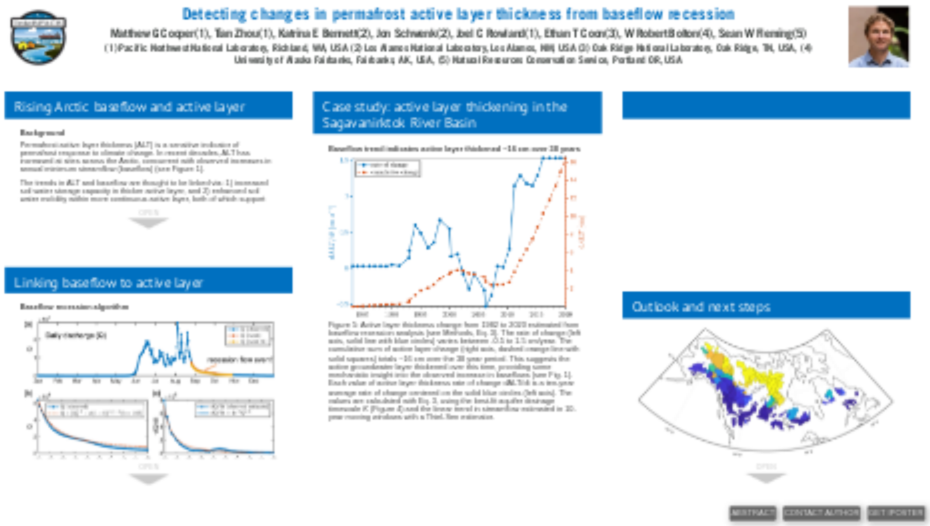
Detecting changes in permafrost active layer thickness from baseflow recession



Matthew G Cooper(1), Tian Zhou(1), Katrina E Bennett(2), Jon Schwenk(2), Joel C Rowland(1), Ethan T Coon(3), W Robert Bolton(4), Sean W Fleming(5)

(1) Pacific Northwest National Laboratory, Richland, WA, USA (2) Los Alamos National Laboratory, Los Alamos, NM, USA (3) Oak Ridge National Laboratory, Oak Ridge, TN, USA, (4) University of Alaska Fairbanks, Fairbanks, AK, USA, (5) Natural Resources Conservation Service, Portland OR, USA

PRESENTED AT:

RISING ARCTIC BASEFLOW: A RESPONSE TO ACTIVE LAYER THICKENING?

Background

Permafrost active layer thickness (ALT) is a sensitive indicator of permafrost response to climate change. In recent decades, ALT has increased at sites across the Arctic, concurrent with observed increases in annual minimum streamflow (baseflow) (Figure 1) (Smith et al. 2007).

The trends in ALT and baseflow are thought to be linked via: 1) increased soil water storage capacity in thicker active layer, and 2) enhanced soil water mobility within more continuous active layer, both of which may support higher baseflow in Arctic rivers (Evans et al. 2020).

Science question

How much has active layer thickness changed in the Sagavanirktok River basin on the North Slope of Alaska?

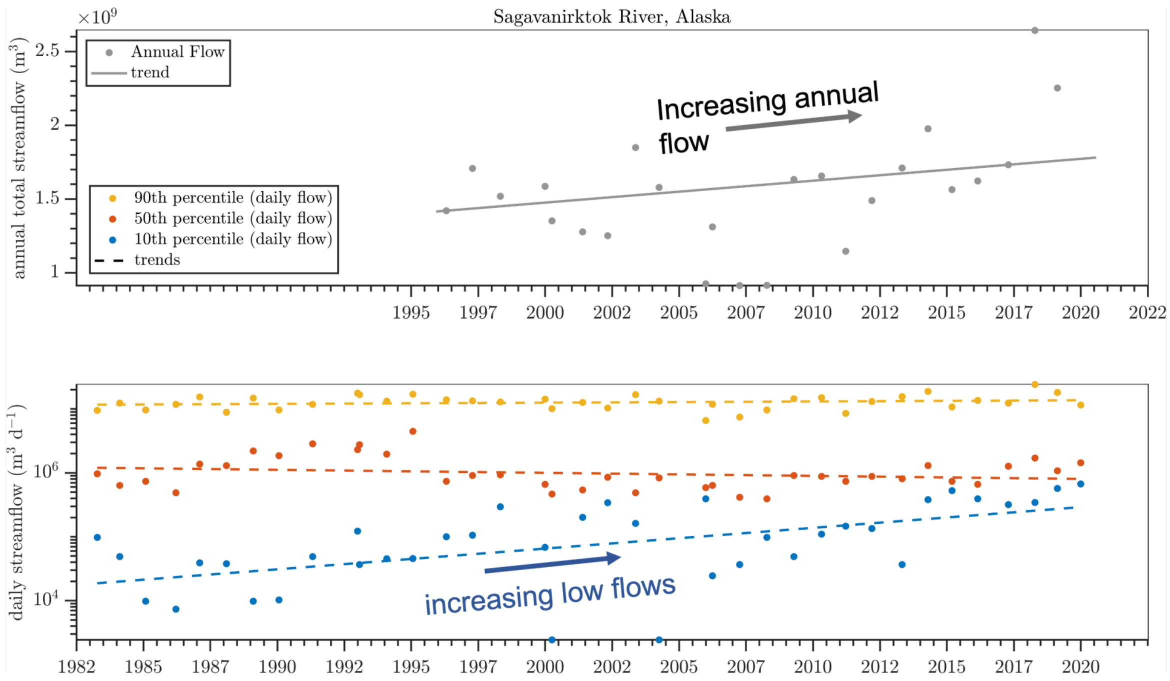


Figure 1: (top panel) Total annual flow measured at USGS gage 15908000 on the Sagavanirktok River on the North Slope of Alaska and the Thiel-Sen linear trend line over the period 1995-2020. (bottom panel) 10th, 50th (median), and 90th percentile daily flow sampled annually, and the Thiel-Sen linear trend lines in each flow quantile. Annual flows and 10th percentile daily flows (proxy for baseflows) are both increasing, consistent with observations of increased minimum flows in permafrost affected catchments globally (Smith et al. 2007)

LINKING BASEFLOW TO ACTIVE LAYER

Baseflow recession algorithm

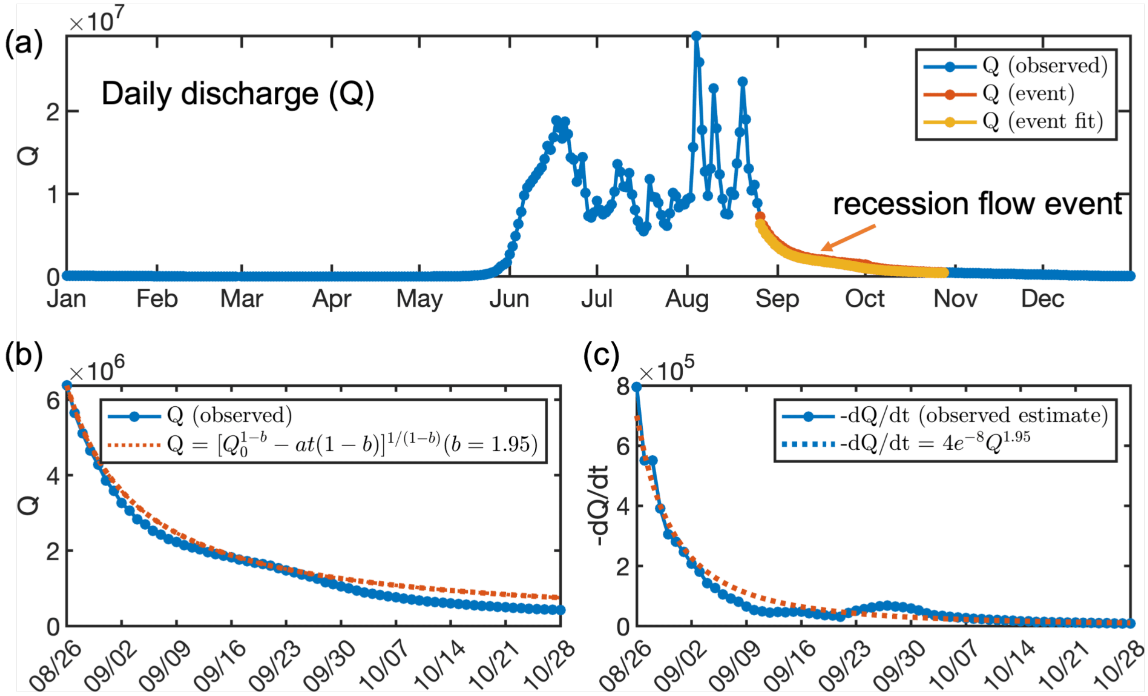


Figure 2: (a) Example of baseflow recession analysis. Recession flow events are detected using an automated algorithm applied to daily discharge data (see highlighted recession event in top panel and (b) in detail). (c) The first derivative of the recession flow is estimated using the exponential time step method (Roques et al. 2017). The parameters a and b are estimated by a curve fit to Eq. 1 using non-linear least-squares regression. Flow values predicted with the estimated parameters (orange dashed lines) are compared with observed flow (solid blue circles) in panel (b) and (c). See methods below for more detail.

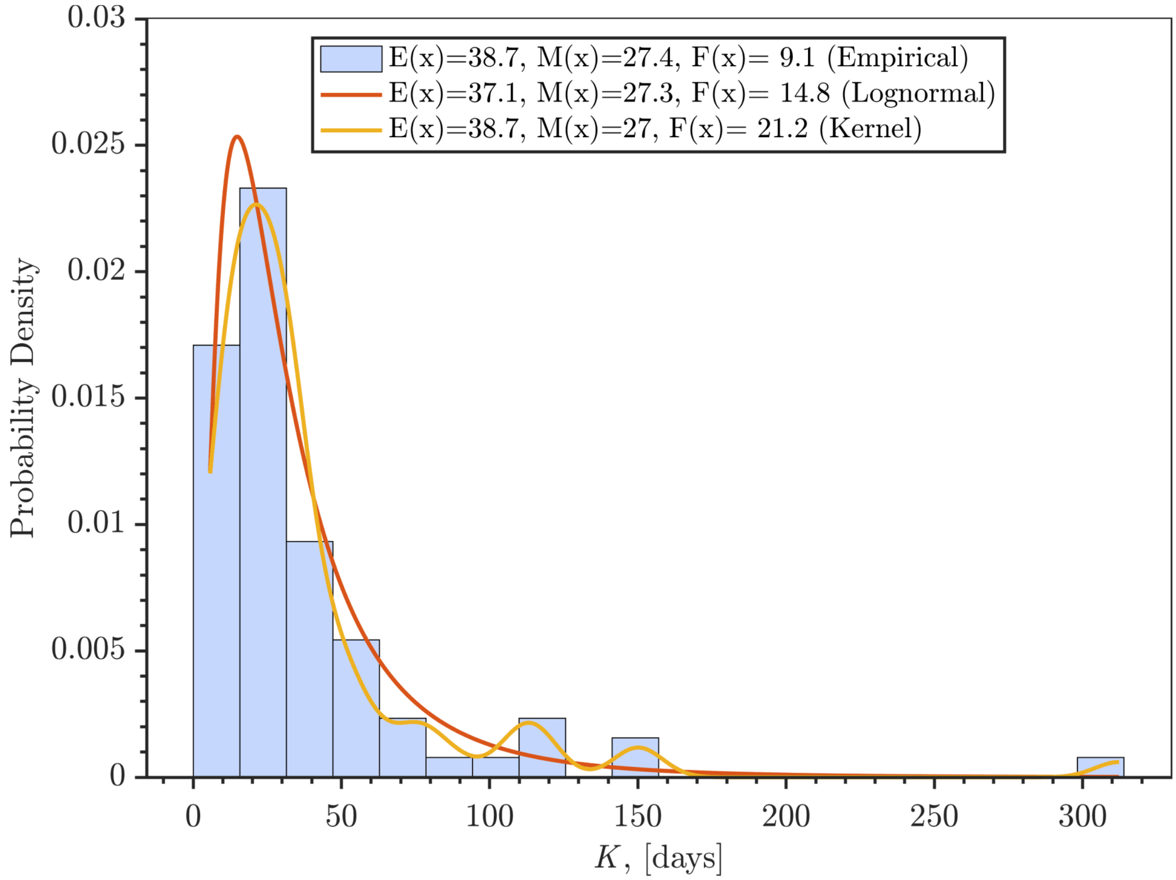


Figure 3: Distribution of fitted aquifer drainage timescale ***K*** values (N=85) (see Eq. 4, Methods) and the maximum likelihood estimate of the best-fit lognormal distribution (orange line, second down in legend) and kernel-density estimate (yellow line, third down in legend). The mean, E(x), median, M(x), and mode, F(x) of the binned data (solid bars) and each distribution (continuous lines) are shown in the legend. The mode of the Kernel density estimate (21 days) is used as a characteristic value to estimate active layer thickness change from trends in annual minimum streamflow (baseflow) (see Eq. 3, methods).

Methods

Baseflow recession analysis is a classical method in hydrology that relates groundwater storage ***S*** to baseflow ***Q*** with a power law-like relationship:

$$S = cQ^d \qquad \text{(Eq. 1)}$$

During baseflow periods when precipitation, evapotranspiration, and any other component of the water budget except baseflow and change in storage are negligible, the rate of change of streamflow can be defined as a power law of streamflow:

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = aQ^b \qquad \text{(Eq. 2)}$$

where the parameters in Eq. 1 and Eq. 2 are related as (Clark et al.2009):

$$c = [a(2-b)]^{1/(2-b)}$$

and:

$$d = 1/(2-b)$$

For the special case of a linear reservoir (***b***=***d***=1), parameters ***a*** and ***c*** carry the dimension inverse time T^{-1}. Their reciprocal $K = 1/a$ (dimension time, T) can be interpreted as the characteristic drainage timescale of the catchment aquifer, and is related to catchment aquifer transmissivity, porosity, slope, and breadth via catchment hydraulic groundwater theory. For a comprehensive discussion see Brutsaert, (2005).

The relationship between ***K*** and aquifer properties provides a physical basis for relating changes in baseflow recession to changes in the active groundwater layer in permafrost affected catchments, under the assumption that groundwater layer thickness change is proxy for active layer thickness change.

We apply baseflow recession analysis to 38 years of daily streamflow in the Sagavanirktok River Basin, a ~4800 km2 catchment that drains the north slope of the Brooks Range in Arctic Alaska. The baseflow recession analysis yields estimates of ***a*** and ***b*** that are used to estimate change in active layer from change in baseflow (Brutsaert and Hiyama, 2012):

$$\frac{\mathrm{d}ALT}{\mathrm{d}t} = \frac{K}{2\phi}\frac{\mathrm{d}Q}{\mathrm{d}t} \qquad \text{(Eq. 3)}$$

where ϕ is specific storage (-) and dQ/dt is the long-term trend in baseflow (not to be confused with dQ/dt in Eq.2, which is the rate of change of daily streamflow).

Because we apply non-linear baseflow recession analysis, we calculate the characteristic aquifer drainage timescale ***K*** from ***a*** and ***b*** to have dimension time:

$$K = \frac{1}{a}\frac{1}{2-b}Q^{1-b} \qquad \text{(Eq. 4)}$$

Maximum-likelihood estimates of ***K*** and ***b*** are obtained from distribution fits to the ensemble of recession-event curve-fits. For this purpose, a continuous log-normal distribution and a kernel-density distribution are assumed. The best-estimate kernel-density fits to ***K*** and ***b*** are used as input to Eq. 3 to estimate trends in ALT. The entire analysis is also conducted using a constant value ***b***=1 to test how this assumption, referred to as "linear reservoir theory", affects estimates of ALT change.

ACTIVE LAYER THICKENING IN THE SAGAVANIRKTOK RIVER BASIN

Baseflow trend indicates active layer thickened ~16 cm over 38 years

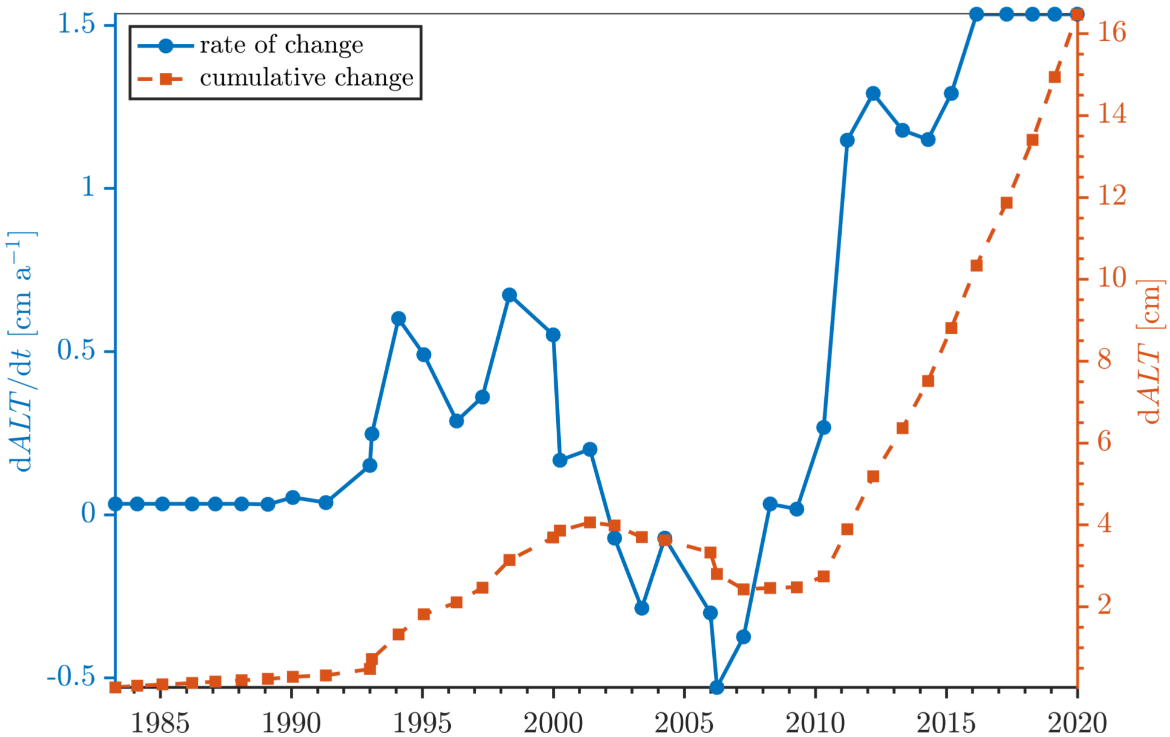


Figure 4: Active layer thickness change from 1982 to 2020 estimated from nonlinear baseflow recession analysis (see Methods, Eq. 3). The rate of change (left axis, solid line with blue circles) varies between -0.5 to 1.5 cm/year, similar to values reported for the Lena River basin over a similar timeframe (Brutsaert and Hiyama, 2012). The cumulative sum of active layer thickness change (right axis, dashed orange line with solid squares) totals ~16 cm over the 38 year period. This suggests the active groundwater layer thickened over this time, and that thicker active layer and enhanced groundwater mobility may have contributed to the observed increase in baseflows (see Fig. 1). Each value of active layer thickness rate of change dALT/dt is a ten-year average rate of change centered on the solid blue circles (left axis). The values are calculated with Eq. 3, using the best-fit aquifer drainage timescale *K* (see Fig. 3) and the linear trend in streamflow estimated in 10-year moving windows with a Thiel-Sen estimator.

LINEAR RESERVOIR ASSUMPTION SUGGESTS LESS ACTIVE LAYER THICKNESS CHANGE

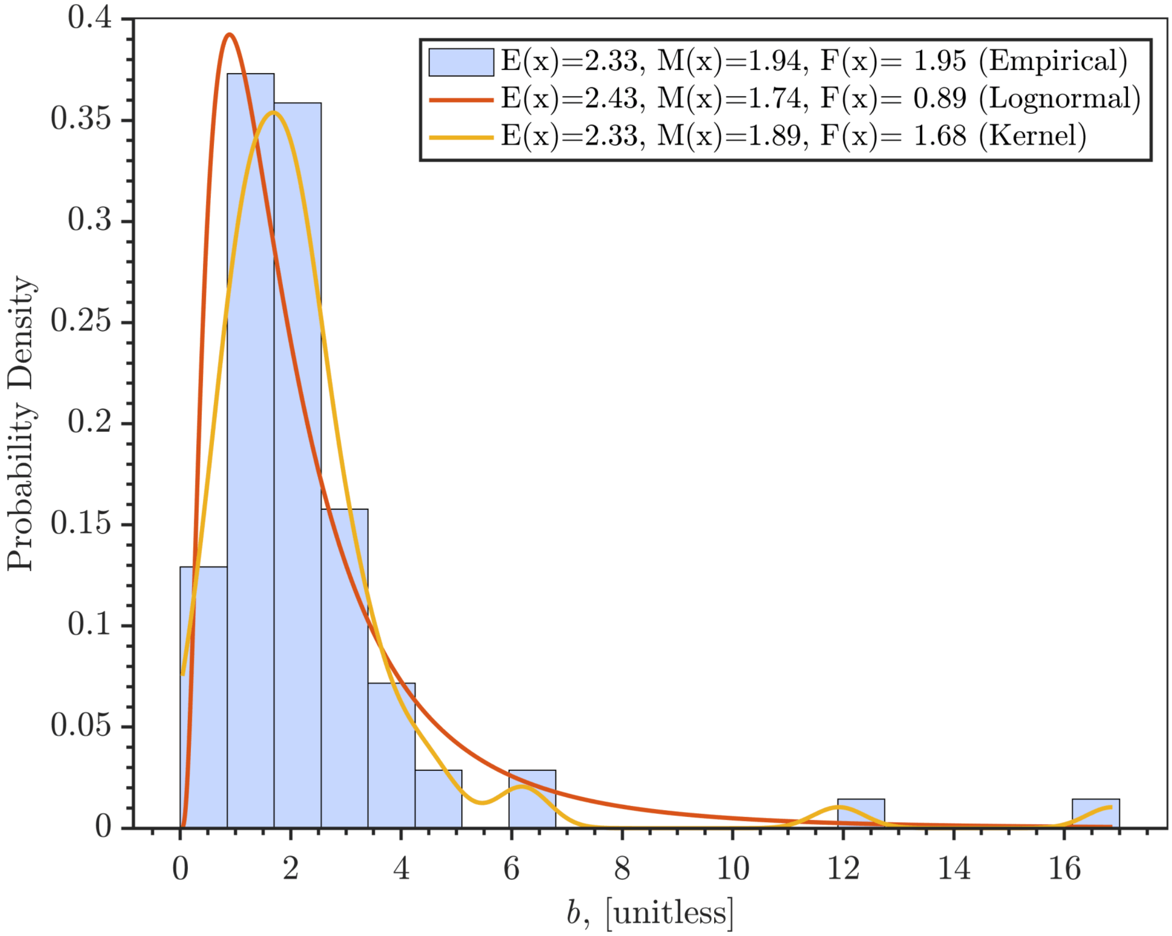


Figure 5: Distribution of fitted ***b*** values (N=85) from non-linear-reservoir recession analysis and the maximum likelihood estimate of the best-fit lognormal distribution (orange line, second down in legend) and kernel-density estimate (yellow line, third down in legend). The mean E(x), median M(x), and mode F(x) of the binned data (solid bars) and each distribution (continuous lines) are shown in the legend. The mode of the kernel-density estimate (1.68) is used as a characteristic value for ***b***. The recession events are then fit a second time using a constant value ***b***=1.7 to estimate variability in the parameter ***a***, from which the characteristic drainage timescale ***K*** is estimated (see Fig. 3). In linear-reservoir recession analysis, a constant value ***b***=1.0 is assumed a-priori, and all recession curves are fit as a one-parameter model in ***a***. Real-world catchment behavior is typically better approximated by non-linear reservoir theory, suggesting that inferences about ALT change derived from baseflow recession analysis may be sensitive to this methodological decision (see Fig. 6, next figure).

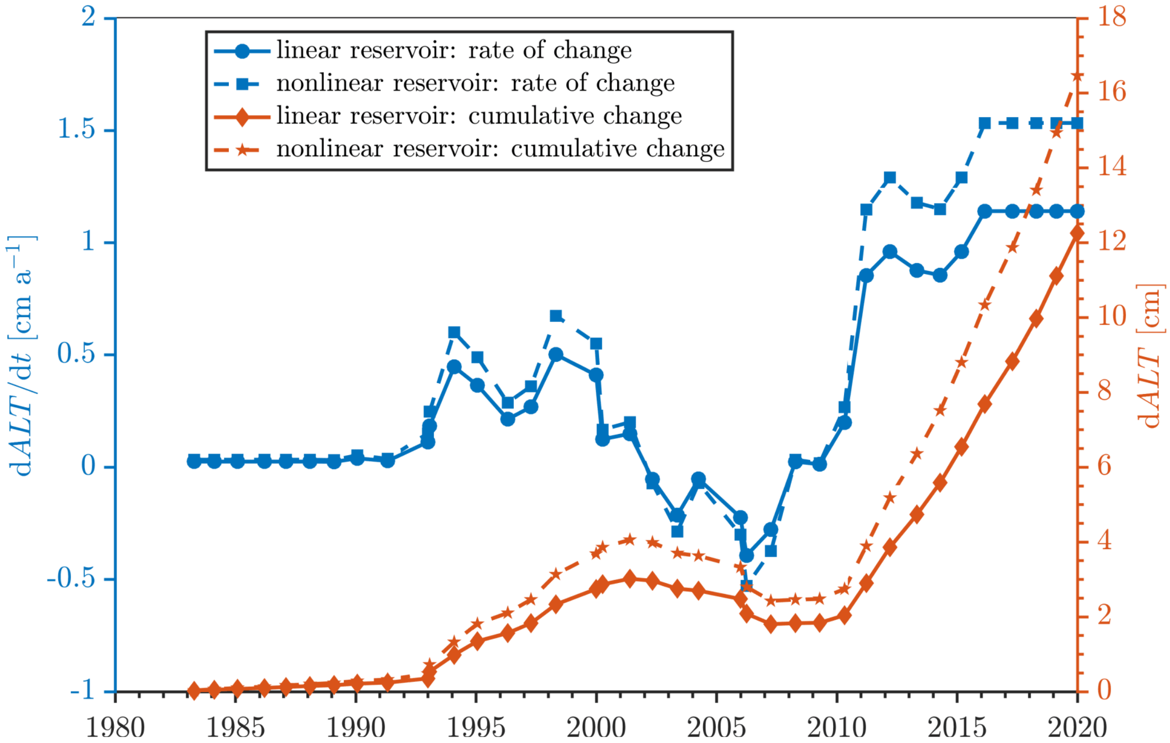


Figure 6: Comparison of active layer thickness change inferred using linear reservoir recession analysis vs non-linear analysis (as in Figure 4). Here, non-linear recession analysis suggests higher rates of ALT change than linear recession analysis. In non-linear recession analysis, the exponent ***b*** is allowed to vary. Or, as in our method, ***b*** is allowed to vary, and then a best-estimate value is obtained by fitting a distribution to all ***b*** values. This best-estimate is then held constant and all recession curve-fits are repeated so that variation in ***a*** drives variation in fitted recession behavior and inferred aquifer properties (Dralle et al. 2017).

CONCLUSIONS AND NEXT STEPS

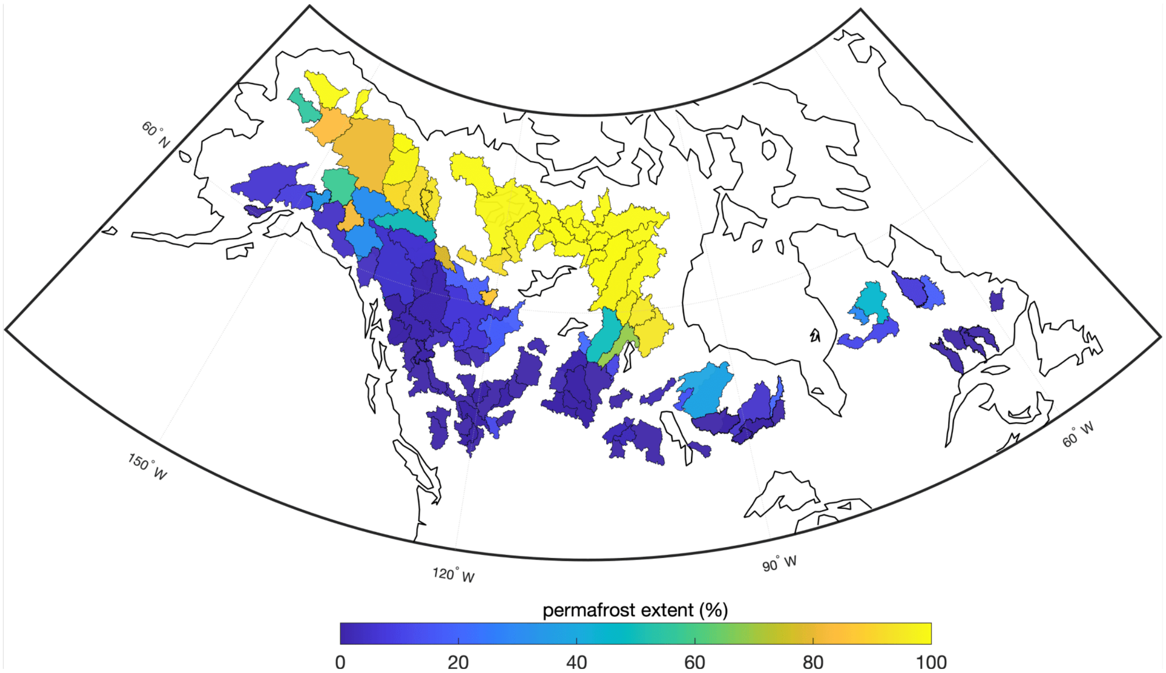


Figure 7: Catchment delineations for 123 river basins in North America shaded by permafrost extent probability (Obu et al., 2019). Daily streamflow data for each catchment shown in this map will be used as input to the baseflow recession analysis algorithm to infer changes in permafrost active layer and associated subsurface controls on baseflow recession.

Conclusions

- Rising baseflows in the Sagavanirktok River Basin on the North Slope of Alaska are consistent with rising baseflows observed in permafrost-affected areas of Northern Eurasia.
- The baseflow trend, combined with the aquifer drainage timescale estimated from non-linear-reservior baseflow recession analysis, suggests the active groundwater layer thickened by ~16 cm between 1983–2020. If linear-reservoir theory is used, the inferred thickness change is ~12 cm.
- Increased groundwater storage in the active layer, and more continuous flow paths through the active layer, may explain rising baseflows in the Sagavanirktok River. More work is needed to corrorborate these findings in permafrost affected catchments across North America.

Acknowledgements

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ABSTRACT

Permafrost active layer thickness (ALT) is a sensitive indicator of permafrost response to climate change. In recent decades, ALT has increased at sites across the Arctic, concurrent with observed increases in annual minimum streamflow (baseflow). The trends in ALT and baseflow are thought to be linked via: 1) increased soil water storage capacity due to an increased active layer, and 2) enhanced soil water mobility within a more continuous active layer, both of which support higher baseflow in Arctic rivers. One approach to analyzing these changes in ALT and baseflow is to use baseflow recession analysis, which is a classical method in hydrology that relates groundwater storage S to baseflow Q with a power law-like relationship $Q = aS^b$. For the special case of a linear reservoir (b=1.0), the baseflow recession method has been extended to quantify changes in ALT from streamflow measurements alone. We test this approach at sites across the North American Arctic and find that catchments underlain by permafrost behave as nonlinear reservoirs, with scaling exponents b~1.5–3.0, undermining the key assumption of linearity that is commonly applied in this method. Despite this limitation, trends in a provide insight into the relationship between changing ALT and changing Arctic baseflow. Although care should be taken to ensure the theoretical assumptions are met, baseflow recession analysis shows promise as an empirical approach to constrain modeled permafrost change at the river basin scale.

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