HOW DOES HILLSLOPE DRAINAGE EVOLVE DURING ACTIVE LAYER THAW ?

Gabriel C. Poirier[1], Jan Franssen[1], Pierre Legendre[2]

[1]Watershed Science Research Group, Département de géographie, Université de Montréal

[2]Département de sciences biologiques, Université de Montréal

Université de Montréal

① Broad and local context

Hillslope hydrology: Emerging from intensive studies of drainage processes conducted in temperate environment, the concept of hydrologic connectivity refers (at the hillslope scale) to upslope - downslope - stream connections, via surface and subsurface flow[1]. Thus, hydrologic connectivity observed at larger scale rarely emerge from linear combinations of processes and choosing the appropriate mathematical approach is an important issue.[2]

Permafrost environment: It has currently been suggested that hydrologic connectivity in Arctic landscapes should increase owing to permafrost degradation.[3] However, hydrological dynamics within the active layer remain difficult to predict due to uncertainties about spatiotemporal variation of thaw depth.[4]

② Objective

Combine ***(i) physical monitoring*** (i.e., evolution of groundwater flow patterns and frost table topography) with ***(ii) statistical analysis*** (i.e., dominant physical controls and extent of hydrological connectivity) to assess ***how hillslope drainage dynamics change through the active layer thawing period.***

③ Hillslope instrumentation

- 19 piezometers equipped with pressure sensor/logger (logging 20min)
- Punctual water level measurements in 9 additional piezometers
- 10 periods of piezometers repositioning's to frost table depth
- 70 point measurements of frost table depth (frequency = twice weekly)
- Streamflow monitoring of the tributary at the foot of the hillslope
- High resolution survey of hillslope topography

④ Datasets

"A dynamic variable to represent dynamic process": Many studies[5,6] showed that different piezometric responses indicate discontinuous subsurface flows. Here, we computed a water level matrix (WLV) and assumed that similar behaviour between piezometers reflected the presence of hydrological connections.

What controls drainage patterns? We computed hydrogeomorphic proxies at each piezometer locations, used as explanatory variables in RDA analysis of the WLV matrices.

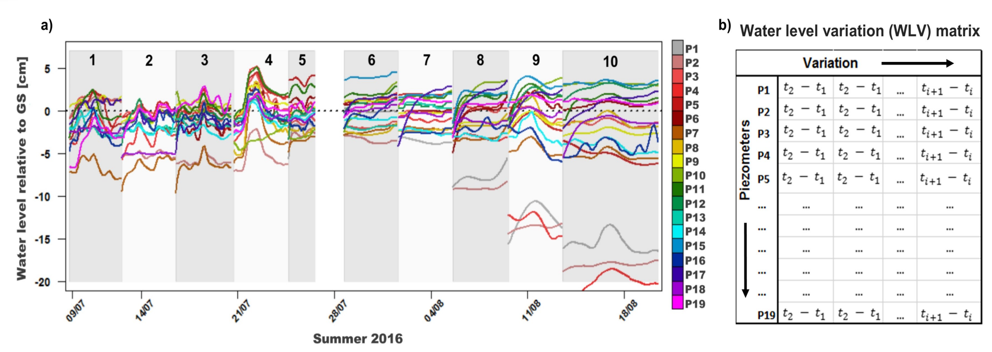

Figure 2: Data and method used to represent the dynamic state of the hillslope drainage, a) plot showing the water level relative to ground surface recorded in the 19 instrumented piezometers. b) Computation of a water level variation (WLV) matrix used as response variable. 10 WLV matrices were computing according to the periods of piezometer repositioning to frost table depth illustrating on the plot. Data gap between periods 5 and 6 is due to datalogger power deficiency.

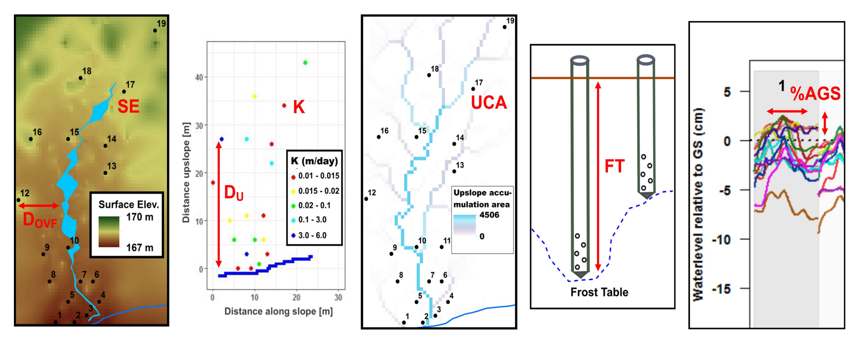

Figure 3: Hydrogeomorphic proxies; DOVF: distance to overland flow track [m], SE: surface elevation [m], DU: distance upslope, K: hydraulic conductivity [m/s], UCA: upslope accumulation area [m²], FT: frost table depth [cm], %AGS: percentage of time of water level above ground surface.

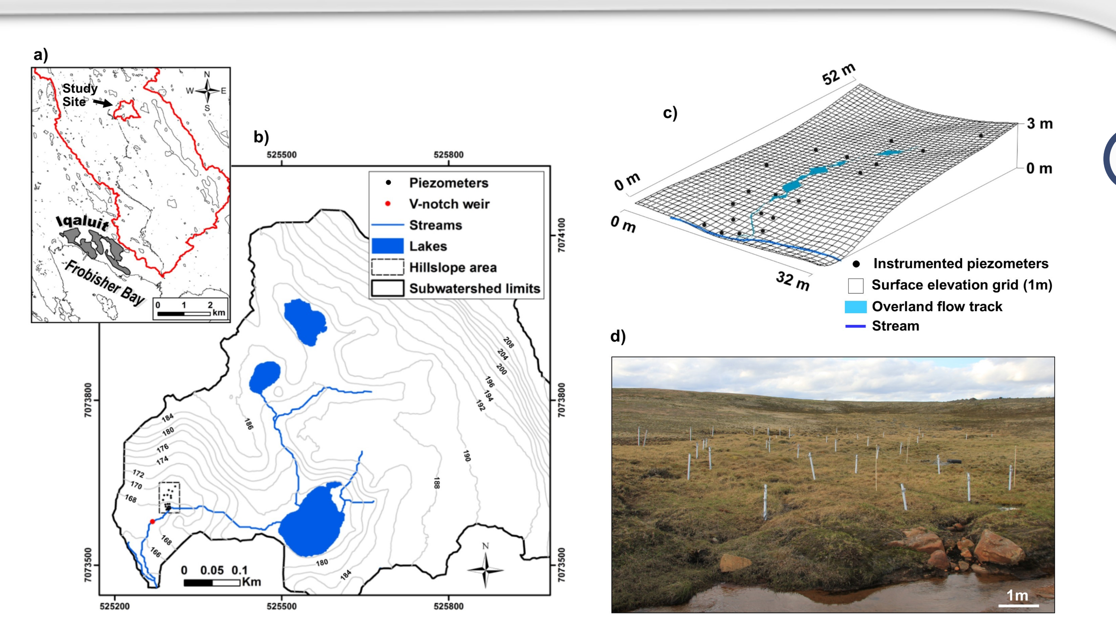

Figure 1: a) Localization of the study site in the Niaqunguk River watershed, b) subwatershed of a headwater tributary adjacent to the hillslope instrumented area, c)surface topography of the hillslope, location of the intrusmented piezometers and transient overland flow track, d) downslope view of the instrumented hillslope.

⑤ Modelling connectivity

We used Asymmetric eigenvector maps (AEM) to produce spatial variables modelling different scale of hydrological connectivity.

Step 1: Directionality (water flow on hillslope). Connections diagrams representing possible connections between sites (e.g., numerated edges).

Step 2: Computation. A site-by-edges matrix (SBE) was first derived from connections diagrams. Transformation of SBE into matrix for which vectors (i.e., eigenfunctions) represent different degrees of spatial autocorrelation between sites.

Step 3: Scale submodels. Produced eigenfunctions were equally separated into submodels depicting different scale of spatial correlation.

Step 4: Investigating WLV. Redundancy analysis used to determine the portion of WLV variance explained by the AEM submodels.

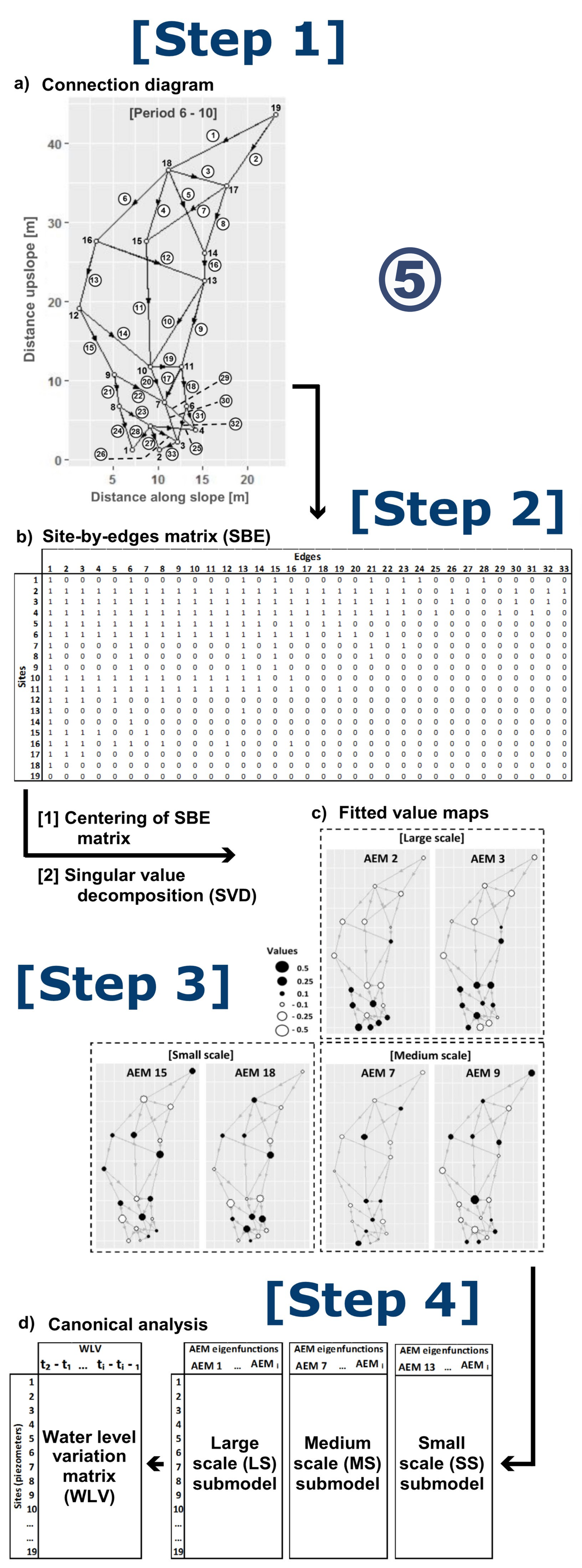

Figure 4: AEM eigenfunctions method used to model extent of hydrological connectivity. a) Connections diagrams representing the links between sites. b) Binary matrix (SBE) derived from the connection diagram (i.e., 0: absence of connection; 1: connection). c) Examples of eigenfunction maps and subdivision into large (LS), medium (MS) and small (SS) scale submodels. d) Canonical analysis using AEM scale submodels as explanatory variables to investigate the variance of the water level variation matrix.

⑥ Physical conditions

Key finding: The association between active layer saturation patterns and evolution of frost table topography, suggest a feedback relation between hillslope drainage and active layer thaw patterns.

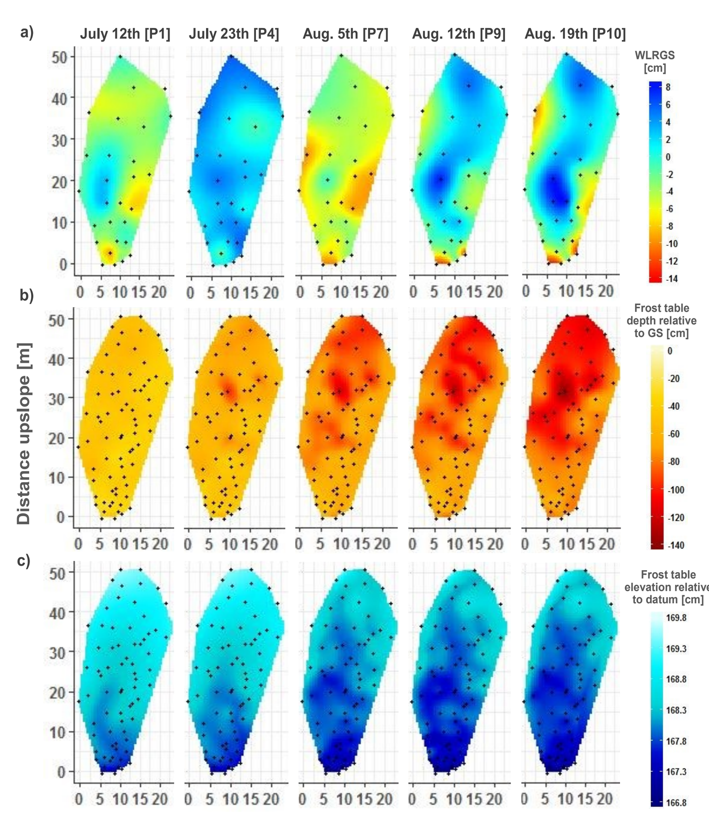

Figure 6: Nearest neighbour's interpolation showing the evolution of a) water levels relative to ground surface (WLRGS); b) frost table depth and c) frost table topography relative to local datum. Black dots show the measurement locations.

⑦ Hydrometeorologic context

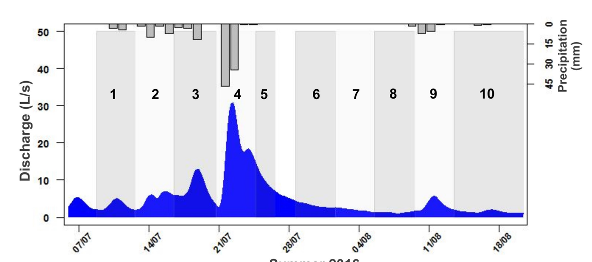

Figure 5: Streamflow of the tributary adjacent to the hillslope foot. Precipitation data, Iqaluit met-station (Environment Canada, #2402596).

⑧ Statistical results

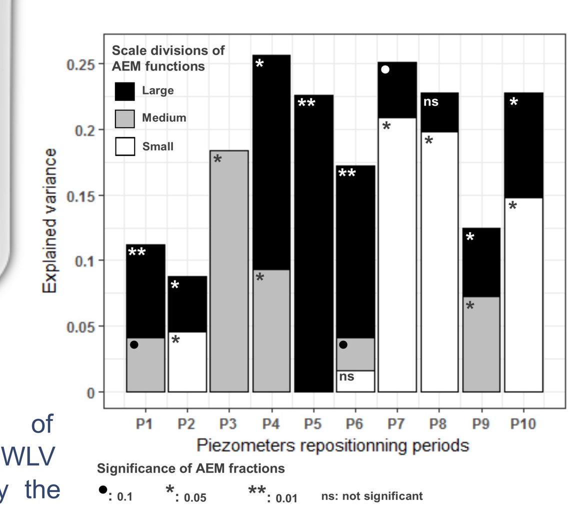

Figure 7: Fraction of variance of the WLV matrices explained by the LS, MS and SS scale submodels of AEM eigenfunctions, for each of the 10 monitoring periods.

Key finding: The agreement between rainfall inputs, streamflow and results of RDA analysis indicates that the produced AEM eigenfunctions allowed us to capture the extent of subsurface hydrological connectivity at the hillslope scale.

Period	Selected proxies (Ind. R²)	R²a	P-value
P1	**%AGS**	0.045	0.05 *
P2	--	--	ns
P3	**K**	0.083	0.098 .
P4	**DU**	0.039	0.091 .
P5	**DU**	0.12	0.016 *
P6	**DU** (0.08) **UCA** (0.07) **DOVF** (0.05)	0.079	0.06 .
P7	**DU** (0.13) **UCA** (0.06) **DOVF** (0.05)	0.19	0.004 *
P8	**K** (0.14) **%AGS** (0.11)	0.169	0.017 *
P9	**K**	0.093	0.007 *
P10	**K** (0.12) **UCA** (0.13)	0.137	0.083 .

Table 1: Results of the redundancy analysis (RDA) involving the significant (*: a=0.05; .: a=0.1) hydrogeomorphic proxies.

Key finding: Relevant physical controls on hillslope drainage evolve with spatiotemporal variation in frost table topography and hillslope saturation conditions.

⑨ Evolution of drainage dynamics

In early phases of thaw, frost table depth as little influence on drainage patterns, variable active layer saturation is attributable to organic throughflow driving by uneven surficial organic layer (Period 1). If surface microtopographic feature become submerged by further water inputs, fast downslope drainage can occur via overland flow (Period 4).

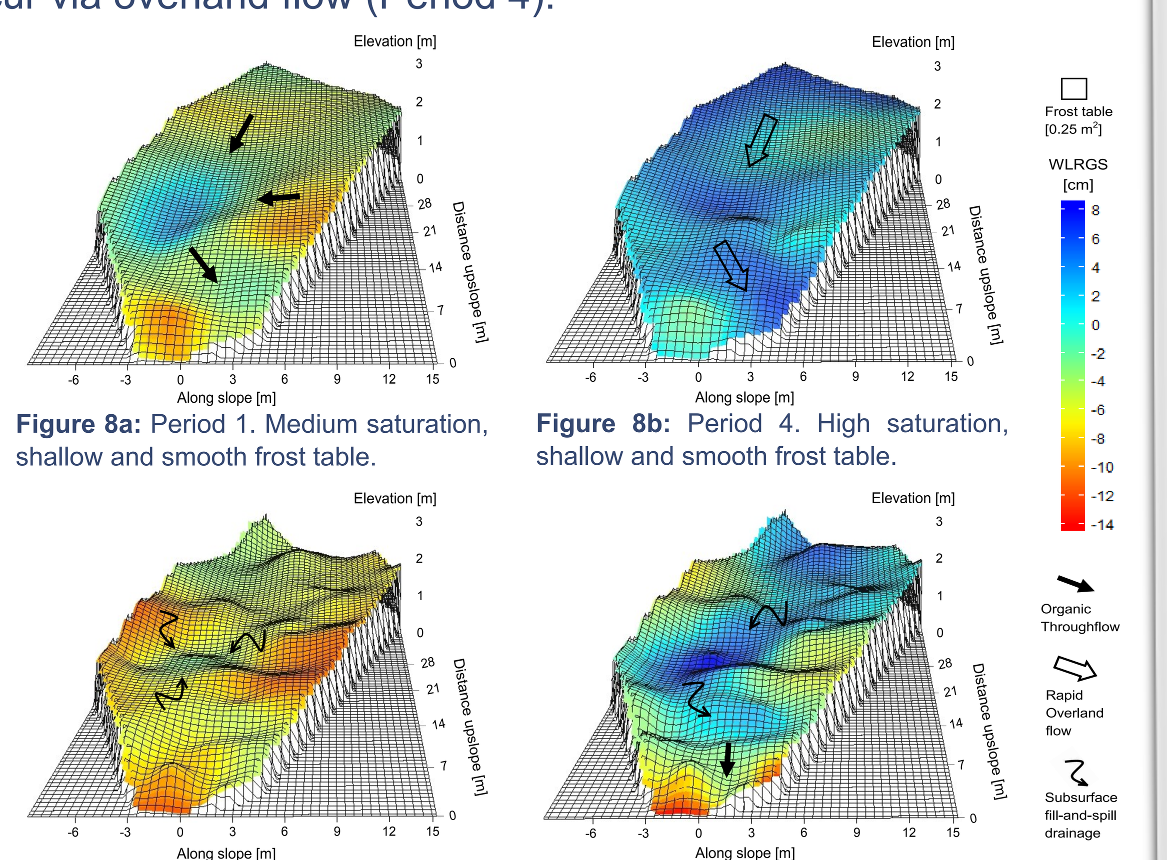

Figure 8a: Period 1. Medium saturation, shallow and smooth frost table.

Figure 8b: Period 4. High saturation, shallow and smooth frost table.

Figure 8c: Period 7. Low saturation, deeper and irregular frost table.

Figure 8d: Period 9. Medium saturation, deeper and irregular frost table.

As the frost table deepens and preferential thaw produces an irregular impeding surface (i.e., frost table), groundwater drains toward and slowly fills frost table depressions (Period 7). Given sufficient water inputs, the "fill-and-spill" mechanism is activated, as water drains across frost table sills and reactivates subsurface flow connections (Period 9).

References

1. Ali, G. & Roy, A. G. (2009). Revisiting sampling strategies for an acurate assessment of hydrologic connectivity in humid temperate systems. *Geography Compass*, 3(1), 350-374.
2. McDonnel, J. J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., ... Weiler, M. (2007). Moving beyond heterogeneity and process complexity: Anew visison of watershed hydrology. *Water Resources Research*, 43(7).
3. Connon, R. F., Quinton, W. L., Craig, J. R., & Hayashi, M. (2014). Changing hydrologic connectivity duw to permafrost thaw in the lower liard River valley, NWT, Canada. *Hydrological Processes,* 28(14), 4163-4178.
4. Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mard, J., Mernild, S. H., ... Woo, M.-K. (2016) Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences,* 121(3), 621-649
5. Anderson, A. E., Weiler, M., Alila, Y., & Hudson, R. O. (2010). Piezometric response in zones of a watershed with lateral preferencial flow as a first-order control on subsurface flow, *Hydrological Processes*, 24(16), 2237-2247.
6. Haught, D. R. & van Meerveld, H. J., (2011) Spatial variation in transient water table responses: differences between an upper and lower hillslope zone. Hydrological Processes, 25(25), 4163-4178.

ArcticNet
NSTP PFSN
NSERC CRSNG
Canadian Northern Studies Trust
Fiduciaire canadienne d'études nordiques