Using a Standardized Event-Based Tool for Drought Analysis

Application to Propagation Predictability Patterns

Ethiopia B Zeleke[a], Celray James Chawanda[b], Assefa M Melesse[a]

a Department of Earth and Environment, Institute of Environment, Florida International University

b Department of Water and Climate, Vrije Universiteit Brussel; Texas A&M AgriLife Research, Blackland Research & Extension Center

2025 Colorado SWAT Conference

October 22-24, 2025

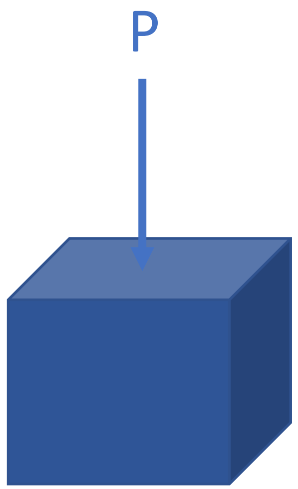
Fort Collins, Colorado USA

Outline

- Drought definitions and propagation background
- SWAT+ model setup and evaluation
- Drought database development and analyses of propagation metrics
- Results, summary and implications

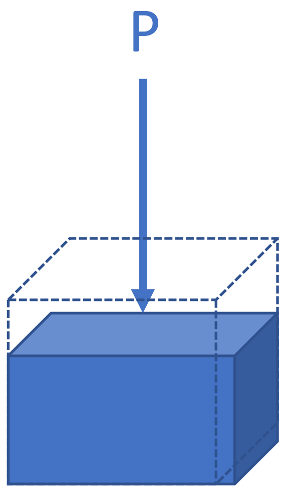
Background

- Types of drought
- Drought propagation
- Drought impacts



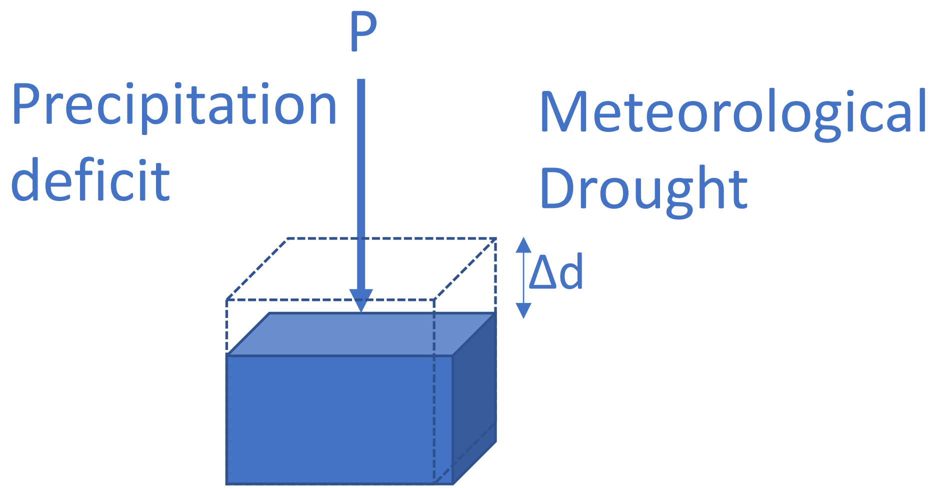
Background

- Types of drought
- Drought propagation
- Drought impacts



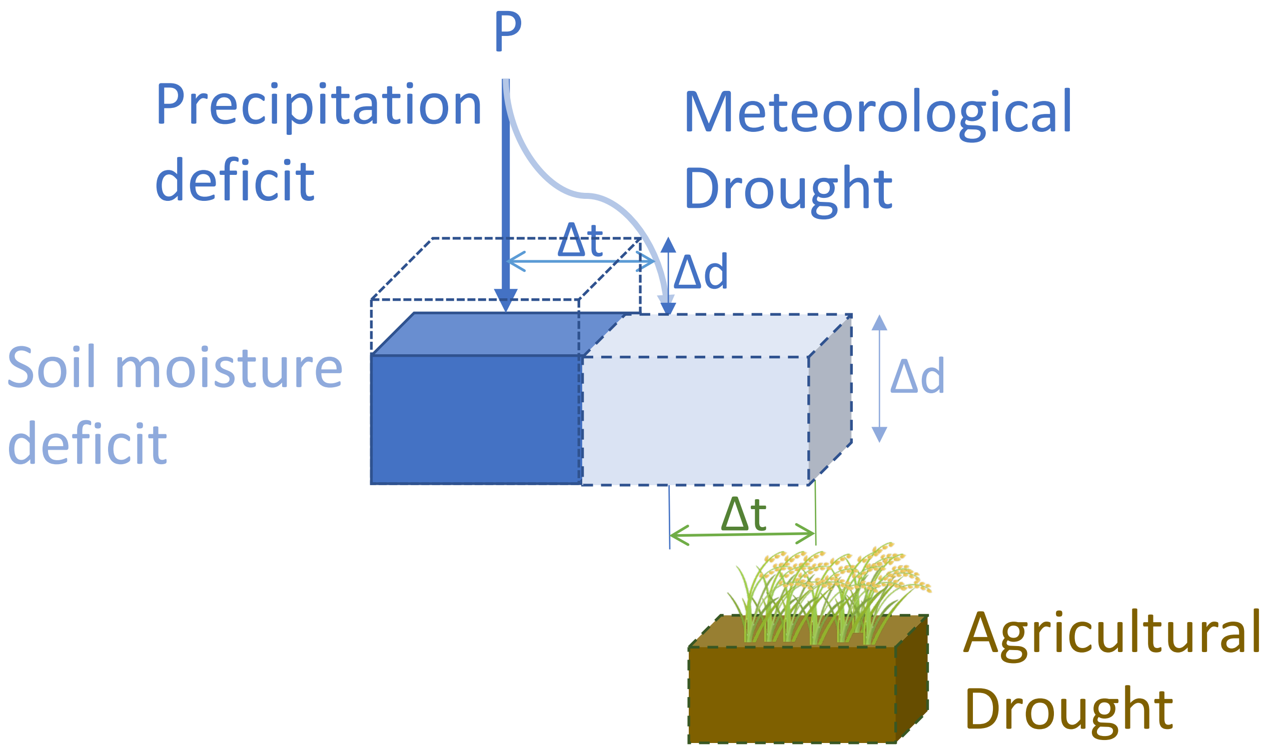
Background

- Types of drought
- Drought propagation
- Drought impacts



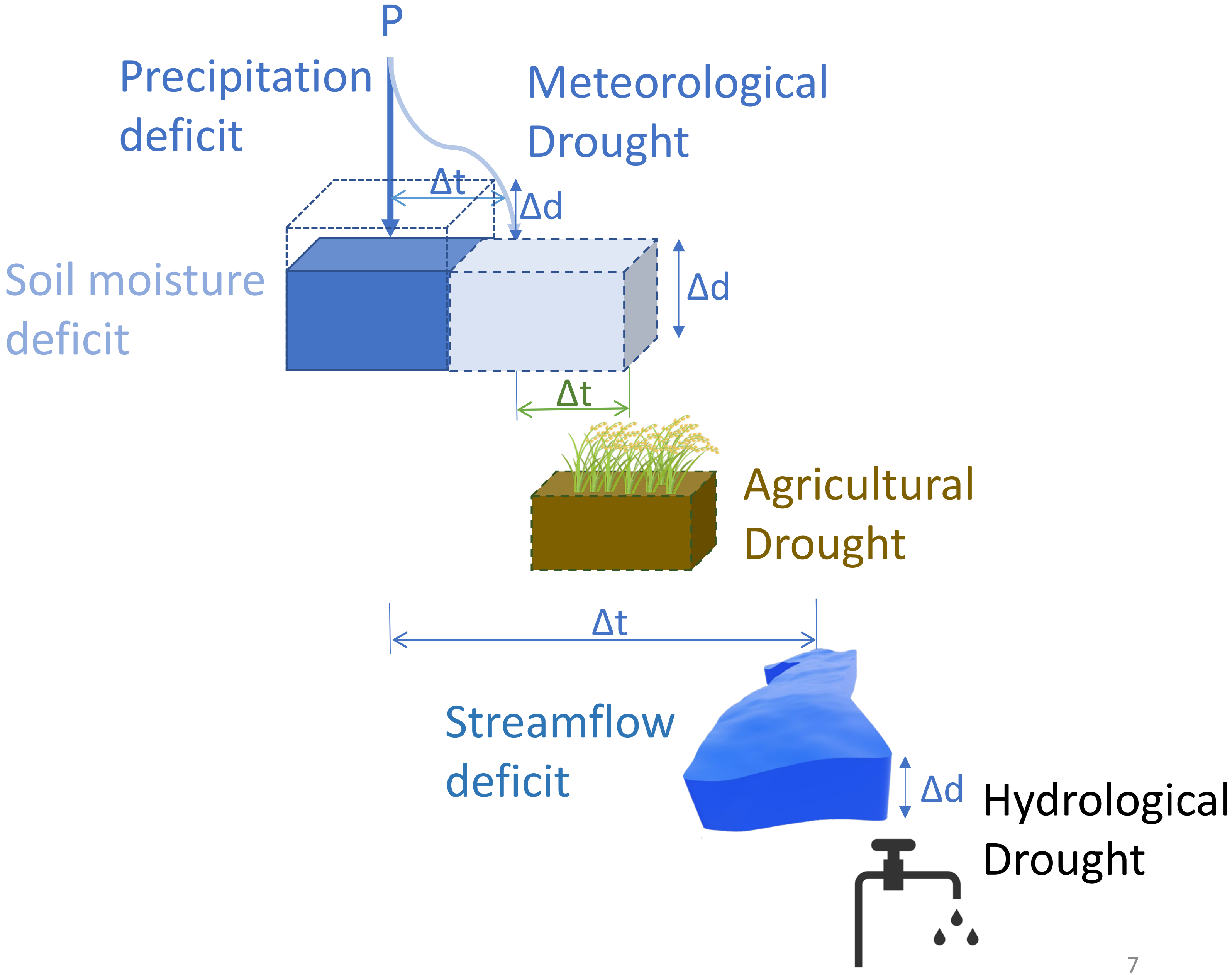
Background

- Types of drought
- Drought propagation
- Drought impacts



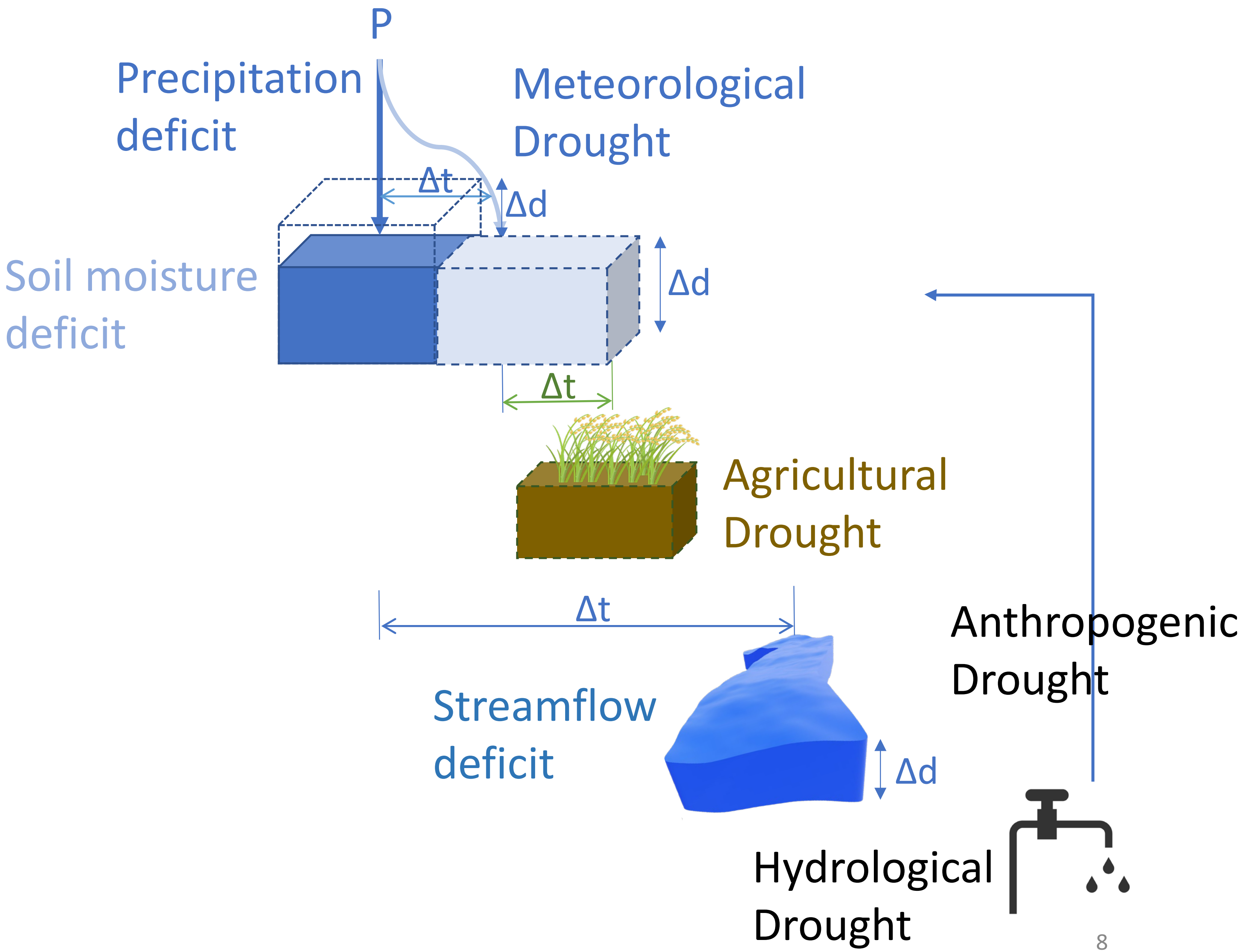
Background

- Types of drought
- Drought propagation
- Drought impacts



Background

- Types of drought
- Drought propagation
- Drought impacts



The Problem

- Drought propagation is complex and non-linear
- Place-specific processes limit predictability
- Observational gaps prevent early warning
- Critical need for mechanistic understanding

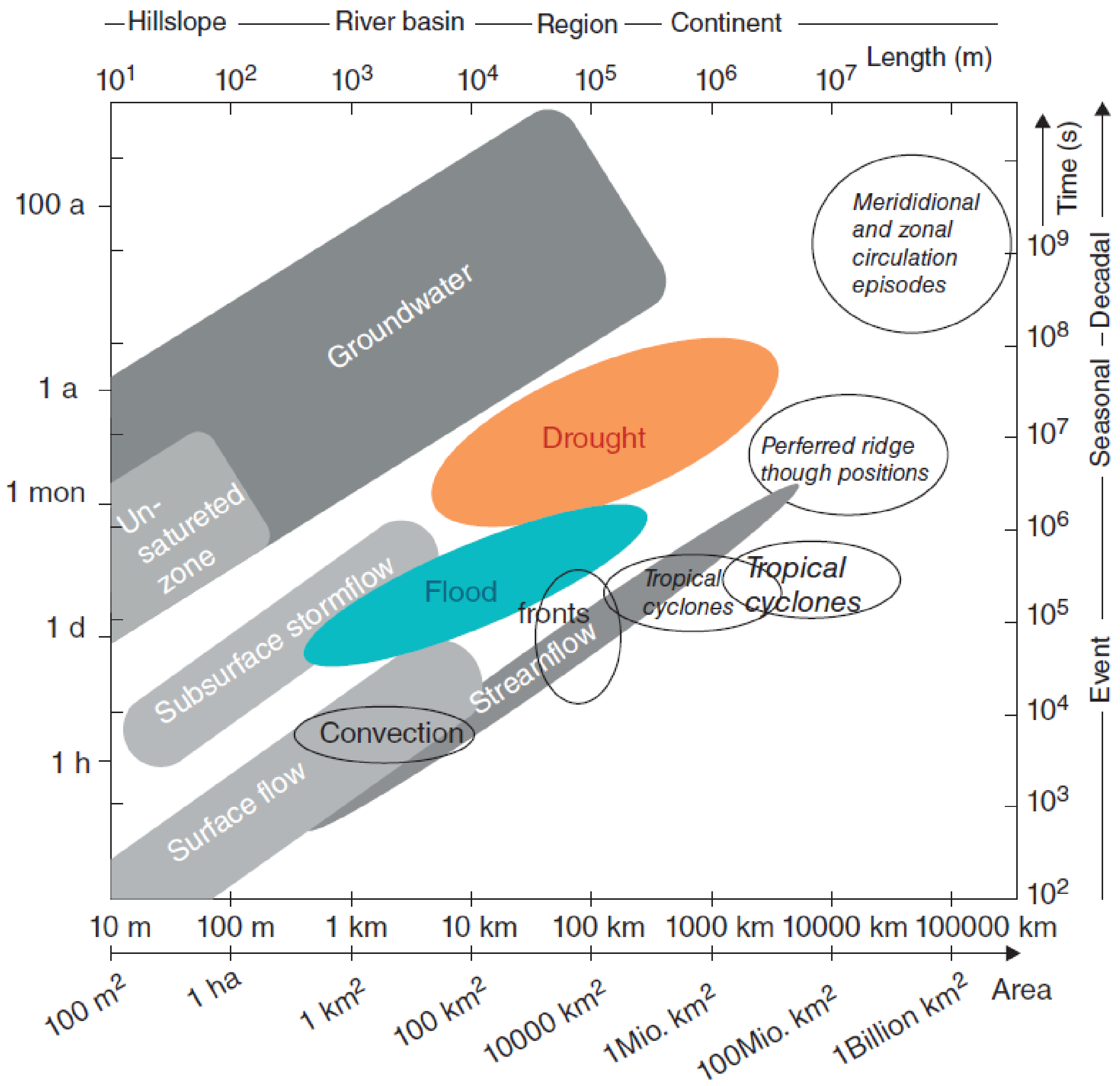
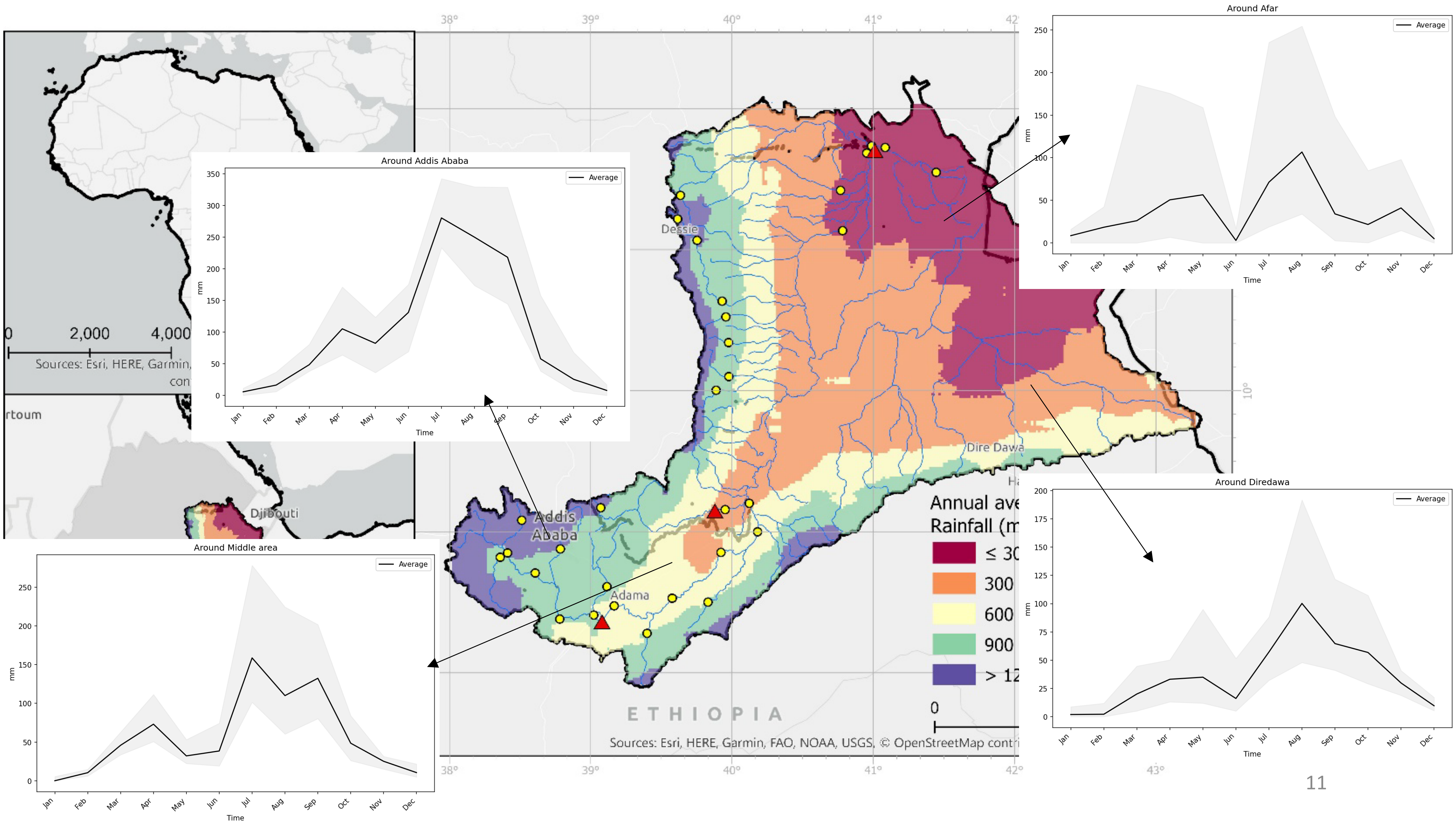


Figure: Spatial and temporal scales of hydrological processes and droughts. (Stahl and Hisdal, 2004)

The objective

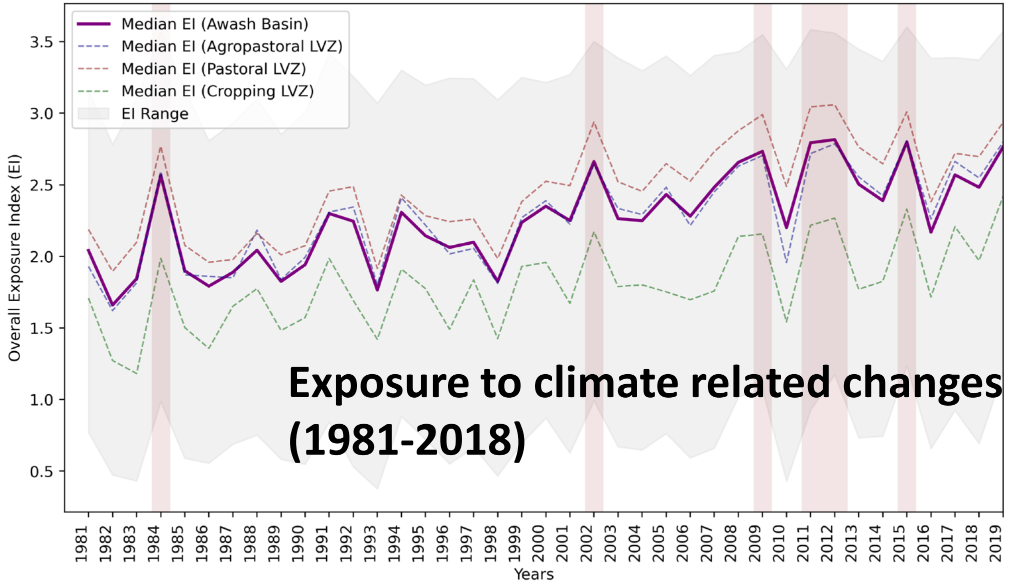
- Develop a reproducible propagation analysis tool for drought detection and pairing from modeled outputs enabling consistent cross-watershed comparisons
- Quantify propagation predictability limits – assess reliability of meteorological deficits and watershed properties in predicting propagation occurrence and characteristics

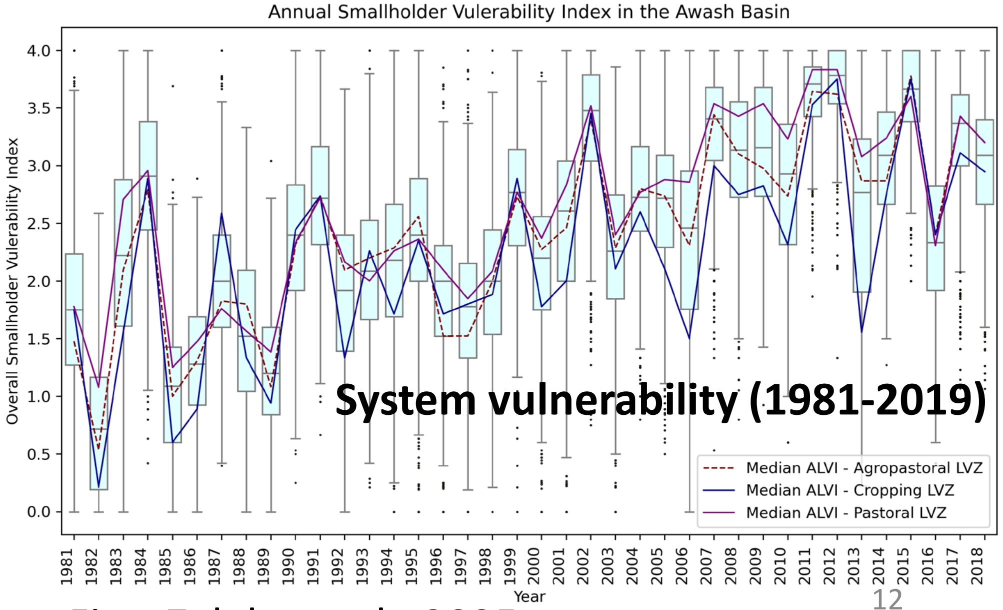
Study area – The Awash River Basin



Study area – Livelihood Vulnerability

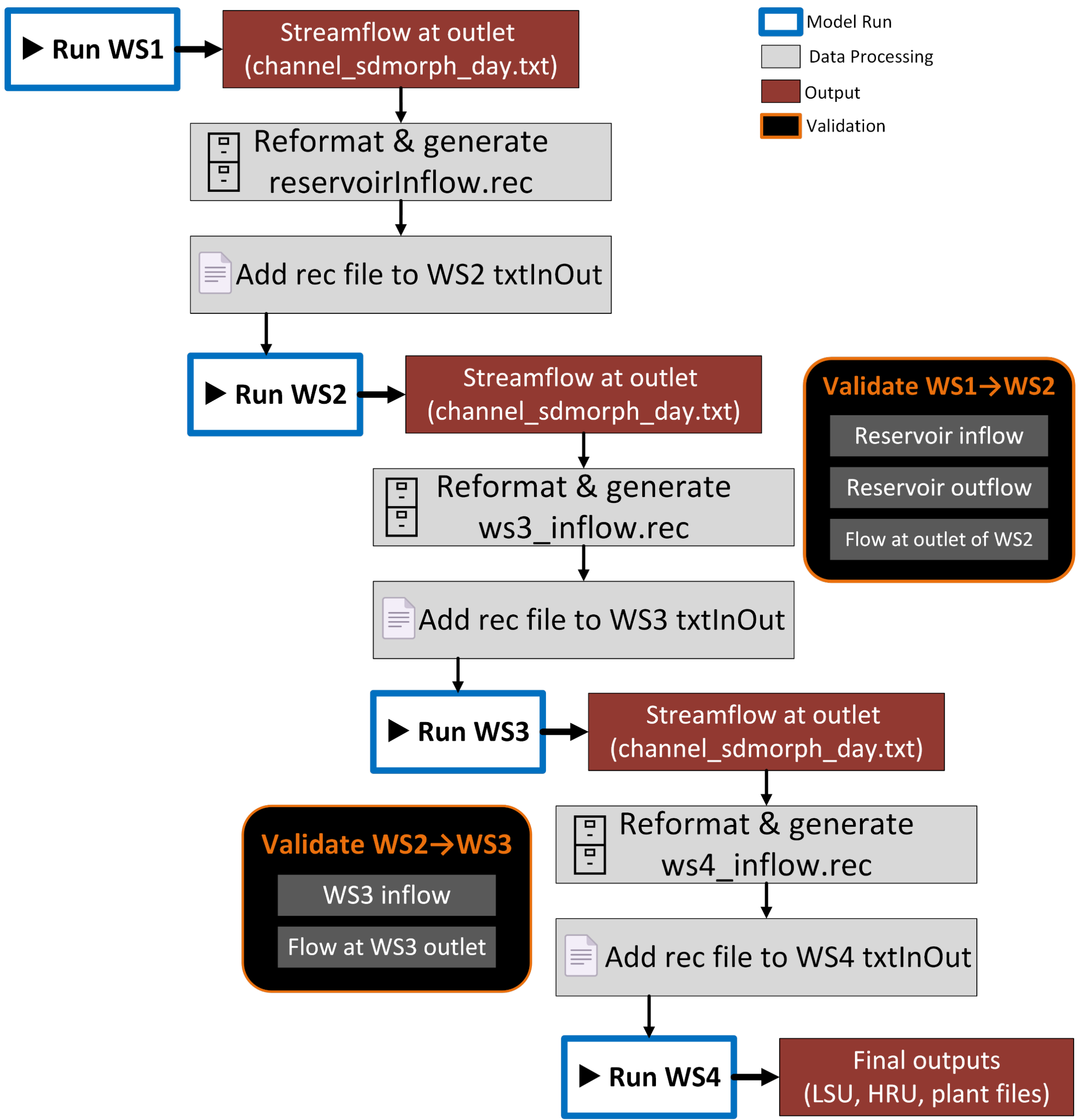
- The basin has experienced recurring drought events over the past four decades similar to other semi-arid, low-latitude regions
- Prominent drought events include: 1972-73, 1983-84, 1997, 2011-12, 2015-16, 2022-23
- High reliance on climate sensitive rainfed production system
- Low resilience of small-scale producers
- Increase in temperature and precipitation anomalies over summer months are getting severe

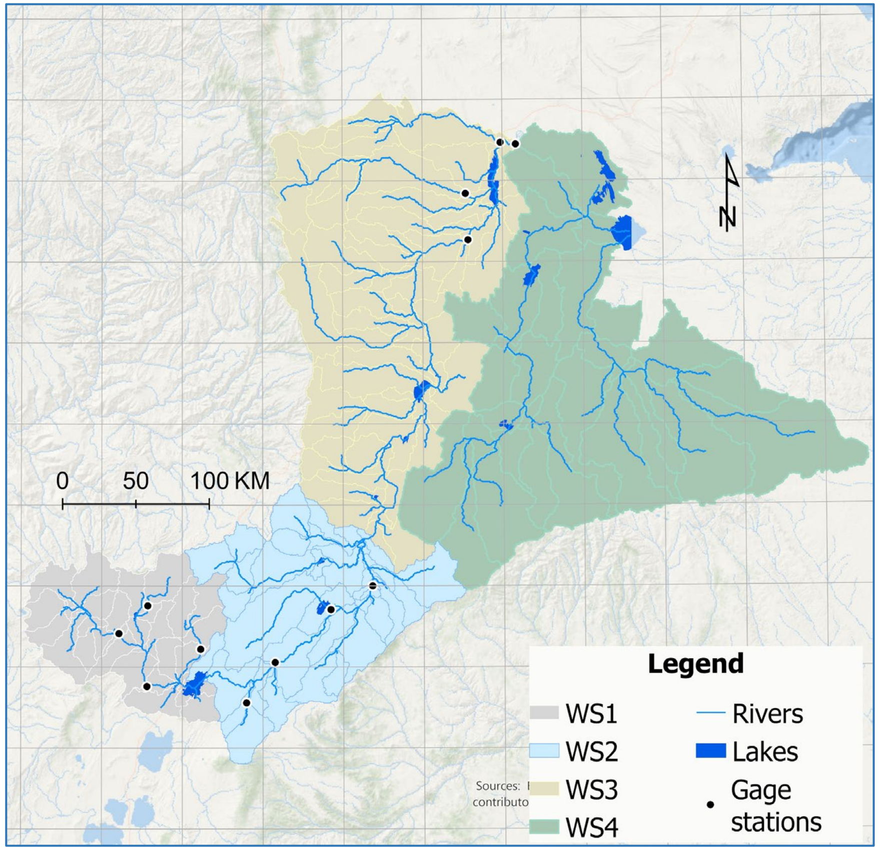




Figs: Zeleke et al., 2025

Watershed Discretization and Cascading Runs (1983-2016) in SWAT +

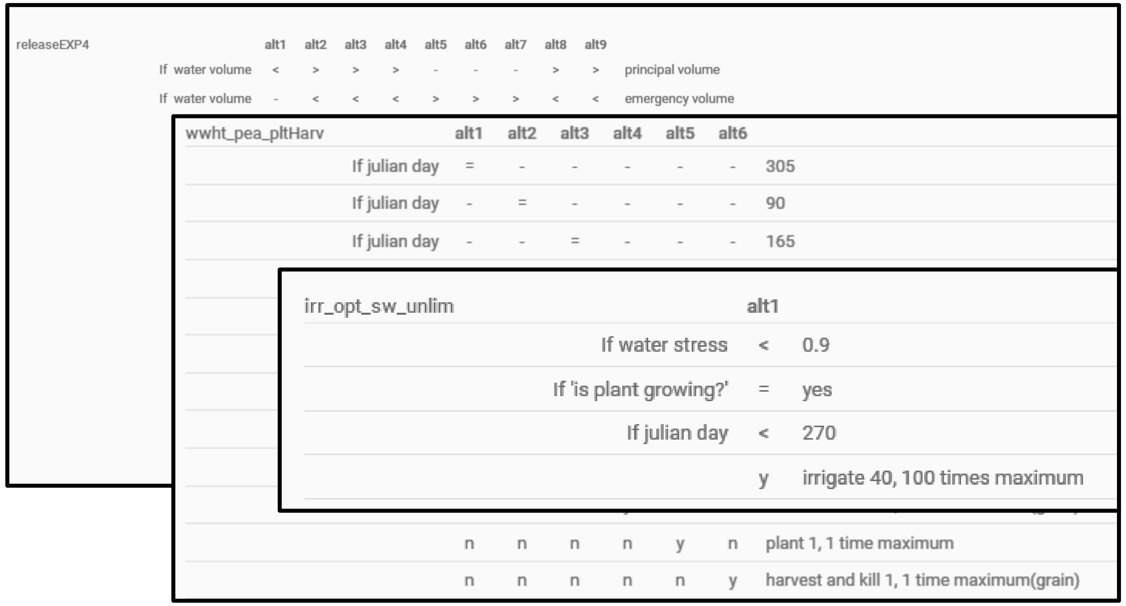




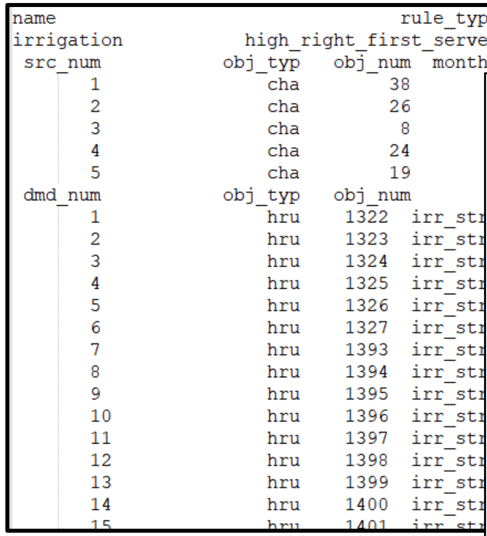
Watershed	Area (Km^2)	Altitude (m)	Extent
WS1	10,935	1590 - 3250	Upper basin to U/S of Koka Dam
WS2	17,501	750 - 3900	Koka Dam to mid-Awash
WS3	35,112	380 - 3233	Mid-Awash to Awash Dubti
WS4	42,272	240 - 2360	Eastern-catchment & Awash Terminal to Lake Abe

Implementation of Water Management Principles

- **Decision Tables**
  - Reservoir [res_rel.dtl] : Fractional inflow releases(res_inflo), constant rate releases, seasonally explicit release rules
  - Lake: volume fraction releases (dyrt) conditioned on jday, res_inflo and lake volume, lake seepage and ET
  - Plant and harvest dates [management.sch]



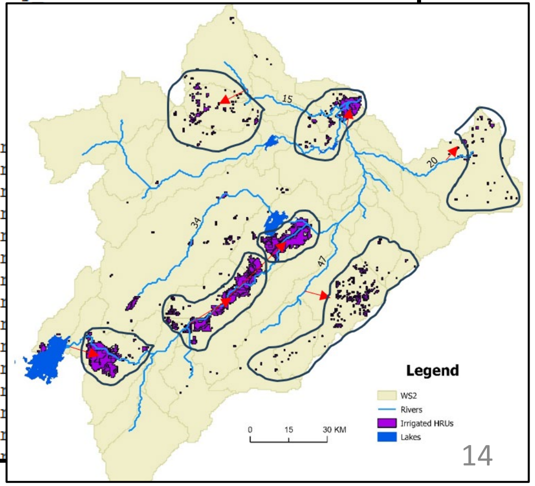
- **Water allocation**
  - Allocate water to irrigated areas (167 hrus) from adjacent rivers: triggered based on soil water stress



name	rule_typ	src_obs	dmd_obs	cha_ob
irrigation	high_right_first_serve	5	167	y

src_num	obj_typ	obj_num	monthly_limit
1	cha	38	
2	cha	26	
3	cha	8	
4	cha	24	
5	cha	19	

dmd_num	obj_typ	obj_num	
1	hru	1322	irr_str
2	hru	1323	irr_str
3	hru	1324	irr_str
4	hru	1325	irr_str
5	hru	1326	irr_str
6	hru	1327	irr_str
7	hru	1393	irr_str
8	hru	1394	irr_str
9	hru	1395	irr_str
10	hru	1396	irr_str
11	hru	1397	irr_str
12	hru	1398	irr_str
13	hru	1399	irr_str
14	hru	1400	irr_str
15	hru	1401	irr_str



Calibration of Average Evapotranspiration

- Comparison of annual average (2009-2016) SWAT+ ET with FAO WaPOR 250m ET
- Largely influenced by landcover

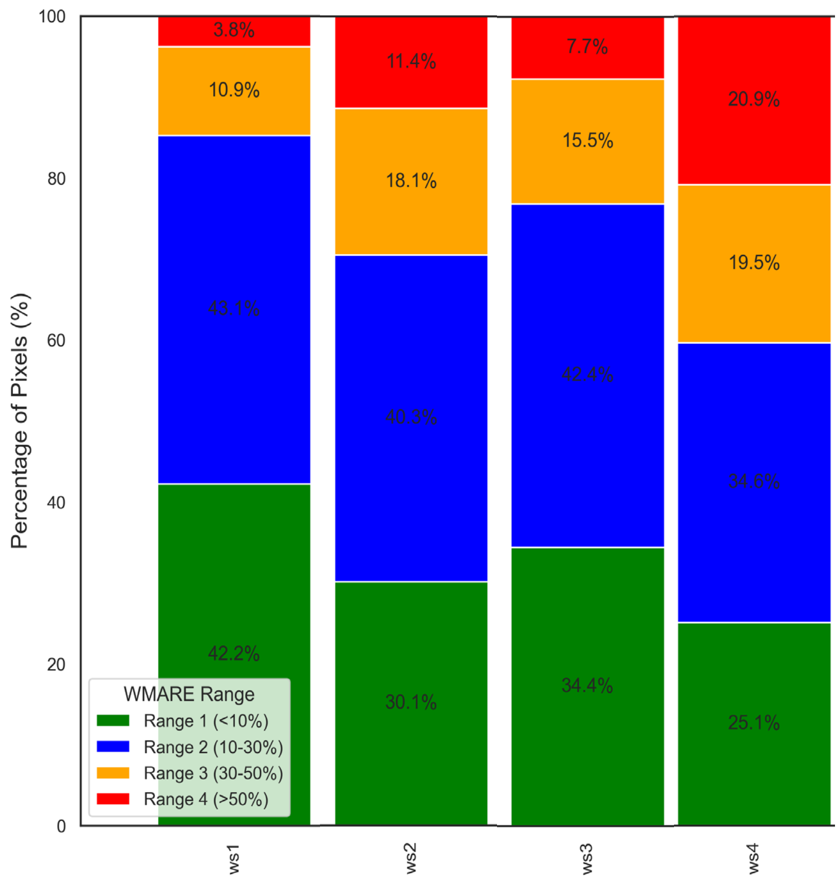
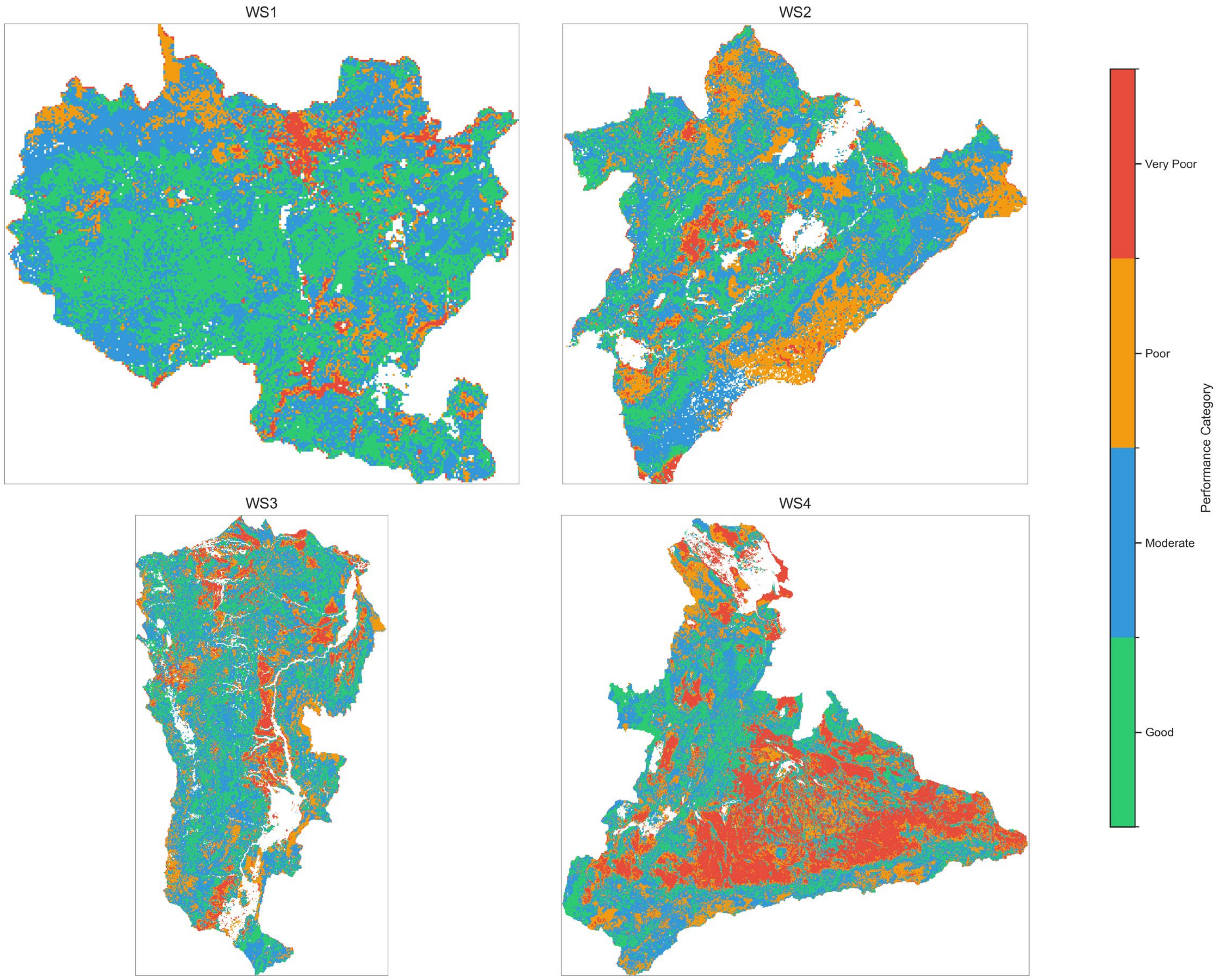


Figure: wMARE Range Distribution by Watershed



Calibration of Average Evapotranspiration

- Comparison of annual average (2009-2016) SWAT+ ET with FAO WaPOR 250m ET
- Largely i

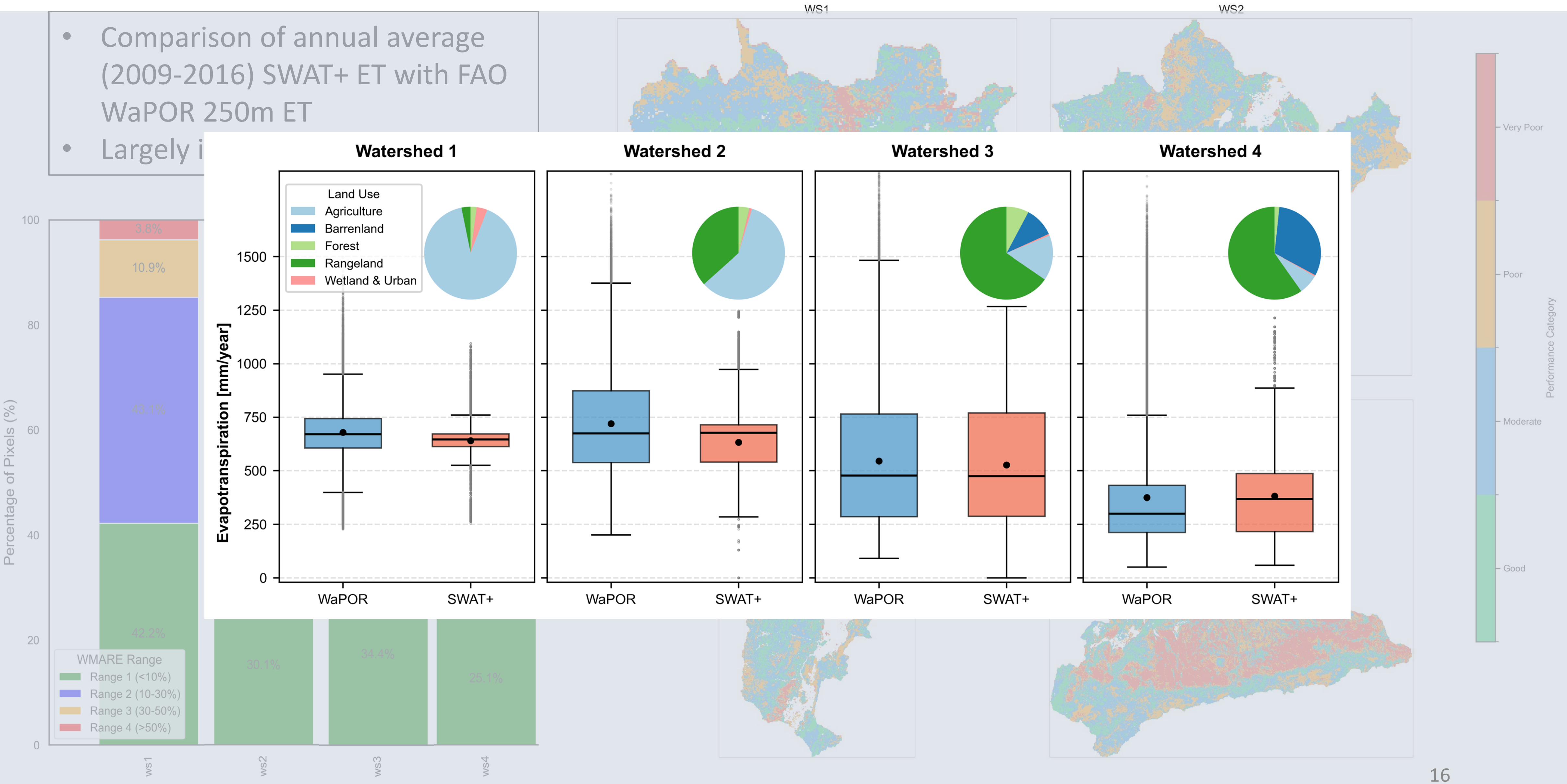
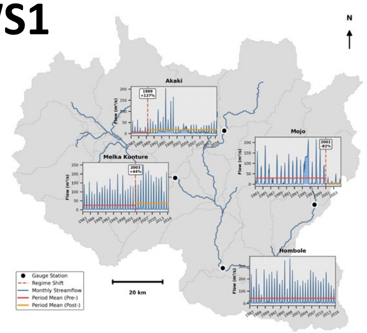
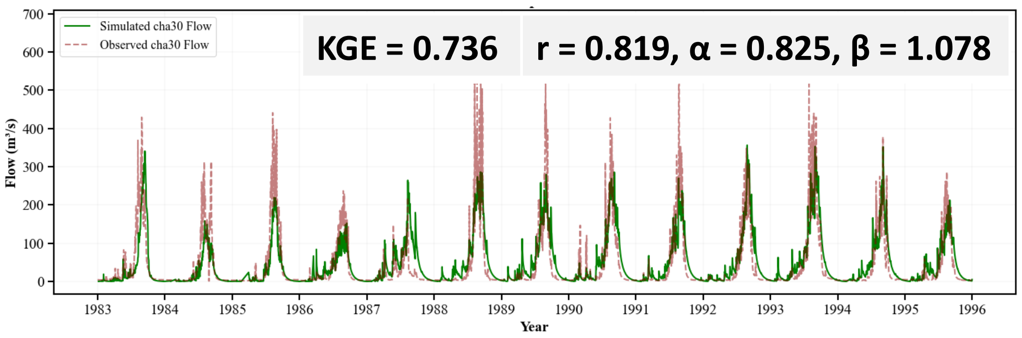


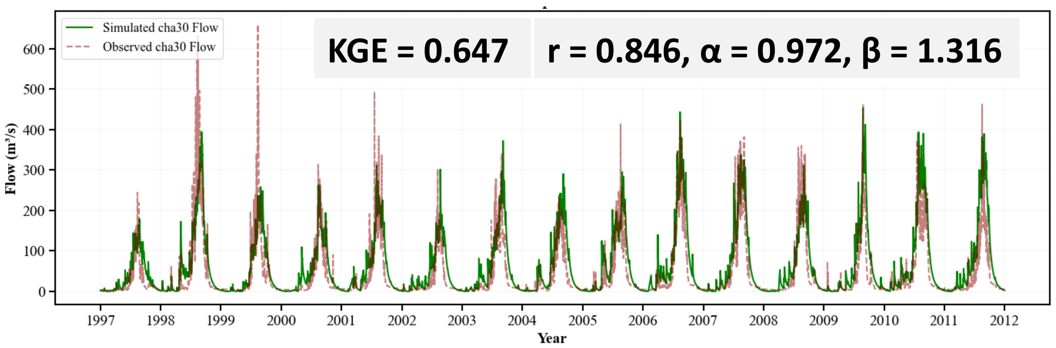
Figure: wMARE Range Distribution by Watershed

Multi-site Calibration of Daily Streamflow

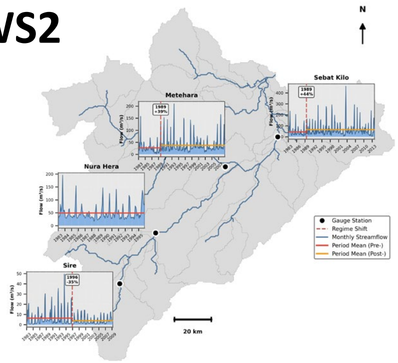
WS1

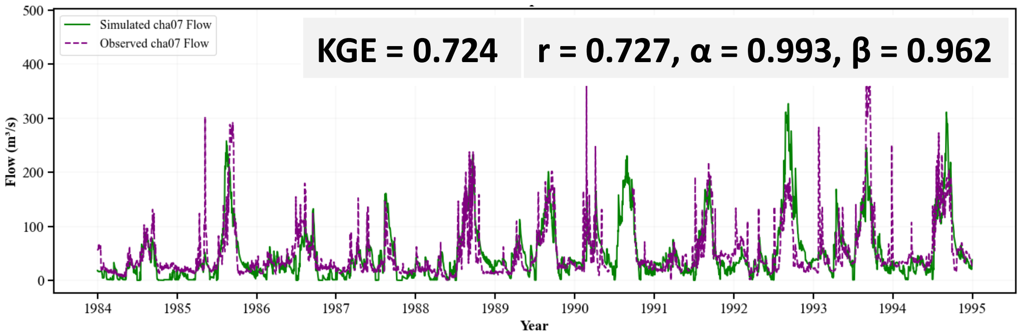


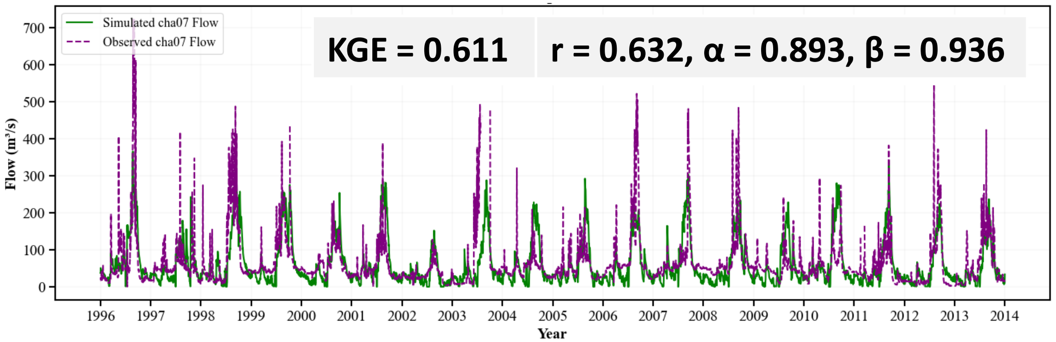




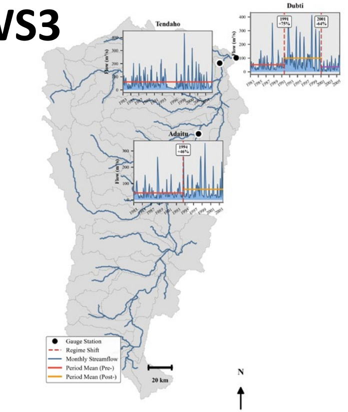
WS2

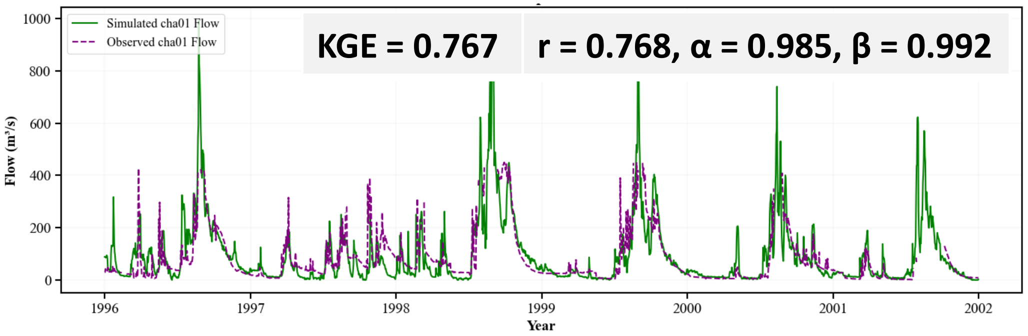


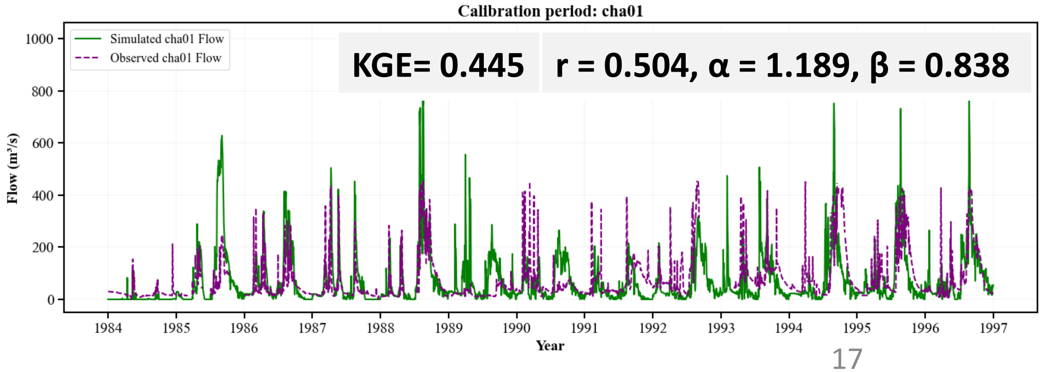




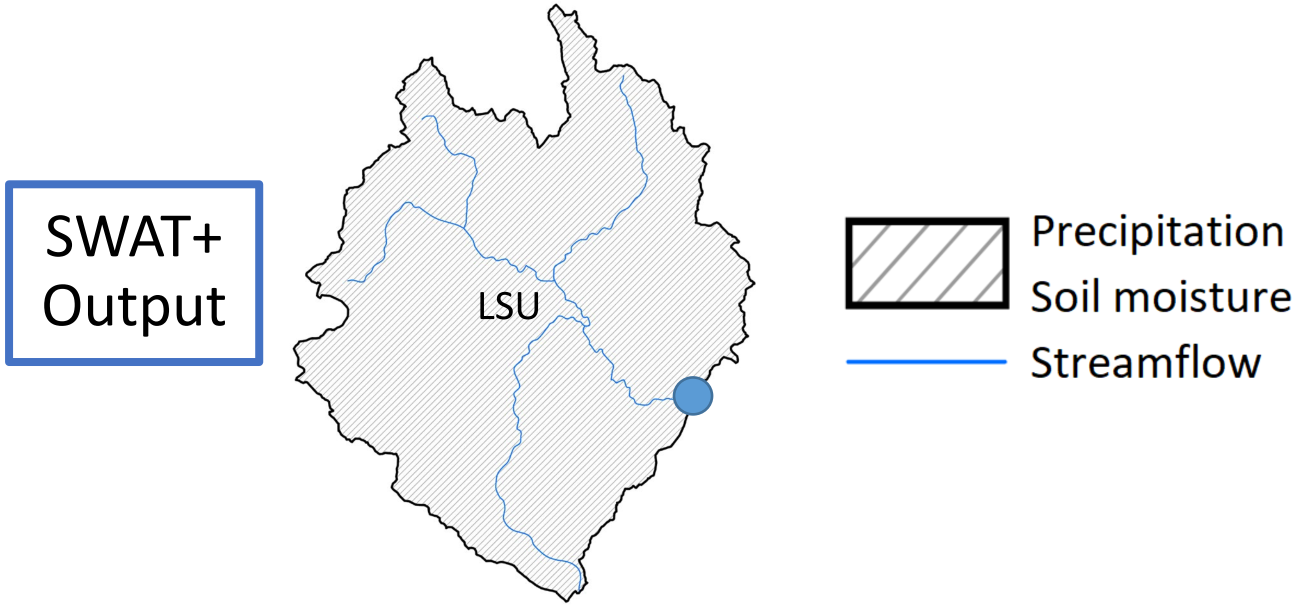
WS3



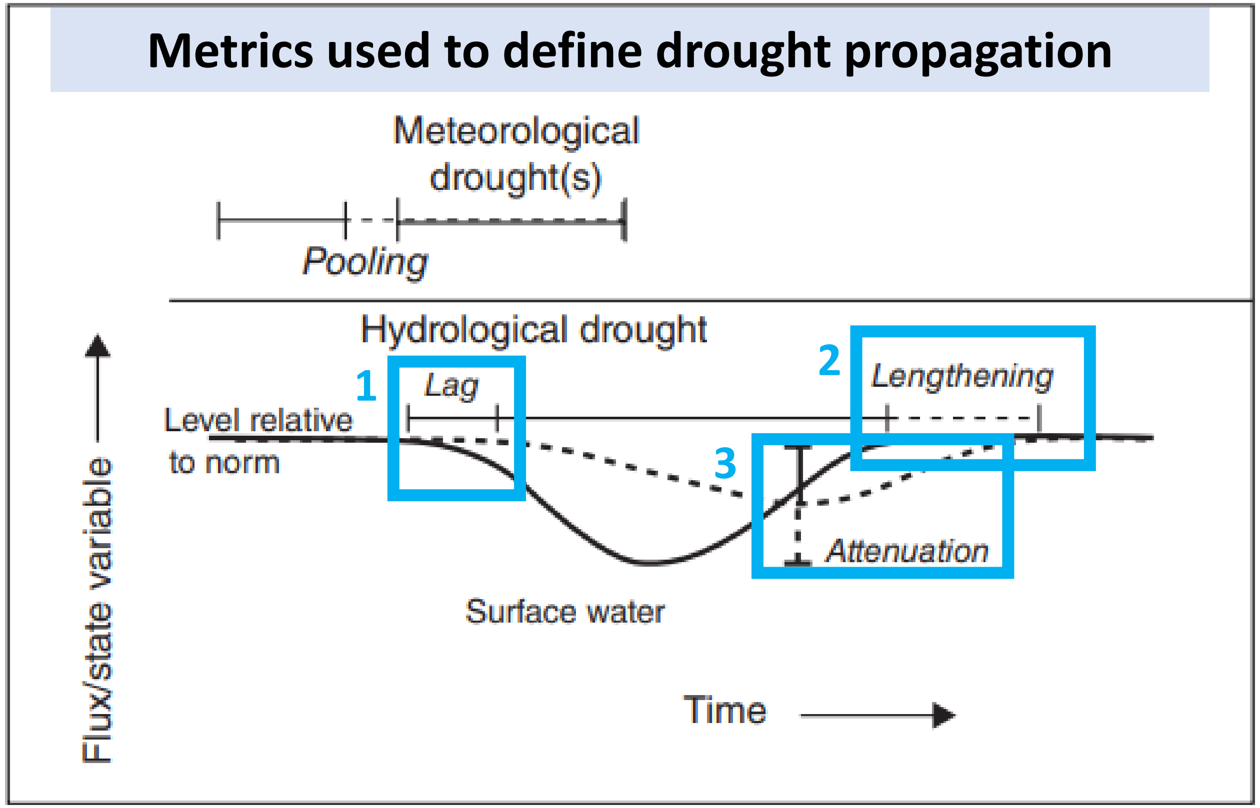


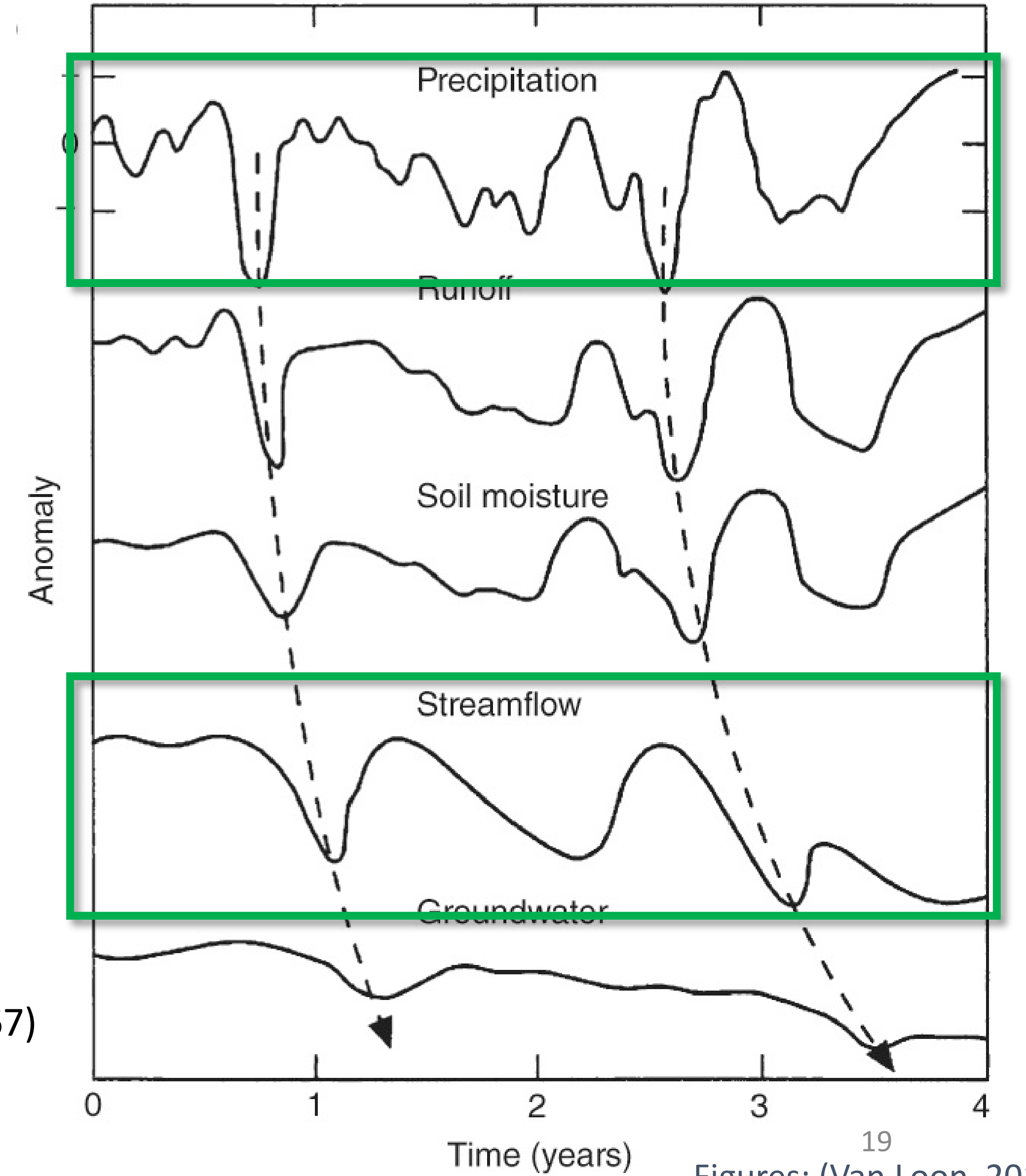


Drought Database Development and Analyses of Drought Propagation



Estimation of Drought Propagation Metrics





- SWAT+ output extraction [lslunit_wb_day.txt; channel_sdmorph_day.txt]
- Pairs a landscape to corresponding channel
- Uses a variable threshold level method (Yevjevich, 1967)
- Defines drought events and quantifies propagation metrics

Figures: (Van Loon, 2015)

Estimation of Drought Propagation Metrics

Metrics used to define drought propagation

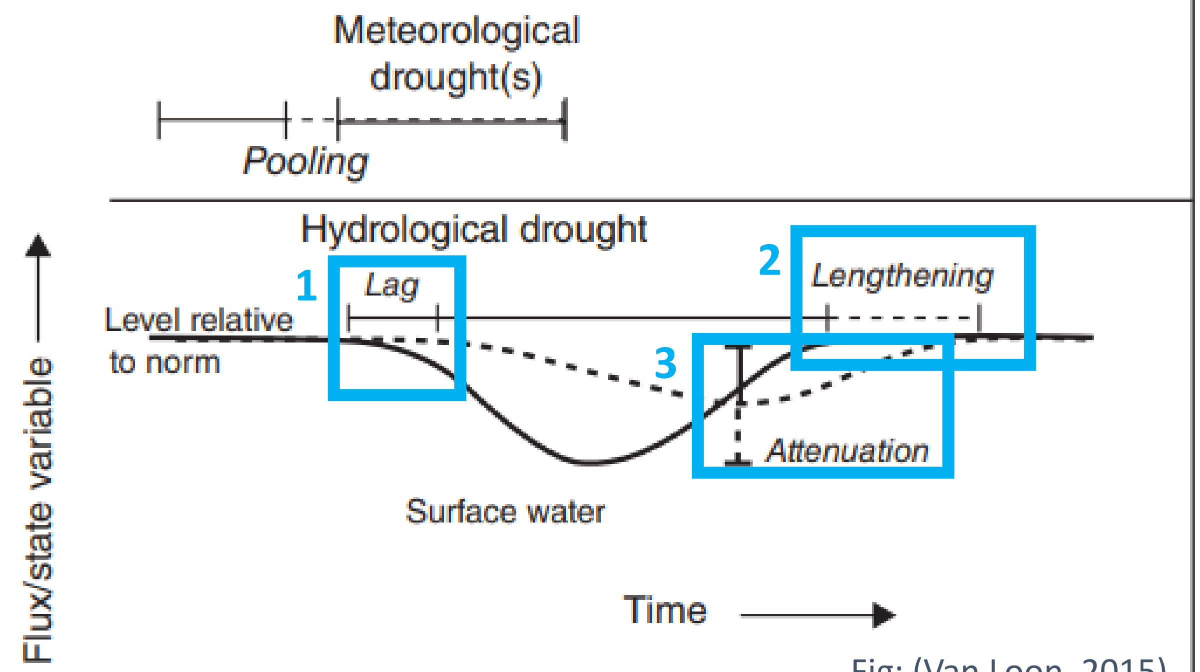


Fig: (Van Loon, 2015)

1. Lag (L): temporal delay between onsets:

$$L = t_{onset,Q} - t_{onset,P}$$

2. Lengthening (ΔD): The difference in duration between the terminations

$$\Delta D = t_{termination,Q} - t_{termination,P}$$

3. Attenuation Ratio (A): The relative change in drought severity

$$A = 1 - \frac{V_Q}{V_P}$$

- SWAT+ output extraction [lslunit_wb_day.txt; channel_sdmorph_day.txt]
- Pairs a landscape to corresponding channel
- Uses a variable threshold level method (Yevjevich, 1967)
- Defines drought events and quantifies propagation metrics

Estimation of Drought Propagation Metrics and Database Development

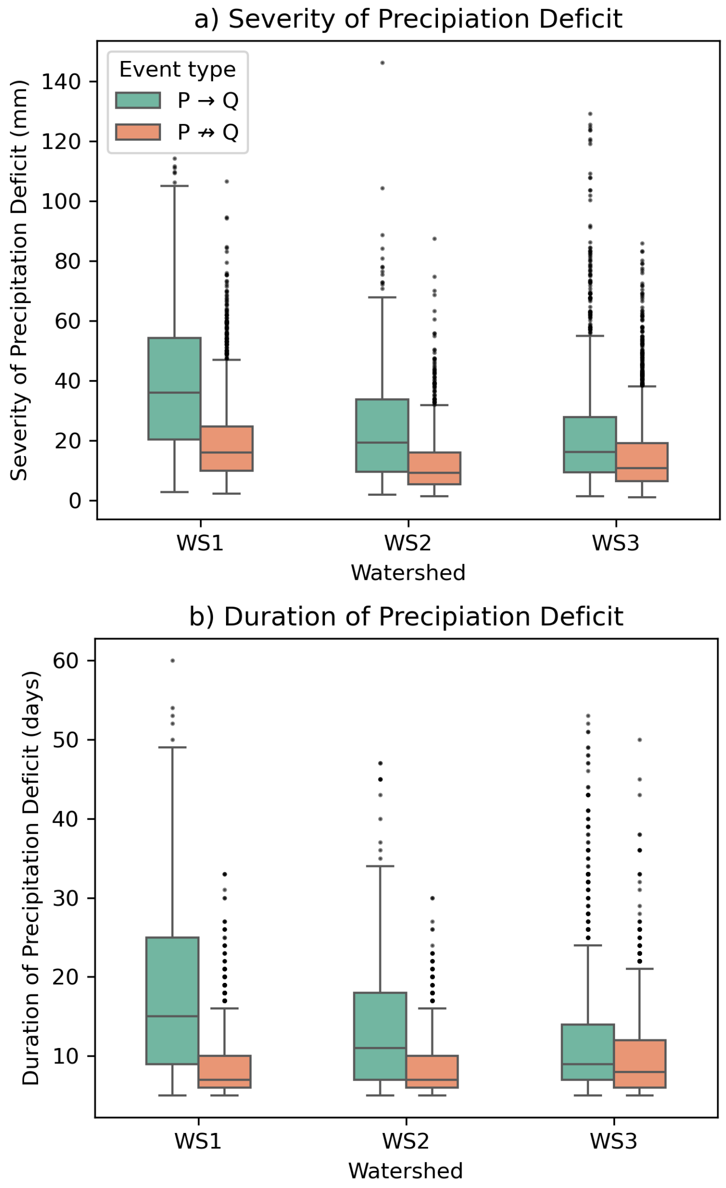
event_id	start_date_p_anomaly	end_date_p_anomaly	num_days_p_anomaly	start_date_Q_anom	end_date_Q_anom	Q_anomaly_volume (mm)	num_days_Q_anomaly	Lag	Lengthening	Attenuation	Relationship type	lsu_id	channel_id	Complex event?	Relationship count
Q19830317	06/23/1983	07/14/1983	21	03/17/1983	06/26/1983	7.4233046	96				sustaining	132	cha13	FALSE	1
Q19840901	08/24/1984	09/02/1984	7	09/01/1984	06/23/1985	75.6776746	295	8	294	0.783405778	initiating	132	cha13	TRUE	3
Q19860621	07/09/1986	07/23/1986	12	06/21/1986	08/10/1986	16.4426	50				sustaining	132	cha13	FALSE	1
Q19860814	08/13/1986	08/18/1986	5	08/14/1986	02/19/1987	74.999899	189	1	185	0.914470996	initiating	132	cha13	FALSE	1
Q19920714	07/13/1992	07/18/1992	5	07/14/1992	08/28/1992	12.04966	45	1	41	0.711626219	initiating	132	cha13	FALSE	1
Q19970831	08/31/1997	09/12/1997	12	08/31/1997	01/10/1998	16.176356	132	0	120	0.961423381	initiating	132	cha13	FALSE	1
Q20020810	08/10/2002	08/27/2002	6	08/10/2002	09/11/2002	10.102	32	0	15	0.277334249	initiating	132	cha13	TRUE	2
Q20020922	09/16/2002	09/25/2002	9	09/22/2002	01/27/2003	11.640227	127	6	124	0.896045641	initiating	132	cha13	FALSE	1
Q20140715	07/24/2014	08/06/2014	11	07/15/2014	03/02/2015	76.6708	230				sustaining	132	cha13	TRUE	2
Q20150612	06/07/2015	06/22/2015	12	06/12/2015	02/24/2016	88.2459643	257	5	247	0.279368737	initiating	132	cha13	TRUE	6
Q19830317	06/22/1983	07/13/1983	21	03/17/1983	06/26/1983	7.4233046	96				sustaining	131	cha13	FALSE	1
Q19830925	07/01/1984	07/10/1984	9	09/25/1983	08/03/1984	74.1659481	313				sustaining	131	cha13	FALSE	1
Q19840901	08/25/1984	09/02/1984	6	09/01/1984	06/23/1985	75.6776746	295	7	294	0.561729006	initiating	131	cha13	TRUE	3
Q19850707	07/07/1985	07/18/1985	11	07/07/1985	08/14/1985	18.9161	38	0	27	0.390476651	initiating	131	cha13	FALSE	1
Q19860621	06/24/1986	07/03/1986	9	06/21/1986	08/10/1986	16.4426	50	0	38	0.823518249	initiating	131	cha13	FALSE	1
Q19860814	08/12/1986	08/18/1986	6	08/14/1986	02/19/1987	74.999899	189	2	185	0.919348926	initiating	131	cha13	FALSE	1
Q19920714	08/07/1992	08/14/1992	5	07/14/1992	08/28/1992	12.04966	45				sustaining	131	cha13	FALSE	1
Q19970831	08/31/1997	09/13/1997	13	08/31/1997	01/10/1998	16.176356	132	0	119	0.952643359	initiating	131	cha13	FALSE	1
Q20020810	08/26/2002	09/10/2002	13	08/10/2002	09/11/2002	10.102	32				sustaining	131	cha13	FALSE	1
Q20120822	08/22/2012	08/29/2012	7	08/22/2012	09/13/2012	4.6584	20	0	15	0.8966558	initiating	131	cha13	FALSE	1
Q20140715	07/24/2014	08/06/2014	11	07/15/2014	03/02/2015	76.6708	230				sustaining	131	cha13	TRUE	2
Q20150612	07/02/2015	07/14/2015	10	06/12/2015	02/24/2016	88.2459643	257				sustaining	131	[illegible]	[illegible]	4
Q19830622	07/04/1983	07/15/1983	11	06/22/1983	09/06/1983	122.26259	76				sustaining	122	[illegible]	[illegible]	2
Q19870731	07/21/1987	08/07/1987	11	07/31/1987	08/10/1987	10.7266	10	10	3	0.461935939	initiating	122	[illegible]	[illegible]	1
Q19870827	08/22/1987	09/09/1987	15	08/27/1987	09/23/1987	37.404	27	5	14	0.561162882	initiating	122	[illegible]	[illegible]	2

1. Form
2. Antecedent
3. Event

Additional LSU/CHA pairs and event (3000 rows)

Additional descriptors (150 columns)

Evaluate Simulated System Responses (P vs NP)



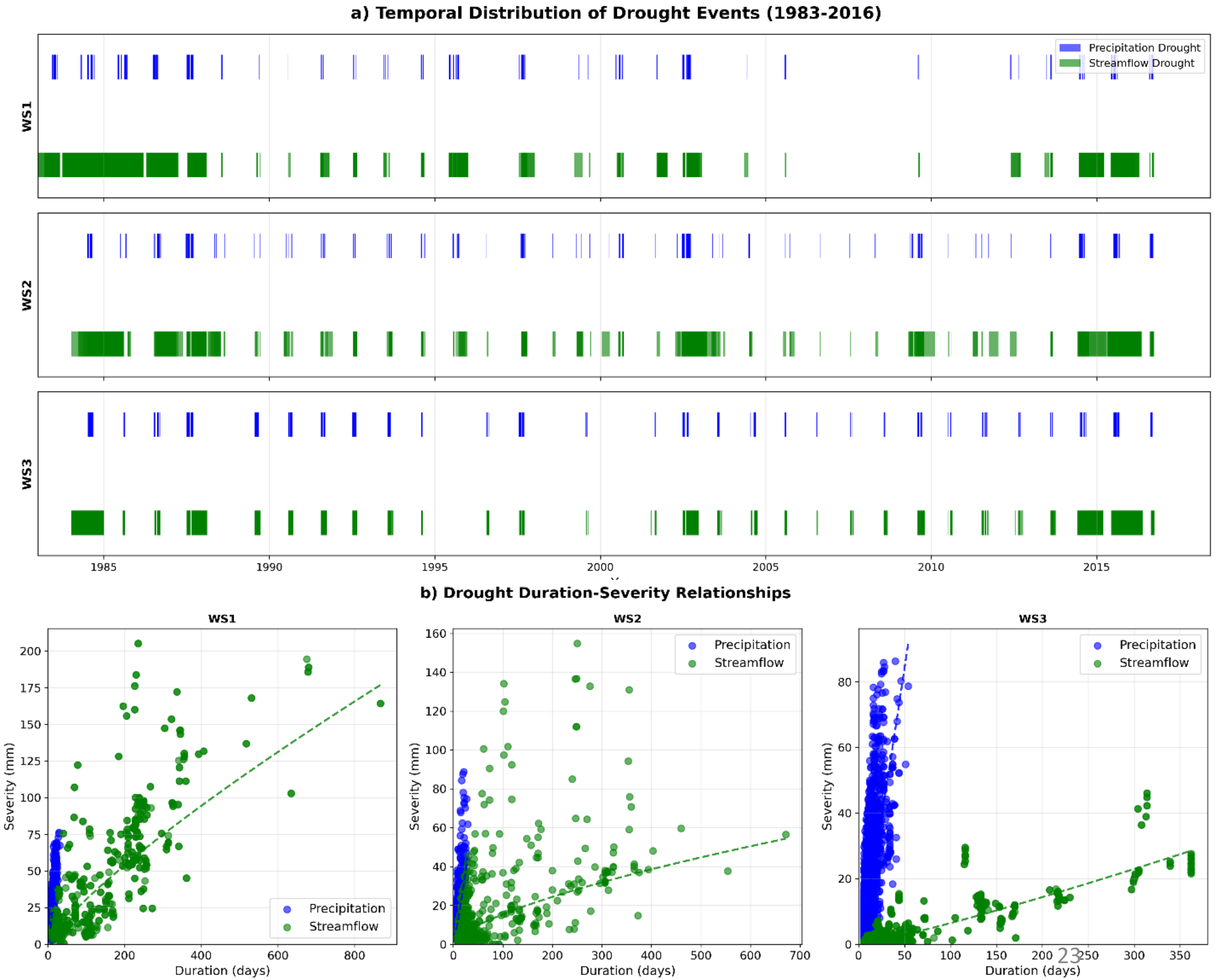
Q. Are precipitation anomalies sufficient to forecast ***which*** droughts will propagate?

- The proportion of propagation events were much lower than non-propagating events
- The percentage of droughts that propagated were
  - 22.4% in WS1,
  - 29.23 % in WS2 and
  - 54.4% in WS3
- WS1 showed the strongest discrimination between event types with progressive reduction to WS2 and 3.
- The variance explained by combined severity and duration of precipitation anomalies decreased from 14.4% in WS1 to 8.4% in WS2 and 2.5% in WS3.

A. Precipitation deficit characteristics provide statistically significant but operationally insufficient discrimination between propagating and non-propagating events

Propagation Characteristics

- Watershed-specific propagation behavior
- Synchronous occurrence with variable transformation
- Progressive change in duration-severity scaling



Temporal Evaluation of Propagation Metrics using Mutual Information

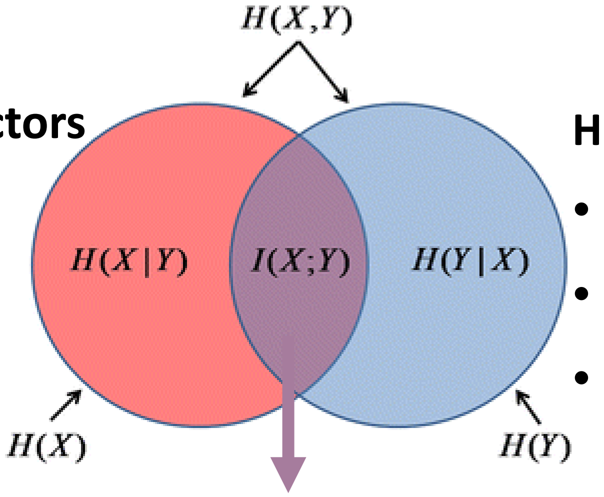
Factors
- Form (physical catchment attributes)
- Antecedent (pre-drought)
- Event (during-drought)

Propagation Metrics
- Lag
- Lengthening
- Attenuation

Temporal Variability

H(X): Driving Factors

- Form
- Antecedent
- Event



H(Y): Propagation Metrics

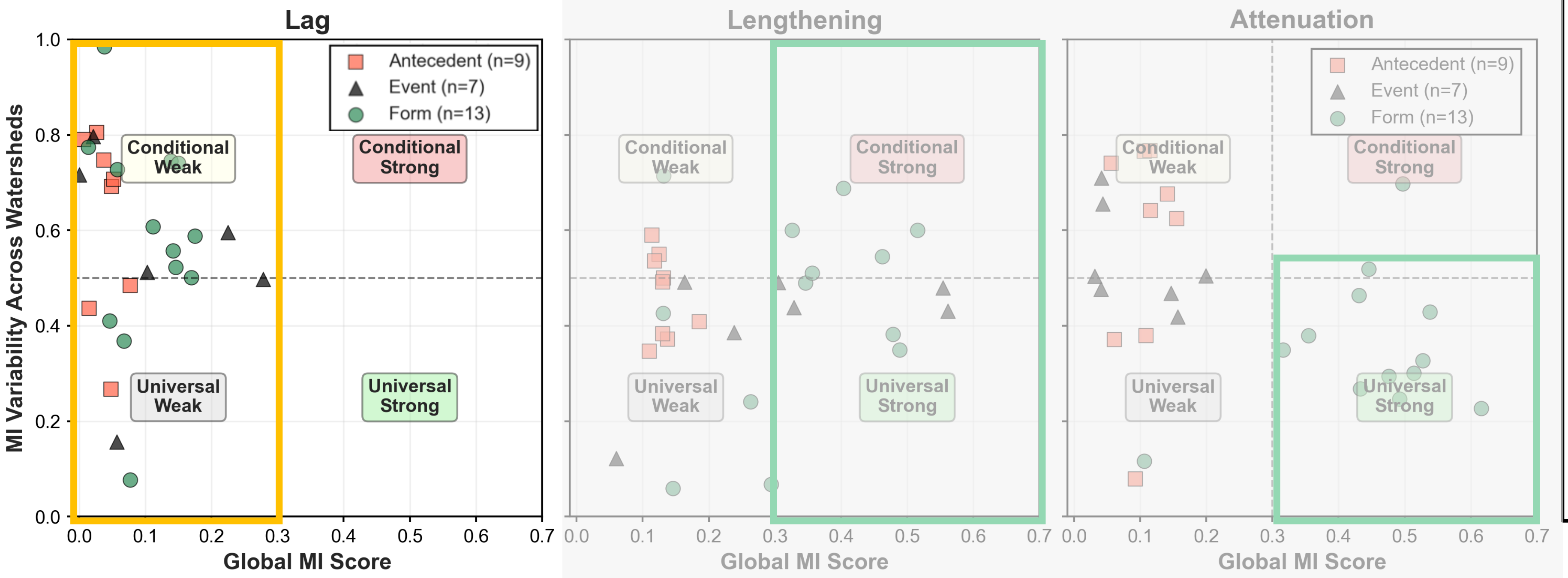
- **Lag**
- Lengthening
- Attenuation

Lag controls

- Lowest MI between all factors and Lag (weak)

Event

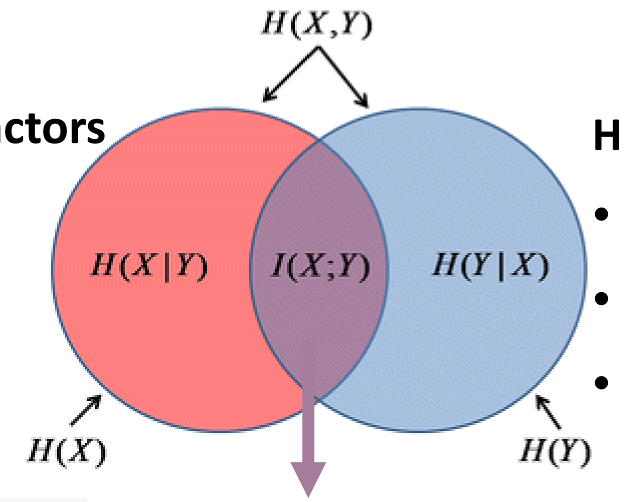
- Duration between rainfall deficits



Temporal Variability

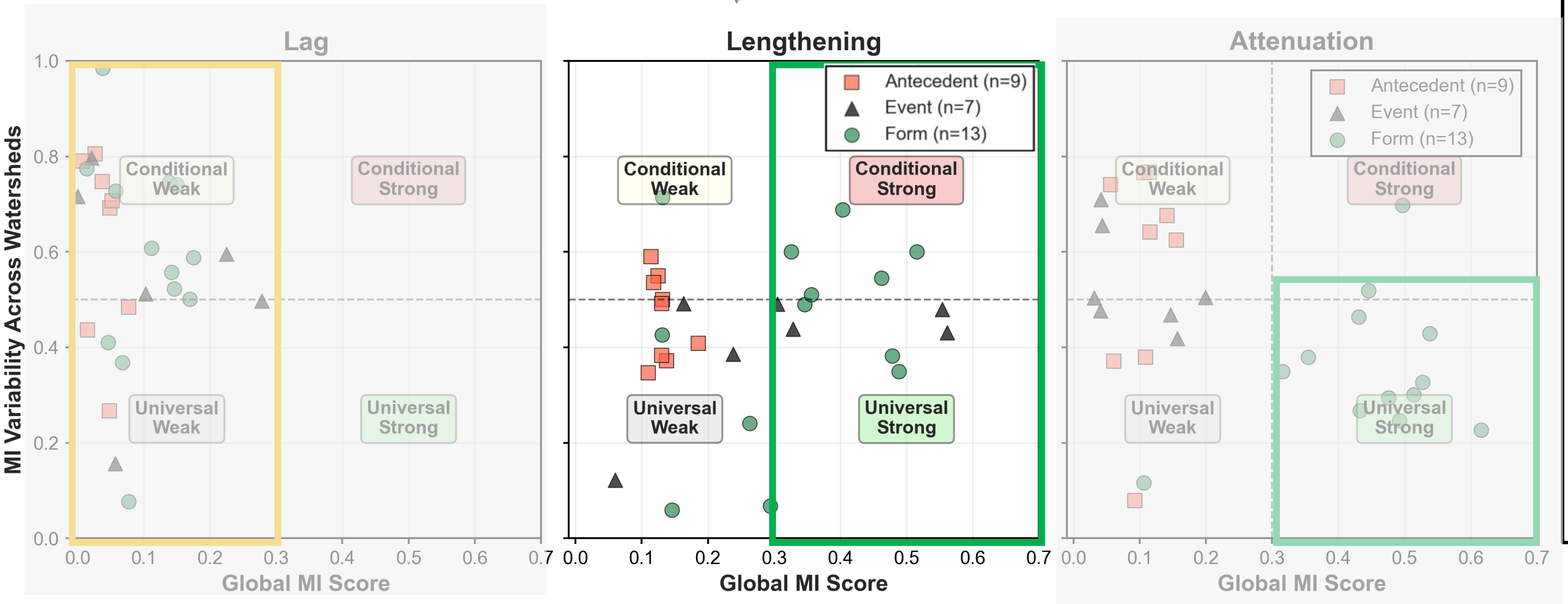
H(X): Driving Factors

- Form
- Antecedent
- Event



H(Y): Propagation Metrics

- Lag
- **Lengthening**
- Attenuation



Lengthening controls

High MI between **Form**; **Event** and Lengthening (strong)

Event

- Timing and duration of initiating deficit
- Sustaining deficits

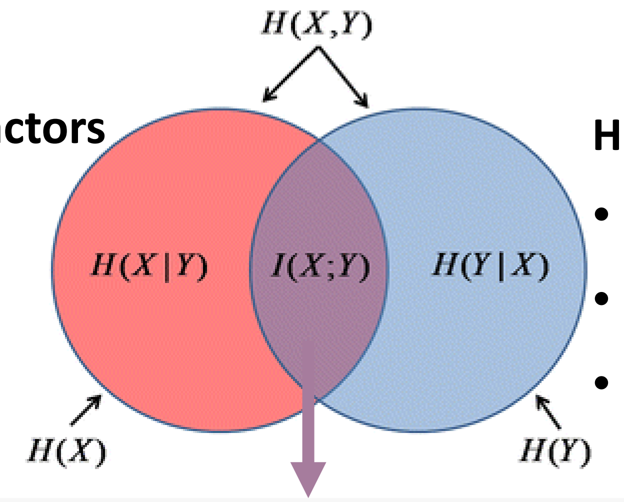
Form

- Stream depth, width, length

Temporal Variability

H(X): Driving Factors

- Form
- Antecedent
- Event



H(Y): Propagation Metrics

- Lag
- Lengthening
- **Attenuation**

Attenuation controls

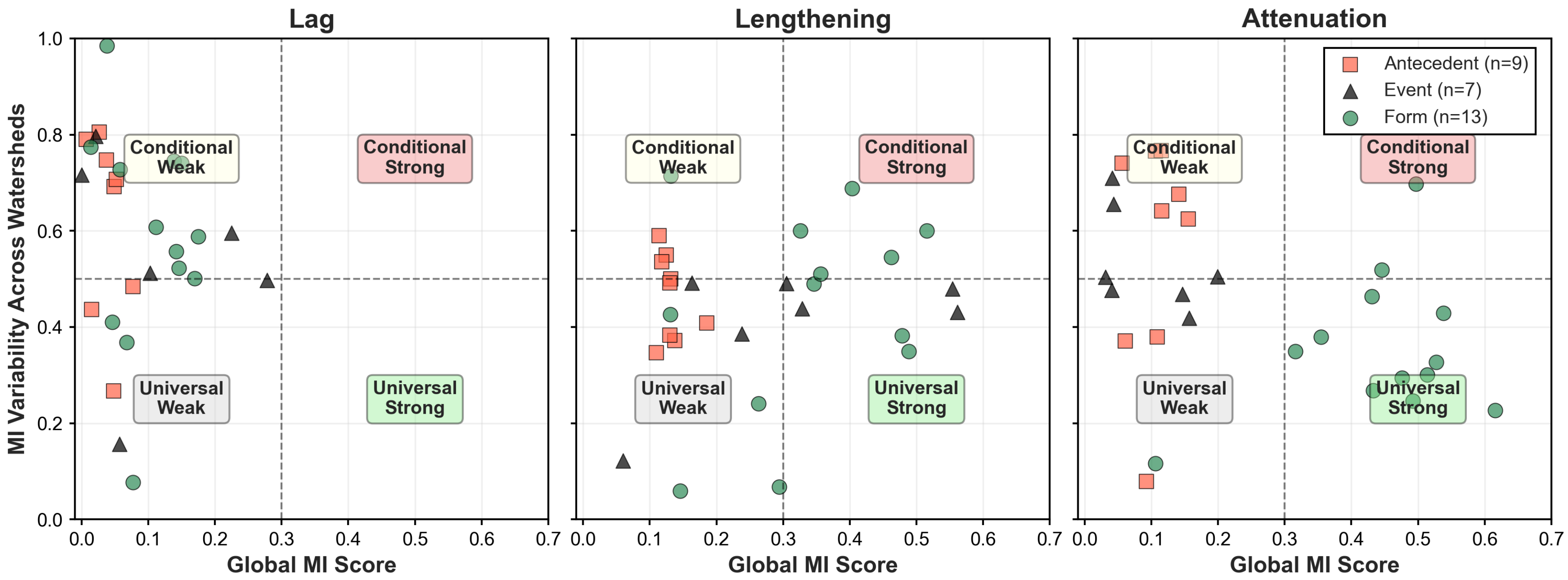
Higher MI between **Form** and Attenuation (universal strong)

Form

- Elevation, location
- Stream length, depth, width
- Time of concentration

Temporal Variability

Q: Which propagation characteristics can be reliably forecast from watershed properties?



A: Attenuation shows deterministic predictability from landscape descriptors, while lag and lengthening exhibit high event-dependency, requiring probabilistic approaches that account for evolving climate conditions rather than fixed watershed-based predictions

Summary

- **Open-source analytical tool** –Python-based tool uses the Threshold Level Method for automated drought detection and pairing from SWAT+ outputs, enabling analysis of propagation across spatiotemporal scales
- **Hierarchical predictability framework** – drought propagation metrics have differing forecast potential: attenuation is reliably predictable from time-invariant landscape properties, while lag and lengthening depend on event-specific conditions and future climate sequences
- **Operational forecast limitations and opportunities** – attenuation may be predictable from catchment properties; lengthening requires conditional assessment; lag is inherently uncertain

Acknowledgements

- The authors acknowledge Florida International University Graduate School, Presidential Fellowship and Dissertation Evidence Acquisition Fellowship for funding to support this research.
- The authors also thank the technical support, guidance and assistance from Texas A&M AgriLife Research Center.

Contact

Ethiopia B Zeleke

ebisratz@fiu.edu

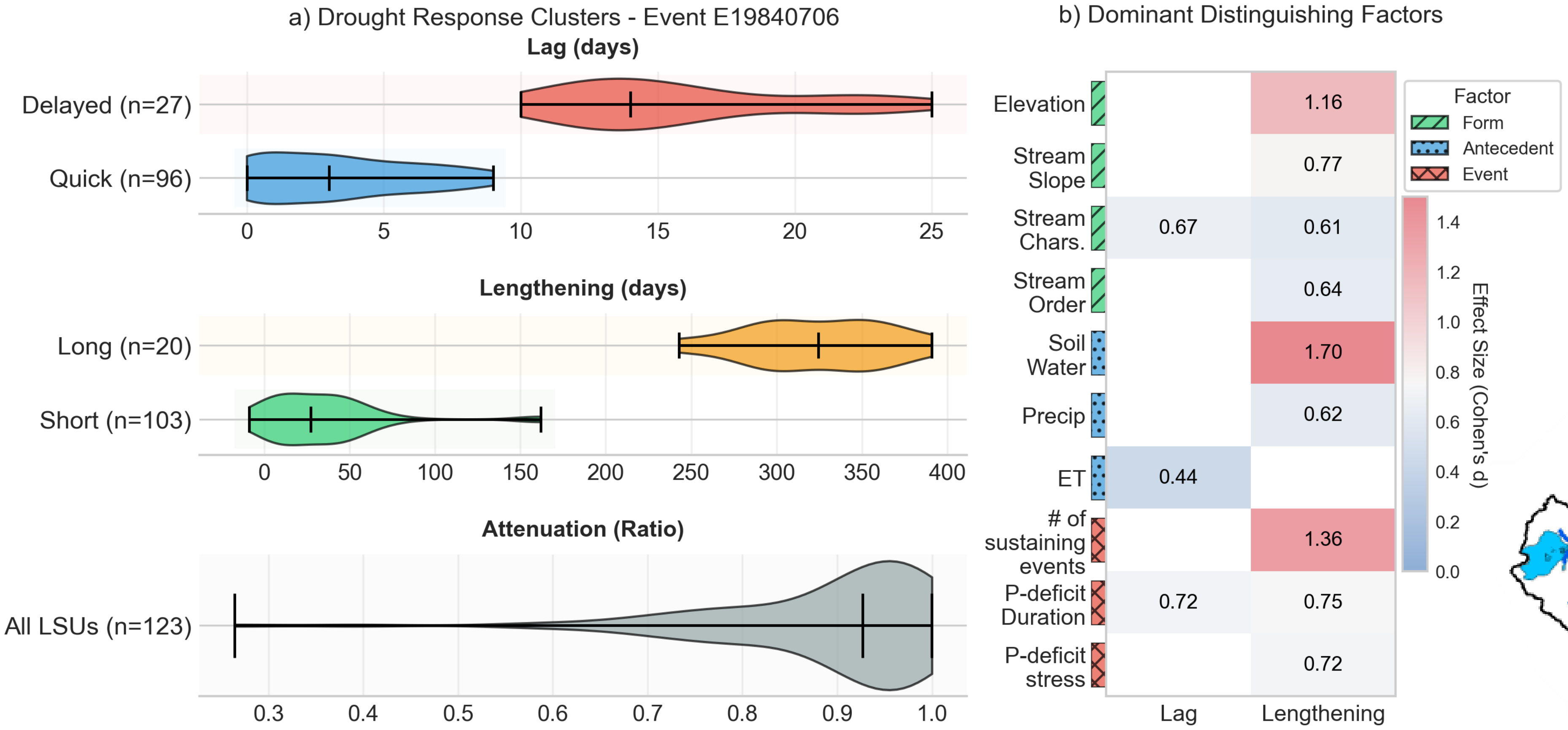
Access the full paper:

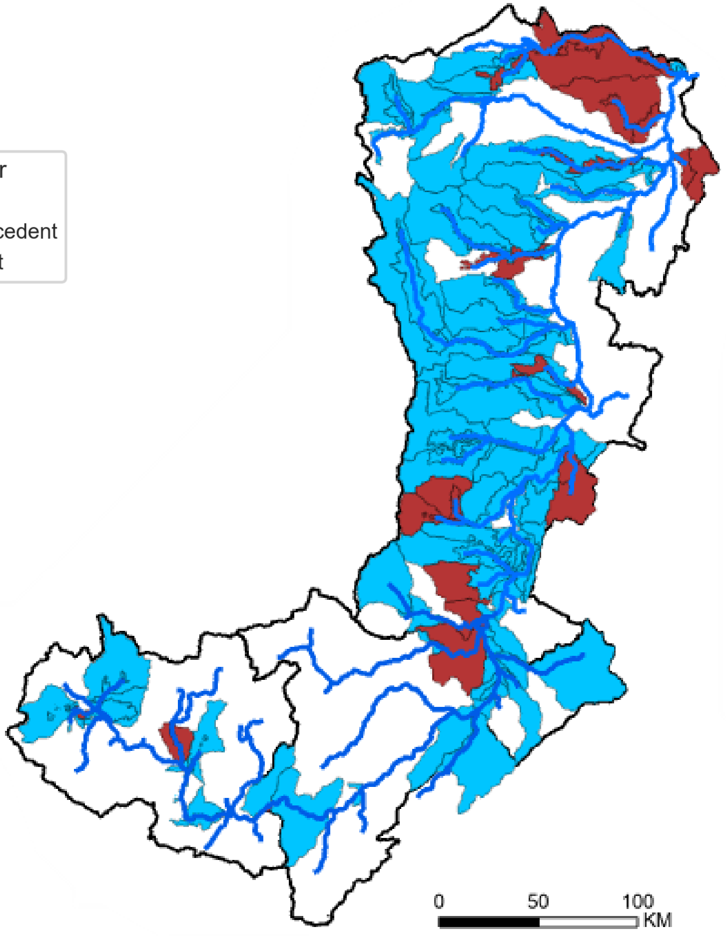
Thank you! Questions?

Spatial Variability

Lag

- Duration of precipitation deficit
- Stream width and depth
- 10-day average pre-drought ET

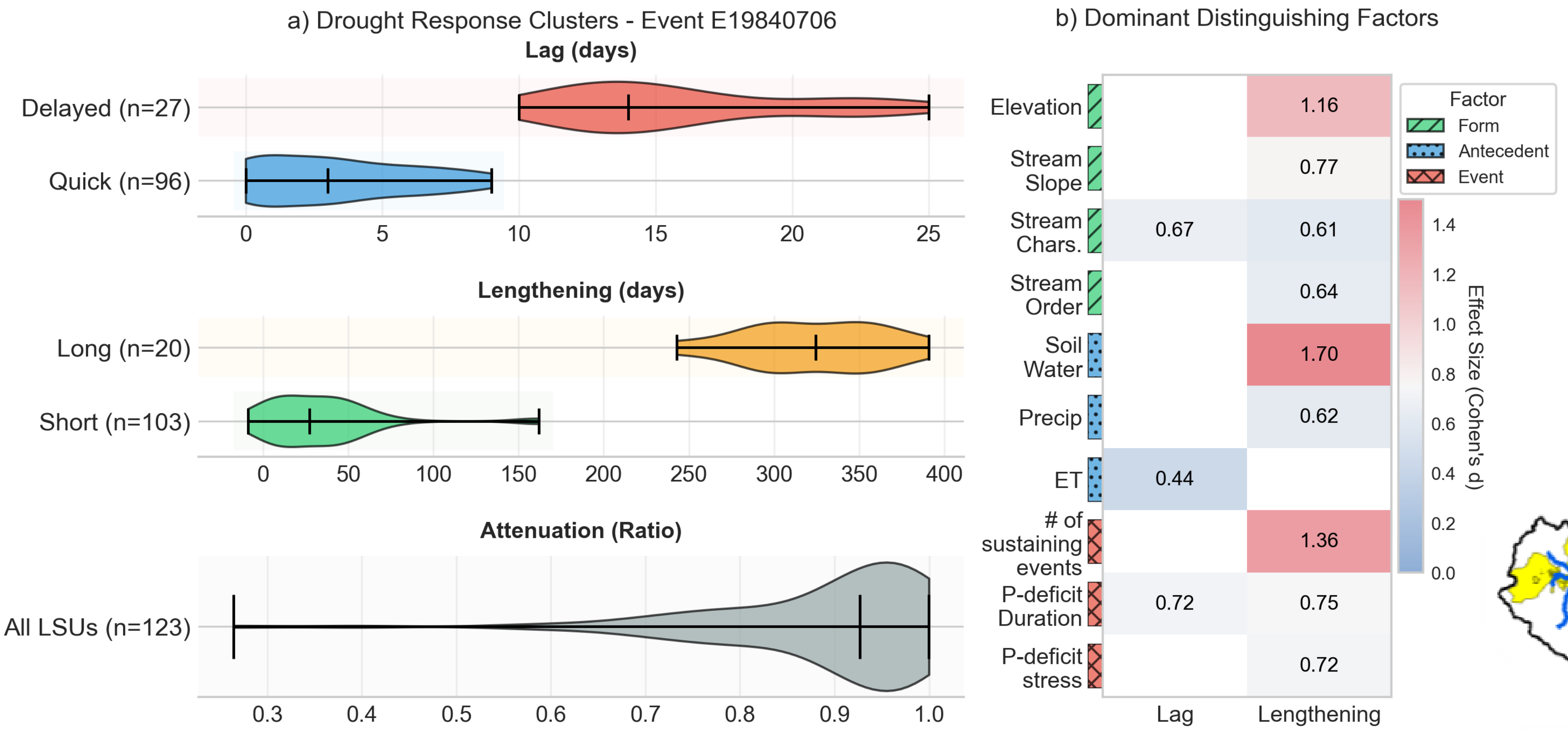


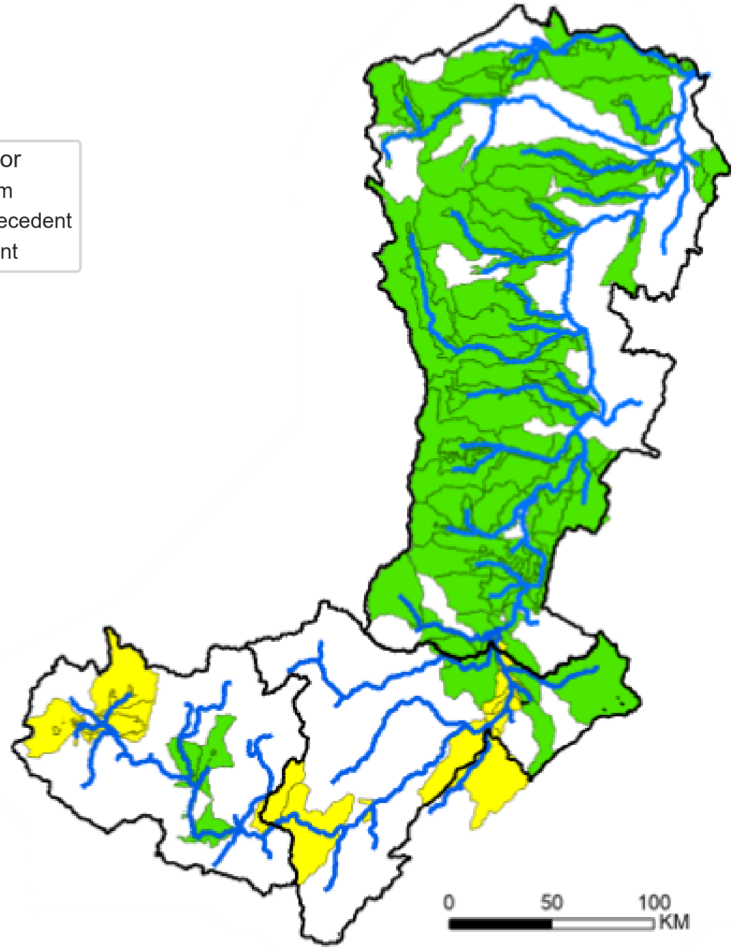


Spatial Variability

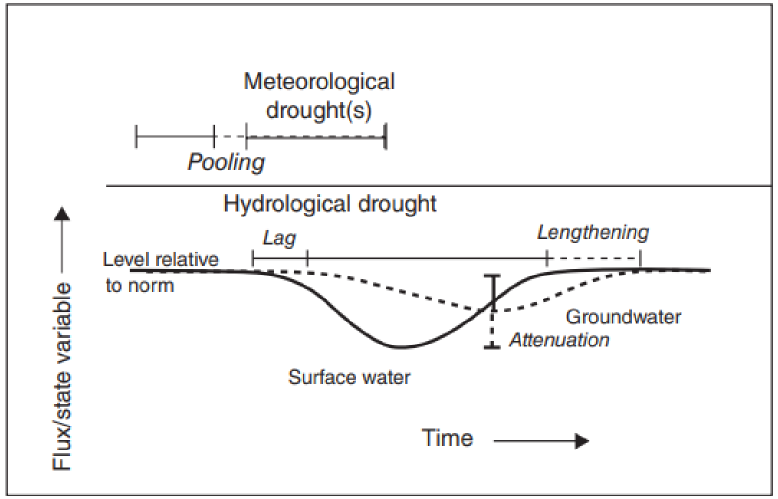
Lengthening

- Average pre-drought near surface soil moisture
- Number of sustaining precipitation deficits
- Catchment and stream elevation

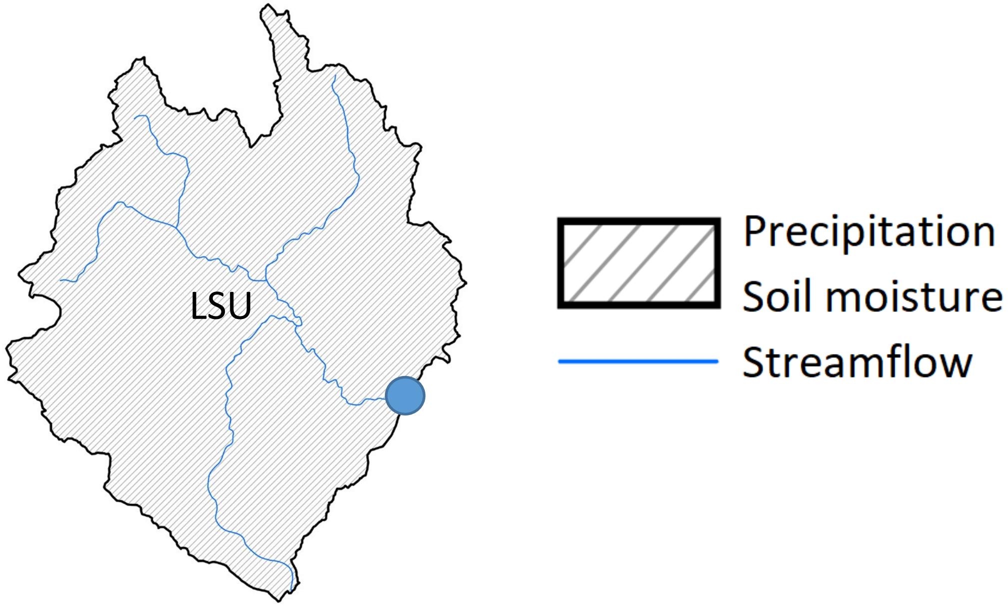




Variable Threshold Level Method – Example



SWAT+ Output



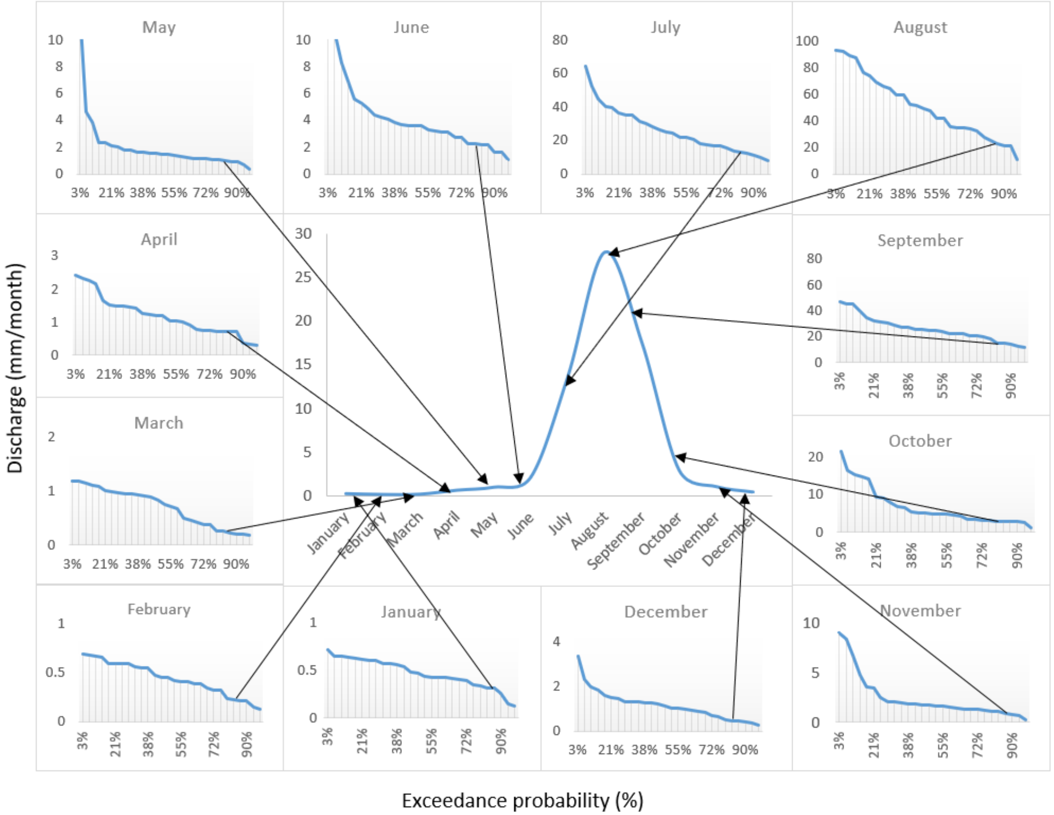


Fig: Derivation of monthly threshold level from monthly streamflow duration curves (Zeleke et al., 2022).

Drought Propagation Demo

Precipitation deficit

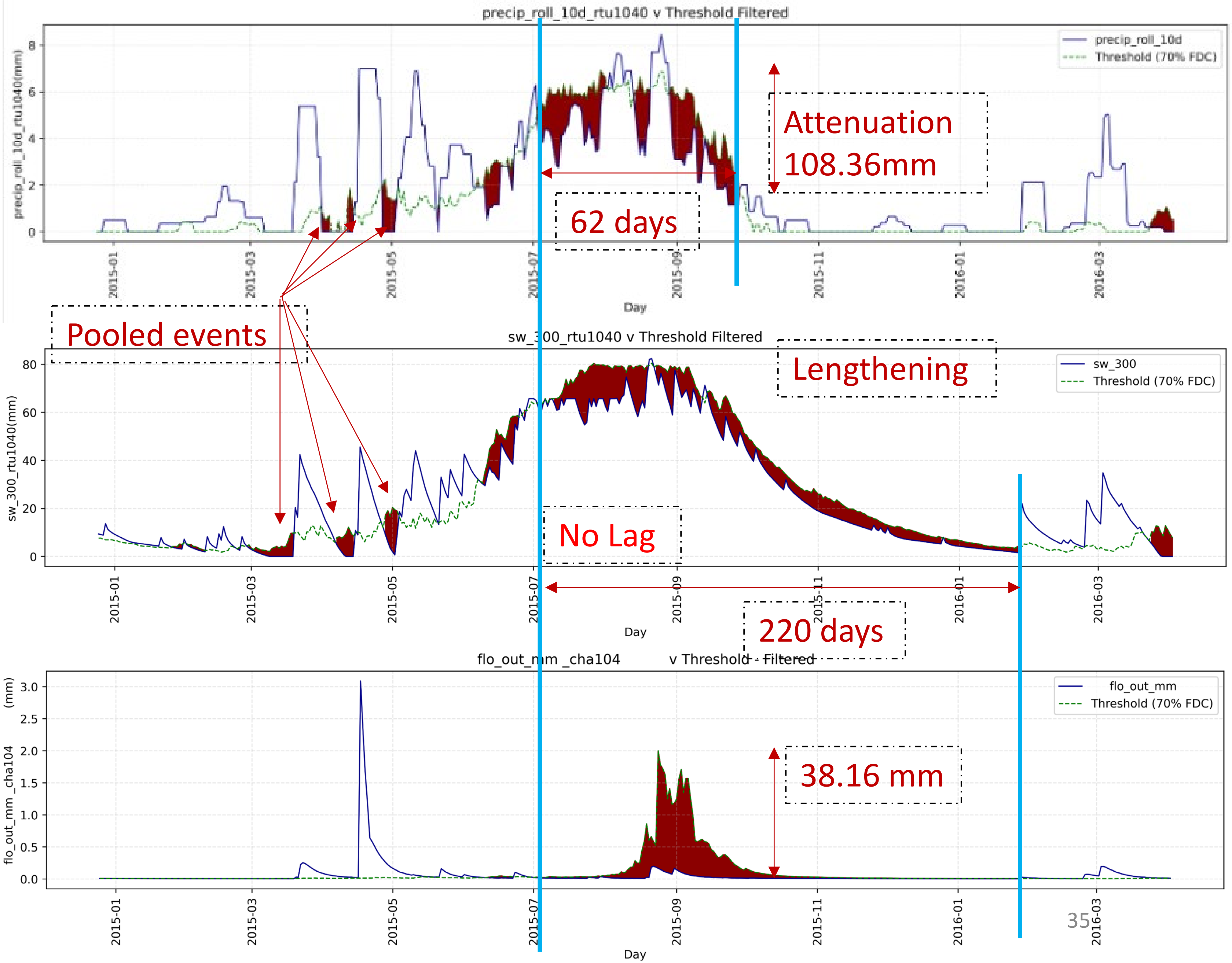
	start_date	end_date	sum_y_values	num_days
0	2015-04-01	2015-04-04	1.8871	3
1	2015-04-08	2015-04-08	0.0000	0
2	2015-04-12	2015-04-14	3.1202	2
3	2015-04-27	2015-05-03	9.8219	6
4	2015-05-21	2015-05-21	0.0000	0
5	2015-06-07	2015-06-07	0.0000	0
6	2015-06-10	2015-06-17	11.1430	7
7	2015-06-20	2015-06-22	0.6618	2
8	2015-06-27	2015-06-27	0.0000	0
9	2015-07-03	2015-08-01	45.4120	29
10	2015-08-04	2015-08-04	0.0000	0
11	2015-08-14	2015-08-20	13.0416	6
12	2015-08-29	2015-09-12	31.5425	14
13	2015-09-14	2015-09-27	18.3727	13

Soil water deficit

10	2015-07-03	2015-07-05	5.927	2
11	2015-07-07	2015-07-08	1.112	1
12	2015-07-10	2015-08-19	505.863	40
13	2015-08-23	2015-09-11	159.987	19
14	2015-09-14	2015-12-24	562.081	101
15	2015-12-26	2016-01-27	58.472	32

Streamflow deficit

	start_date	end_date	sum_y_values	num_days
0	2014-12-25	2015-03-19	0.11184	84
1	2015-06-11	2015-06-22	0.21990	11
2	2015-07-02	2016-01-27	38.16740	209
3	2016-02-15	2016-02-15	0.00000	0



Methodology – Evaluating Response of a Sub-basin

Temporal Evaluation

Response of subbasin to varying drought events

Within the same range of lag, lengthening and attenuation

Consistent

Hydrologic response is stable and predictable

- Greater influence of structure than forcing
- Stress threshold can be estimated

Variable

Hydrologic response is dependent on the specific drought event

- Magnitude/intensity of forcing
- Initial conditions
- Upstream influence
- Scaling

Group drought events based on typology

– classical rainfall deficit drought
– wet-to-dry-season drought
– composite drought

(Van Loon and Van Lanen, 2012)

Table s1: List of all factors evaluated in determining mutual information and cohen's d for each metric (lag, lengthening and attenuation)

	Form	Antecedent	Event
	Area	7 - day surface soil moisutre	Intesity of initiating precipitation deficit
	Slope	10 - day surface soil moisutre	Duration of initiating precipitation deficit
	Stream Order	20 - day surface soil moisture	Number of days since last precipitation deficit
	Stream morphology (length, width, depth)	7 - day ET	Day of year of precipitation deficit onset
	Steam elevation (min, max)	10 - day ET	Number of sustaining events
	Stream slope	20 - day ET	Duration of sustaining evnets
	Time of concentration	7 - day precipitation	Average sustaining event intensity
	Latitude, Longitude	10 - day precipitation	
	Average LSU elevation	20 - day precipitation	
Total	13	9	7

Factors

- Form (physical catchment attributes)
- Antecedent (pre-drought)
- Event (during-drought)

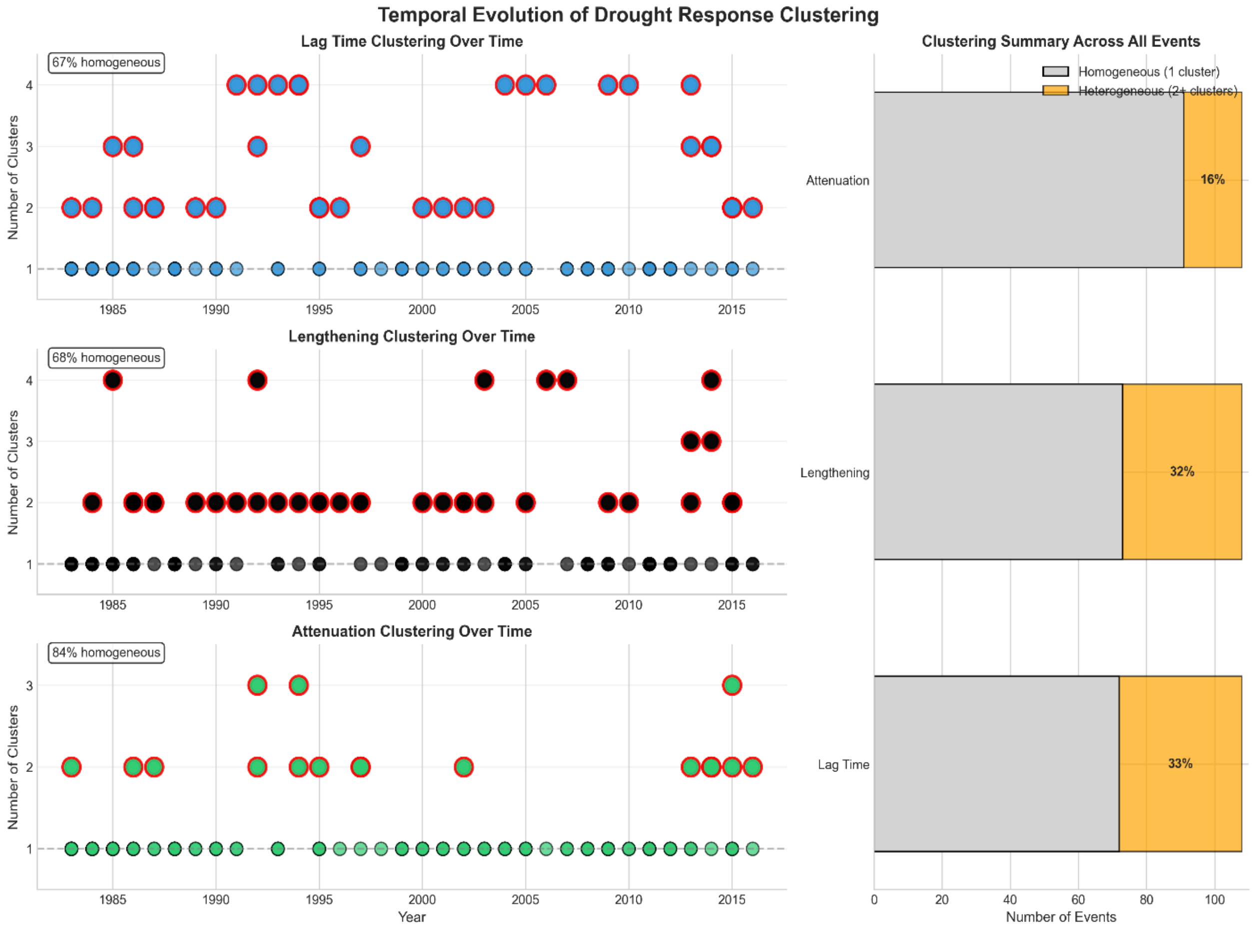
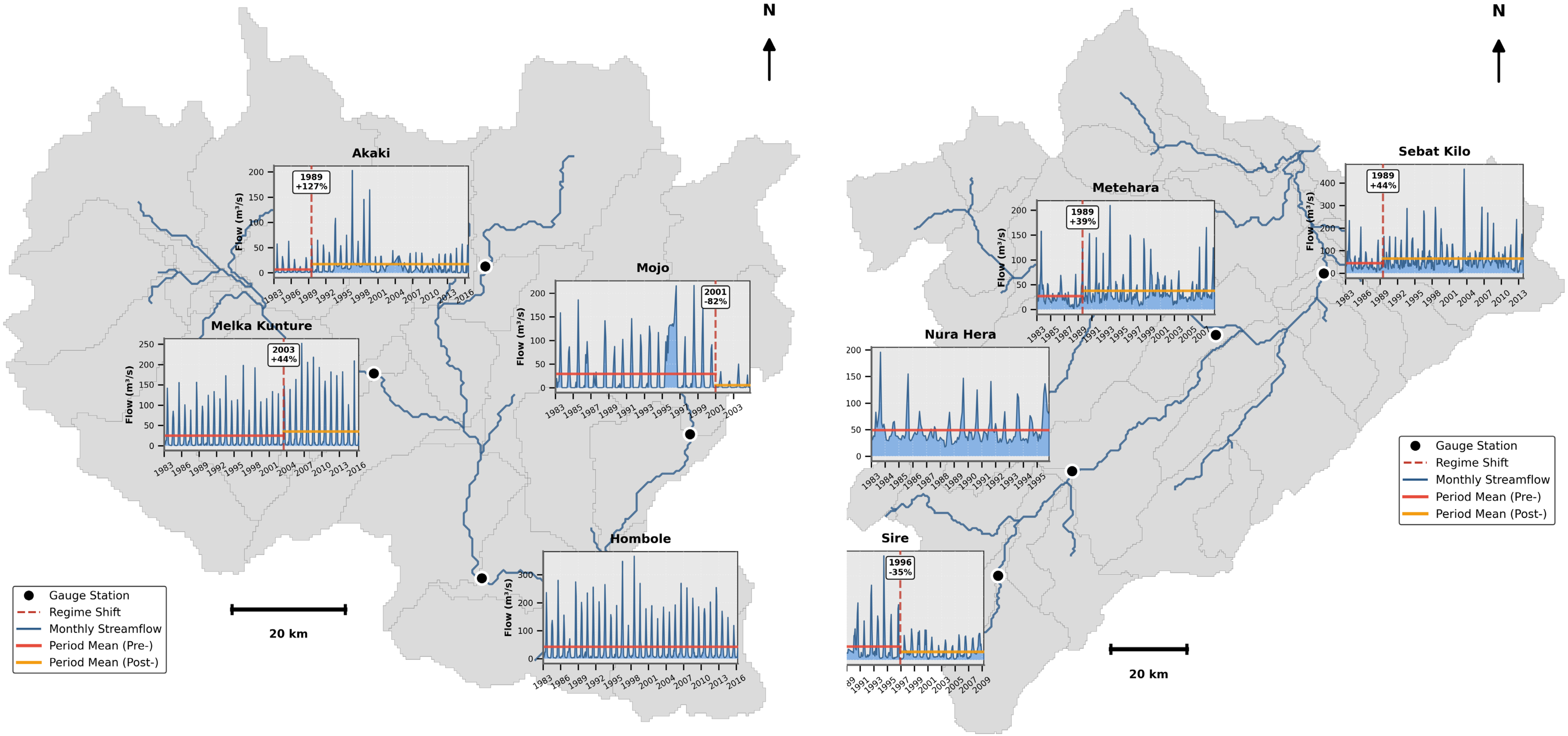


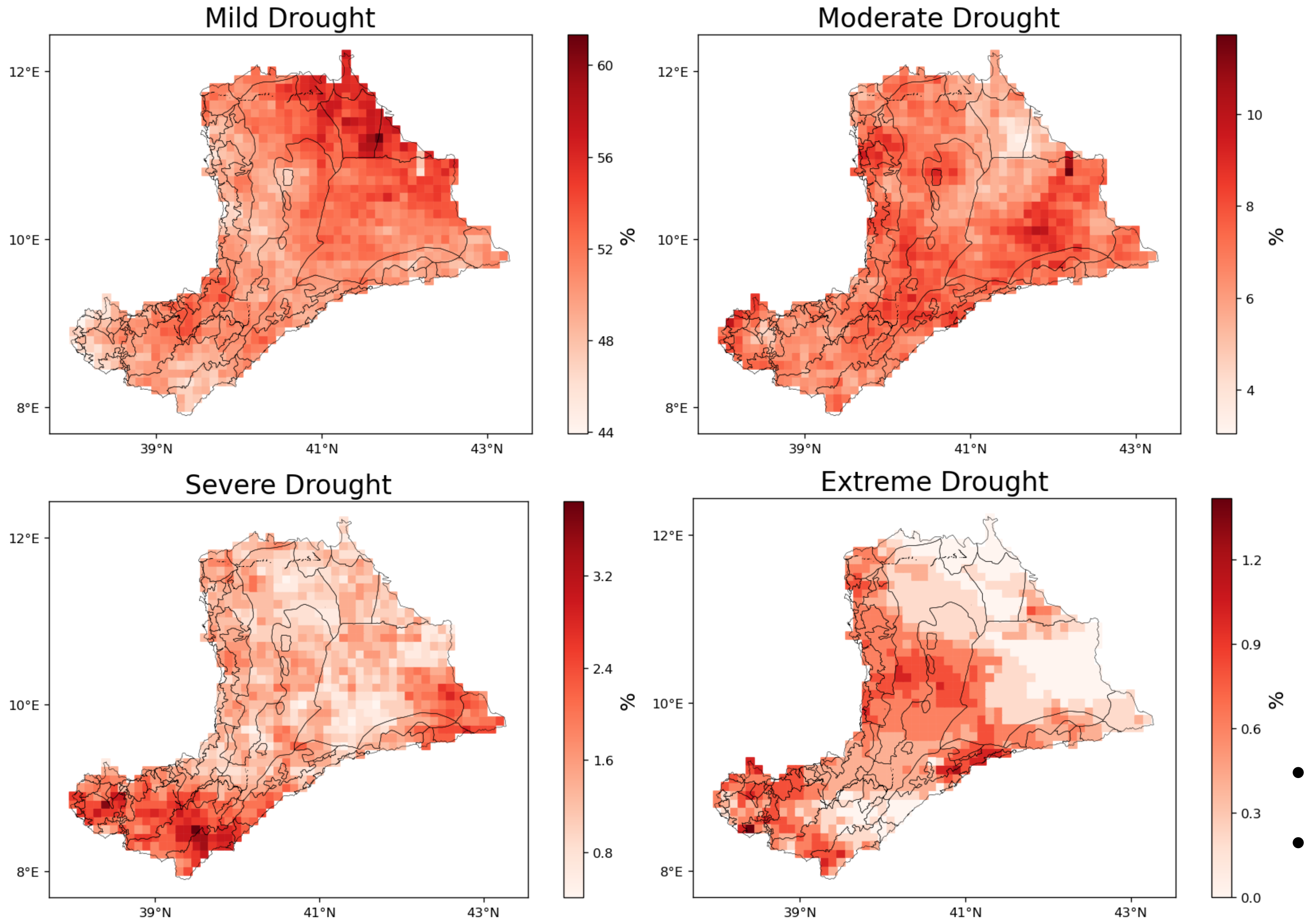
Figure s2: Derived clusters for lag, lengthening and attenuation for each event between 1983-2016 along with a summary of the percentage of events that required clustering (heterogeneous response) and did not require clustering (homogenous response)

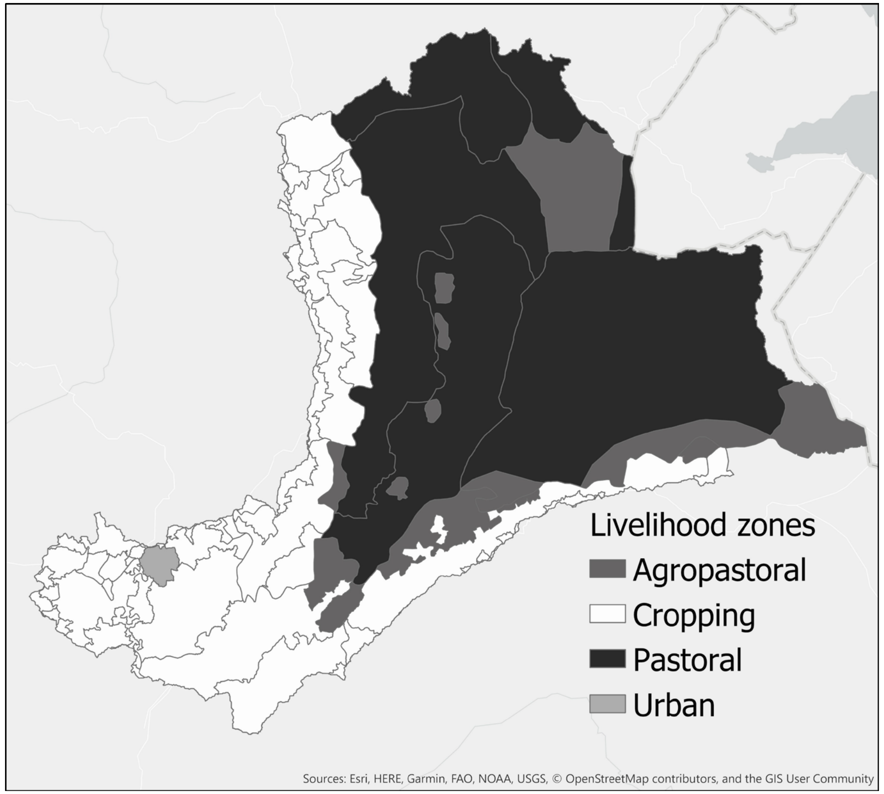


N
Akaki
1989 +127%
Melka Kunture
2003 +44%
Mojo
2001 -82%
Hombole
Flow (m³/s)
Gauge Station
Regime Shift
Monthly Streamflow
Period Mean (Pre-)
Period Mean (Post-)
20 km
N
Metehara
1989 +39%
Sebat Kilo
1989 +44%
Nura Hera
Sire
1996 -35%
Gauge Station
Regime Shift
Monthly Streamflow
Period Mean (Pre-)
Period Mean (Post-)
20 km

Study area – The Awash River Basin

Meteorological Drought frequency over the past 40 years





- >100M people affected in Ethiopia
- ~$3B in total damages