Investigation of High-Elevation Drivers of Snowpack and Streamflow Characteristics in the American West

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1. Introduction & Background

In the American West, more than 40 million people depend on snowpack/melt for their **hydropower**, **irrigation**, and **drinking water** (University of Nevada Reno, 2022). As a result of warming temperatures, April 1 snowpacks have been decreasing in their extent across the west (**Figure 1).**

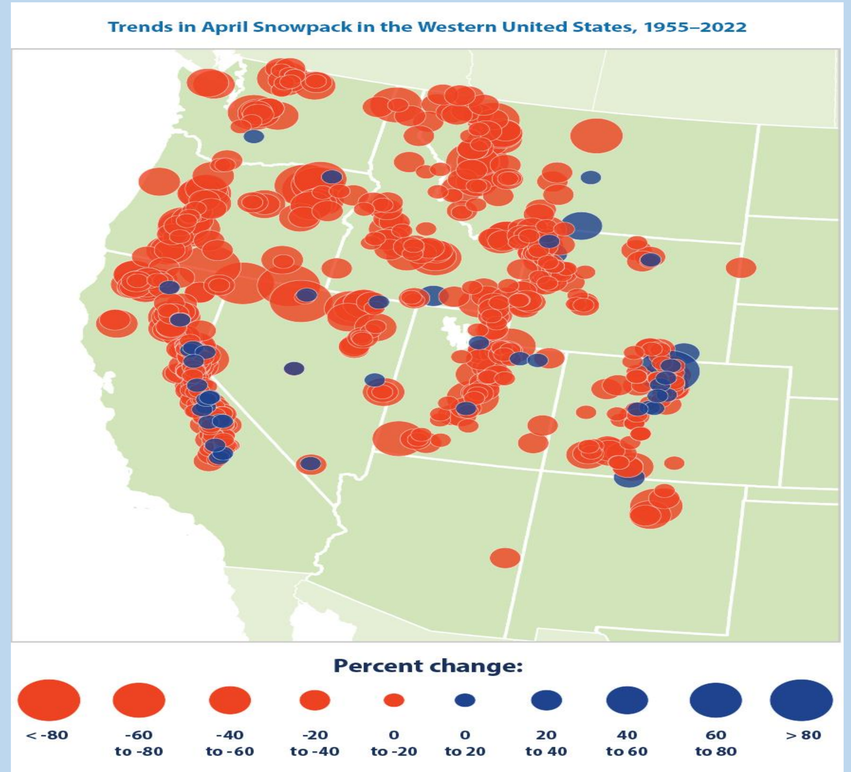


Figure 1 Percent changes in snowpack magnitude, 1955-2022. Red (blue) dots correspond to decreases (increases) in April snowpack. From US EPA (2016).

The April 1 Assumption:

- The date of peak snowpack is often assumed to be on April 1
- This is a relic of pre-automated snow monitoring in this region
- Snowpack trends and patterns are often computed using April 1
- Found to cause underestimations of peak snowpack with wide variances (Montoya et al., 2014)

2. Objectives and Hypotheses

H1: The selection of April 1 as date of peak snow water equivalent (SWE) imparts underestimations of the magnitude of peak SWE, particularly at high-elevation sites.
H2: The selection of the April 1 date masks decadal or longer-term patterns in snowpack characteristics, particularly at high-elevation sites.
H3: Peak snowmelt discharge increases with basin area in northern latitude or high elevation watersheds, but may decrease at lower latitudes and elevations.
H4: Time intervals between peak snowpack and peak snowmelt discharge increase with basin size.
Null: April 1 does not underestimate peak snowpack or affect trends; Peak snowmelt shows no relationship with basin area

3. Data & Methods: 1980-2022

Snow Telemetry Network (SNOTEL) Data:

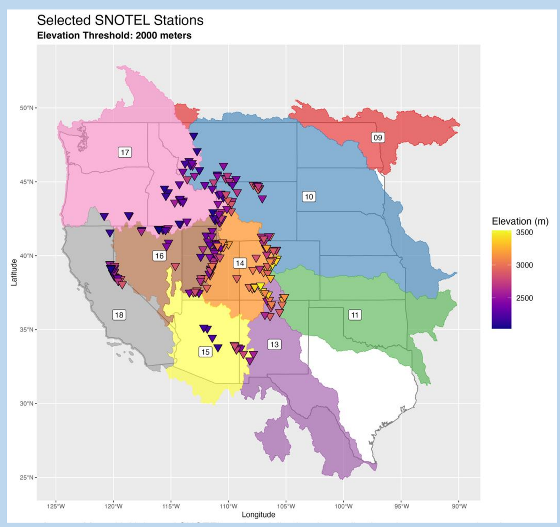
- In situ measurements of (SWE) and air temperature
- ~200 individual locations in the American West
- Daily SWE and air temperature collected (mm, °C)

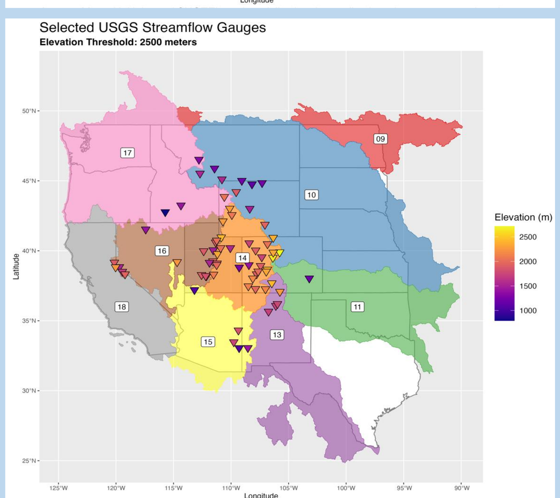
USGS Streamflow Data:

- Mean daily discharge (m^3/s)
- 99 different small watersheds (Hydrologic Unit 8, HUC8s)
- Collected discharge at the outflow point of each
- Multiple SNOTEL stations in each watershed

Pertinent Snowpack and Streamflow Characteristics:

1. Magnitude and Date of Peak SWE
2. Date of Snowmelt Onset
3. Date of Peak Snowpack
4. Snowmelt Rise Time: duration from onset to peak





Figures 2, 3, & 4 (Top Right) U.S. SNOTEL stations above 2000 m. (Bottom Right) USGS streamflow gauges for 2000 m sample. (Left) Panel plot used to pick snowmelt onset dates.

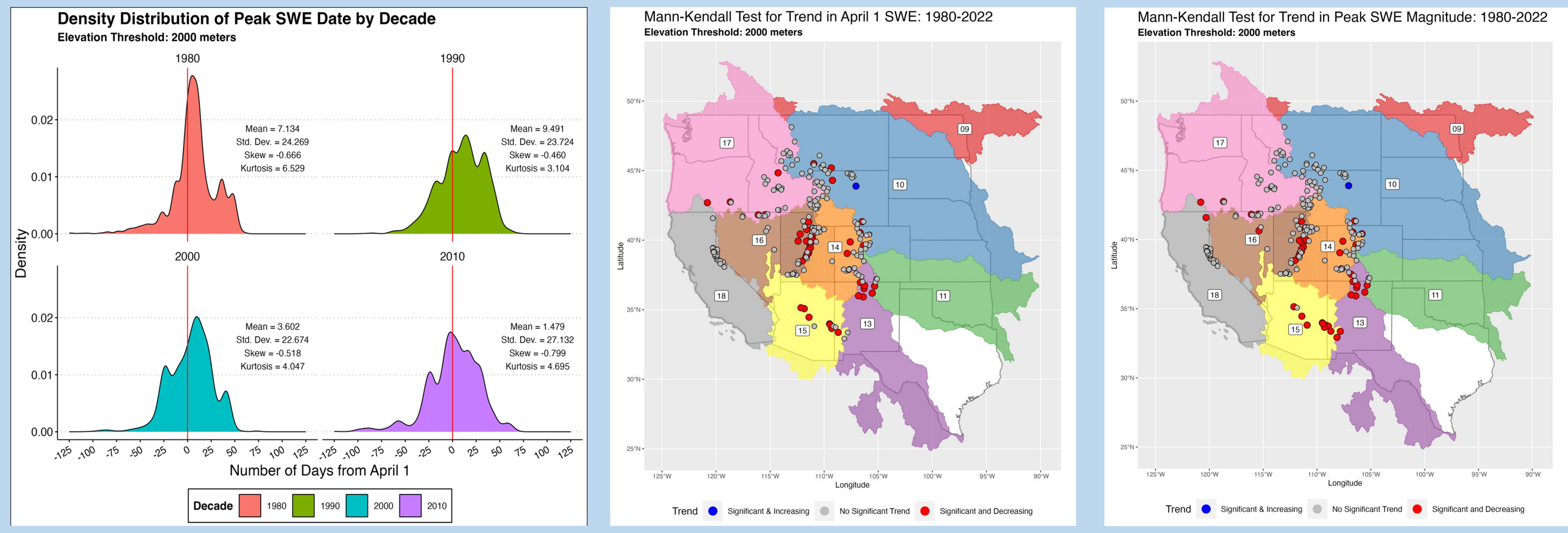
Selecting Date of Snowmelt Onset Each Year

1. Smoothed snowpack & streamflow hydrographs
2. Cumulative Frequency Distribution
3. Air Temperature Curve

Snowmelt onset is identified as the date when the discharge (green) slope steepens and air temperatures rise above 0°C. Often coincides with date of peak SWE.

4.1 Testing the April 1 Assumption

Test of the April 1 Assumption on peak snowpack trends for elevations > **2000 meters**



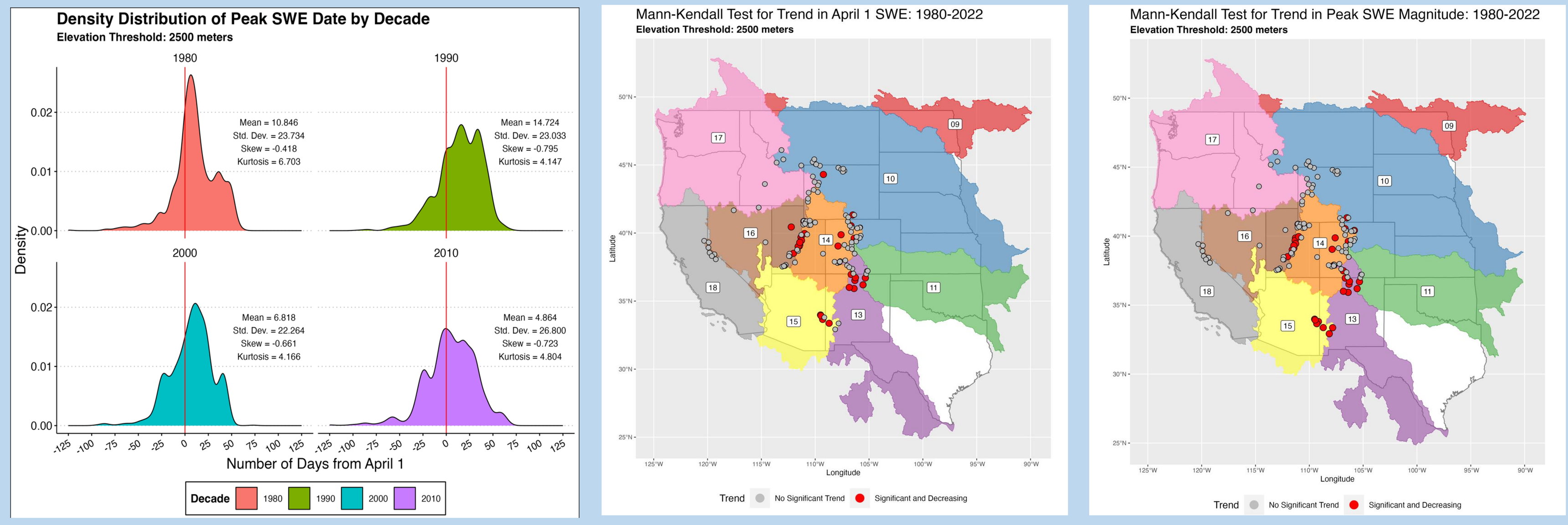
Figures 5, 6, & 7
Left: Density distributions of Peak SWE date by decade (red vertical line represents April 1)

Middle: Mann-Kendall trend test result for April 1 SWE. Blue dots are significant and increasing, red dots are significant and decreasing, grey is no trend.

Right: Mann-Kendall trend test for Peak SWE magnitude.

1. Mean date of peak SWE is later than April 1. **Sample mean is April 6**
2. Wilcoxon Test of Means: April 1 is statistically inaccurate ($p < 0.01$)
3. Mann-Kendall Test for Trend ($p < 0.05$)
   - Majority (>75%) of locations do not display significant snowpack trends
   - Highest-elevation locations show decreasing trends
4. April 1 assumption potentially produces false decreasing trends in the higher latitudes

Test of the April 1 Assumption on peak snowpack trends for elevations > **2500 meters**



Figures 8, 9, & 10
Left: Density distributions of Peak SWE date by decade (red vertical line represents April 1)

Middle: Mann-Kendall trend test result for April 1 SWE. Blue dots are significant and increasing, red dots are significant and decreasing, grey is no trend.

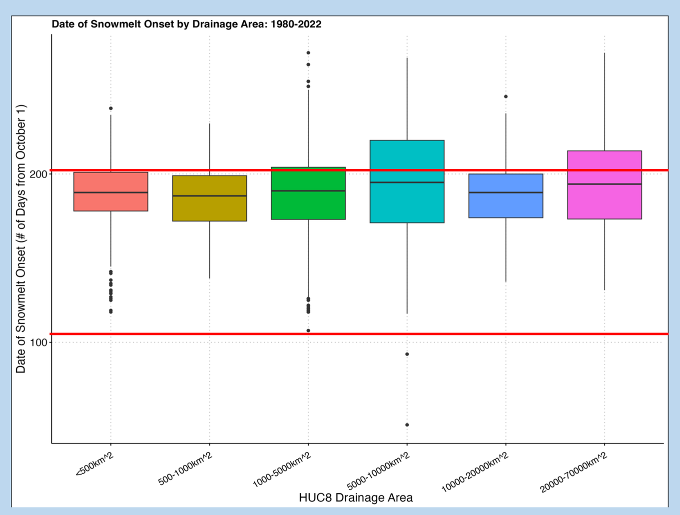
Right: Mann-Kendall trend test for Peak SWE magnitude.

1. **Mean date of peak SWE is even later: April 9**
   - Still appears to approach April 1 in each consecutive decade
2. Wilcoxon Test of Means: April 1 is again statistically inaccurate ($p < 0.01$)
3. Mann-Kendall Test for Trend
   - Majority of stations do not display significant snowpack trends (~75%)

4.2 Drivers of Snowpack and Streamflow: Latitude and Basin Area

1. Peak SWE increases exponentially with date of peak SWE
2. Both peak SWE Date and SWE magnitude increase with latitude
3. Smallest basins have weaker relationship with latitude

Figure 10 (Left) Peak SWE magnitude vs date of peak SWE. Vertical blue line represents June 8, the upper bound for peak SWE date.



1. Dates of snowmelt onset consistent across basin area
2. Snowmelt onsets concurrent with date of peak SWE
3. Largest basins have largest variability

Figure 11 (Left) Snowmelt onset dates by basin size (increasing from left to right). Bottom red line is January 9, top red line represents April 19.

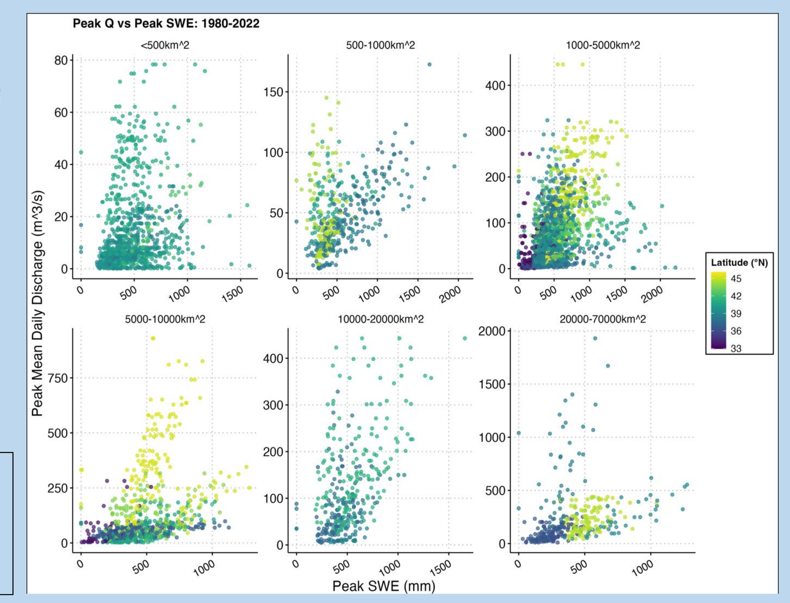


Figure 12 (Above) Peak snowmelt discharge versus peak SWE, broken up by basin area. Colored by latitude with brighter colors representing northerly locations.

1. In middle to large basins, peak snowmelt is related to latitude
2. Smallest basins have unclear relationship with latitude
3. Peak snowmelt generally increases with basin area

5. Conclusions

Hypothesis 1: The April 1 assumption was found to be statistically inaccurate at both the 2000-meter and 2500-meter elevation thresholds, supporting *H1*.

Hypothesis 2: The April 1 assumption had some influence on the interpretation of snowpack trends, most notably in the northerly stations.

Hypothesis 3: Discharge increased with basin size, but regional and elevation influences are not as clear.

Hypothesis 4: No relationship between rise time and basin area was observed, the null hypothesis is supported.

Low elevation stations were particularly susceptible to rain events and had chaotic hydrographs. This made snowmelt trends difficult to discern or compute.

Snowpack trends based on post-1980 data did not match the results shown in **Figure 1**, which were derived using April 1 as peak snowpack and combined manual and automated measurements (Mote et al., 2004 ; Mote, 2006; Mote et al., 2018). **Figure 1** includes low elevations, which are more susceptible to changing snow/rain ratios (Knowles et al., 2006). Thus, the observed trend in **Figure 1** may reflect changes in lower elevations from 1955-1980. My results shown here were based on post-1980 data.

6. Future Directions

1. Continue to address the April 1 impact on snowpack trends
   - How much underestimation of peak SWE occurs?
   - Where does it underestimate the most?

2. Consider not just high-elevation snowpacks. Trends in snowpack will become more significant as snow/rain ratios continue to change.

3. Quantitatively explore the regional variations in snowmelt characteristics as a function of latitude and basin area.

4. Establish a more rigorous set of criteria to select the date of snowmelt onset. Including region-specific criteria to account for catchments subject to complex hydrographs (Southwest, lower elevations)

7. References

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