Regionalized active layer thickness trends from nonlinear baseflow recession

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Abstract

Thawing of permanently frozen ground (permafrost) has increased in recent decades with negative implications for human and non-human adaptation to climate change. Impacts include reduced ground stability, increased transportation risk, and changes in water availability. Direct measurements of permafrost active layer thickness (the depth of thawed ground overlying permafrost) are sparse. Measurements currently exist for a few hundred sites located primarily in the Northern Hemisphere supported by the Circumpolar Active Layer Monitoring (CALM) Program. The sparsity of direct active layer thickness measurements limits broad-scale understanding of changes in permafrost thaw and confidence in future projections. To address the sparsity of direct active layer thickness measurements, we developed a method to estimate active layer thickness change from streamflow measurements, which integrate processes over broad spatial areas and are more common than point-scale active layer thickness measurements. The method uses classical principles of hydraulic groundwater theory and nonlinear baseflow recession analysis, which sets it apart from prior methods based on linear recession analysis. The method is applied to catchments in the continuous and discontinuous permafrost zone of the North American Arctic containing co-located streamflow and CALM active layer thickness measurements. We find good agreement in the magnitude and direction of measured and predicted active layer thickness trends. This suggests that regional-scale estimates of active layer thickness change can be obtained from streamflow measurements, which may open the door to retrospective estimation of active layer thickness change in data sparse Arctic regions with short, sporadic, or even nonexistent ground-based active layer measurements.

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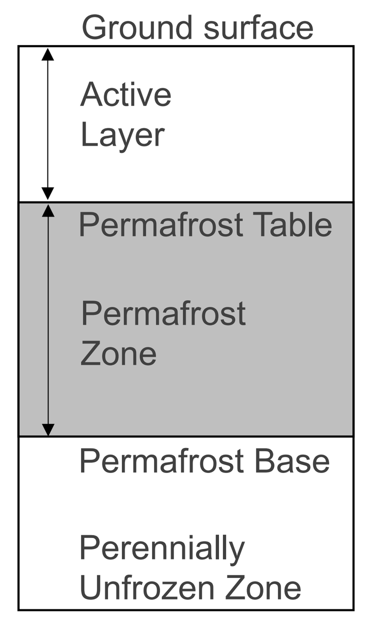
Baseflow trends indicate active layer is thickening ~0.3 cm a^{-1} in Northwest American Arctic and Subarctic river basins

Overview

Permafrost active layer thickness (ALT) is increasing as the climate warms[1,2], but direct measurements of ALT are limited to a few hundred sites primarily in the Northern Hemisphere supported by the Circumpolar Active Layer Monitoring (CALM) program[1]. To address the sparsity of direct ALT measurements, we developed a method to estimate ALT change from streamflow measurements[3]. This is useful because streamflow measurements integrate processes over broad spatial areas and exist in regions that lack direct ALT measurements. An application of the method to 20 river basins (Fig. 1) located along a permafrost extent gradient in North America is presented here.



Permafrost diagram (after Kurylyk *et al* 2014).

Methods and Data

Baseflow recession analysis is a classical method in hydrology commonly used to estimate groundwater layer thickness from daily fluctuations in streamflow[4]. In permafrost-affected landscapes, the groundwater layer thickness can be considered as a proxy for the active layer thickness[5]. We derived a relationship between interannual groundwater layer thickness change and interannual baseflow change using the principles of baseflow recession analysis[3]:

$$\hat{\phi}\frac{\mathrm{d}\eta}{\mathrm{d}t} = \frac{\langle\tau\rangle}{4-2\hat{b}}\frac{\mathrm{d}Q}{\mathrm{d}t} \quad (1)$$

where ϕ is drainable porosity, η is groundwater layer thickness, τ is a drainage timescale that represents the sensitivity of streamflow to groundwater storage changes, b encodes the degree of nonlinearity in the storage-discharge relationship, and Q is baseflow. The essential parameters $\langle\tau\rangle$ and $\hat{b}$ were estimated from Pareto distribution fits to populations of τ-values generated from nonlinear baseflow recession analysis applied to measured streamflow (Fig. 1).

Streamflow, Active Layer Thickness, Permafrost Probability, and Geomorphic Data

Streamflow data for 20 river basins in the Northwest (<125 °W) American Arctic and Subarctic zones with at least one CALM site were used for baseflow recession analysis (Fig. 1, 3). Ten basins with >10 years of overlapping streamflow and ALT data were used for validation of Eq. 1 (Fig. 2). Drainage area, drainage density[6] (channel length per unit area), and permafrost extent probability[7] were extracted for each basin to test regionalization of recession behavior (Fig. 4).

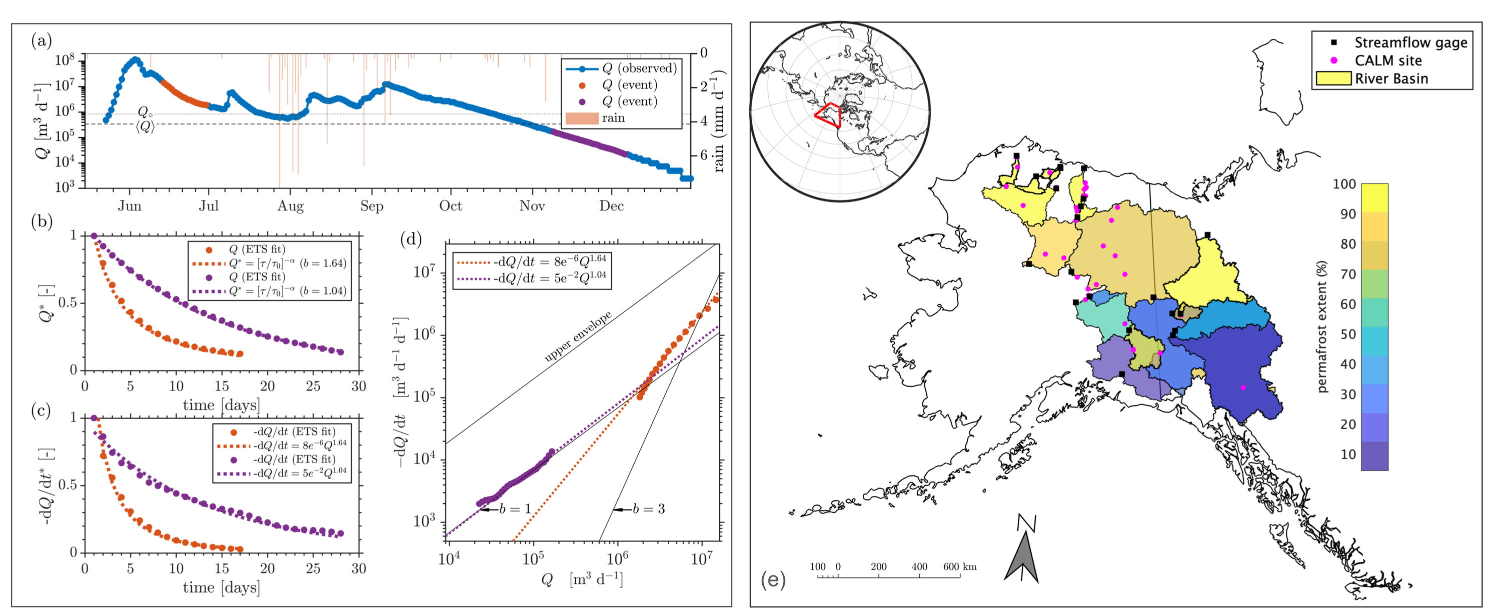


Figure 1. (a–d) Example baseflow recession analysis to estimate essential hydraulic parameters a, b, and τ from recession events identified on daily hydrographs. (b) North American Arctic/Subarctic study area with CALM[1] sites, streamflow gages, and permafrost extent probability[7] mapped on river basin outlines. The method in (a–d) was applied to daily streamflow measured at each streamflow gage in (e) to infer active groundwater layer thickness trends from Eq. 1 and then compared with trends in measured ALT from CALM sites (Fig. 2).

Results

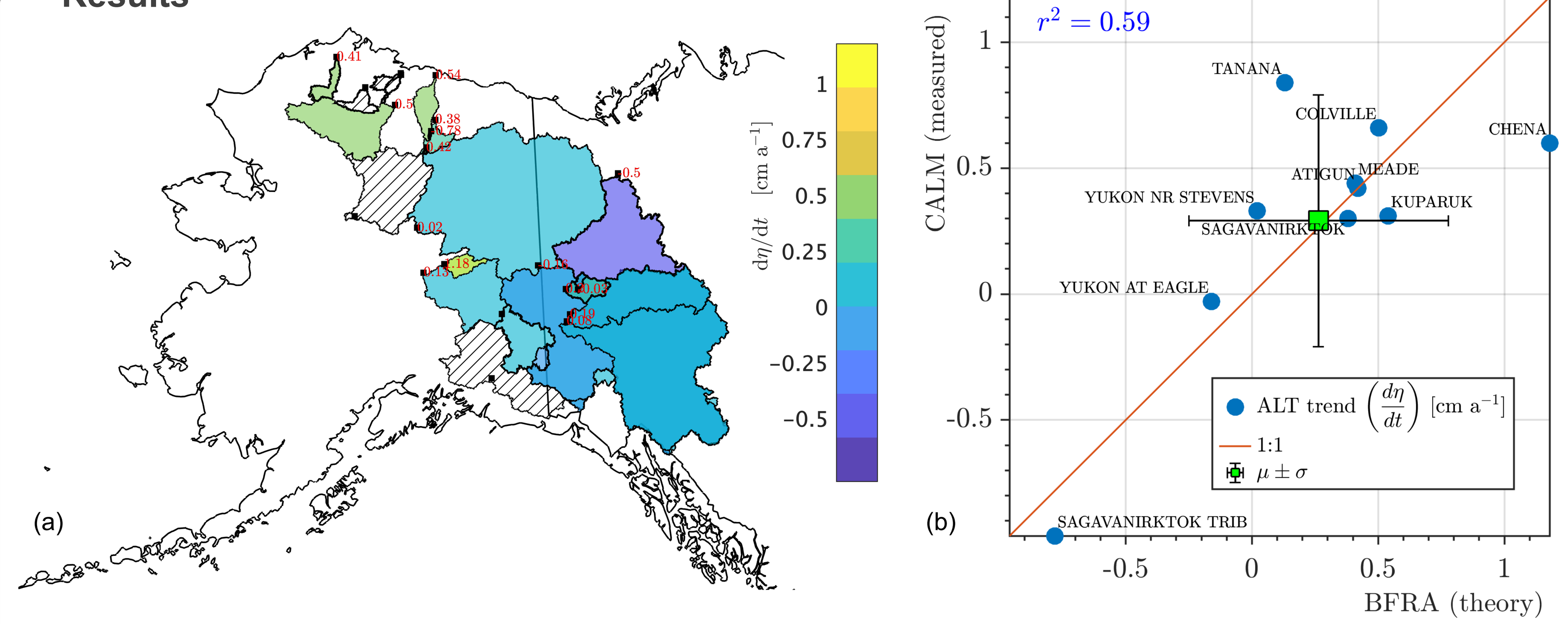


Figure 2. (a) Linear trends in active groundwater layer thickness estimated from baseflow recession analysis mapped on river basin outlines (trend values are printed in red text). Five basins with <10 years of streamflow data are omitted from the trend analysis (hatched outlines). (b) Linear trends in active layer thickness (ALT) from field measurements at Circumpolar Active Layer Monitoring (CALM)[1] sites compared with trends in active groundwater layer thickness predicted with baseflow recession analysis (BFRA) (Eq. 1) for sites with >10 years of overlapping streamflow and ALT data. Correlation coefficient (r^2) is printed in upper left. The mean (± one standard deviation) (green square) is 0.26±0.54 cm per year (cm a^{-1}) for basin-scale BFRA predictions and 0.29±50 cm a^{-1} for plot-scale CALM measurements.

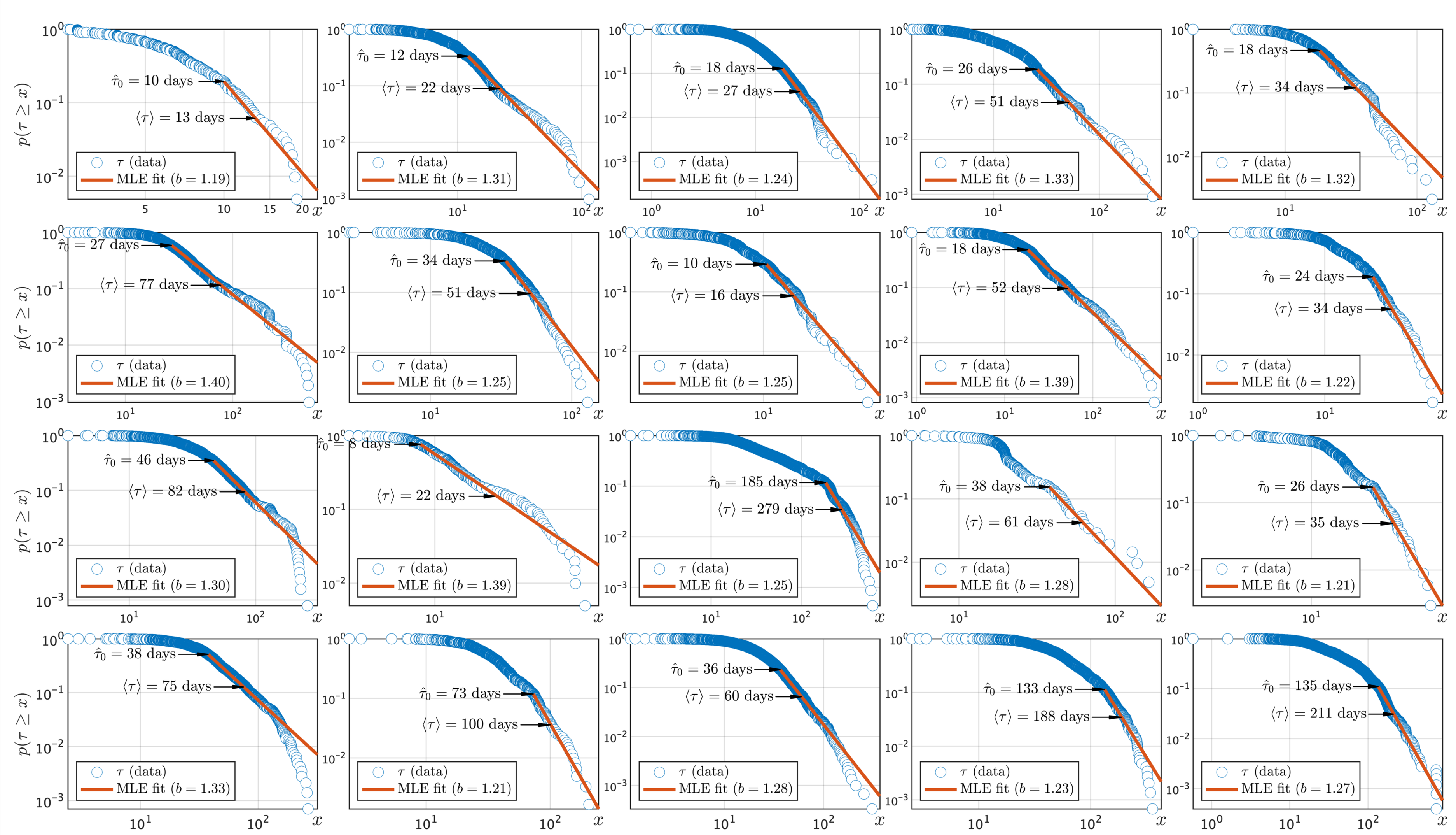


Figure 3. Pareto distribution fits to drainage timescale τ from baseflow recession analysis for 20 river basins (Fig. 1). The tail of the distribution is controlled by recession parameter b. Together with the baseflow trend and porosity (not shown), τ and b are essential inputs to Eq. 1. Panels are ordered from high to low drainage density (D_d) (upper left to lower right). The expected value $\langle\tau\rangle$ tends to increase as D_d decreases, indicating that basins with fewer channels per unit area have larger τ-values, which reflects greater influence of slow groundwater drainage relative to fast surface-water drainage.

Discussion

The rate of change of baseflow is fundamentally linked to the amount of water stored in upstream catchment aquifers, which can be imagined as a layer of water spread evenly over a river basin[5]. We estimated the thickness of this "active groundwater layer" in Northwest American Arctic and Subarctic river basins using baseflow recession analysis (Fig. 1) and found good correlation with plot-scale measurements of actual active layer thickness (Fig. 2). Relationships between hydraulic parameters τ and a appear to be mediated by geomorphic parameters drainage density D_d and L^* (Fig. 3 and Fig. 4), which suggests a hidden regularity that underlies streamflow recession in permafrost-affected river basins and deserves further attention.

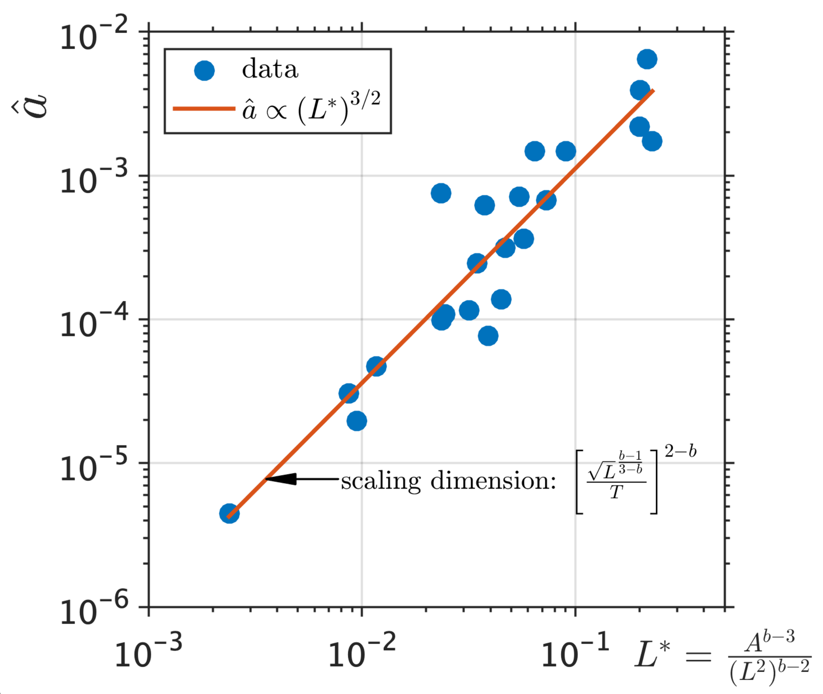


Figure 4. Scaling relationship between length scale L^* and recession parameter $\hat{a}$. L^* reflects the influence of stream channel length L and basin area A on streamflow recession. Groundwater theory predicts a power-law between L^* and $\hat{a}^4$, validated here at the regional scale, where $\hat{a}$ is the intercept of the event-scale recession equation $-dQ/dt = aQ^b$ (Fig. 1d) and is related to drainage timescale $\tau = a^{-1}Q^{1-b}$. This relationship reveals a hidden regularity underlying streamflow recession behavior and an initial inroad into regionalization of active groundwater layer thickness in permafrost-affected regions.

Conclusions

- We estimated permafrost active layer thickness change from baseflow recession for river basins along a permafrost gradient in Northwest America (Fig. 1).
- Results indicate that the active layer thickened ~0.26 cm a^{-1} between 1990–2020.
- Direct field measurements from Circumpolar Active Layer Monitoring (CALM)[1] sites indicate the active layer thickened ~0.29 cm a^{-1} between 1990–2020.
- The correlation between basin-scale predictions and plot-scale measurements (Fig. 2) suggests that baseflow recession can provide active layer thickness trends for regions or time periods lacking direct active layer measurements.
- Future work will test if regionalization of recession behavior using geomorphic parameters (Fig. 4) holds across different climatic settings.

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