Response of stream ecosystems to climate change (III): characterizing and predicting flow regimes

David Tarboton, Sulochan Dhungel, Charles P. Hawkins, Jacob J. Vander Laan, Ryan A. Hill and Jiming Jin

Utah State University

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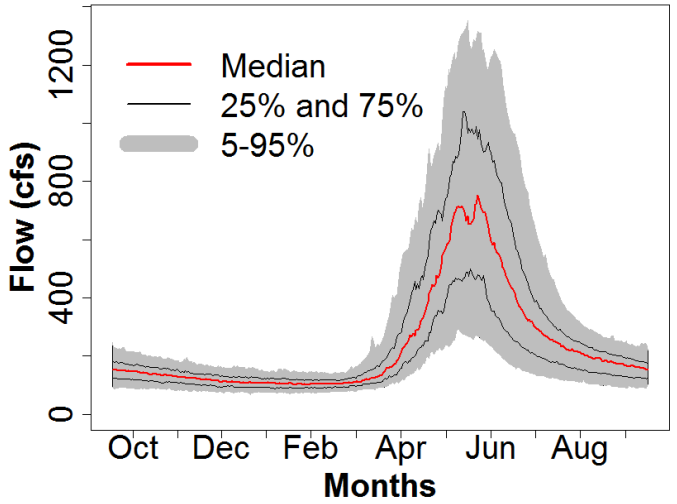
The Western Center for Monitoring & Assessment of Freshwater Ecosystems

Objectives

- Characterize current spatial patterns in ecologically important streamflow properties across the USA

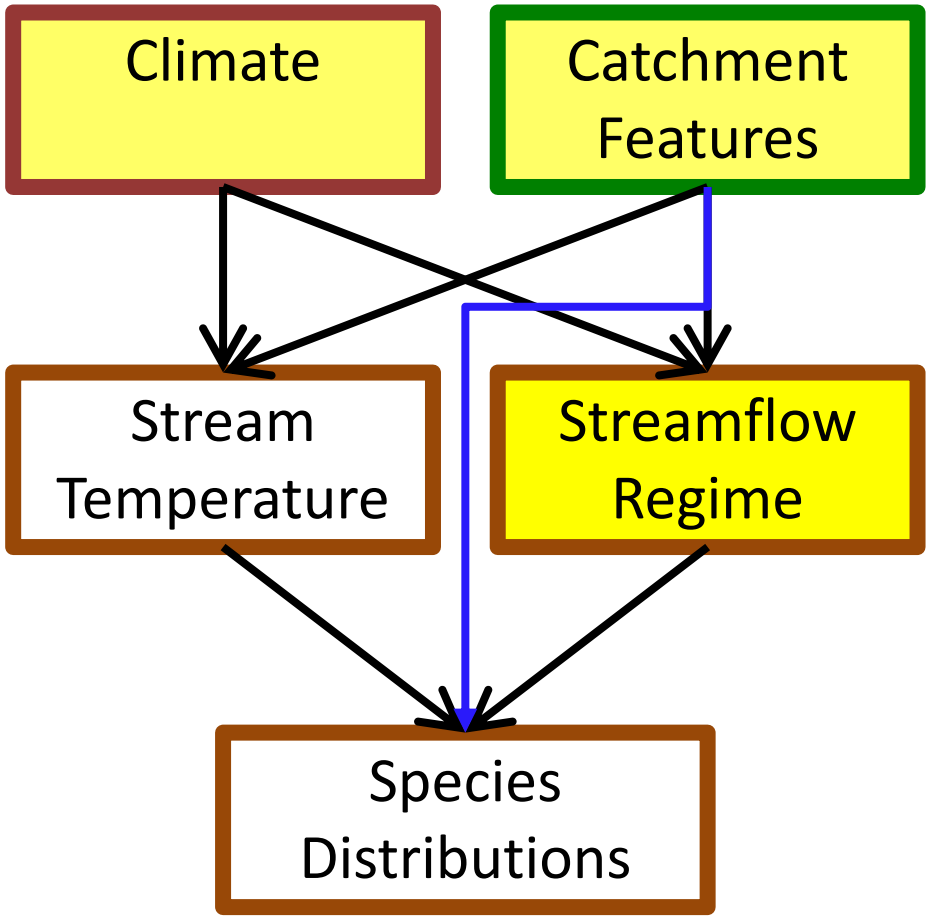
- Assess likely effects of climate change on streamflow regimes



- Support stream biodiversity modeling

Outline

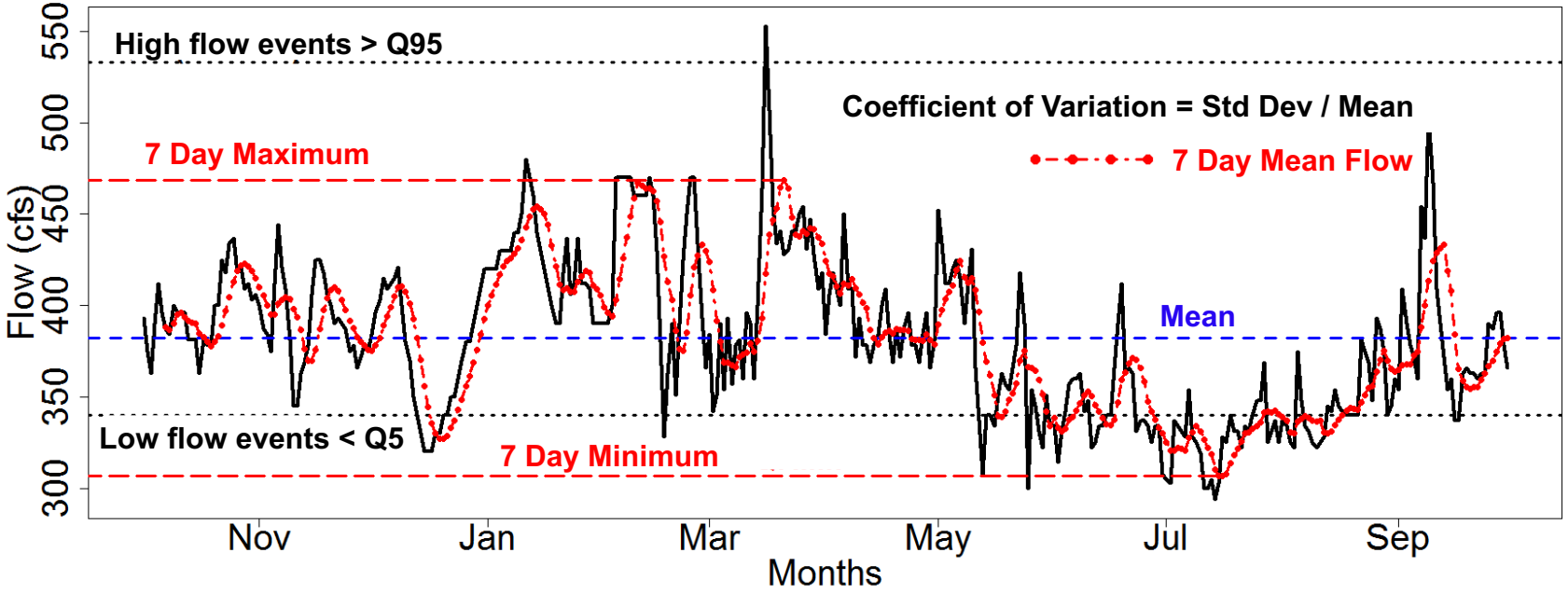
- Selection of ecologically relevant streamflow properties (streamflow regime)
- Data (USGS GAGES, Catchment Features, Climate)
- Flow regime classification and prediction
- Predicted climate-driven changes in flow regimes



16 variables used to characterize 5 ecologically important aspects of streamflow

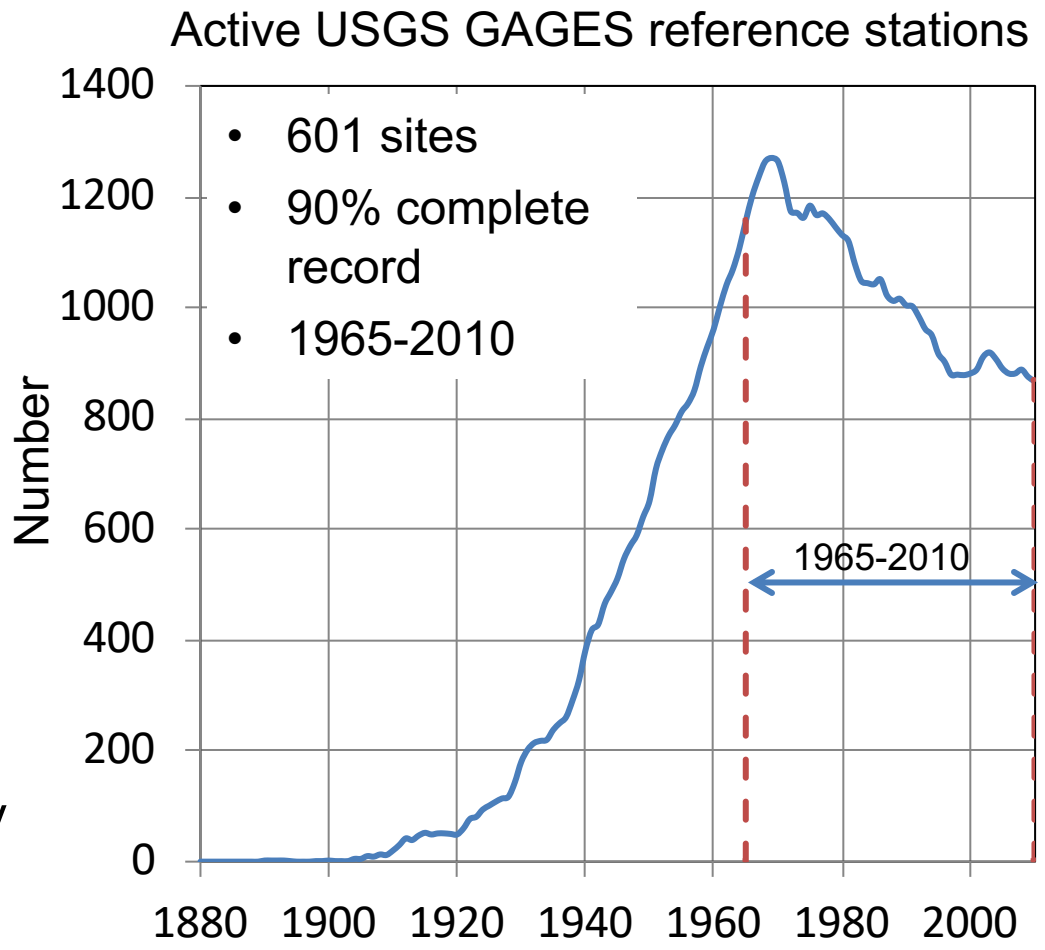
(Magnitude, Timing, Rate of Change, Duration, Frequency)

1. Extended Low Flow Index
2. Coefficient of Variation
3. Mean Daily Discharge
4. 7 Day Minimum
5. 7 Day Maximum
6. Bank Full Flow (Q167)
7. Flood Duration (Days > Q167)
8. Colwell's Index of Predictability
9. Colwell's Index of Constancy
10. Colwell's Index of Contingency
11. Flow Reversals Per Year
12. 50% Flow Date
13. Time of Peak
14. Number of High Flow Events (>Q95)
15. Number of Low Flow Events (<Q5)
16. Number of Zero Flow Events



Data

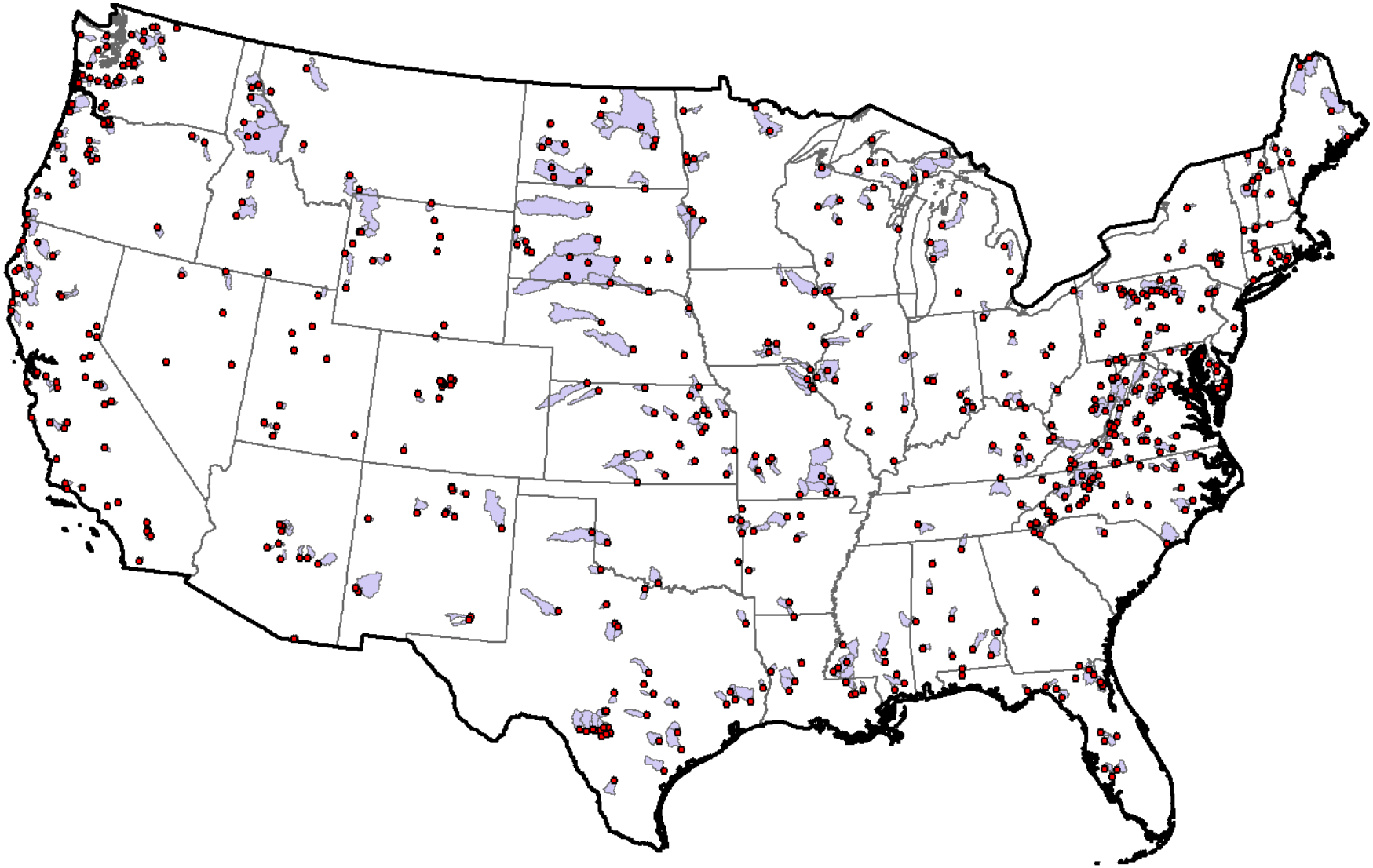
- Daily streamflow USGS GAGES reference stations (Falcone et. al., 2010)
- PRISM precipitation and temperature (Daly et al., 2008)
- Downscaled Climate forecasts. CCSM A2 scenario -> WRF at 50 km scale downscaled statistically to 4 km based on PRISM



James A. Falcone, Daren M. Carlisle, David M. Wolock, and Michael R. Meador. 2010. GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States. *Ecology* 91:621.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis and P. P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* 28: 2031-2064.

Reference-quality USGS GAGES Stations



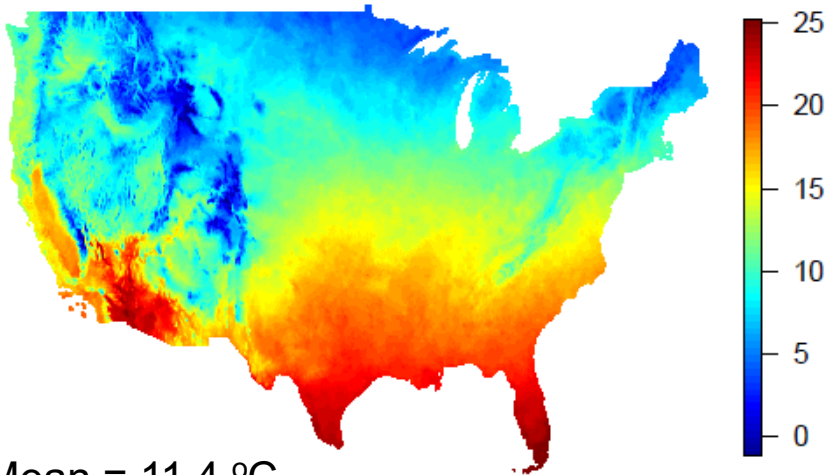
Characterized each catchment with 34 climate, 7 soil, and 10 geomorphology variables

Climate Projections CCSM A2 + WRF

Precipitation 2001-2010

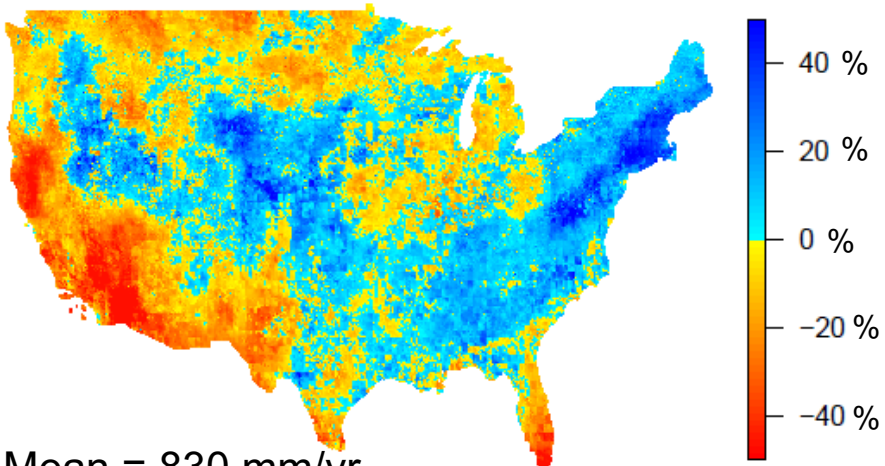
Mean = 829 mm/yr

Temperature 2001-2010



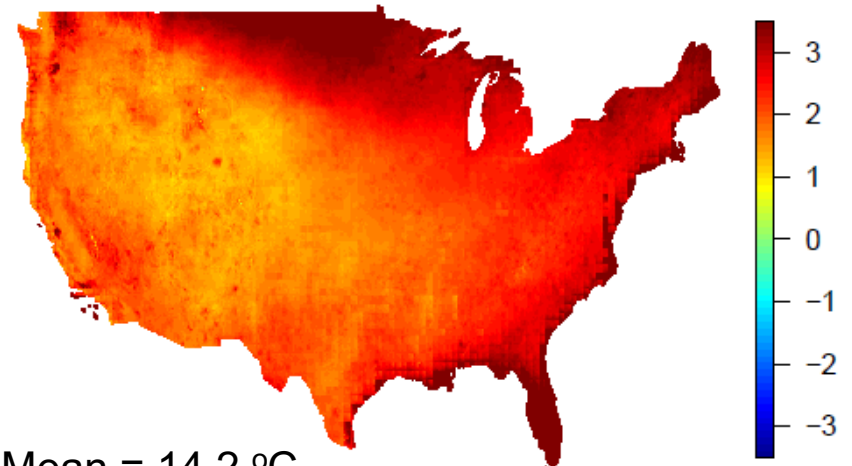
Mean = 11.4 °C

Precipitation Percent Change from 2000-2010 to 2090-2099



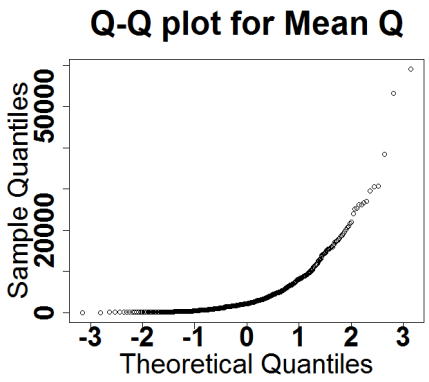
Mean = 830 mm/yr

Temperature Change from 2000-2010 to 2090-2099

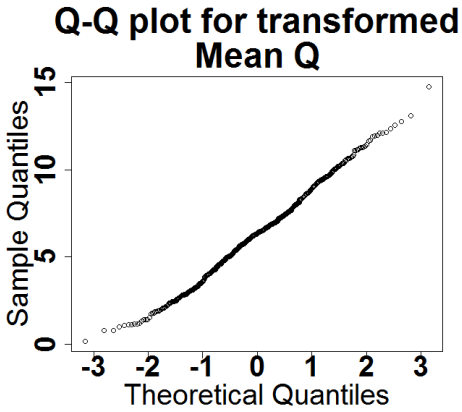


Mean = 14.2 °C

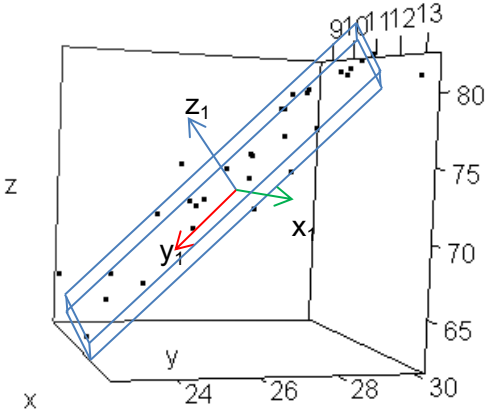
Analysis Steps



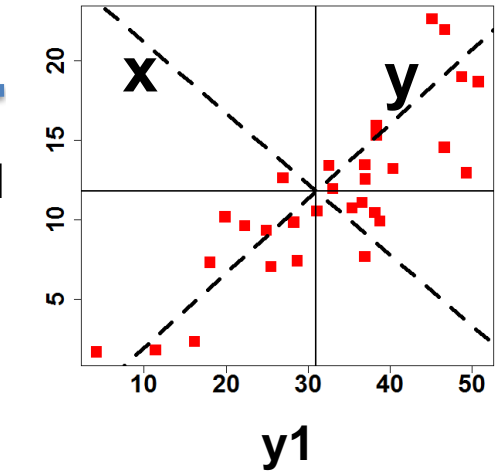
Normalize



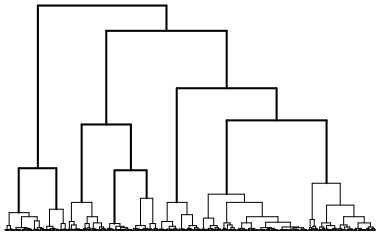
PCA



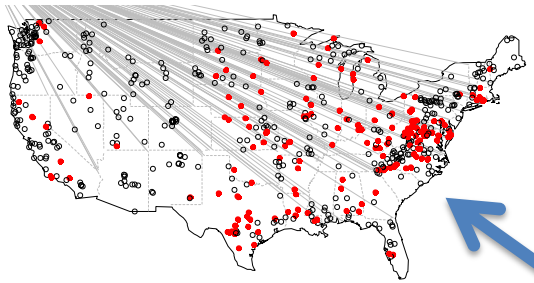
Varimax Rotation



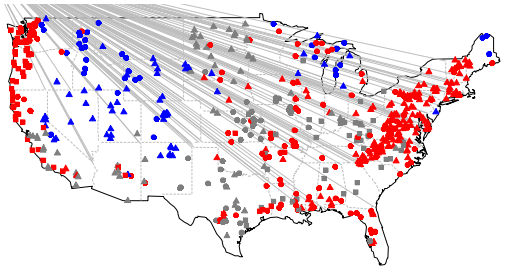
Classification



Ward's Clusters



Regime Class Change Due to Climate Change

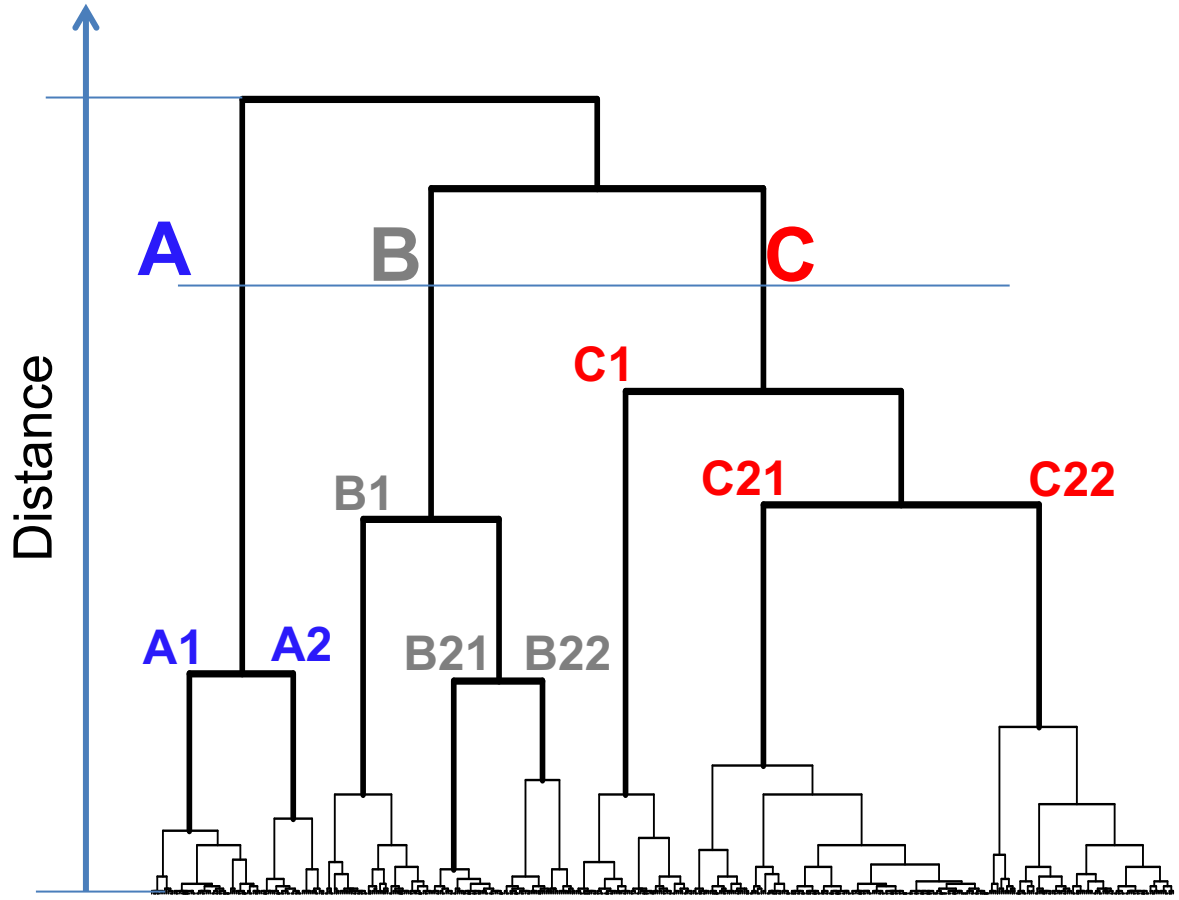


PCA (Loadings)

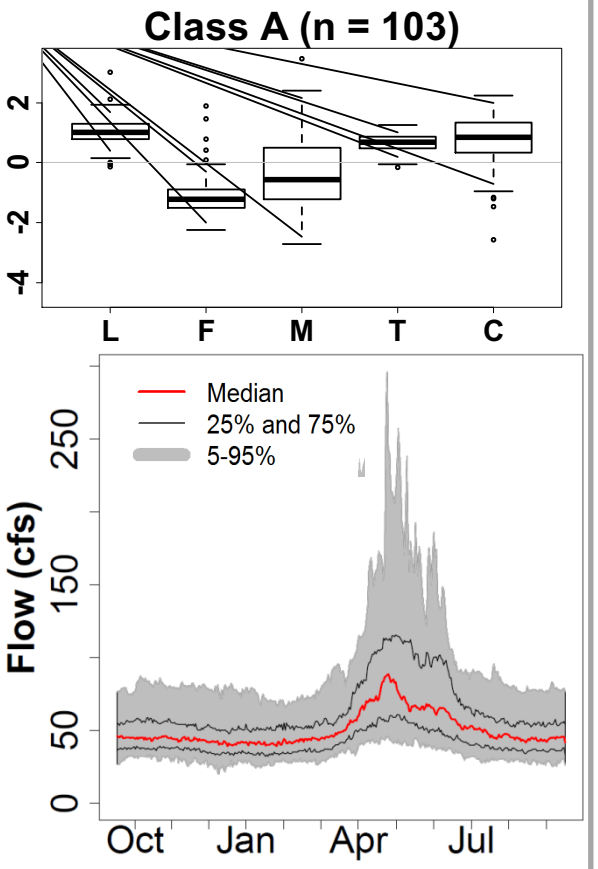
	PC1	PC2	PC3	PC4	PC5
Extended Low Flow Index (ELFI)	0.83	0.05	0.05	0.15	-0.14
Coefficient of Variation of Daily Flows (DAYCV)	-0.82	-0.07	0.07	0.04	0.36
Contingency (M)	0.67	-0.01	-0.44	-0.23	0.1
Low Flow Event (LFE)	0.84	0.13	0.29	0.02	-0.05
Zero Flow Event (ZFE)	-0.85	-0.17	-0.01	0.05	0.22
Average 7 day Minimum Flow (Qmin7)	0.71	0.58	0.01	0.07	-0.25
Mean daily discharge (QMEAN)	0.31	0.93	0.03	-0.08	-0.14
Bank Full Flow (Q167)	0.01	0.97	0.21	-0.12	0
Average 7 day Maximum Flow (Qmax7)	0.08	0.99	0.03	-0.07	-0.01
Flow Reversal(R)	0.54	0.12	0.68	0	-0.14
Flood Duration (FLDDUR)	0.09	-0.07	-0.84	0.2	0.18
High Flow Event (HFE)	0.02	0.1	0.91	-0.22	-0.07
50% timing of flow (T50)	0.04	-0.11	-0.36	0.79	0.2
Time of Peak (Tp)	-0.02	-0.09	-0.08	0.89	-0.01
Predictability (P)	-0.3	-0.08	-0.36	0.05	0.86
Constancy (C)	-0.56	-0.11	-0.1	0.2	0.73
Proportion of variance explained (cumulative)	**0.28**	**0.21 (0.49)**	**0.16 (0.65)**	**0.1 (0.75)**	**0.11 (0.86)**
Interpretation	**Low Flow (L)**	**Magnitude (M)**	**Flashiness (F)**	**Timing (T)**	**Constancy (C)**

(Magnitude, Timing, Rate of Change, Duration, Frequency)

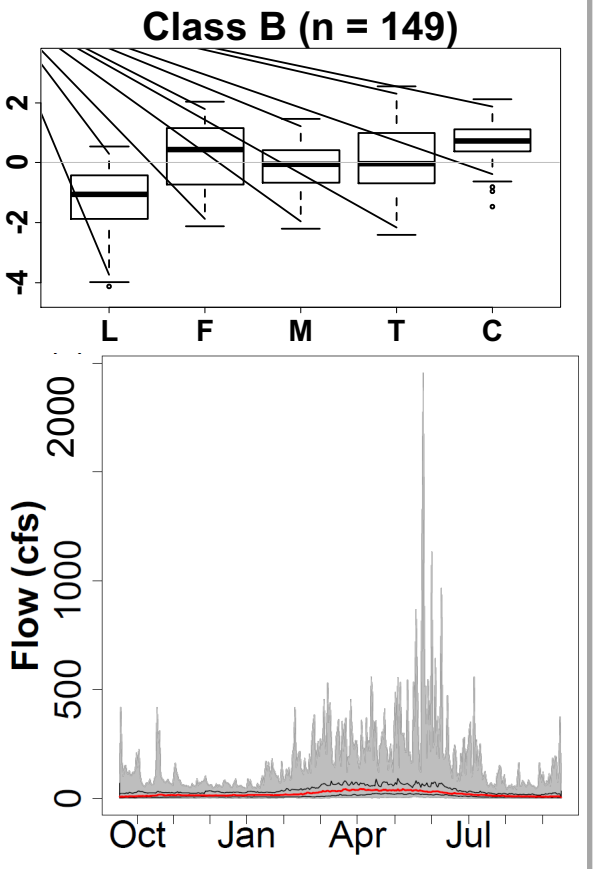
Ward's Hierarchical Cluster Analysis (Euclidean Distance on Rotated PCAs)



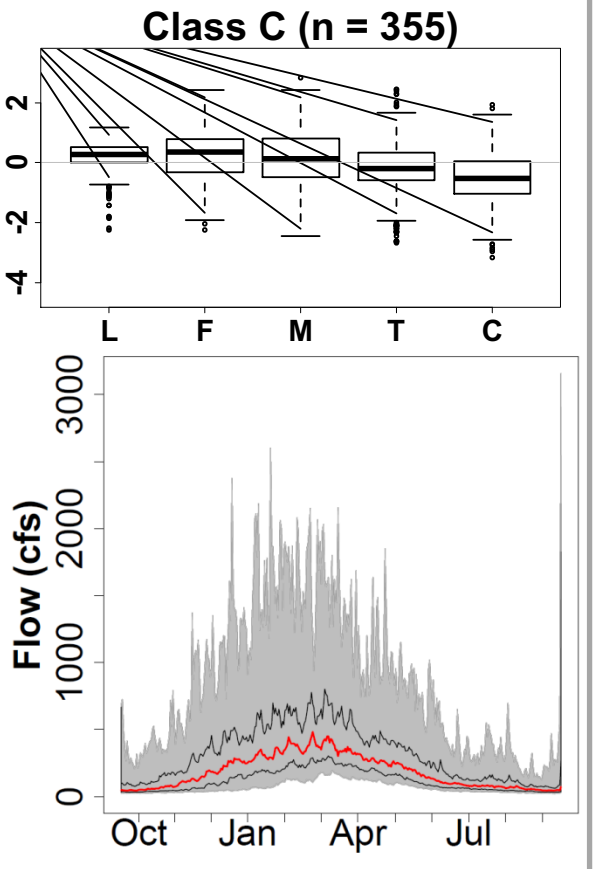
Characteristics of 3 Coarse Stream Classes



A. Perennial with low flashiness and high low-flow factor (snow fed)



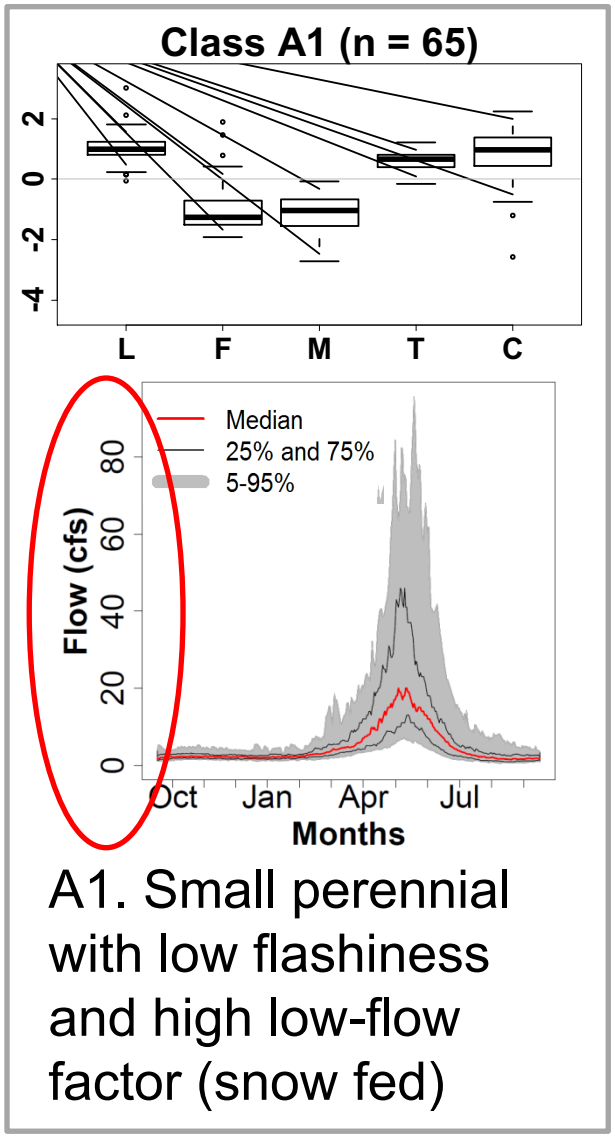
B. Intermittent (low low flow factor and higher flashiness)



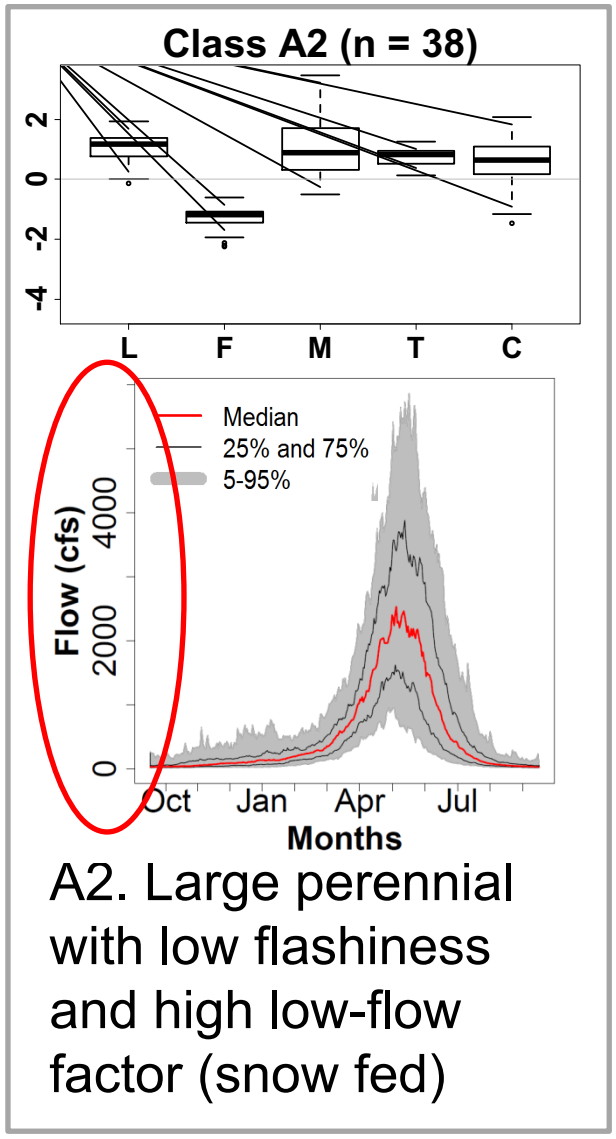
C. Perennial with higher flashiness and intermediate low-flow factor (rain fed)

L = Low Flow **F = Flashiness** **M = Magnitude** **T = Timing** **C = Constancy**

Characteristics of A-Type Streams



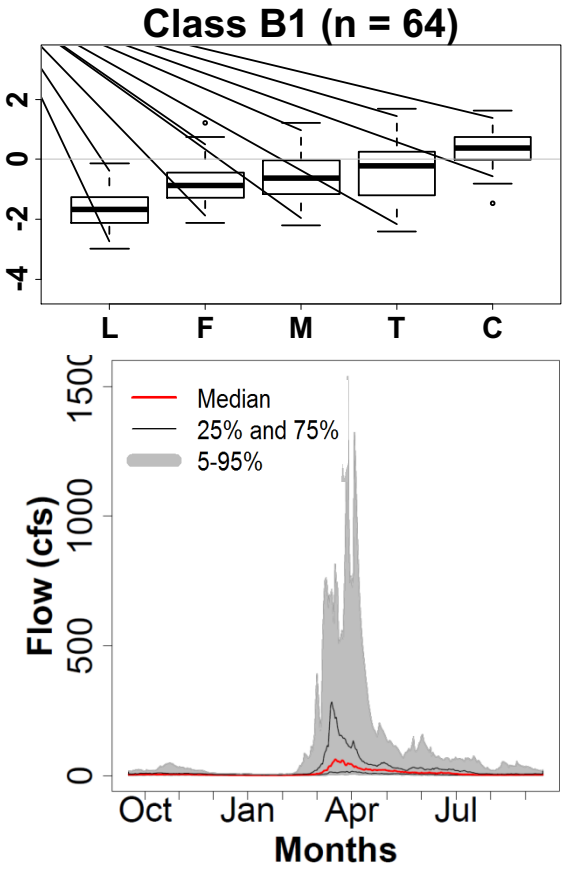
A1. Small perennial with low flashiness and high low-flow factor (snow fed)



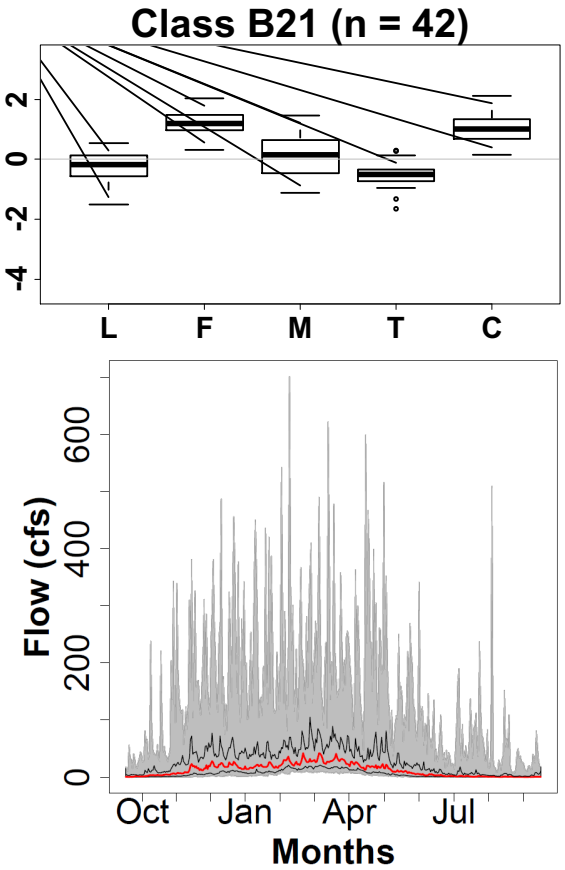
A2. Large perennial with low flashiness and high low-flow factor (snow fed)

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

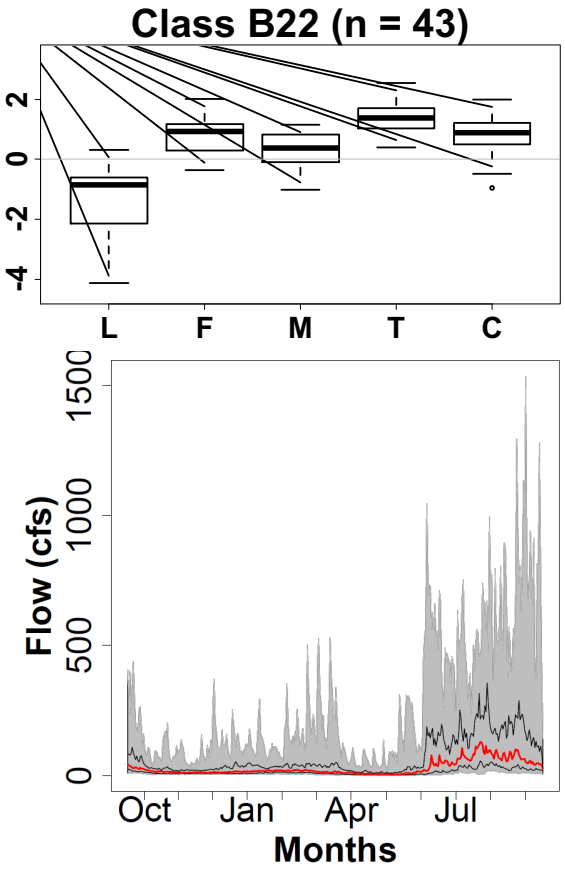
Characteristics of B-Type Streams



B1. Intermittent with low flashiness



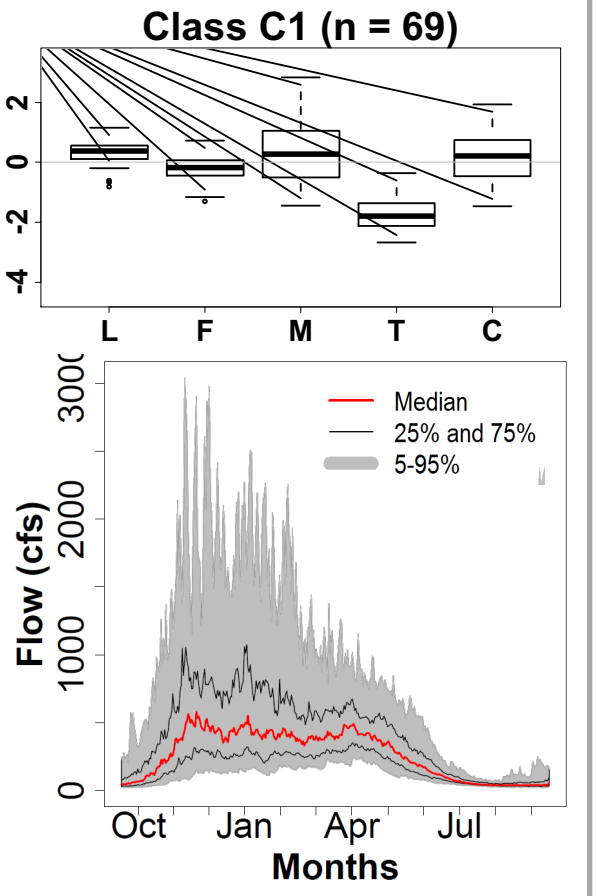
B21. Intermittent with higher flashiness and early timing



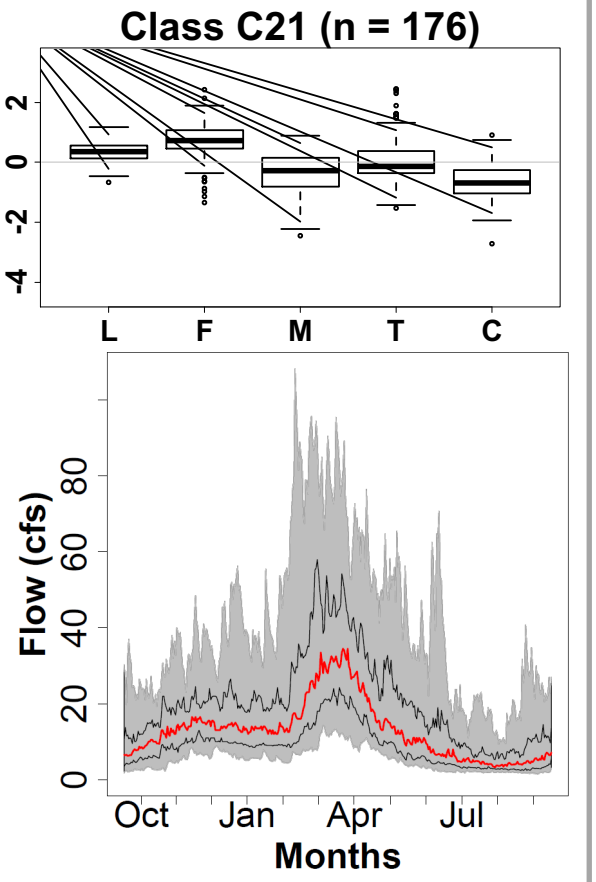
B22. Intermittent with higher flashiness and later timing

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

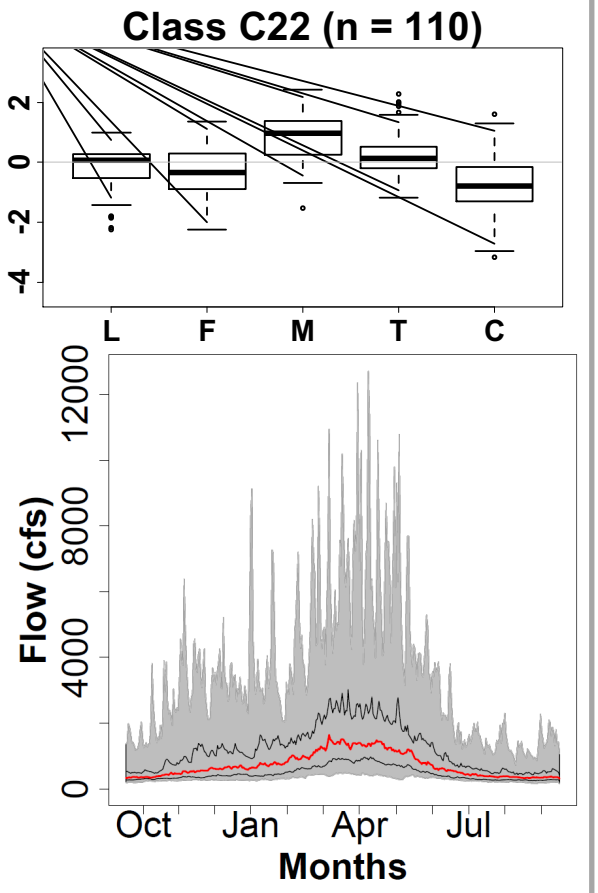
Characteristics of C-Type Streams



C1. Perennial with early flow



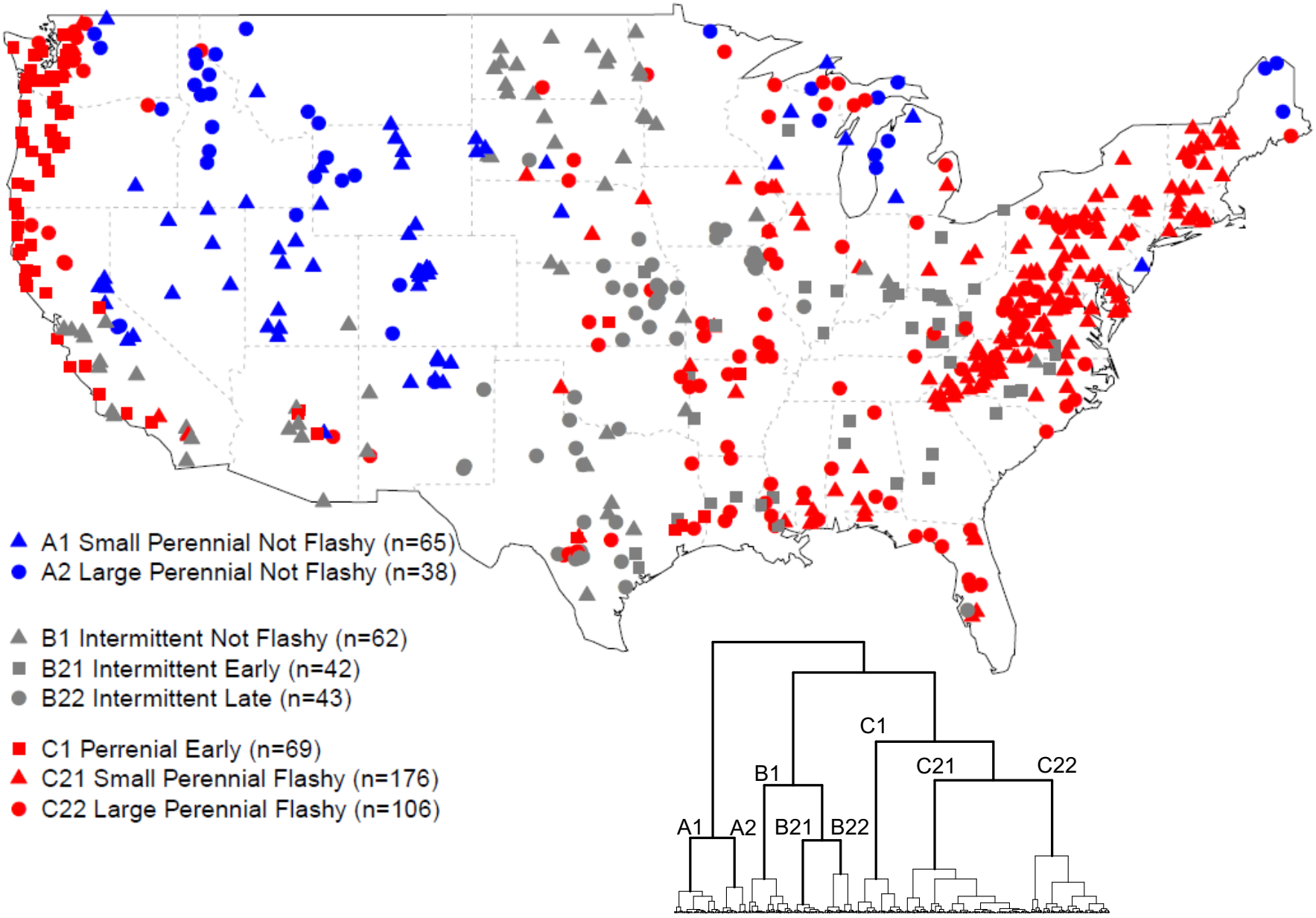
C21. Smaller perennial with later, more flashy flow



C22. Larger perennial with later, less-flashy flow

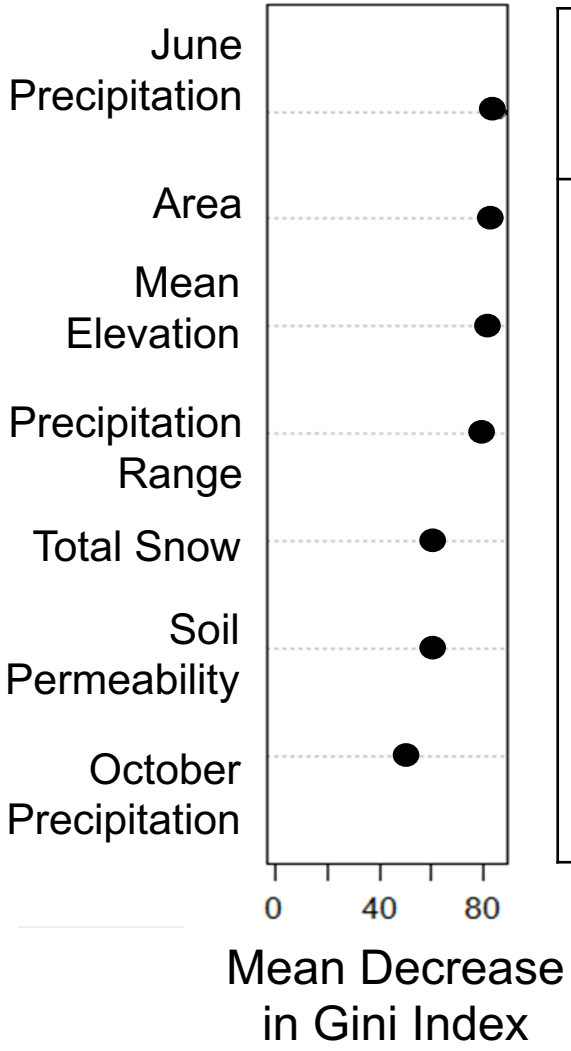
L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

Geography of Stream Regime Classes



Random Forest Model Performance

Variable Importance

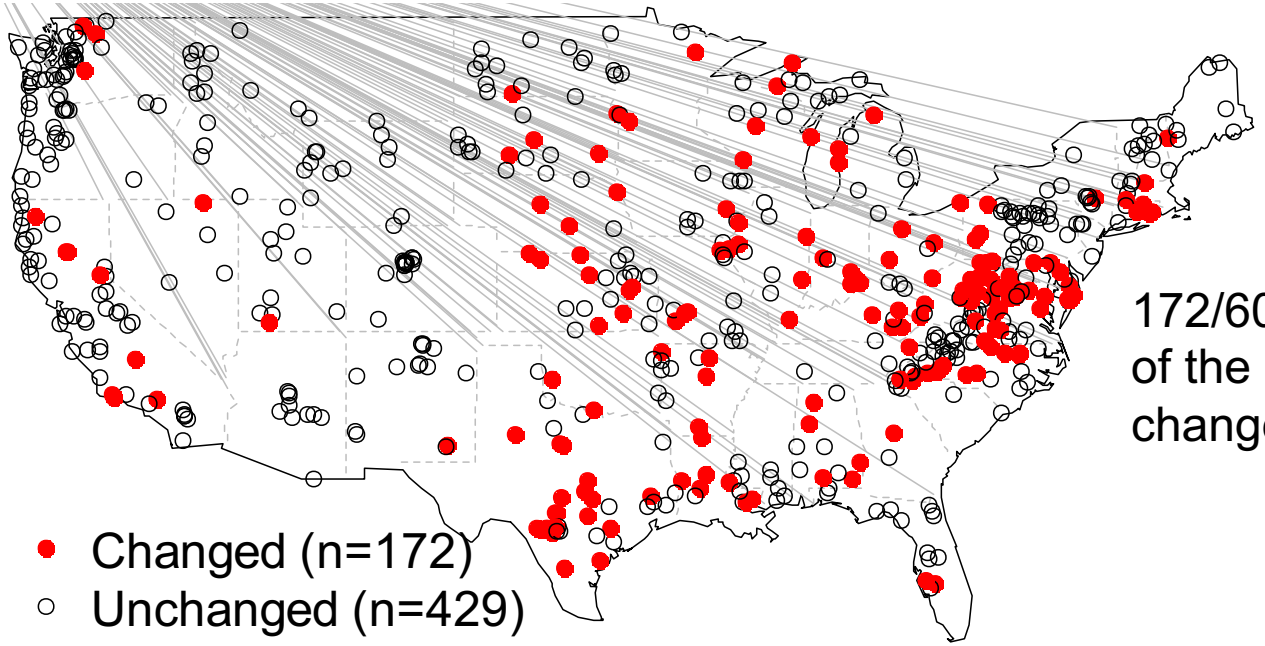


Classification error

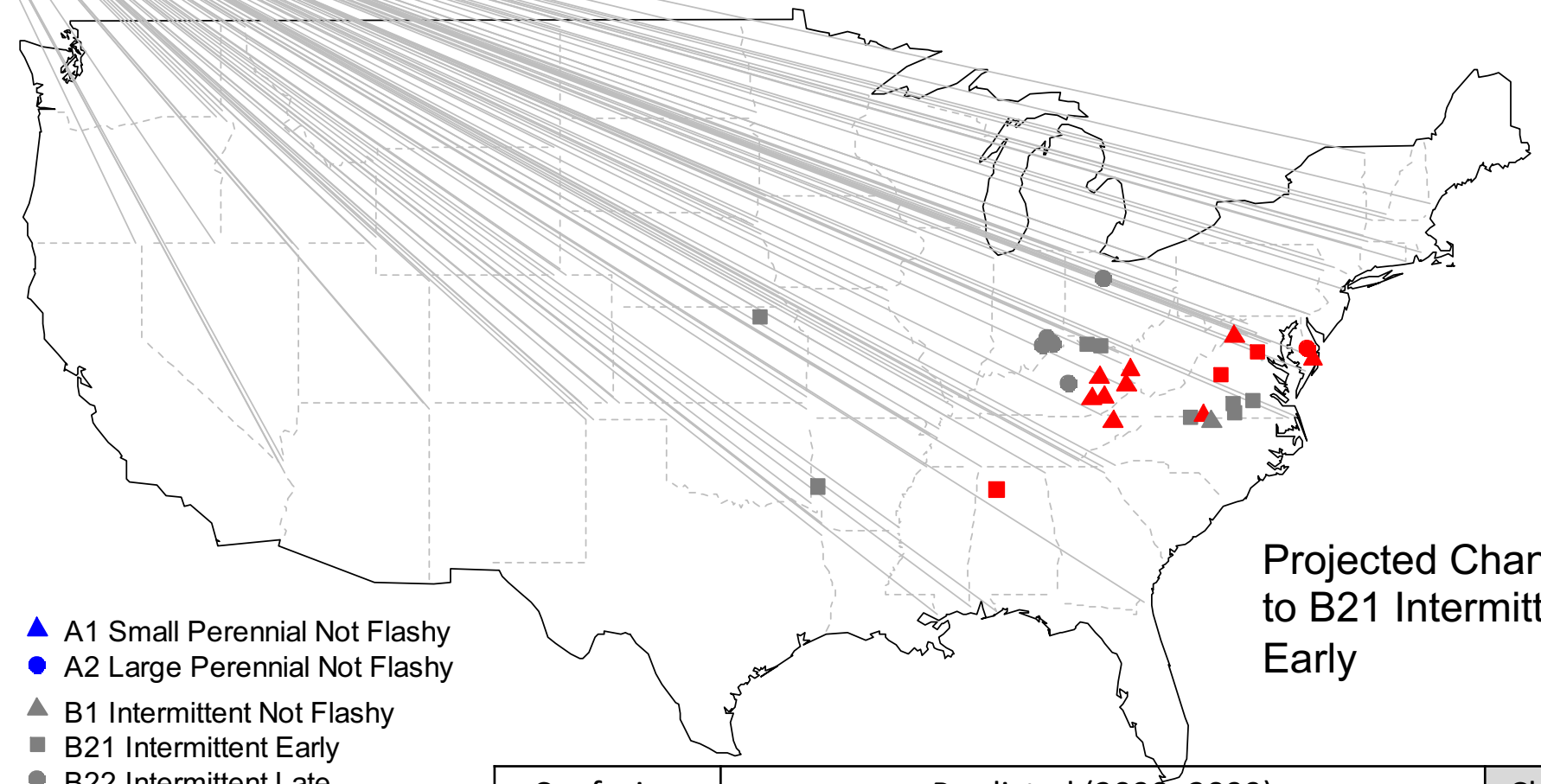
		Predicted								Class Error
		A1	A2	B1	B21	B22	C1	C21	C22	
Original	A1	**54**		2			1	7	1	17%
	A2	4	**28**						6	26%
	B1	3		**36**	3	8	4	5	3	42%
	B21			1	**24**	3	1	11	2	43%
	B22			1	1	**33**		2	6	23%
	C1			6	1		**54**	3	5	22%
	C21			5	4	1	2	**151**	13	14%
	C22	4	3	5	2	3	5	14	**70**	34%

Predicted Climate-Driven Changes in Stream Classes (present to 2090s)

Confusion Matrix (2090-2099)		Predicted (2090 -2099)								
		A1	A2	B1	B21	B22	C1	C21	C22	Change %
Model 2001 - 2010	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%



172/601 = 29%
of the sites
change class

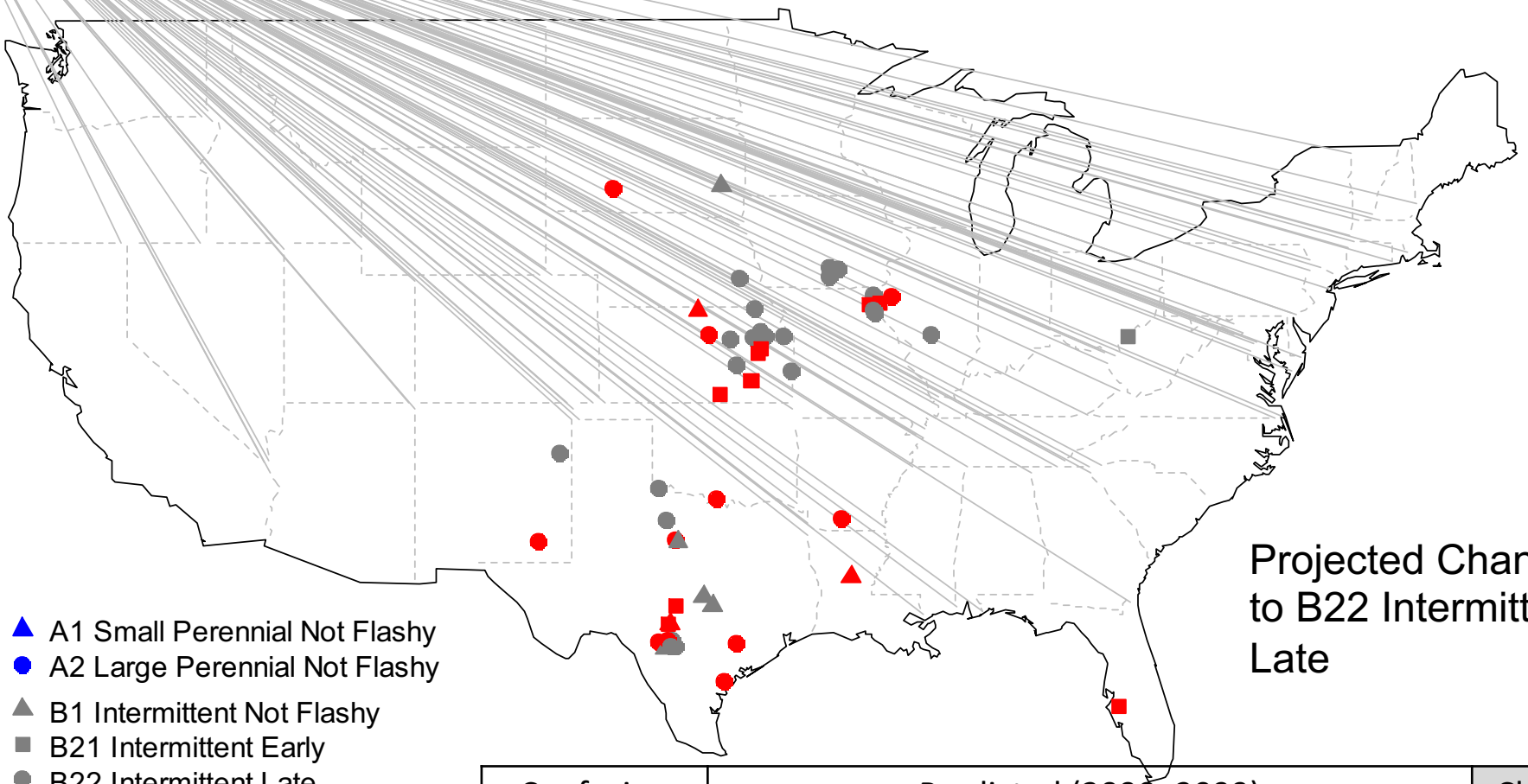


Projected Changes to B21 Intermittent Early

- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Changing to perennial, rain-fed streams with later flow

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%

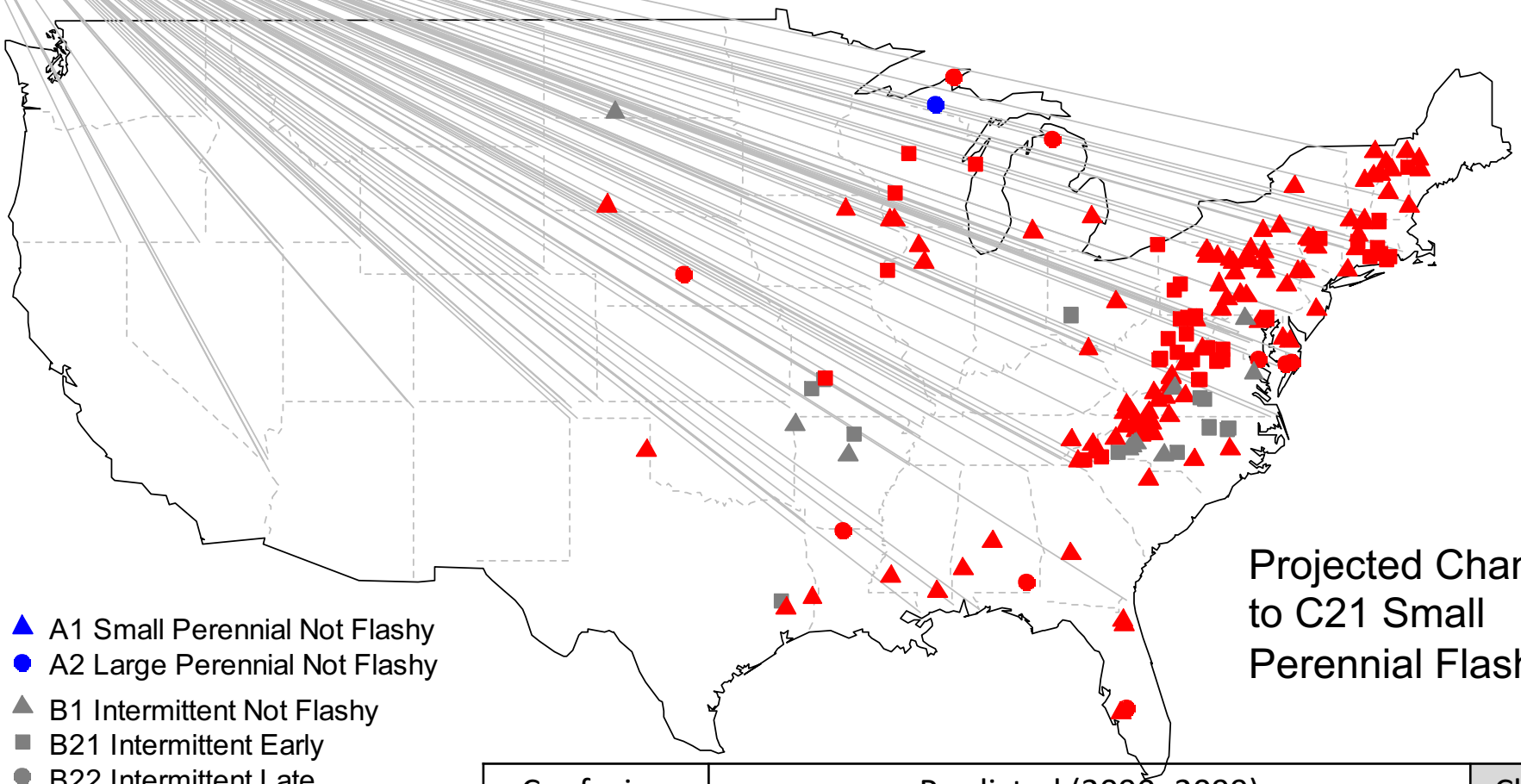


- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to B22 Intermittent Late

Changing to perennial rain-fed streams

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%



- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to C21 Small Perennial Flashy

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%

Change to earlier and increased intermittency

Concluding Remarks

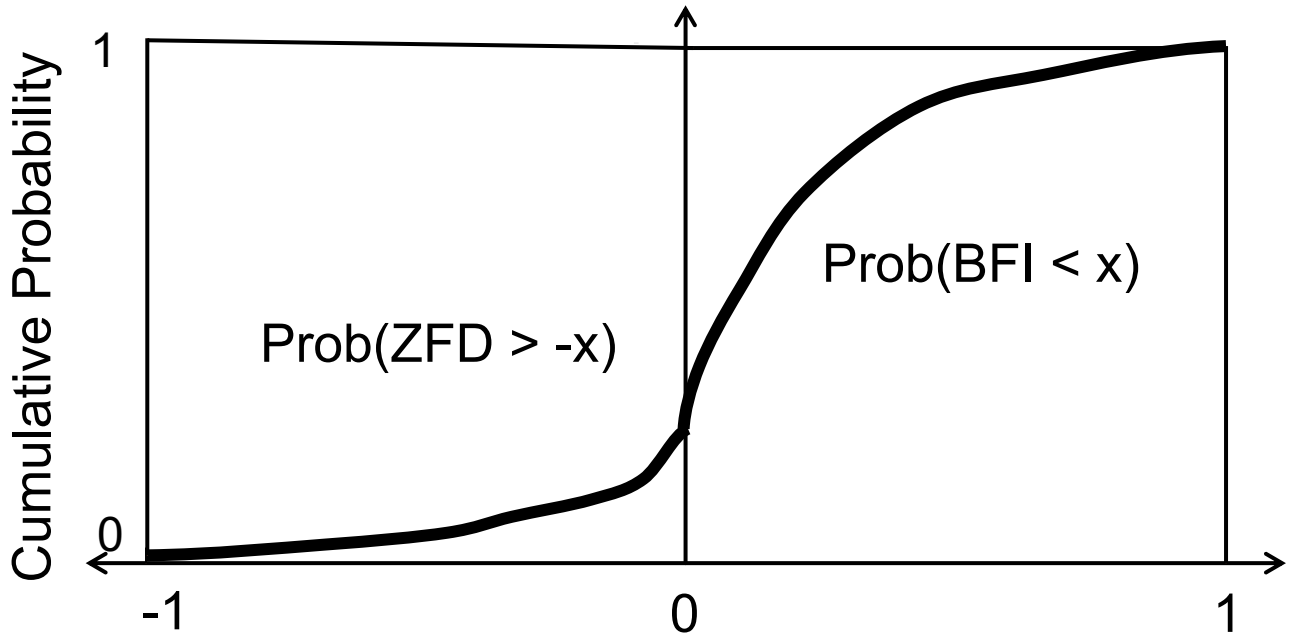
- Did we adequately characterize ecological important aspects of flow?
- Prediction to ungauged (or future) streams is a critical challenge. Low-flow is most problematic.
- Will streams switch between perennial and intermittent? These types of changes have very different implications for stream biodiversity.

Questions?

Extra slides

Extended Low Flow Index (ELFI)

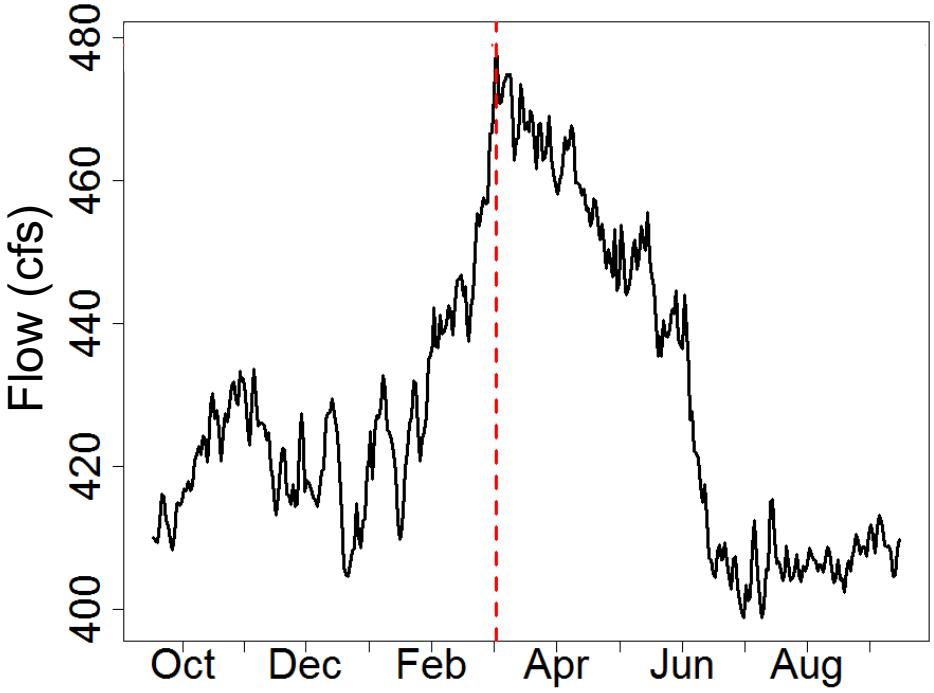
Combined Fraction of Zero Flow Days (ZFD) and Baseflow Index (BFI) to characterize low flow



ELFI = BFI - ZFD

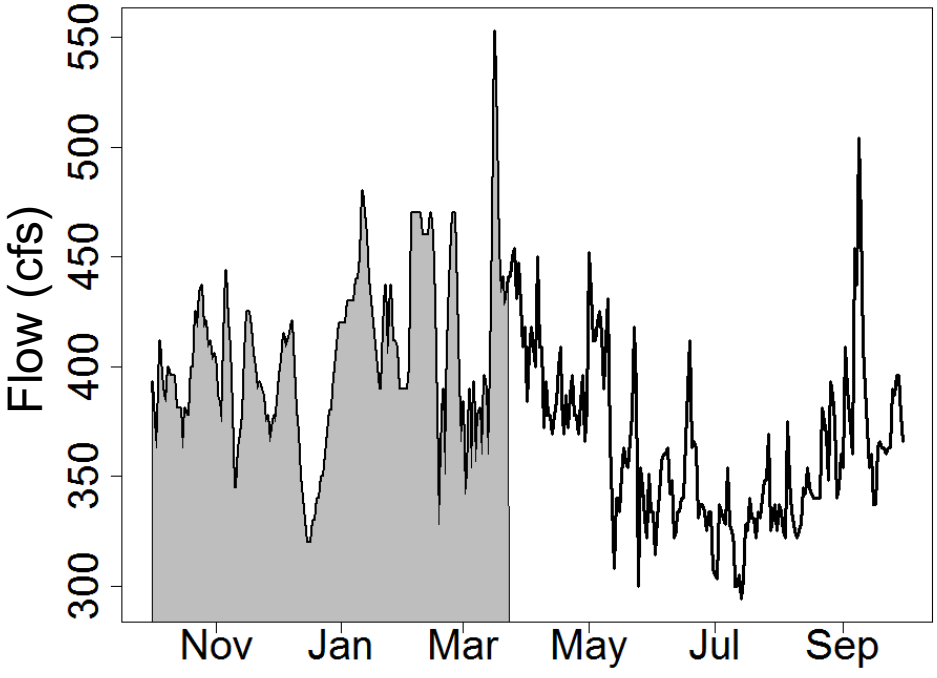
Timing variables

Time of Peak



Average day of peak
in water year

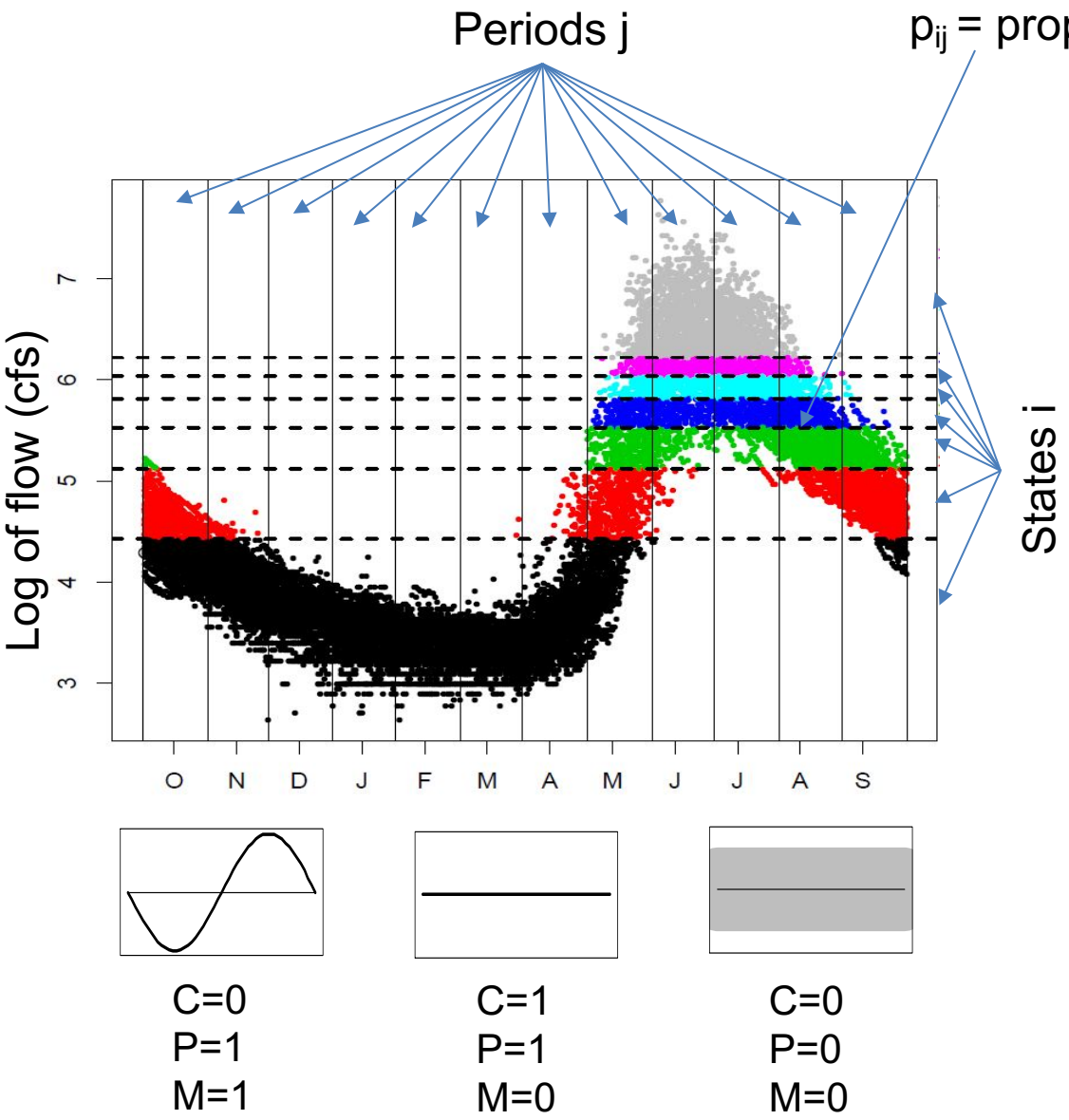
50% Flow date



The day of water year by which
50% of total flow has occurred

All the streamflow variables were calculated based on water year (Oct – Sep)

Streamflow Predictability (P), Constancy (C) and Contingency (M) Colwell (Ecology 1974, 55:1148-1153)



Entropy measure of uncertainty

$$H = -\sum p \log p$$

- Predictability (P) is entropy measure of uncertainty scaled from 0 (uncertain) to 1 (certain)
- Constancy (C) is entropy measure of uncertainty scaled from 0 to 1 without regard for period
- Contingency (M=P-C) scales the mutual information of time and state from 0 (unrelated) to 1 (dependent)

Colwell's Predictability (P), Constancy (C) and Contingency (M)

Periods / States	1	2	3	4	Total
> 3 * Qmean			50		50
2 - 3 * Qmean	50				50
1 - 2 * Qmean		50			50
< Qmean				50	50

P=1, C=0, M=1

P=C+M

Periods / States	1	2	3	4	Total
> 3 * Qmean					
2 - 3 * Qmean					
1 - 2 * Qmean	50	50	50	50	200
< Qmean					

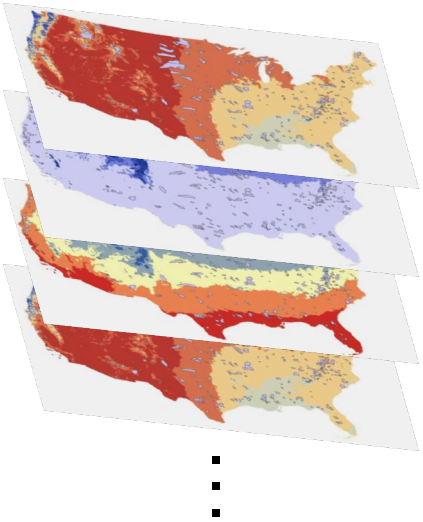
P=1, C=1, M=0

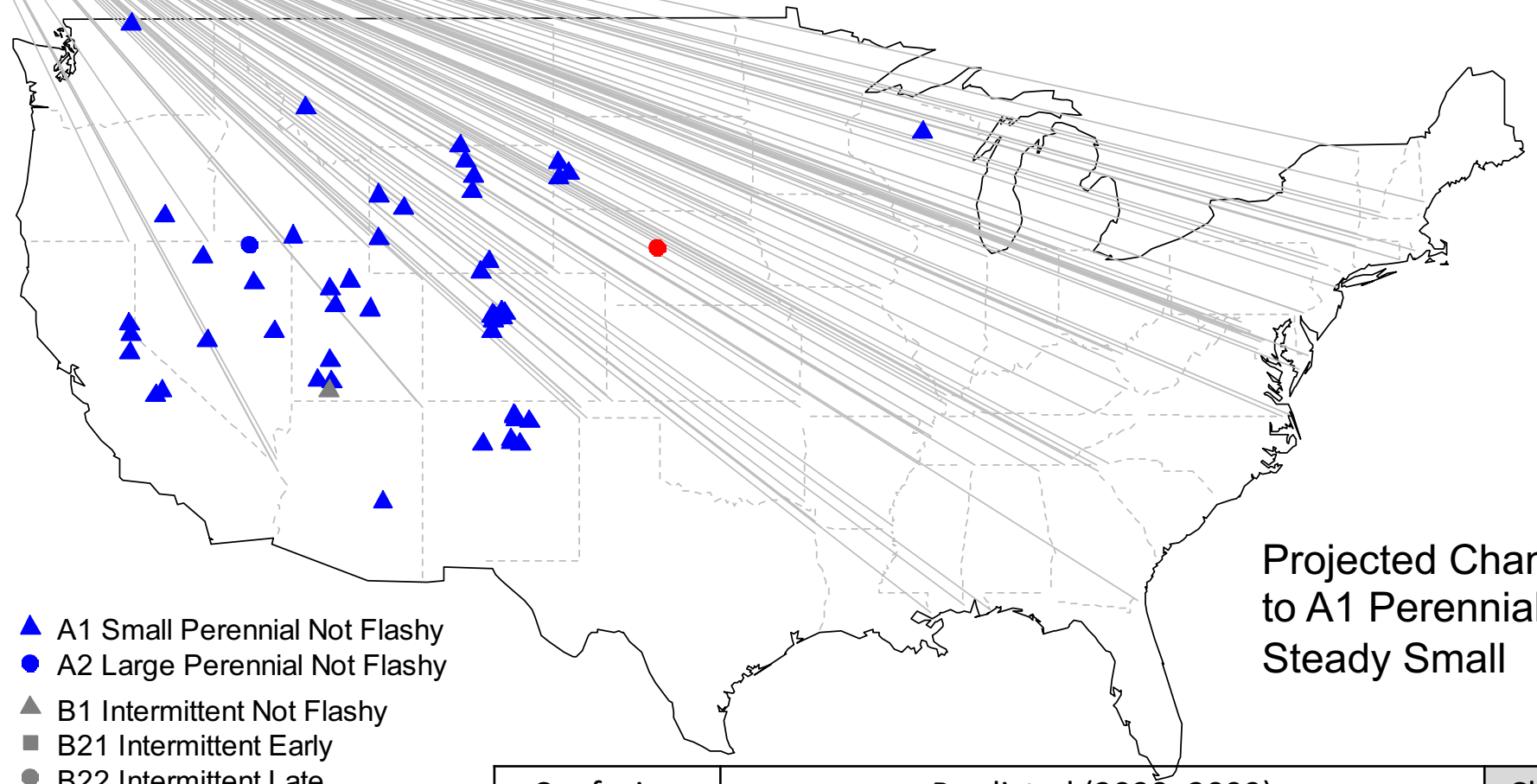
Climate, Soil and Geomorphological Properties Evaluated for each Watershed

Climate
Minimum Temp
Maximum Temp
Diff in Temp
Amplitude of Temp
Standard Deviation of Max Temp
Standard Deviation of Min Temp
Potential Evapotranspiration
Dryness Index
Potential Evapotranspiration Amplitude
Seasonality
Total Snow (Mean T)
Mean Temp
Mean Precipitation
Minimum Precipitation
Maximum Precipitation
Precipitation Range
Amplitude of Precipitation
Timing of 50% Precipitation
Relative Humidity
Monthly scaled Precipitation (12 months)
Percent of Snow
Total Snow
Percent Snow (Mean T)

Soil
Available water capacity of soil
Soil Bulk Density
Soil organic matter content
Soil Permeability
Average Water table height
Depth to bedrock
Gleeson Permeability

Geomorphology
Minimum Elevation
Maximum Elevation
Elevation Range
Standard Deviation of Elevation
Hypsometric Convexity
Mean Slope
Standard Deviation of Slope
Area
Shape
Mean Elevation

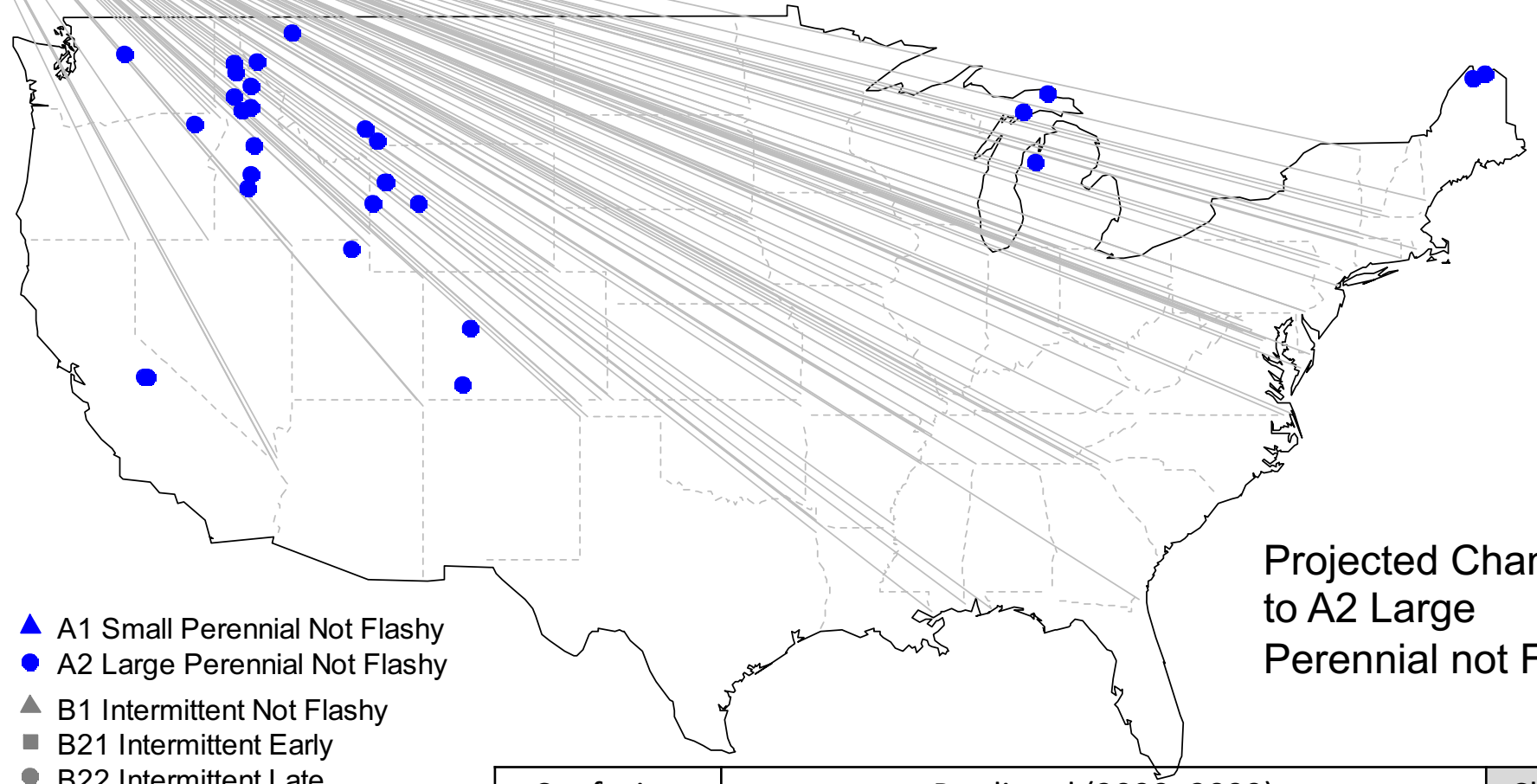




- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to A1 Perennial Steady Small

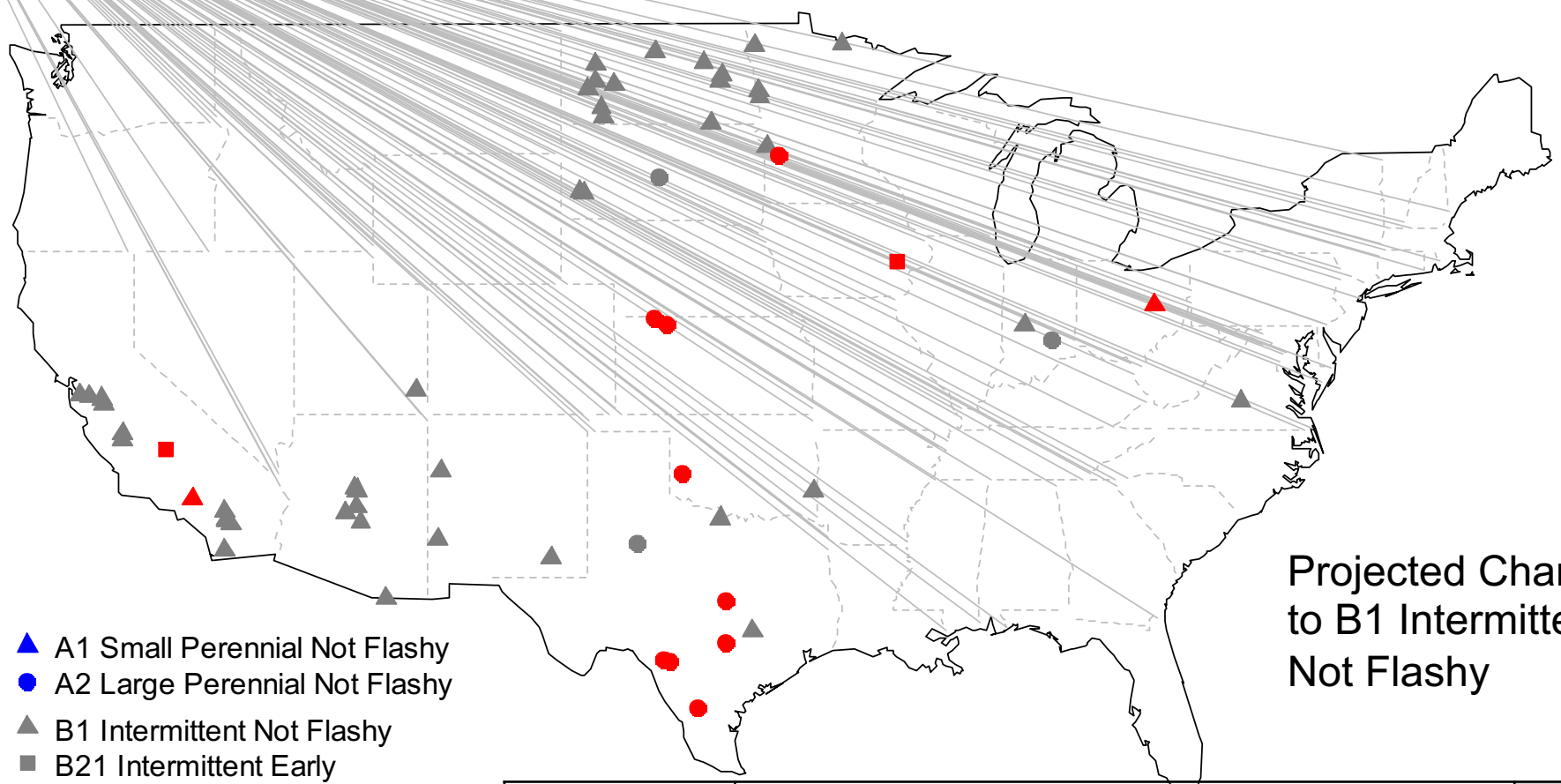
Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%



- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to A2 Large Perennial not Flashy

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%

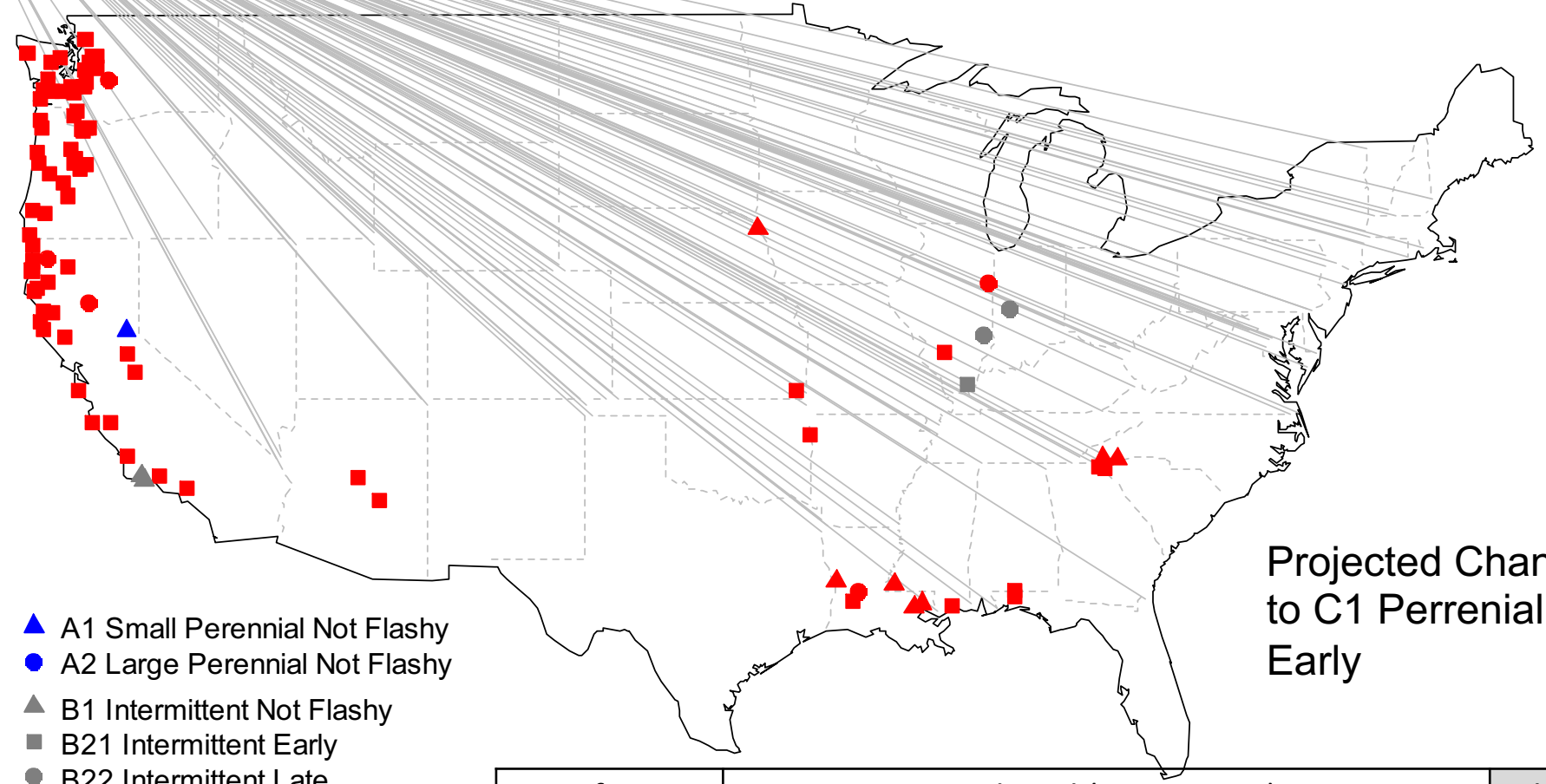


- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to B1 Intermittent Not Flashy

Moving to Perrenial rain fed

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%

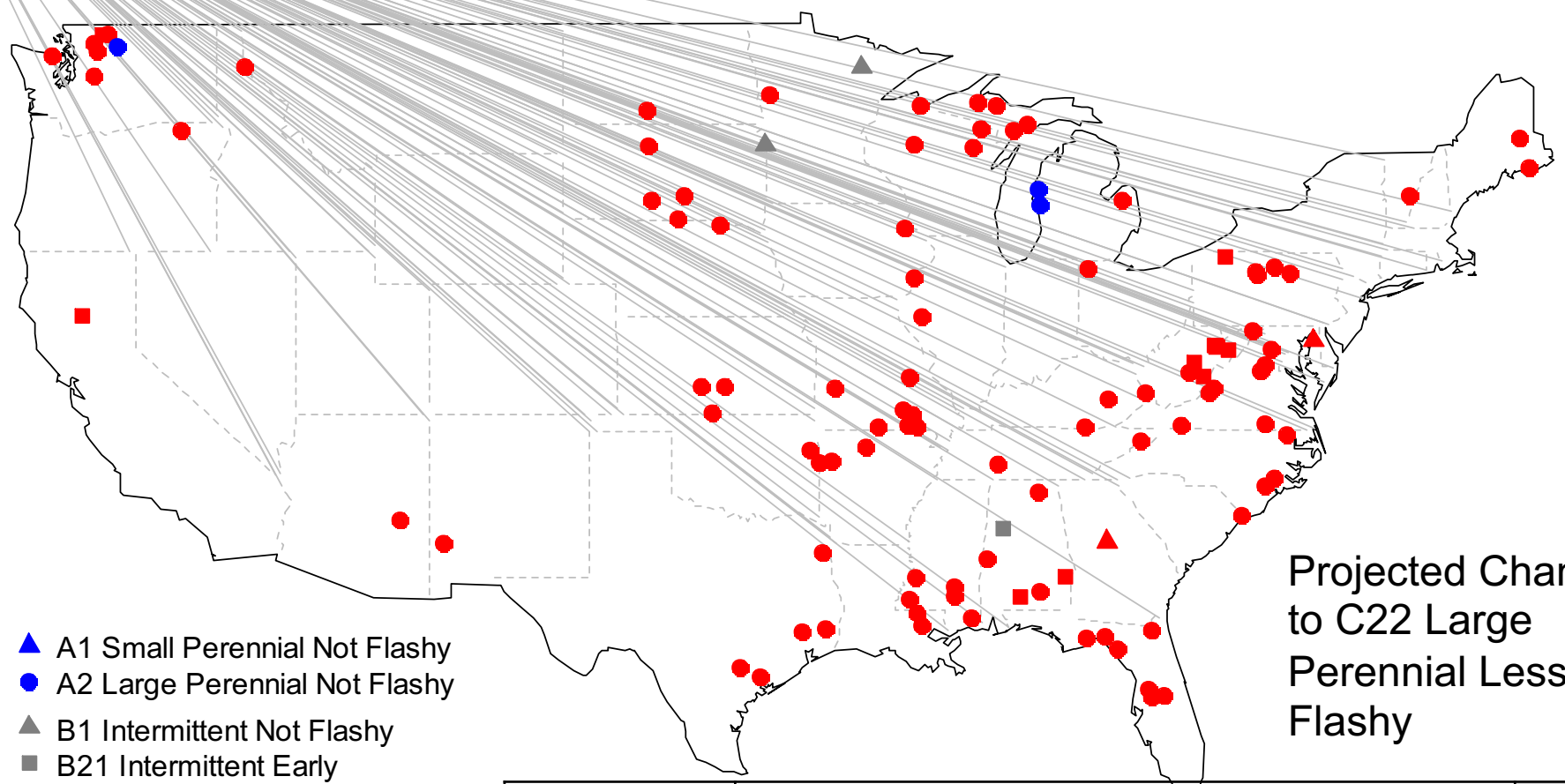


- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Projected Changes to C1 Perrenial Early

Little change

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%



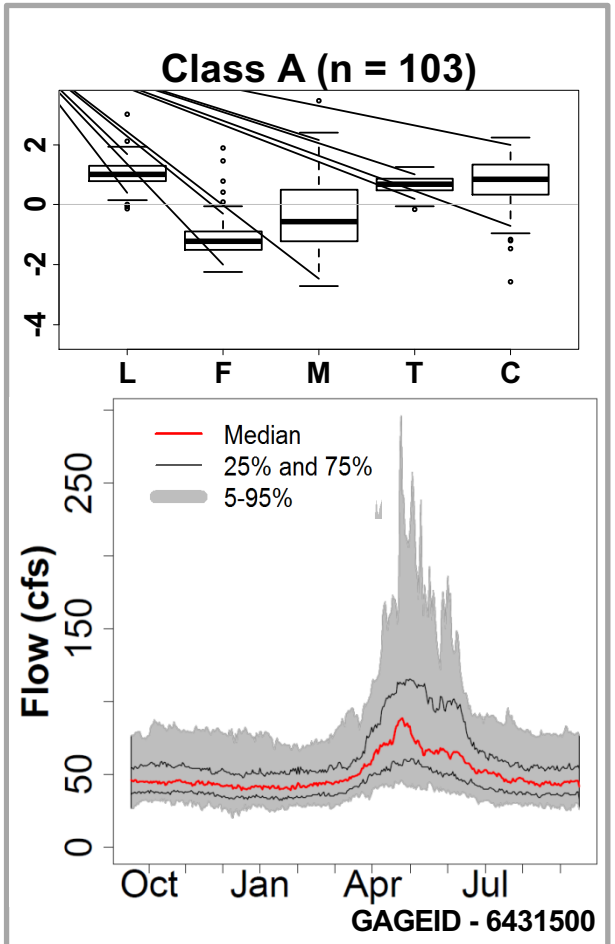
- A1 Small Perennial Not Flashy
- A2 Large Perennial Not Flashy
- B1 Intermittent Not Flashy
- B21 Intermittent Early
- B22 Intermittent Late
- C1 Perrenial Early
- C21 Small Perennial Flashy
- C22 Large Perennial Less Flashy

Some moving earlier

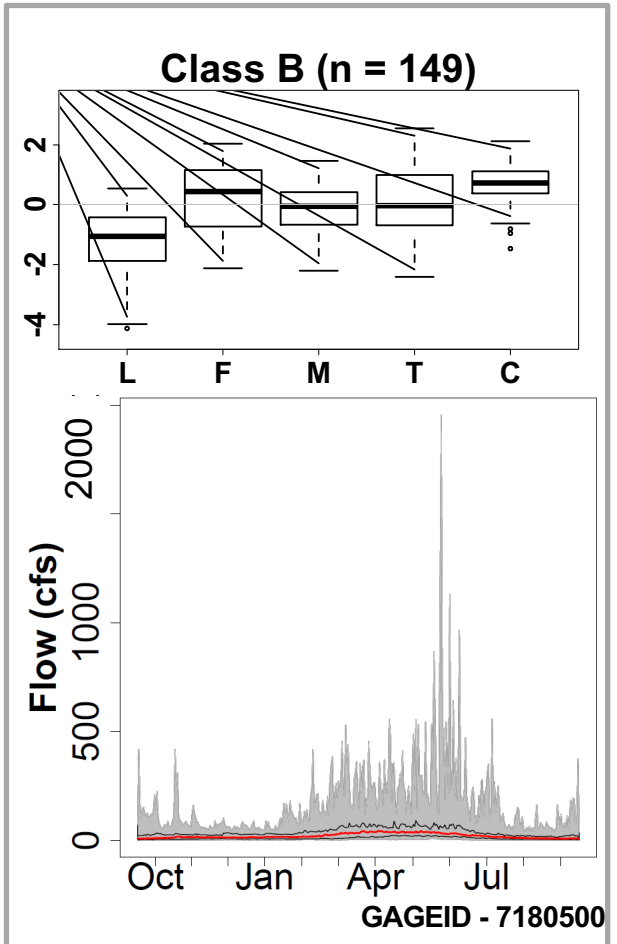
Projected Changes to C22 Large Perennial Less Flashy

Confusion Matrix		Predicted (2090_2099)								Change
		A1	A2	B1	B21	B22	C1	C21	C22	%
Original (Model prediction 2001 - 2010)	A1	**56**	1	1					1	5%
	A2		**29**							0%
	B1			**45**		3	2	2	9	26%
	B21			1	**8**	5	3	9	1	70%
	B22			5	1	**22**	9	3	13	58%
	C1	1		2	1	2	**75**	7	5	19%
	C21		1	10	12		35	**104**	9	39%
	C22		3	2	1		10	2	**90**	17%

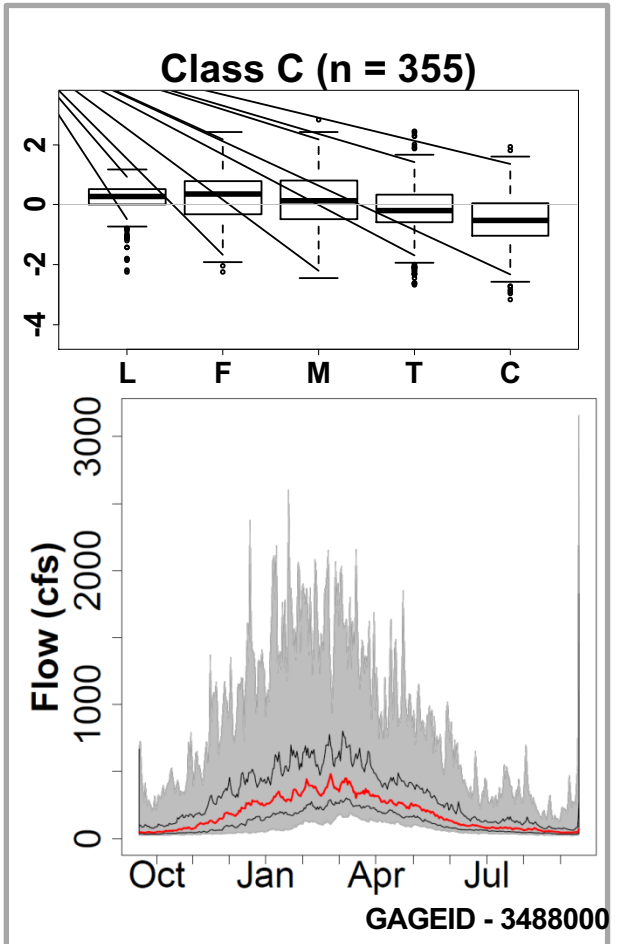
Characteristics of 3 Coarse Stream Classes



A. Perennial with low flashiness and high low-flow factor (snow fed)



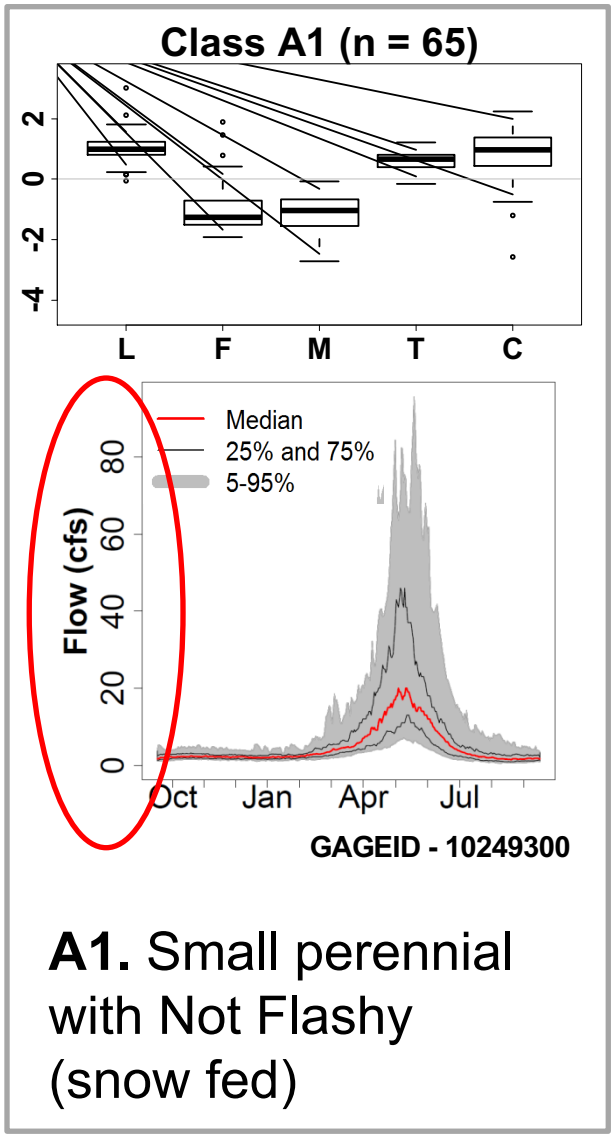
B. Intermittent (low low flow factor and higher flashiness)



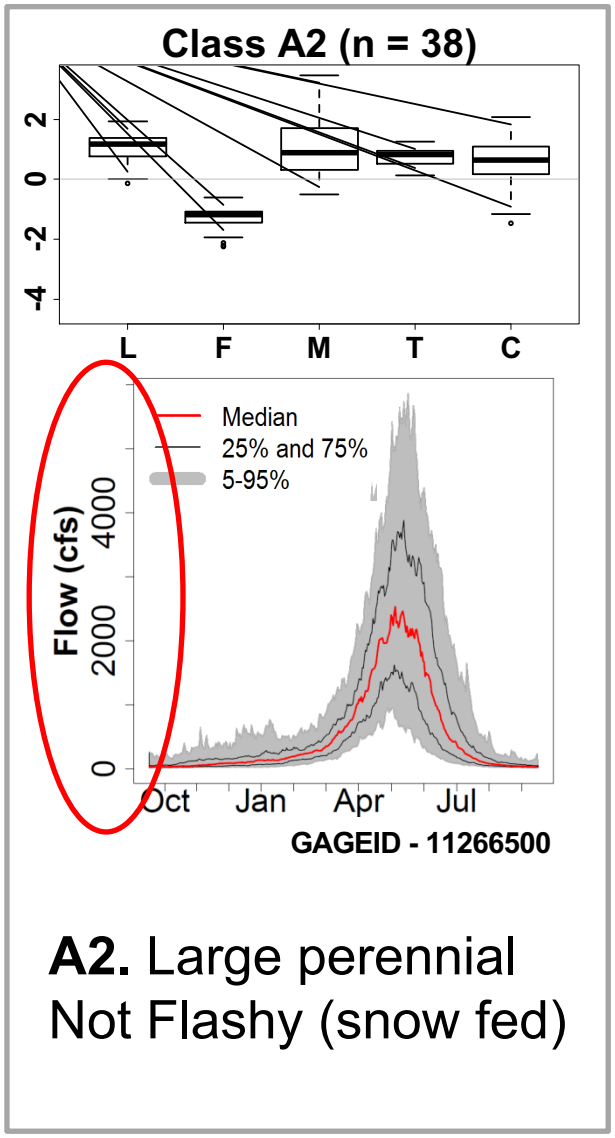
C. Perennial with higher flashiness and intermediate low-flow actor (rain fed)

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

Characteristics of A-Type Streams



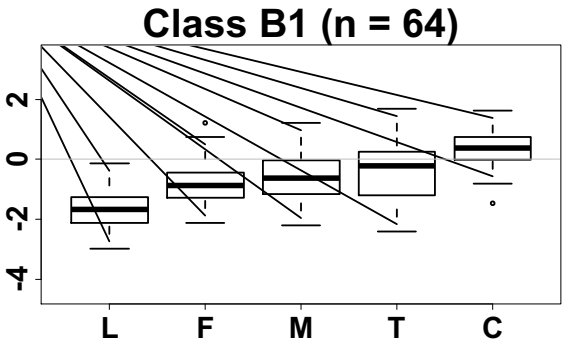
A1. Small perennial with Not Flashy (snow fed)



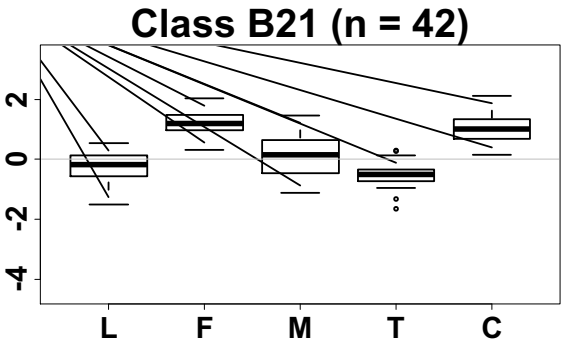
A2. Large perennial Not Flashy (snow fed)

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

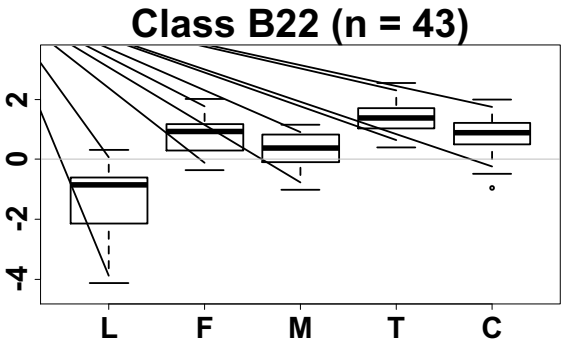
Characteristics of B-Type Streams



B1. Intermittent Not Flashy



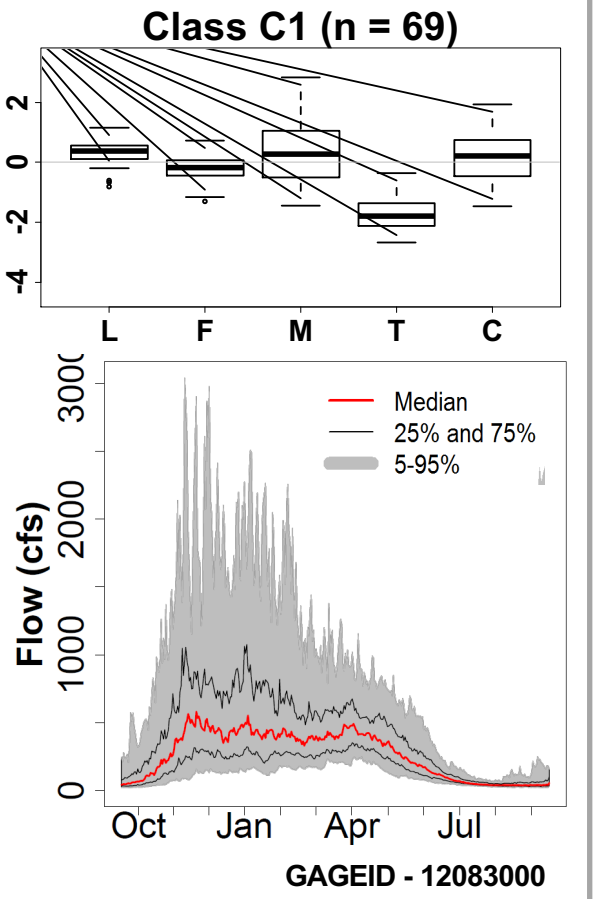
B21. Intermittent early



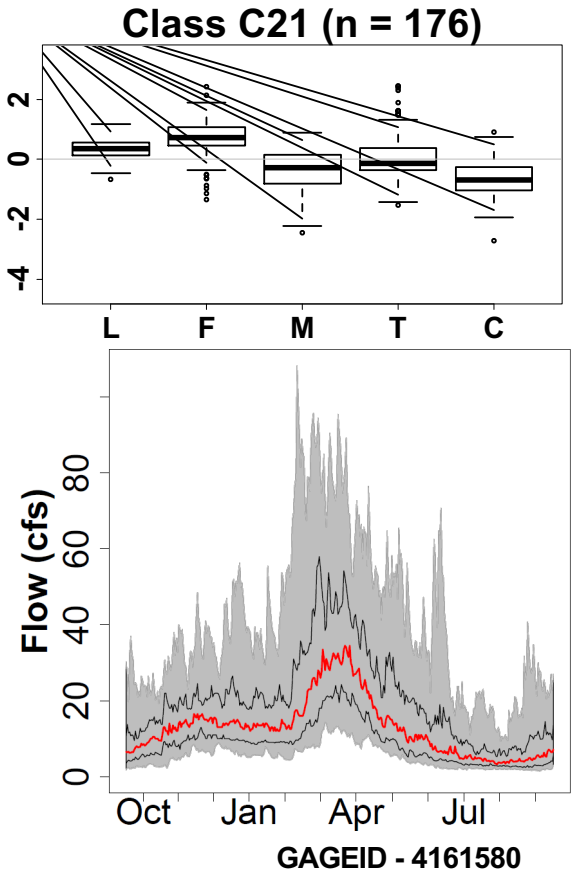
B22. Intermittent late

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy

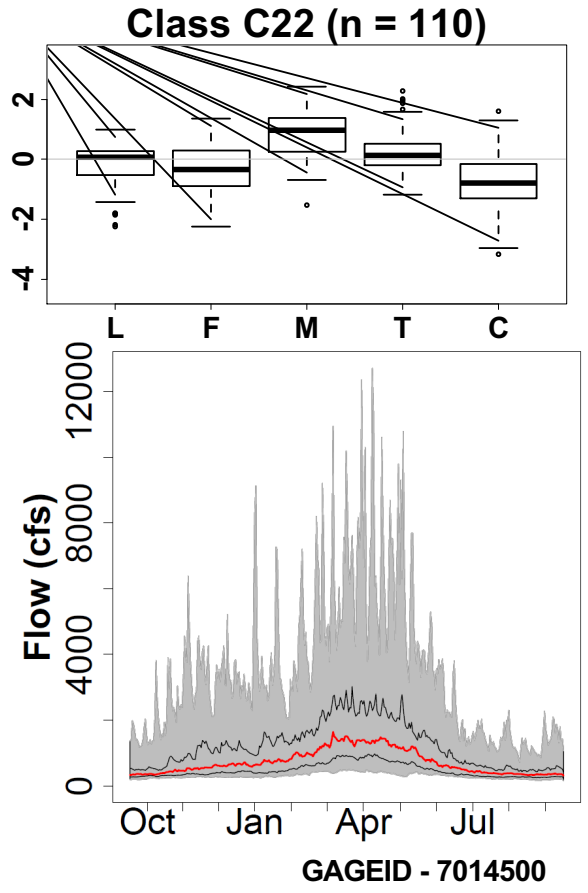
Characteristics of C-Type Streams



C1. Perennial Early



C21. Small perennial Flashy



C22. Large perennial Less Flashy

L = Low Flow F = Flashiness M = Magnitude T = Timing C = Constancy