

## ***Interactive comment on “Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis” by S. W. Lyon et al.***

**S. W. Lyon et al.**

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Overall, this reviewer finds the research and approach taken in this study interesting. The reviewer concedes that 'there has been significant thaw (as validated by direct field observations)' in the catchment, but questions if 'this recession analysis is appropriate to discern a thaw rate' and questions whether the recession flow analysis can capture the complex nature of permafrost thawing at the catchment scale. We provide a detailed response to all the reviewer's comments in the following response.

### **Comment on the approach being too simple**

The reviewer voices concern that 'the method outlined here is highly equivocal and some of the associated data point to a much more complex picture'. The reviewer comments that the method would make more sense to a continuous permafrost catchment, but that the complex geo-hydrologic nature of discontinuous permafrost excludes

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such a simple recession analysis approach.

*Response:* While process conceptualization may be more straightforward for a continuous permafrost layer, the aim and strength of the recession flow analysis is its ability to capture the **integral effect** of the process complexity present in a catchment's subsurface on the catchment's runoff recession characteristics with a much simpler set of equations than if all the complexity components were modeled in detail. Kirchner (2009) demonstrated that if a catchment can be represented by a single storage element in which discharge is a function of storage alone, the form of this storage-discharge function can be estimated from analysis of streamflow fluctuations. When permafrost thaws (as has been observed in this catchment) the storage-discharge relationship function of the catchment (regardless of its having continuous or discontinuous permafrost) will change (more mobile water, different locations where water is stored and released, etc). The proposed recession flow analysis in this paper quantifies the likely direction and also presents the possibility to quantify the rate of change. For the latter, one must assume how catchment properties are related to the storage-discharge dynamics and we show how this can be done for quantifying a possible thawing rate.

The reviewer does not express doubt that permafrost thawing has been and is occurring in this catchment, and this paper shows that: a) the runoff data series from the catchment is fully consistent with the recession flow analysis indication of how runoff characteristics should change if permafrost thawing is occurring, and b) the estimated permafrost thawing rate by the recession flow analysis is fully consistent with entirely independent thawing rate estimates for this area. As is commonly the case in geosciences, these positive results do not prove that recession flow analysis is generally applicable for detection and quantification of permafrost thawing, but they certainly do not disprove it either. The large benefits of the possible relatively simple detection and quantification of permafrost-thawing from commonly available runoff data series should be sufficient for accepting publication of this paper and allowing other investigators to further test the applicability of recession flow analysis for this purpose; the fact that

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a useful analysis can be simple is generally considered as a beauty and benefit of science and not as a drawback.

### **Comment on references to previous work**

The reviewer comments that the original manuscript lacks a proper representation of the hydrological cycle and runoff pathways in this environment. Specifically, the reviewer requests references to be included on previous work relating changes in recession coefficients as the seasonally thawed active layer thickens and deeper (and slower) runoff pathways are activated.

*Response:* This is a valid comment and we have, thus, included a literature review of such research as follows in the revised manuscript (Introduction, Paragraph 4):

'Previous process-based studies have used flow and recession characteristics to help quantify the response of and characterize the hydrologic processes of arctic and sub-arctic hydrologic systems. Dingman (1966, 1973) used hydrograph characteristics to describe the influence of permafrost position on formation of high water tables leading to surface runoff. Ice layers at the interface of the organic and mineral soils have often been cited as the main cause of lateral runoff (Kane et al., 1981; Roulet and Woo, 1988; McNamara et al., 1997), with much research emphasizing their role in water storage and restriction of transmittance properties (Santeford, 1979; Slaughter and Kane, 1979; Hinzman et al., 1993; McNamara et al., 1998). Subsurface flow can, thus, become a main mechanism for the rainfall-runoff generation on mountainous slopes (Kuchment et al., 2000). Carey and Woo (2001) used recession analysis to identify contributing areas to runoff production, which varied greatly between events. Yamazaki et al. (2005) looked at recession gradients and attributed monthly variations to seasonal changes in active layer thickness. While such studies have advanced our understanding of the hydrologic processes that occur in arctic and sub-arctic regions, they have often been limited to relatively short (typically <10 years) of observations and, thus, unable to investigate the long-term responses of arctic and sub-arctic systems to changes in climate (Woo et al., 2008).'

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Much of this previous work thus focuses on the recession gradient term and is based on a limited number of events or a short period (<10 years) of observation. Our study is novel in that it takes advantage of a long record of observation with focus on the intercept term of the recession flow expression. We have highlighted this throughout the revised manuscript.

### **Comment on seasonal variability effects**

The reviewer comments that, due to previous research that highlights seasonal variability in recession coefficients as a reflection of changes in active layer thickness, 'it is difficult to use binned data to detect long-term trends, even if they are integrated over several month periods'.

*Response:* The 'binning' we perform, in effect, encapsulates 5 years of late summer recession flows. The observed significant positive linear trend still holds when we evaluate on 'binning' based on 10 years of late summer recession flows (see original manuscript, Pg 70 Ln 12). This consistency over different 'binning' scales points to long-term changes in the recession intercept value, independently of possible seasonal variations. Seasonal variations in recession coefficients could, in fact, explain the more 'short-term', high frequency variations observed in our recession flow analysis (Figure 3). This is something that would warrant further research.

### **Comment on terminology**

The reviewer requests that the terminology in the manuscript be made more consistent with that used in existing permafrost literature, suggesting that the 'statement that there is no mechanism involved to decrease the original pre-thawing groundwater flow or depth ignores large inter-annual variations in active layer thaw'.

*Response:* We have clarified this statement in the revised text to reflect that we are considering long-term trends. We have, thus, inserted the following sentence in the revised manuscript: 'This is, of course, considering permafrost thawing as a long-term process, in addition to the seasonal fluctuations of the active layer.' In addition, we have

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made our terminology consistent with previous research throughout the manuscript.

### **Comment on hydraulic conductivity**

The reviewer questions the assumption of little variance in hydraulic conductivity with depth into the soil profile.

*Response:* We agree with the reviewer that much research suggests a likely decay (typically assumed exponential) of hydraulic conductivity with depth. Our assumption (paraphrasing the original manuscript at Pg71, Ln 25) is that, in the depth region where thawing occurs, the change in hydraulic conductivity with depth is relatively constant compared with the change close to the surface (assuming some type of exponential decay with depth). This implies a relatively small change in hydraulic parameters in the relevant depth region (clearly added to revised text).

Note also that, to explain the trend found in our recession flow analysis, an increase rather than a decrease in hydraulic conductivity with depth is required (see Equation 3). So, if one wishes to interpret the present results in terms of hydraulic conductivity change with depth, one would have to explain a depth-increase in hydraulic conductivity, which (as pointed out by the reviewer) would be 'in fact against all published literature for subarctic and organic-mantled permafrost soil'. Therefore, it appears that the observed change in recession flow intercept over the long-term analysis performed in this study should be attributed to catchment characteristics like those quantified in Equation 3 rather than to hydraulic conductivity change with depth. This supports the assumptions made in the original text. We have added text demonstrating this (Discussion and result comparison, Paragraph 3).

### **Comment on absolute flow changes**

The reviewer comments on the use of changes in flow volume to infer increasing storage at the catchment scale, as has been done in previous research.

*Response:* Change in storage is precisely what is captured through the recession flow analysis. Observation of such storage changes via changes in total magnitude of flows

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(or winter flows) is arguably more difficult. Namely, stream flows are the integral products of many different subsystem fluxes within a catchment, of which all may change in a changing climate. This makes it difficult to relate absolute stream flow changes to a specific individual subsystem flow change. An advantage of using the recession flow analysis outlined in this study is that it indicates a process function change (the recession flow intercept), rather than an absolute flow change, and thereby allows detection of permafrost changes independently of the absolute stream flow changes that integrate and thus may mask different subsystem flow changes within a catchment.

As the reviewer points out, several studies in North America and Russia have used increases in winter flows as evidence of permafrost thawing. This follows the logic that 'thawing leads to deeper flow paths and percolation and more recharge, etc.' It must be noted, however, that there is no inherent link between thawing permafrost and increased recharge. Without good knowledge of the spatial distribution of permafrost and recharge areas, it is difficult to assume *a priori* what influence permafrost thawing will have on recharge and (subsequently) winter flows. The observed decreases in winter flows in this study, in spite of direct observations of thawing permafrost, speak directly to this point. There is permafrost thawing occurring (confirmed via direct permafrost observation) and, yet, at the same time decreasing winter flows over the past 90 years. This fact has nothing to do with us using or not using a recession flow analysis.

What could these decreasing winter flows mean? If we assume that winter discharge derives from deeper groundwater reservoirs, decreasing flows indicate that this reservoir receives less input. Due to the discontinuous permafrost in the Abiskoajokken catchment, there is always recharge to this deeper reservoir, but because of increasing temperatures, the P-ET balance may decrease. As the summer flows do not have a significant downward trend, this can only mean that the total recharge decreases. The latter assumes that summer streamflow is dominated by shallow subsurface flow above the growing active layer. This assumption is supported by the higher DOC in summer (release from organic soils) and higher alkalinity in winter (release from deeper inorganic

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aquifers) (see supplemental material). Thus, 'quick' shallow subsurface flow compensates for decreasing 'slow' groundwater flow, which continues during summer since the slow reservoir never shuts down.

### **Comment on multi-catchment validation**

The reviewer concludes that 'for this methodology to be validated in any manner, it MUST be utilized in other permafrost catchment where similar data exists'.

*Response:* We agree that the methodology outlined in this study requires additional testing and application in catchments of various sizes and in catchments underlain by permafrost of various qualities. This is stated in the original manuscript at Pg 75, Ln 8 as 'future work is needed to test this approach in other catchments containing permafrost to determine its general applicability across different geomorphologic and climatic settings'. This initial study in Abiskoajokken, however, applies the methodology taking advantage of quite a unique dataset covering 90 years of hydrologic and climatic observations and 29 years of direct permafrost observation. This provides a useful first proof-of-concept for the possible application of recession flow analysis for estimating catchment-scale permafrost thawing. We have attempted to highlight this throughout the revised manuscript.

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