Transitions in the semiarid mountain west: Snow to rain and streamflow to ET

Snowmelt is a Critical Water Resource

- Western U.S. snowmelt is responsible for 70% of the total runoff (Li *et al.*, 2017)
- 60 million people rely on mountain snowpack as a water resource (Barnett *et al.*, 2005)
- In the western United States two-thirds of the water supply originates from forested environments (Brown *et al.*, 2008)

Ephemeral snowpacks are more susceptible to energy inputs (i.e. rain-on-snow, increased temperatures)

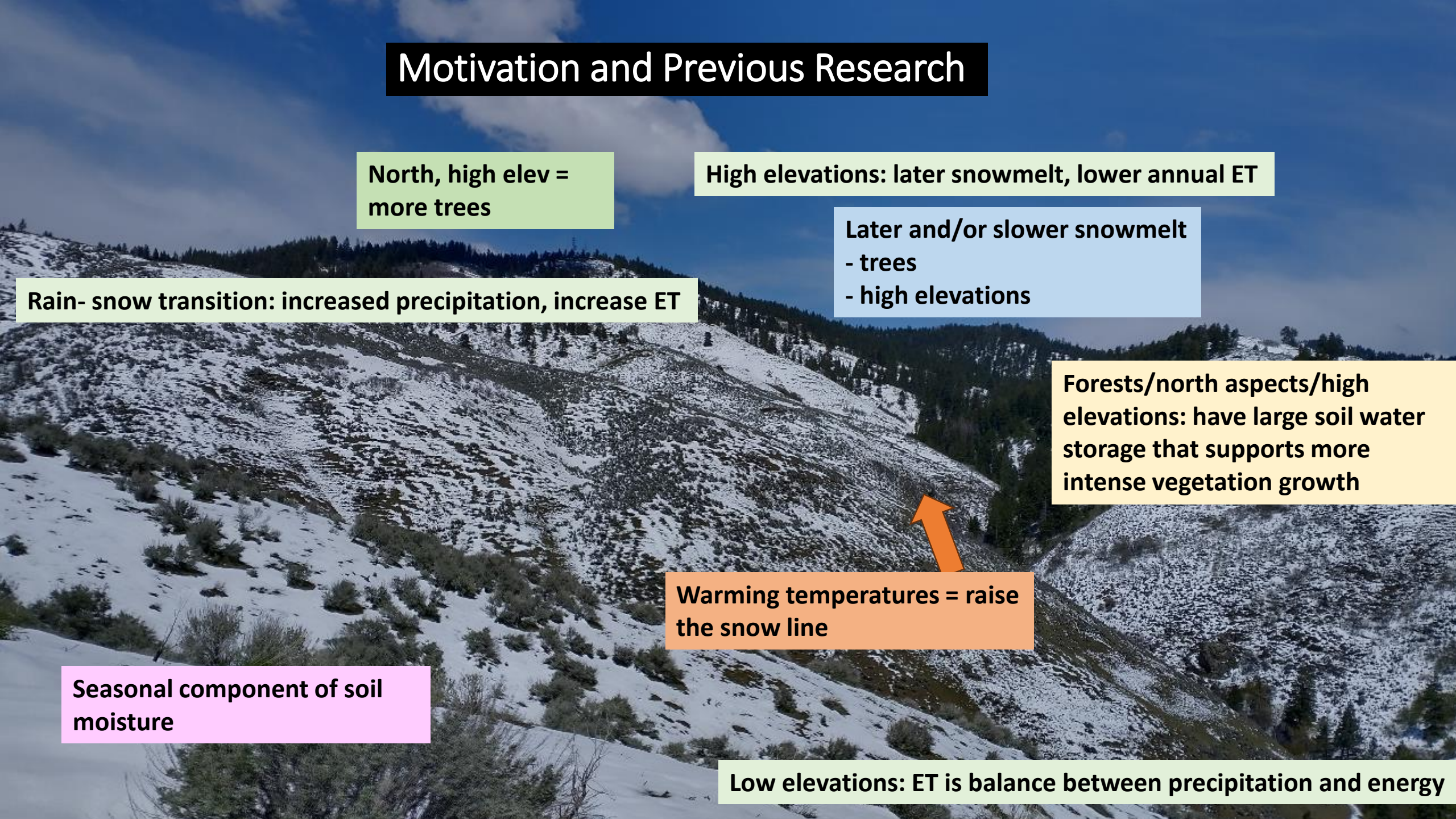
	Seasonal	Ephemeral/ Marginal
Snow Depth (Sturm et al., 2021)	> 1 m	< 1 m
Snow cover days between Jan 1st and July 3rd (Moore et al., 2015)	> 50%	<50%
In Western U.S. (Moor et al., 2015, Hammond et al., 2018, Harrison et al., 2021)	- Covers ~ 13% of the land surface - Most of our water resources	- Covers ~ 25% of the land surface

Warming temperatures will shift the rain-snow transition

- Areas near the rain-snow transition have an ephemeral snowpack
  - more susceptible to temperatures, rain on snow events etc.

- Propagate into evapotranspiration (ET) and streamflow

Motivation and Previous Research



North, high elev = more trees

High elevations: later snowmelt, lower annual ET

Later and/or slower snowmelt
- trees
- high elevations

Rain- snow transition: increased precipitation, increase ET

Forests/north aspects/high elevations: have large soil water storage that supports more intense vegetation growth

Warming temperatures = raise the snow line

Seasonal component of soil moisture

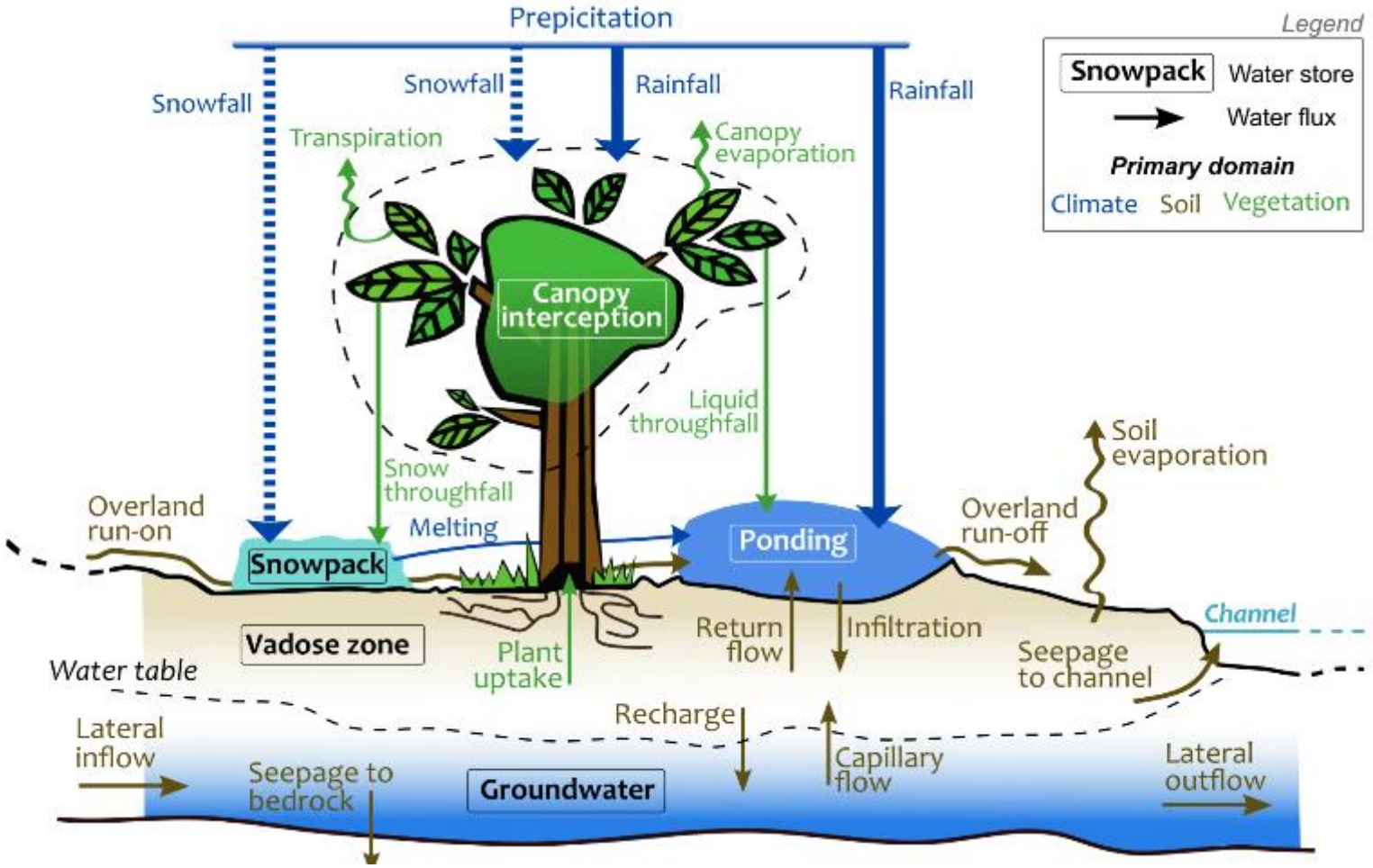
Low elevations: ET is balance between precipitation and energy

Questions:

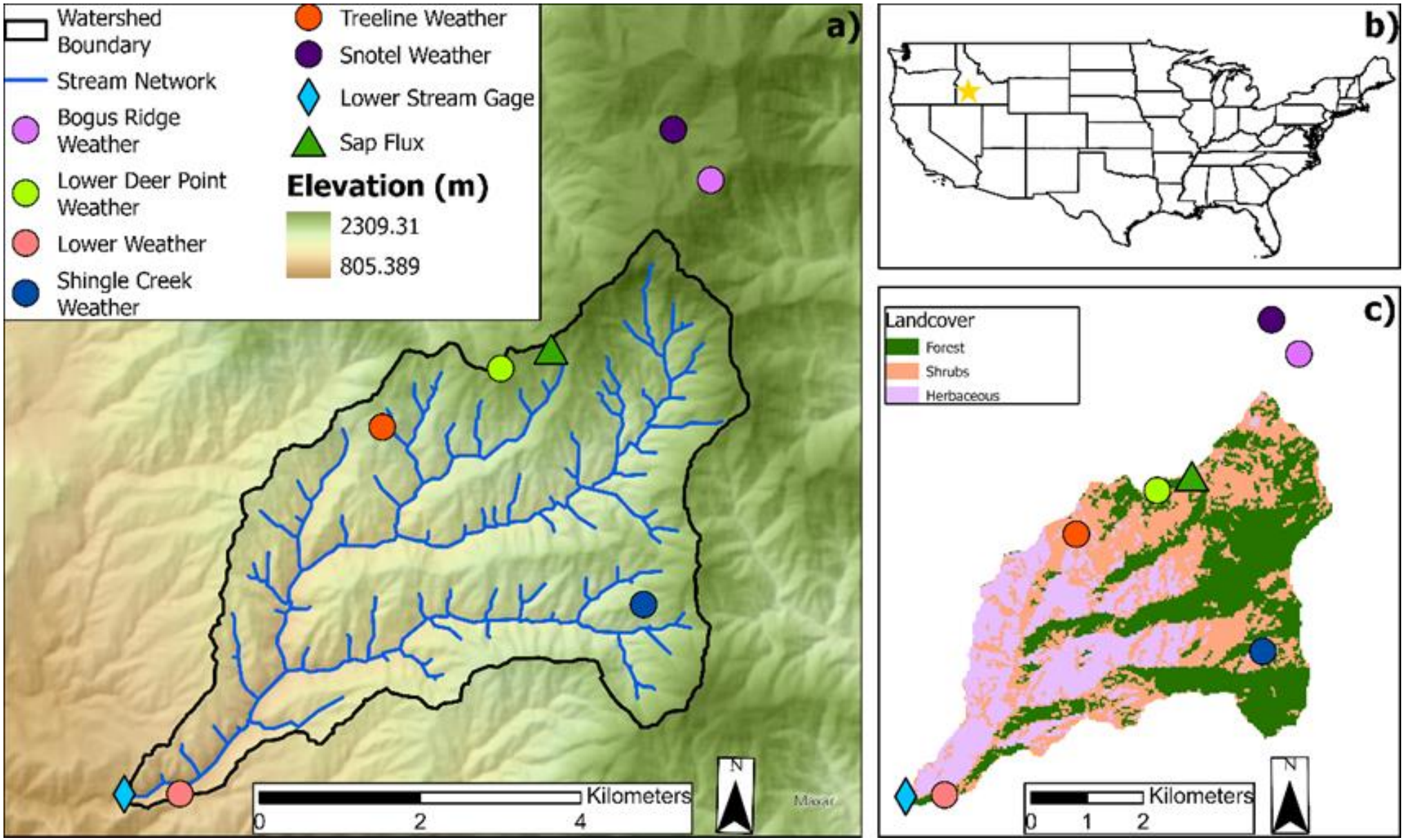
- How will warming temperatures alter snow water input, streamflow and ET?
- How does seasonal variability in warmer temperatures affect ET?

Vegetation-hydrology model

- ECH2O
- Physically based
- Represent snow cover, soil moisture, and runoff, Evaporation, Transpiration
- Aimed at representing vegetation and hydrology
- Input: weather data, DEM, vegetation, soil

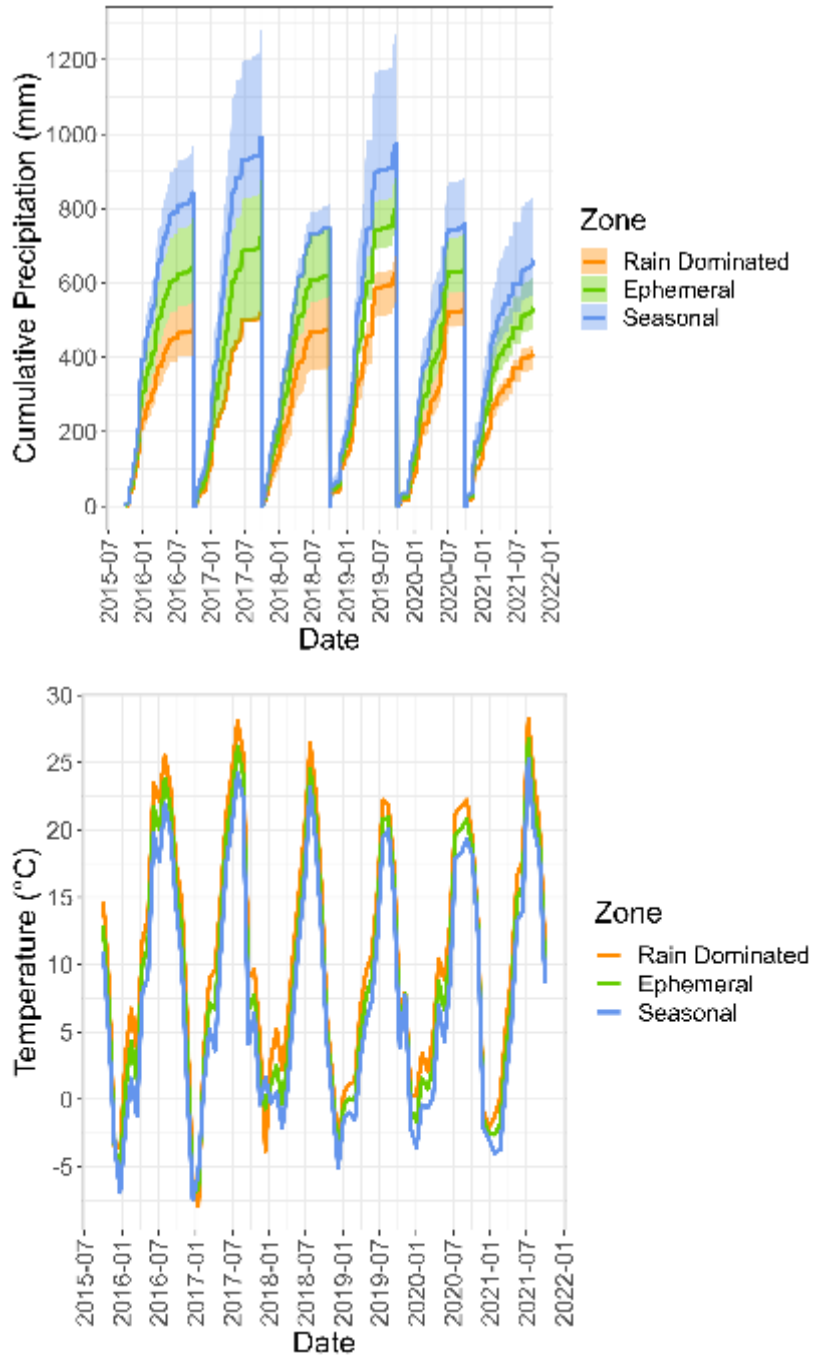


Study Site: Dry Creek Watershed



Model Setup

- 30x30 m^2 resolution, WY 2016 -> 2021
- Distributed weather data into 12 elevation bands and 4 aspects- 44 total climate zones
- National Land Cover Database (NLCD) to designate vegetation classes into herbaceous, forest, grass
- Lidar data for LAI and vegetation density
- SSURGO soil data to designate soil classes
- Split basin into rain, ephemeral, and seasonal snow zones in each water year (Sturm and Liston, 2021)
  - Rain: < 0.4 m
  - Ephemeral: 0.4 – 1.0 m
  - Seasonal: > 1.0 m



Model Calibration

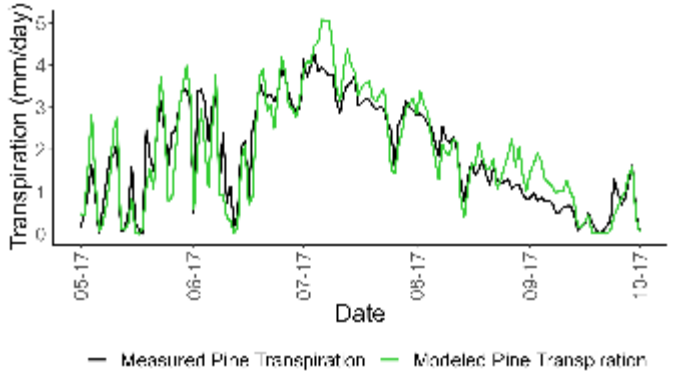
- Multi-criteria optimization approach- transpiration (T), streamflow (Q), soil moisture (SM), snow water equivalent (SWE)
- Dynamically Dimensioned Search Algorithm (DDS)
- Minimize Kling Gupta Efficiency (combines bias, correlation, and variability) Ranges from 0-1 where 1 is a perfect match between observed and predicted.

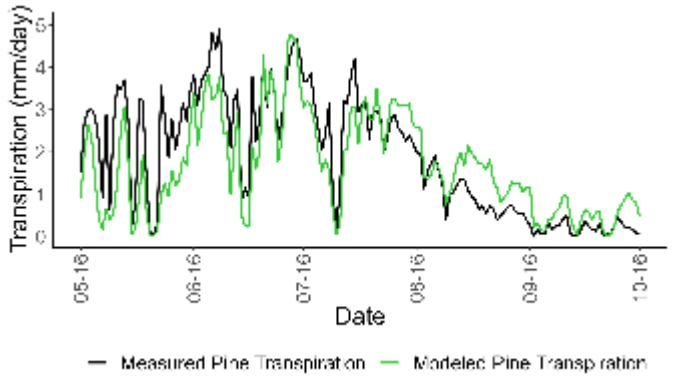
$$Obj = \left(1 - KGE_Q\right) + (1 - KGE_T) + (1 - KGE_{SM}) + (1 - KGE_{SWE})$$

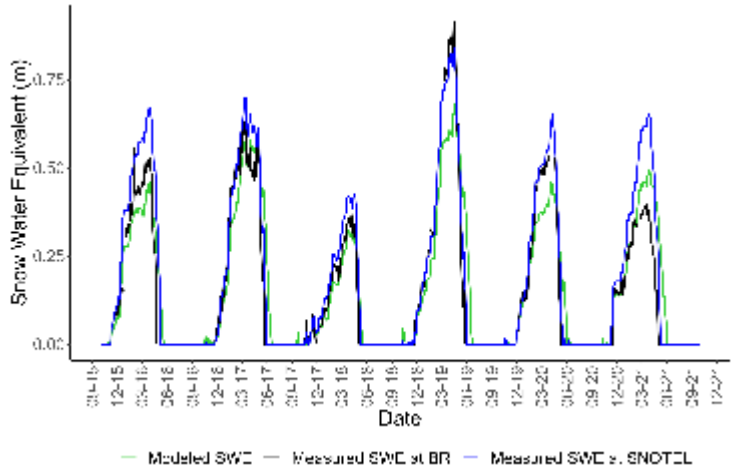
$$KGE = 1 - \sqrt{(r-1)^2 + \ (\beta - 1)^2 + (\alpha - 1)^2}$$

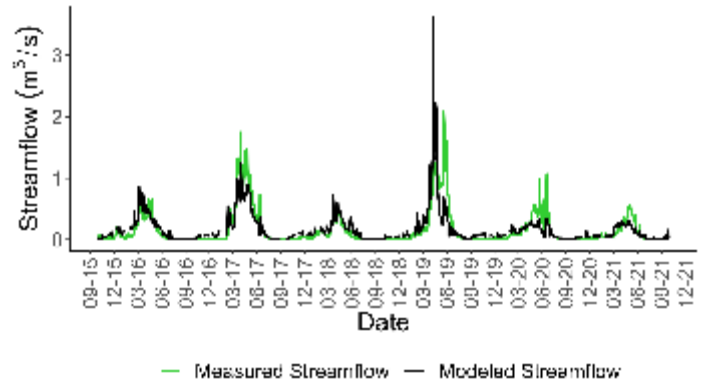
Calibration Results

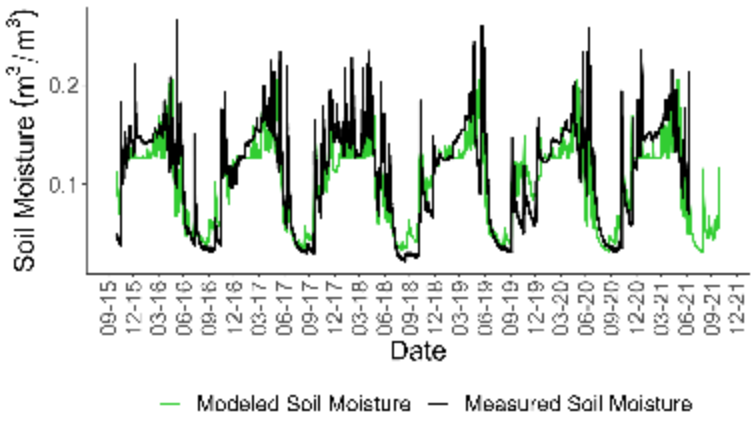
- KGE of 0.80 with values Ranging between 0.74 and 0.87
- Peak SWE is biased -13% and occurs later in the season
- Timing of peak streamflow and spring recession occur later than observed











Scenarios- Evaluate how changes in the rain-snow transition will affect ET

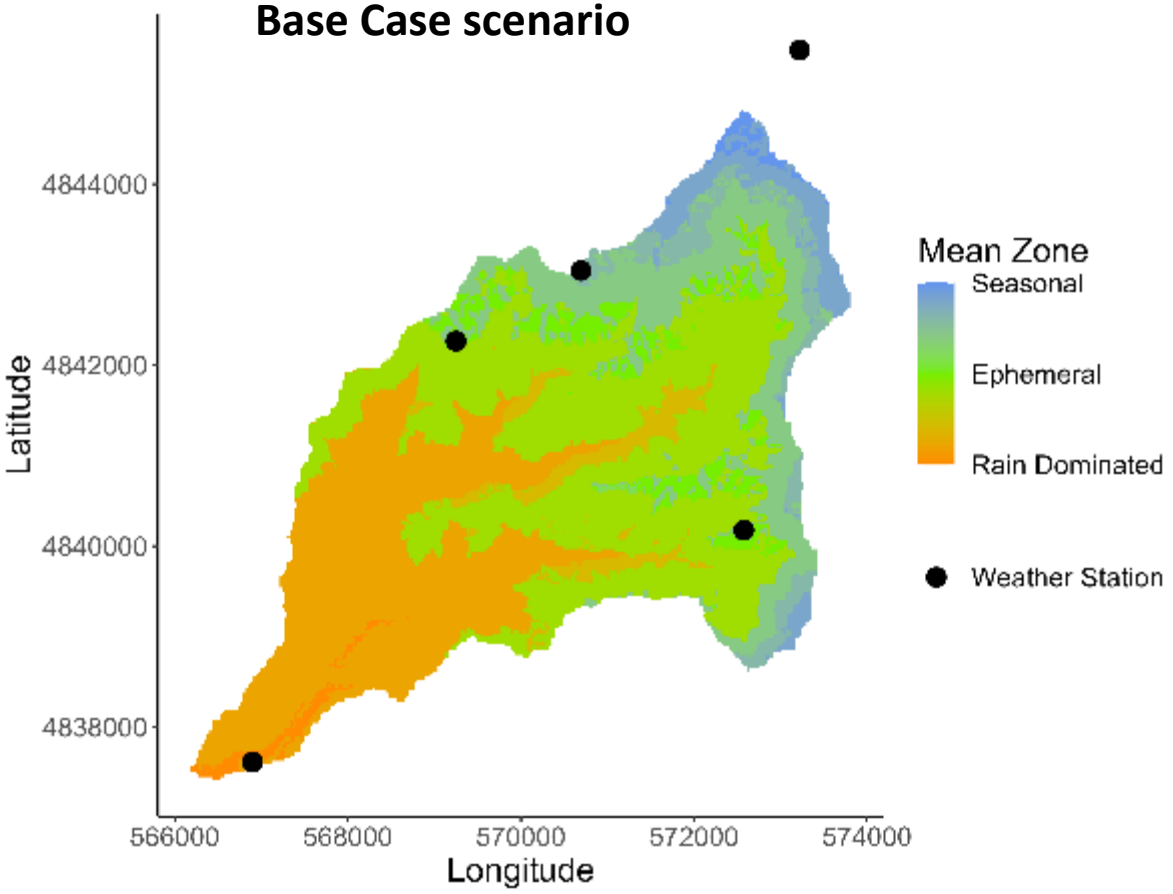
- No change scenario = base case

- Increased air temperatures by 2°C (Guided by SSP2-4.5 IPCC report):
  - During the snow cover season, October 1st – June 1st → 8-month scenario
  - Individual months: November, December, March, and April

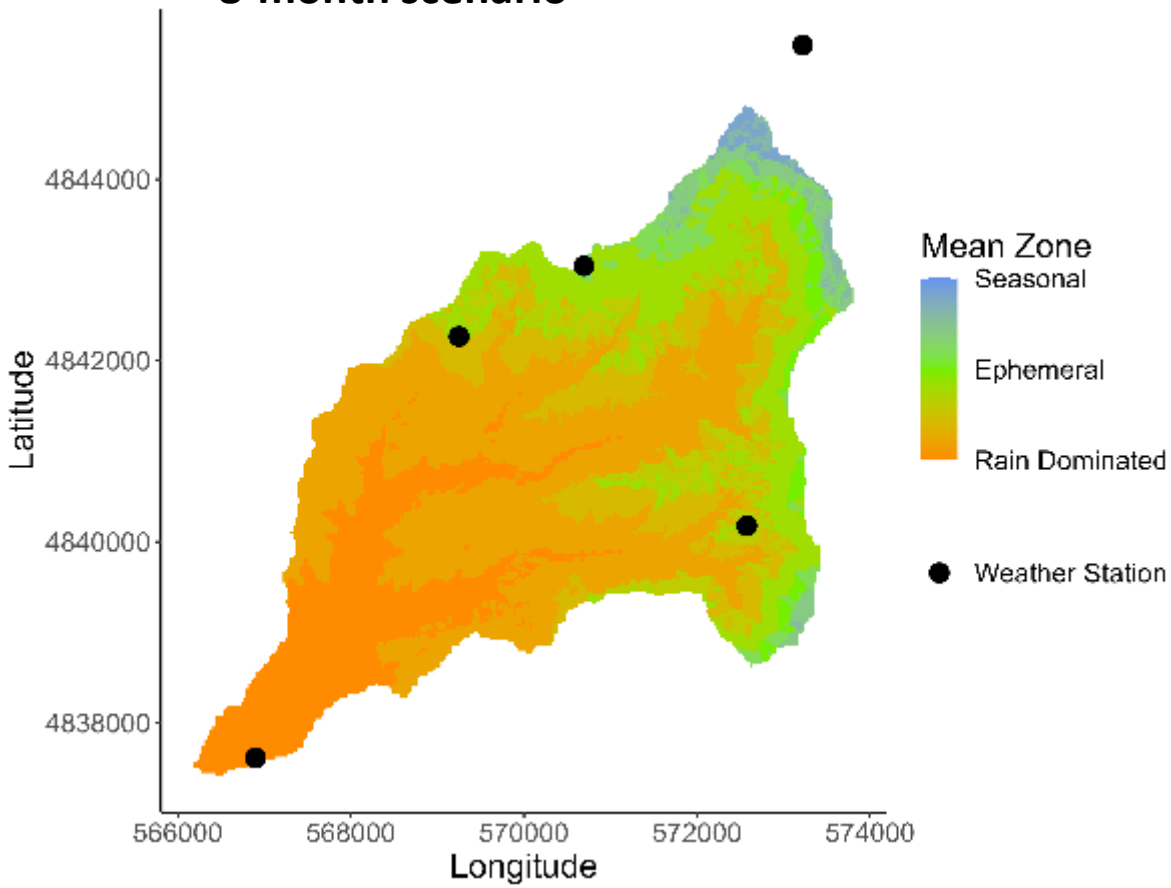
Snow Zones

- On average, fraction area:
  - Rain dominated zone increased 28%
  - Ephemeral decreased 17%
  - Seasonal decreased 10%
- Decreased in snow:
  - Seasonal zone by 16%
  - Basin wide by 14%

Base Case scenario



8-month scenario



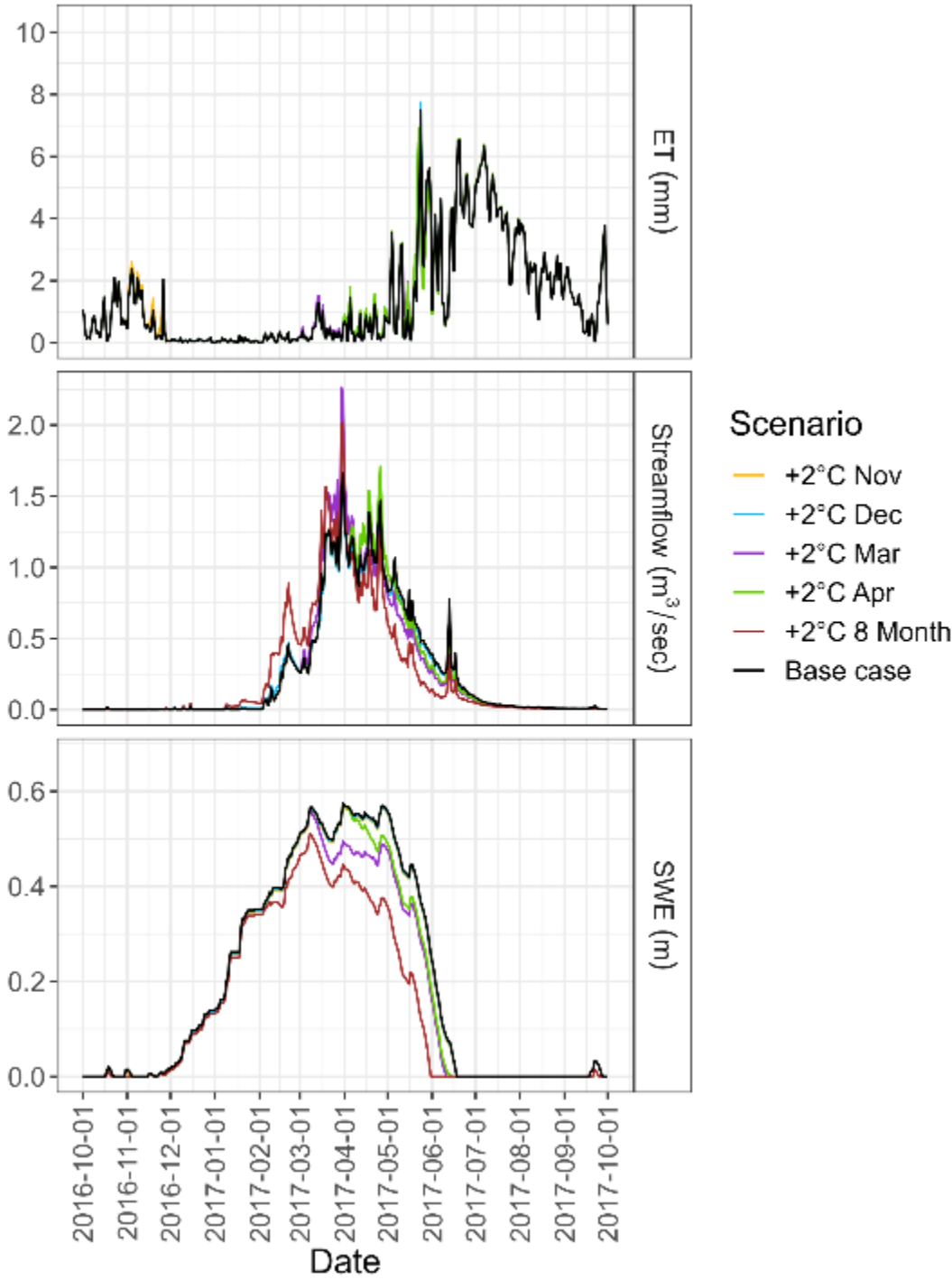
Annual water balance:
Spring streamflow ↓ ET ↑

- 8-month scenario -14.3% streamflow
  - Higher fall and mid-winter streamflow but lower spring streamflow

- March and April:

  Streamflow recession began earlier **but similar annual volume**
  - Greatest change: April ET +2.5%

- December and November:
  - Increase fall streamflow
  - December: **SWE -9.4%, Q -4.9%,** ET +0.53%

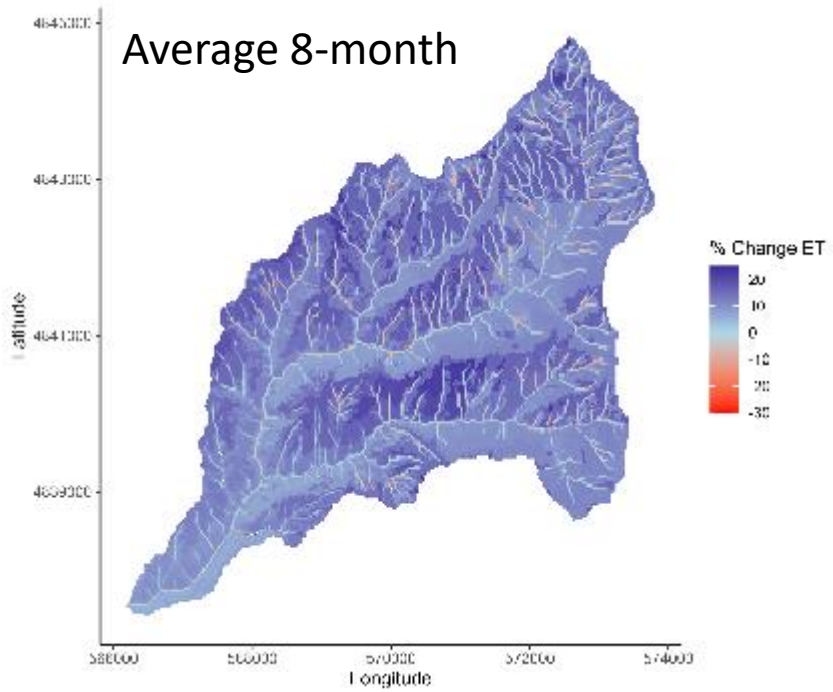


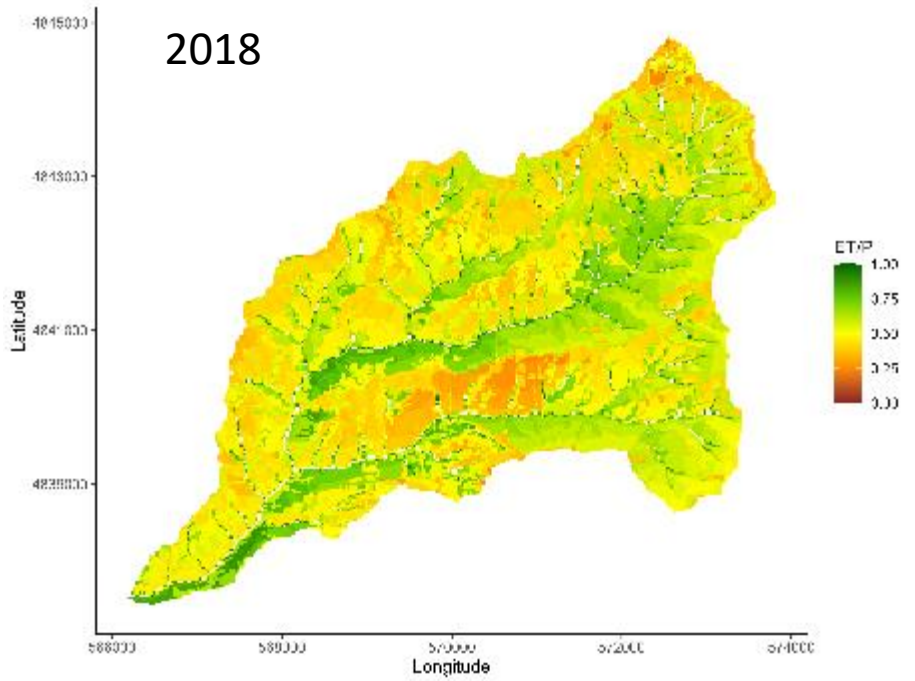
Ratios

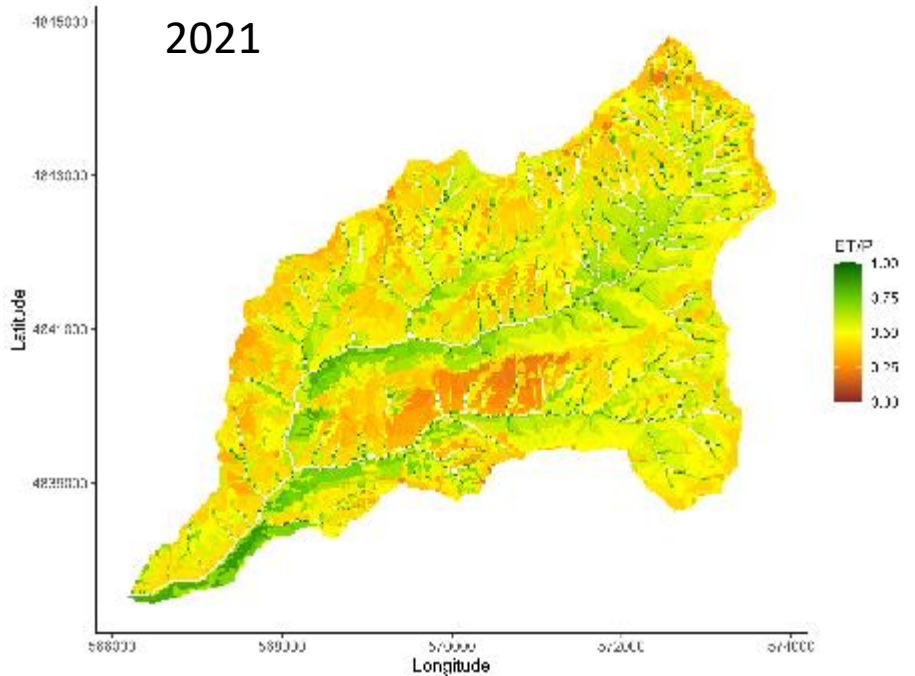
$P = Q + ET + \Delta S$

$ET = E + T$

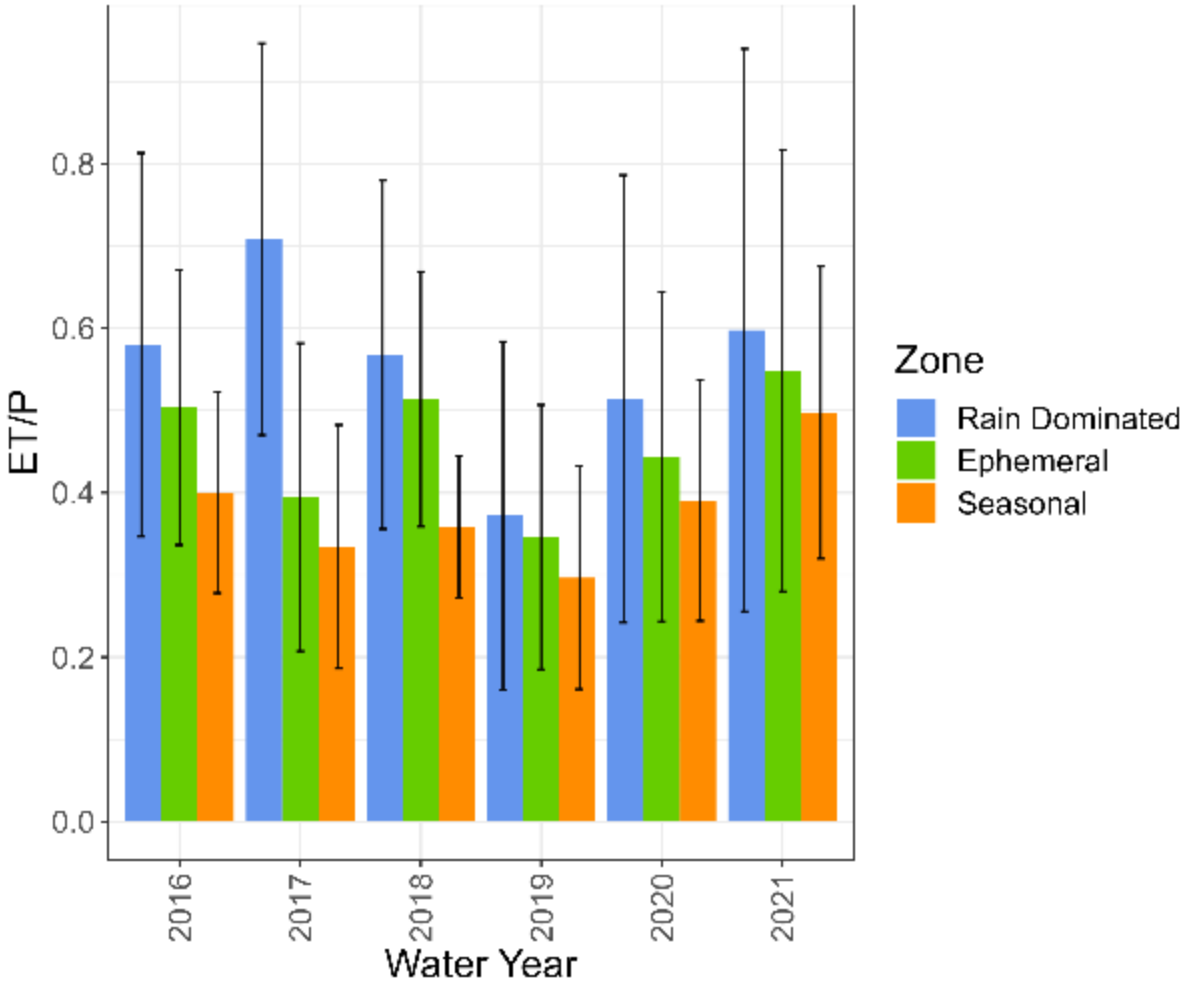
- Streamflow/Precipitation, Q/P
- Evaporation/Precipitation, E/P
- Transpiration/Precipitation, T/P
- Evapotranspiration/Precipitation, ET/P





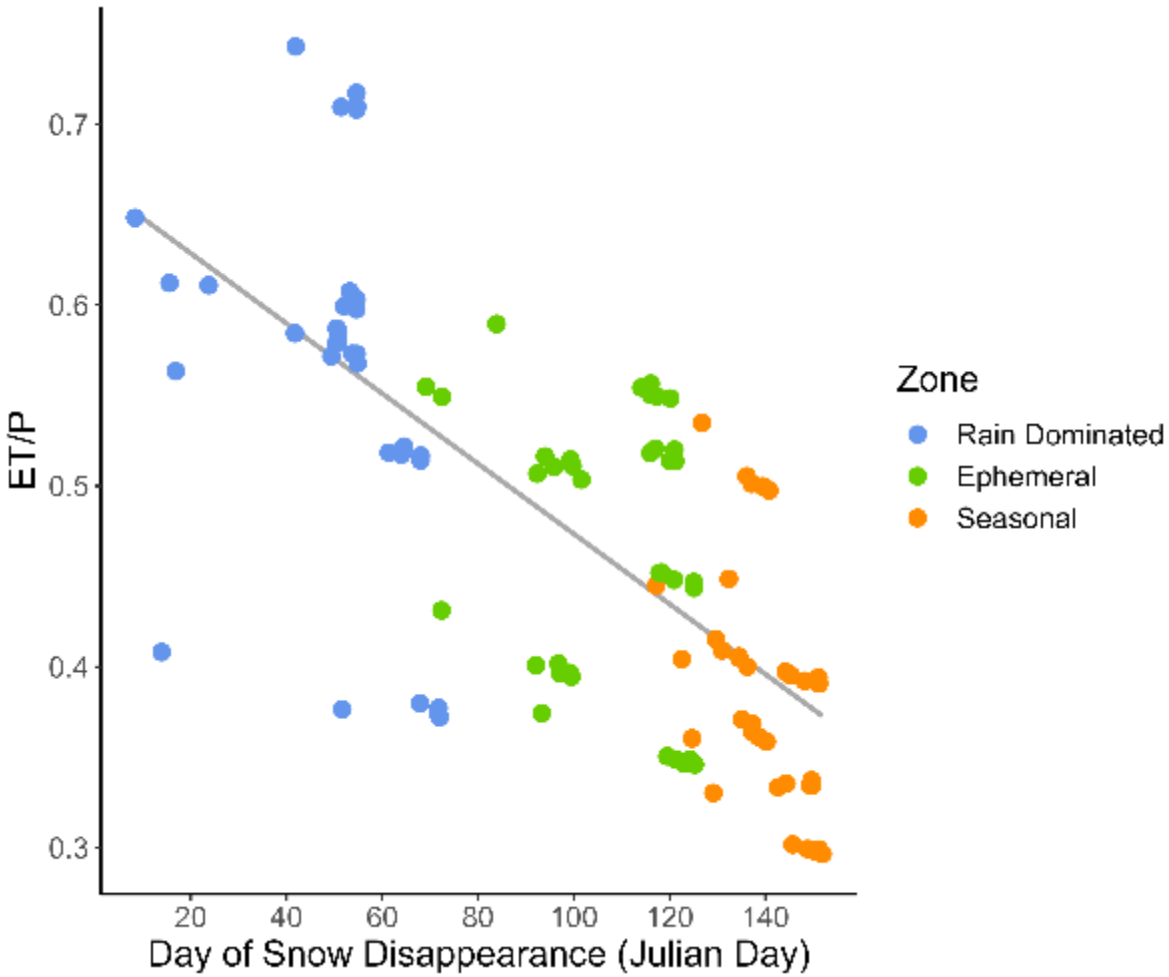


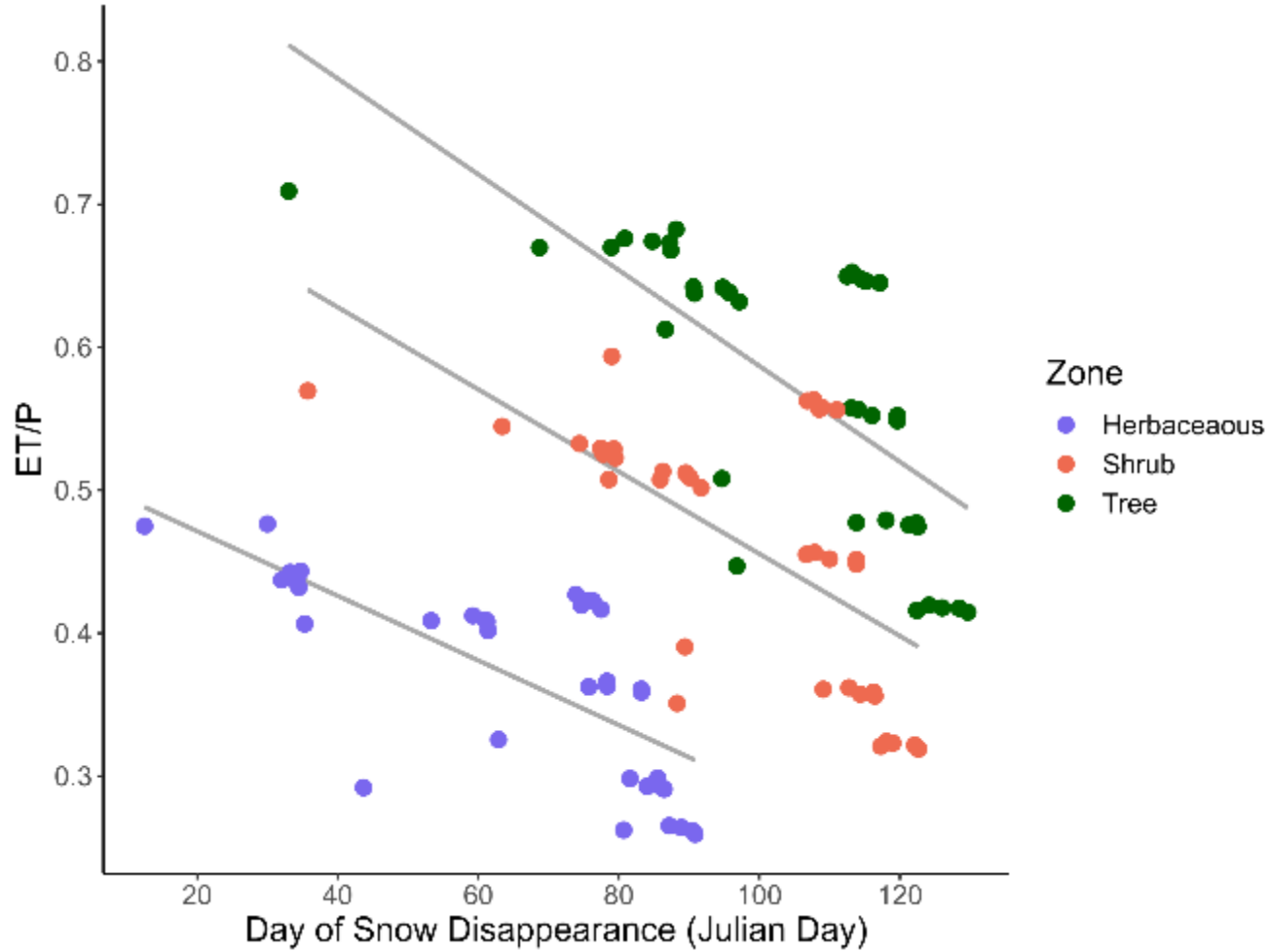
- Watershed scale change
  - Consistently in each scenario, **Q/P decreased while E/P and T/P increased**
  - GW storage component fluctuated to account for the differences
    - WY2020, 8-month scenario: -6.32% (Q/P), and 5.9% (ET/P)



- Zone
  - **Highest ET/P in rain dominated and lowest ET/P in seasonal zone**
  - Lowest water year (WY 2021) had highest ET/P in ephemeral and seasonal zones

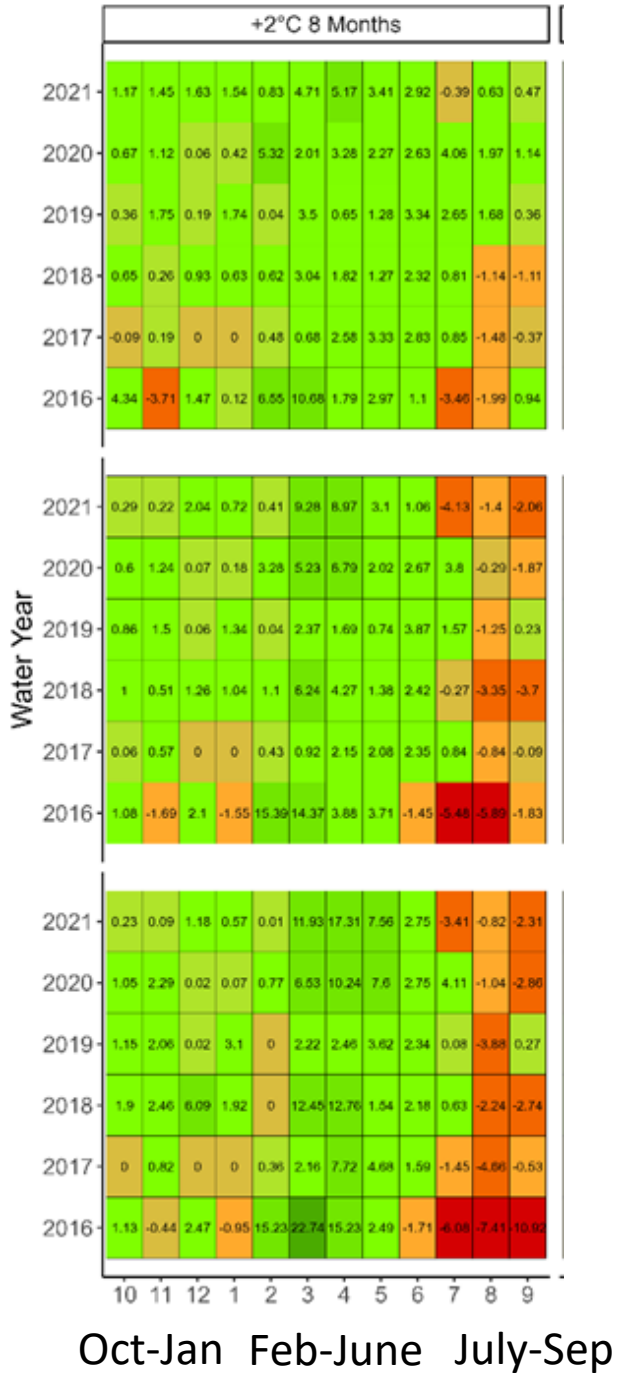
Negative trend ET/P and snow disappearance





Monthly % change ET

- ET increases early in the spring season then declines in late summer
- Increased temperatures in one month propagates to other months
- Soil Moisture Stress



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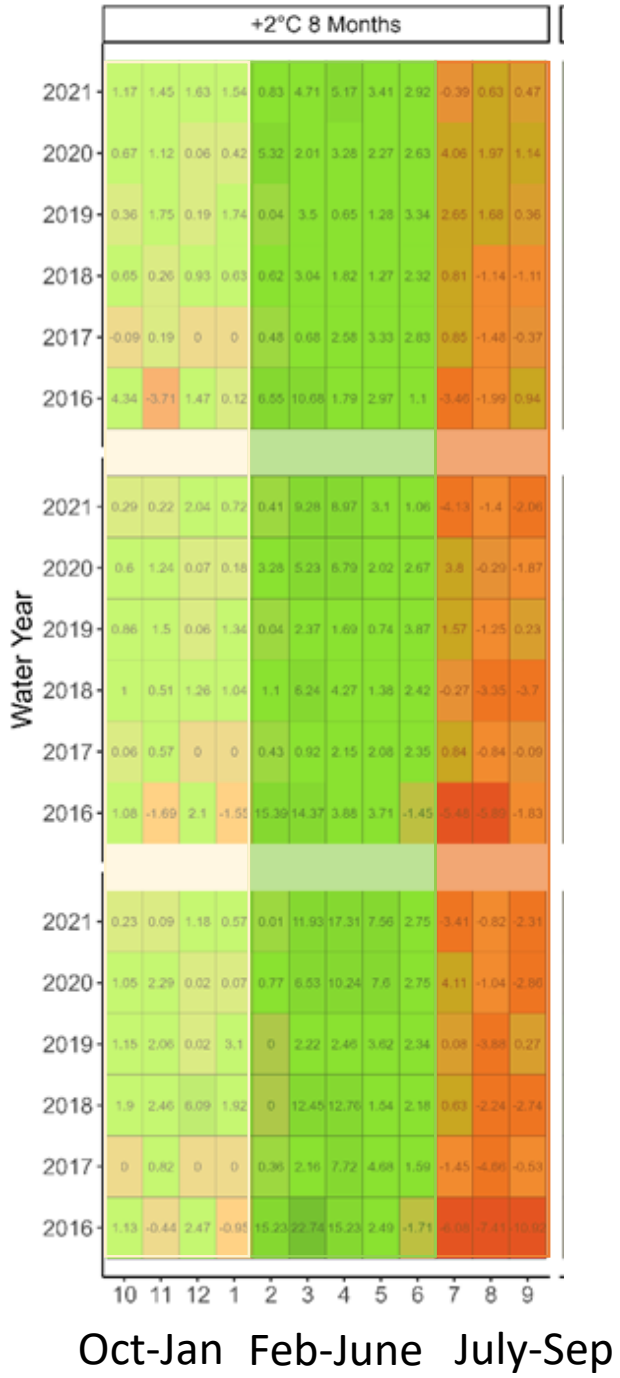
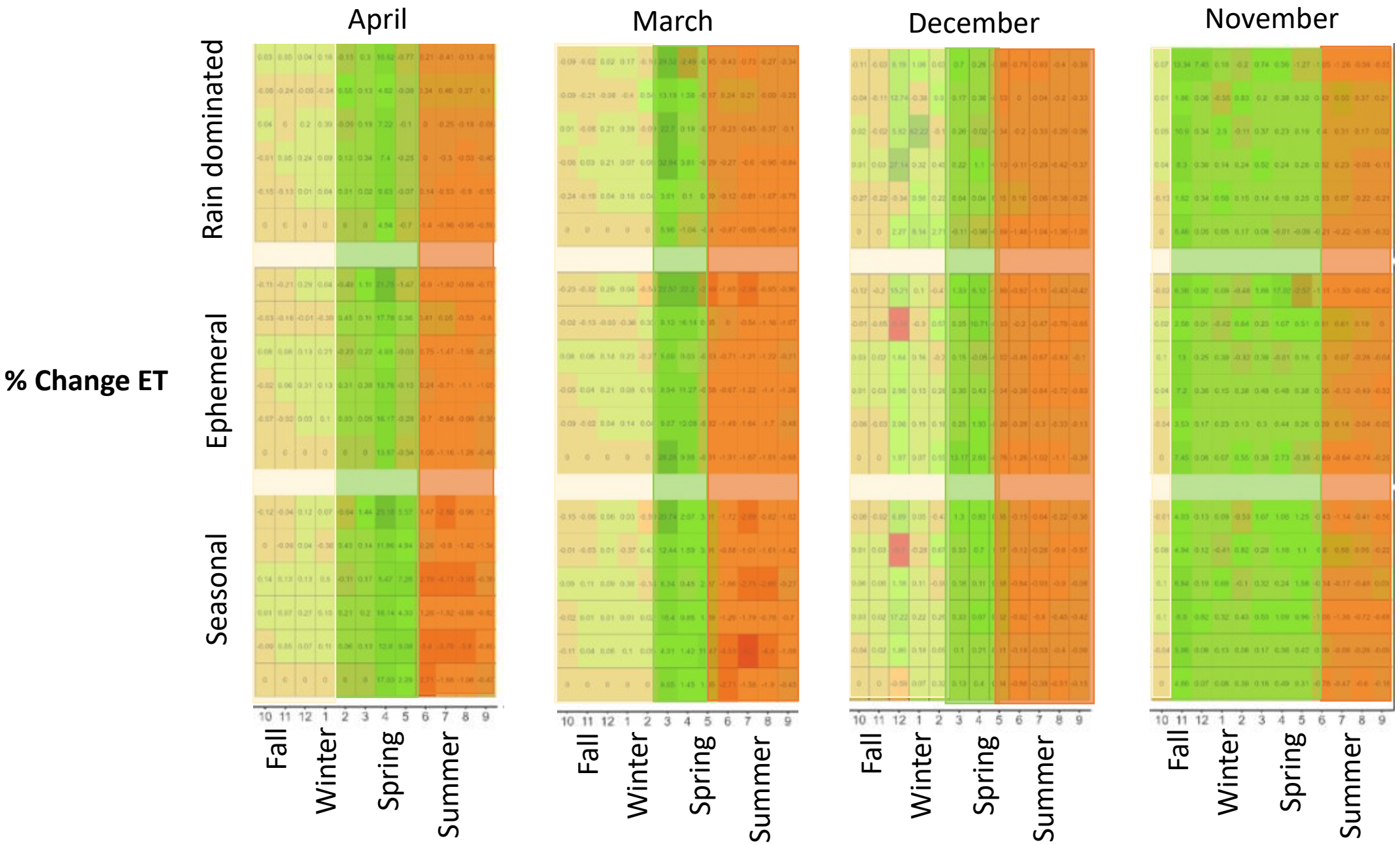
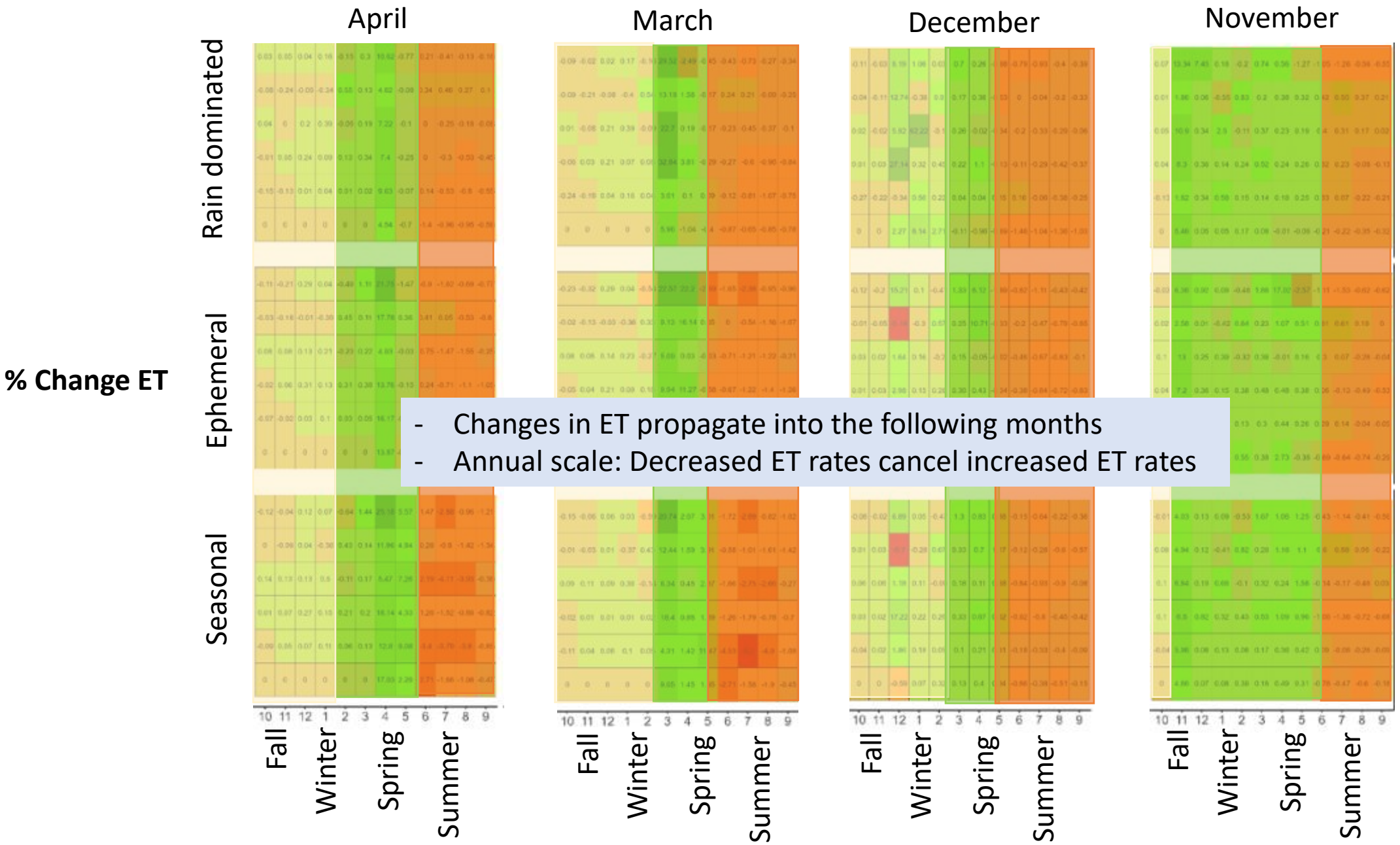
Rain dominated

Ephemeral

Seasonal




April
March
December
November
Rain dominated
Ephemeral
Seasonal
% Change ET
10 11 12 1 2 3 4 5 6 7 8 9
Fall
Winter
Spring
Summer


April
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Rain dominated
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% Change ET
10 11 12 1 2 3 4 5 6 7 8 9
Fall
Winter
Spring
Summer
- Changes in ET propagate into the following months
- Annual scale: Decreased ET rates cancel increased ET rates

Summary

- **+2°C fall temperatures ->**
  - **Increased fall streamflow,**
  - **Decreased SWE (phase change during initial snow accumulation),**
  - **Limited change in ET (not synchronized with energy)**
- **+2°C spring temperatures->**
  - **Increased snowmelt rate,**
  - **Earlier snow disappearance,**
  - **Earlier streamflow (similar annual volume)**
- **Warming temperatures in one month propagate into the following months- high ET rates followed by low ET rates**
- **Warming temperatures most sensitive in the seasonal and forested zone**