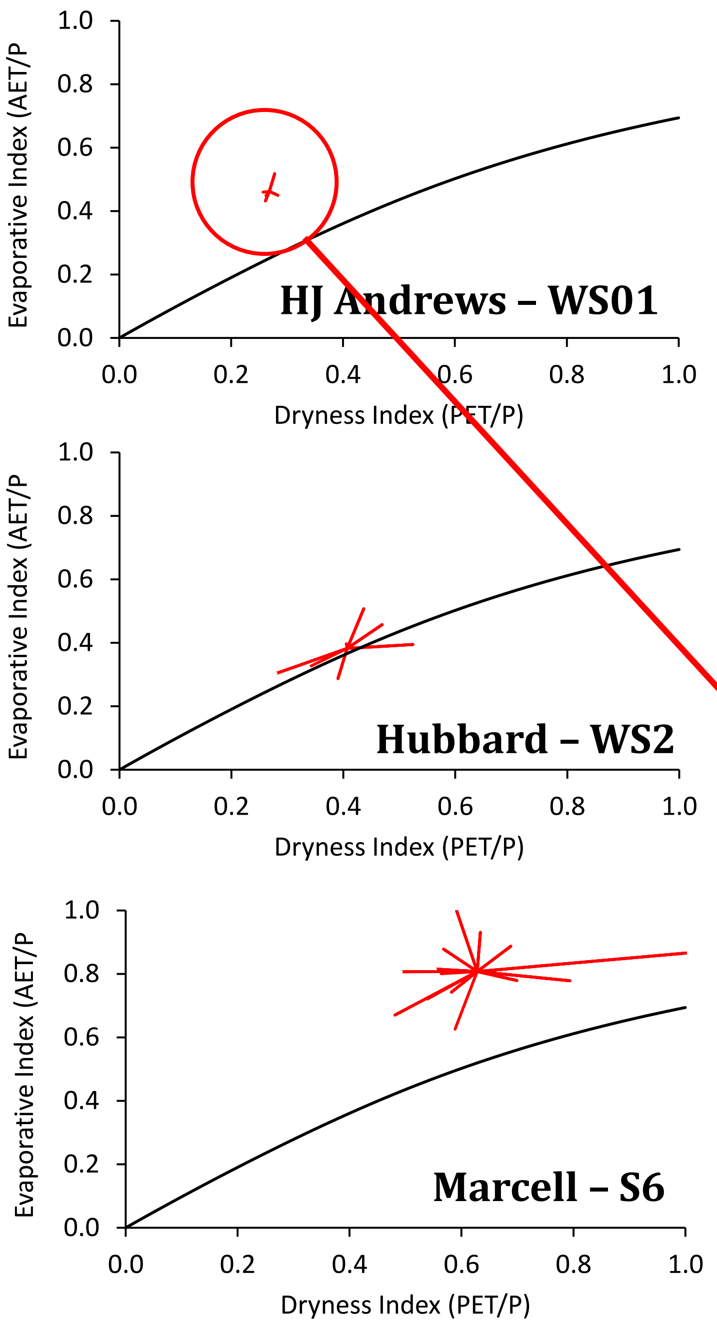


Study Area	HJ Andrews	Hubbard	Marcel
Location	Oregon	New Hampshire	Minnesota
Treated Watershed	WS01	WS2	S6
Control Watershed	WS02	WS3	S2
Cut (year/percent)	1963 / 100%	1964 / 100%	1980 / 87%
Data period pre cut	5 years	7 years	13 years
Data period post cut	47 years	43 years	27 years
Vegetation Type	Coniferous	Deciduous	Deciduous



Elasticity metrics for study sites

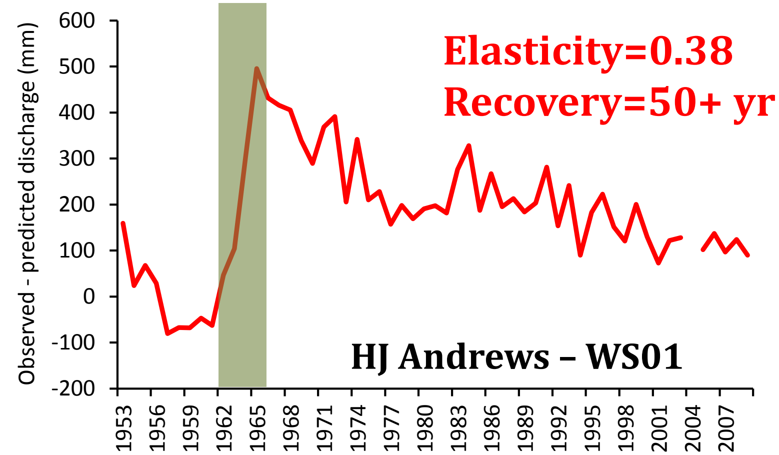
Study Sites	HJA	HUB	MAR
Treated Watershed	WS01	WS2	S6
Vertical Variation (V)	0.08	0.18	0.37
Horizontal Variation (H)	0.03	0.24	0.54
Ratio of Horizontal to Vertical (H/V)	0.38	1.36	1.46

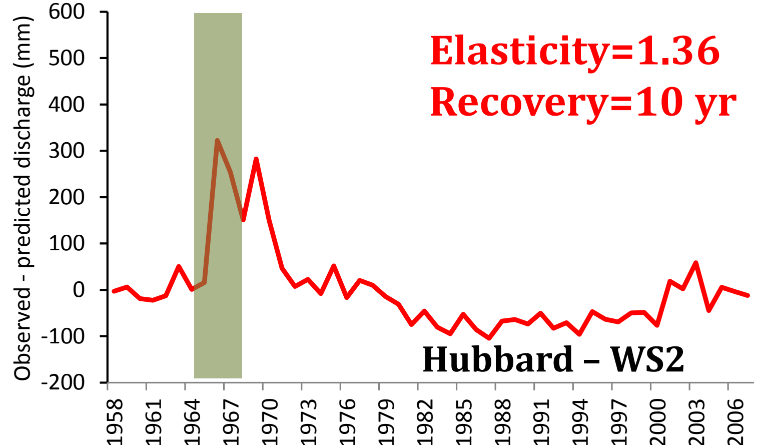


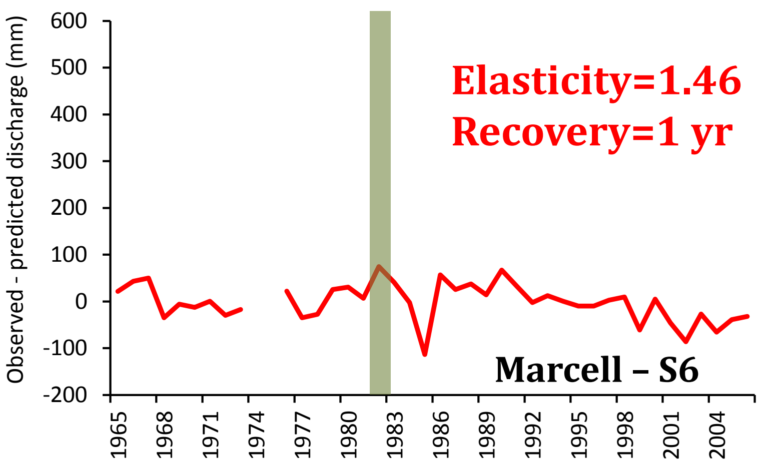
Elasticity metrics for study sites

Study Sites	HJA	HUB	MAR
Treated Watershed	WS01	WS2	S6
Vertical Variation (V)	0.08	0.18	0.37
Horizontal Variation (H)	0.03	0.24	0.54
Ratio of Horizontal to Vertical (H/V)	0.38	1.36	1.46

If elasticity is linked to time required to return to pre-disturbance water yields, then we expect HJ Andrews to have a **long** recovery.







Elasticity metrics for study sites

Study Site	HJA	HUB	MAR
Treated Watershed	WS01	WS2	S6
Vertical Variation (V)	0.08	0.18	0.37
Horizontal Variation (H)	0.03	0.24	0.54
Ratio of Horizontal to Vertical (H/V)	0.38	1.36	1.46

Lower elasticity results in longer recovery times in water yields following disturbance.

Summary

Budyko curve described partitioning of P into ET and Q

Deviations (average) provide insight into

- Inaccurate or incomplete representation of water balance components (HJA, MAR)
- Natural disturbances and their legacies (LUQ)

Deviations (year to year) provide insight into responsivity (resistance) and elasticity (resilience) of water yields to global change

Future work will focus on:

- Incorporating uncertainty estimates in water balances
- Discriminating climate signal from natural or anthropogenic disturbance effects
- Exploring future scenarios and how they may result in changes in water yields
- Considering downstream consequences to water supplies

Acknowledgements

- “LTER Synthesis Workshops” funded by the LTER Network Office
- NSF LTER grants to participating USA sites
- USFS and USGS for initial establishment and continued support of watershed studies at many of the study sites
- NCE-SFM funded project on HydroEcological Landscapes and Processes (HELP) and the participating Canadian sites

Future Changes in Water