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## RESEARCH LETTER

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### Key Points:

- Increased landcover height appears positively correlated with increased recharge
- As land cover increases in height, the date of the first recharge event in a given hydrologic year moves later into the summer
- Increased recharge is driven by greater snow thickness and prolonged snowmelt due to snow entrapment and shading under taller land cover

### Supporting Information:

- Supporting Information S1

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## A Conceptual Model for Anticipating the Impact of Landscape Evolution on Groundwater Recharge in Degrading Permafrost Environments

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**Abstract** Temperatures in the arctic and subarctic are rising at more than twice the rate of the global average, driving the accelerated thawing of permafrost across the region. The impacts of permafrost degradation have been studied in the discontinuous permafrost zone at Umiujaq, in northern Quebec, Canada, for over 30 years, but the effects of changing land cover on groundwater recharge are not well understood. The water table fluctuation method was used to compute groundwater recharge using 4 years of water level data and soil moisture readings from five field sites characteristic of different stages of permafrost degradation and vegetation invasion. Results indicate that as vegetation grows taller, groundwater recharge increases, likely due to increased snow thickness. Results were then combined with a preexisting conceptual model that describes the evolution from tundra to shrubland and forests to create a new model for describing how groundwater recharge is affected by landscape evolution.

**Plain language summary** Thawing permafrost (ground that is below 0°C for at least 2 years) allows for vegetation to grow in areas where growth was not previously possible. This paper examines how different types of vegetation affect the ability of water to infiltrate the soil and flow toward the water table, a process called groundwater recharge. Using field data from five typical types of vegetation in the discontinuous permafrost zone in northern Quebec, Canada, we estimated how much groundwater recharge occurred under these different types of vegetation: tundra/permafrost mound, lichens and herbs, lichens and low shrubs, medium shrubs, and trees. Based on the results, as the plants grow larger, more groundwater recharge is possible. This increase in recharge occurs because taller plants trap more snow in winter, resulting in the production of more meltwater in spring. We then combine our results with the findings from another study in the same area, which stated that the five types of land cover represent a model for how the landscape will change as the permafrost thaws. Our new combined model allows for the estimation of how groundwater recharge will change as a result of permafrost thaw and ecological change.

## 1. Introduction

Temperatures in high-latitude regions are currently rising at more than twice the rate of the global average (Box et al., 2019). Increasing temperatures have already begun to transform the physical, chemical, and biological systems in the arctic (AMAP, 2017). One consequence of this continued warming is the thawing of permafrost across the arctic and subarctic, with model simulations predicting a 20% reduction in permafrost extent by 2040—regardless of changes to global emissions (Overland et al., 2019). From the perspective of the water cycle in the North, permafrost degradation represents a significant physical shift and has been shown to significantly alter the hydrological and hydrogeological characteristics of northern watersheds (Lafrenière & Lamoureux, 2019; Walvoord & Kurylyk, 2016). For instance, the thawing of permafrost can shift the hydrological cycle within a given watershed from primarily surface-water dominated to groundwater dominated (Lamontagne-Hallé et al., 2018). Yet understanding the hydrological implications of continued permafrost degradation is complicated by the extensive geomorphological and ecological transformations that often occur simultaneously (Grosse et al., 2016; Kokelj & Jorgenson, 2013; Walvoord & Kurylyk, 2016).

Geomorphological changes resulting from permafrost thaw have been shown to have significant effects on both regional hydrology and ecology. In the peaty, wetland-dominated landscapes of the boreal region of

Canada, the formation of thermokarst has resulted in the lowering of permafrost plateaus, subsequently expanding the extent of wetlands and altering the timing, volume, and geochemistry of fluid fluxes within drainage areas (Hayashi et al., 2004; Quinton et al., 2011). While the lowering of plateaus in the boreal region of Canada has rendered the existing plant life susceptible to inundation, further north, in the discontinuous permafrost region, the formation of thermokarst has helped to promote the expansion of shrubs into drier, mineral-soil-dominated landscapes that were previously tundra (Baltzer et al., 2014; Pelletier et al., 2018). Though shrubification in these regions is most closely linked to warming temperatures, recent work has shown that this process preferentially occurs in lower, wetter regions, such as the hollows formed by thermokarst (Lemay et al., 2018; Pelletier et al., 2018; Tremblay et al., 2012). While previous research in permafrost-dominated landscapes has investigated the relationships between geomorphological and hydrological changes, the effects of long-term ecological change on catchment-scale hydrology in these areas, particularly how ecological shifts influence groundwater recharge, are not well understood (Connon et al., 2015; Quinton et al., 2011; Walvoord & Kurylyk, 2016).

The effects of permafrost degradation on local hydrology, hydrogeology, and ecology have been studied in the region around the Tasiapik Valley, near the Inuit community of Umiujaq, in Northern Quebec, Canada, since the 1980s (Seguin & Allard, 1984). Aerial photos provide qualitative evidence that the vegetated area has been increasing since the 1950s, while Landsat and remote sensing data show a 21% increase in shrub and tree cover since 1986 (Beck et al., 2015). Local hydrology and hydrogeology within the valley have been studied since 2012, as part of continuing research conducted by the Centre d'études nordiques (CEN) at Laval University.

Recent work in the Tasiapik Valley by Pelletier et al. (2018) demonstrated how the different forms of land cover can evolve over a 90-year chronosequence (Johnson & Miyanishi, 2007), which can be used as a proxy for the landscape evolution of the northern tundra. The objective of the study presented herein is to assess how the progression of this chronosequence can influence groundwater recharge in northern catchments. To meet this objective, the water table fluctuation (WTF) method described by Sophocleous (1991) is used to compute groundwater recharge under five different kinds of land cover within the Tasiapik Valley, each corresponding to a landscape stage in the chronosequence of Pelletier et al. (2018). Recharge values are then combined with the preexisting chronosequence, allowing for the creation of a new conceptual model that describes how the landscape and hydrology of the Tasiapik Valley could change over the period of 2020–2100 in response to continued climate warming.

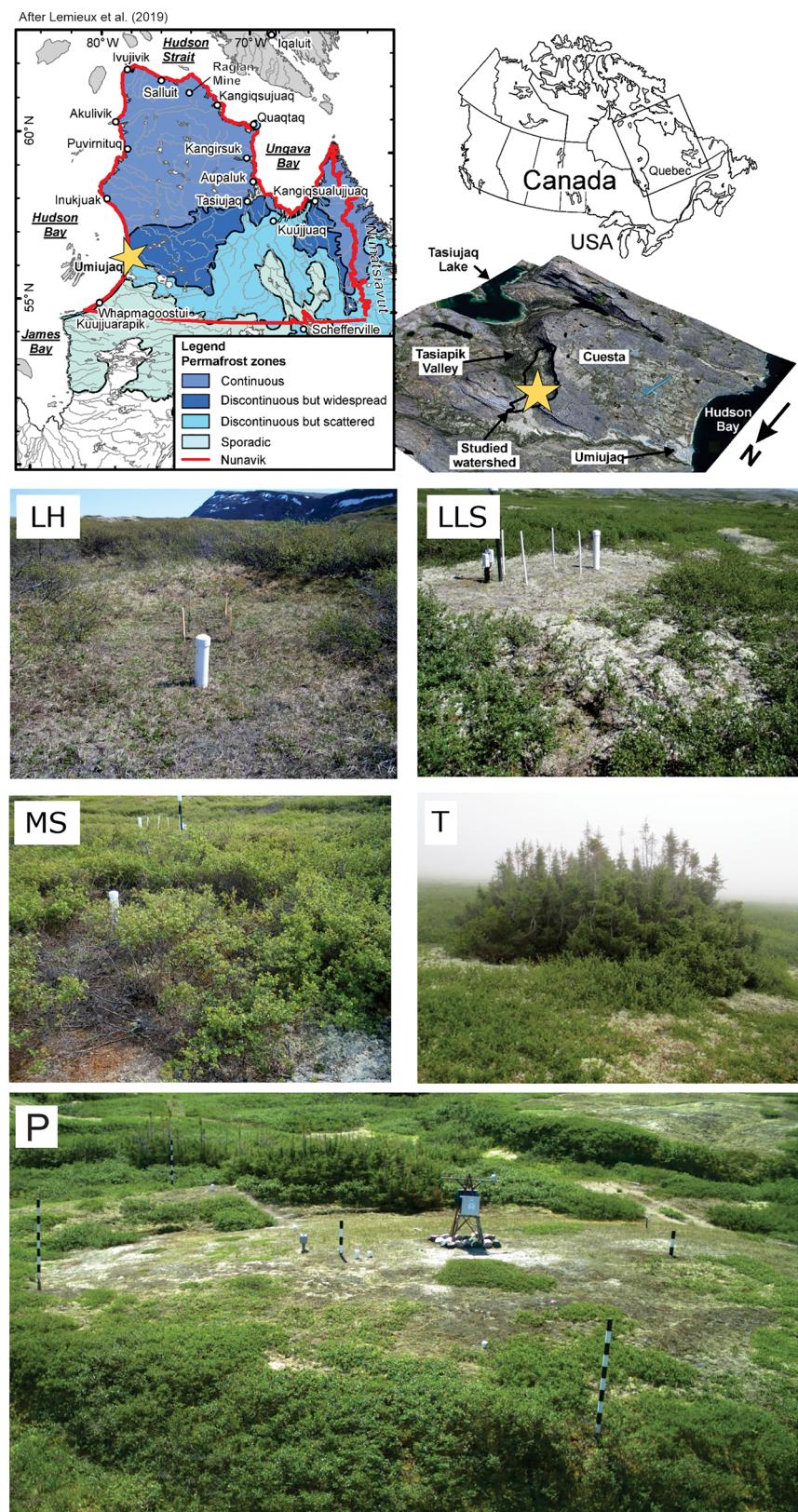
## 2. Materials and Methods

### 2.1. Geologic Setting of the Tasiapik Valley

The Tasiapik Valley is a 2.23 km<sup>2</sup> watershed on the eastern shore of Hudson Bay, near the Inuit community of Umiujaq (Inuktitut: ᐃᓄᒃᑎᑐᑦ: ዳᖅᐸᖅ), located within the discontinuous permafrost zone in Northern Quebec, Canada (Figure 1, top panel). The watershed lies between a cuesta to the southwest and a hill to the northeast. Surface running water leaves the watershed via a small stream that discharges into Tasiujaq Lake to the southeast. The valley is composed of Quaternary sedimentary deposits overlying sandstone and basalt (see Fortier et al. (2020) for a detailed description of the site geology). The superficial aquifer of the study site is located above an aquiclude made of frost-susceptible silts, which have been invaded by discontinuous permafrost. A detailed description of the hydrogeology of the valley can be found in Lemieux et al. (2020).

### 2.2. Land Cover Within the Tasiapik Valley

The ecosystem within the Tasiapik valley has experienced significant greening since the 1950s (Beck et al., 2015). This greening, occurring primarily as a result of climate warming, has involved both an increase in the extent of shrubs (e.g., *Betula nana* or dwarf birch), as well as the expansion of black spruce forests (*Picea mariana*; Truchon-Savard et al., 2019). In this study, the classification system from Pelletier et al. (2018) is used, in an effort to link the chronosequence of landscape evolution to changing patterns of recharge. This system includes six distinct categories of land cover: lichens and herbs, lichens and low shrubs, low shrubs and lichen, medium shrubs, tall shrubs, and trees. The permafrost mounds are also included in this system, in order to qualitatively describe the changes in recharge dynamics that occur before



**Figure 1.** Location of the five study sites in the Tasiapik Valley, near Umiujaq, Quebec, Canada. Instruments were installed beneath five different types of land cover: lichens and herbs (LH), lichens and low shrubs (LLS), medium shrubs (MS), trees (T), and permafrost (P) (after Fortier et al., 2020; Lemieux et al., 2020).

and after permafrost thaw. As such, the types of land cover on instrumented sites used in this study are tundra (permafrost), lichens and herbs, low shrubs and lichens, medium shrubs, and trees (Figure 1).

### 2.3. Instrumentation

For each type of land cover, different instruments were installed during two separate field campaigns (2012 and 2014, respectively) to monitor groundwater recharge. The site dominated by lichens and low shrubs (LLS) was instrumented first. The instrumentation includes a piezometer (4.8-m depth; 1.5-m screened interval) and 20 water content and temperature probes (5TM, Decagon Instruments). These probes constitute a vertical profile from the surface to a depth of 4 m, which, aside from short periods of time in the winter, is the approximate depth to the water table (Lemieux et al., 2020). Piezometers at the sites with permafrost (P), lichens and herbs (LH), medium shrubs (MS), and trees (T) were installed in 2014 (Dagenais et al., 2020; Murray, 2016). Core logs from Sites LLS, LH, MS, and T show an approximately uniform hydrogeologic setting across all wells (Murray, 2016). Site P exhibits different hydrostratigraphy, due to the presence of permafrost in the frost-susceptible silts underlying the aquifer. However, since no liquid water was observed in the piezometer during the period of study, this site was included for qualitative comparison only.

Precipitation and air temperature data were measured using the instrumentation at the SILA meteorological station operated by the CEN at Laval University. The SILA station has been in operation since 1997 and includes a Geonor T-200B all-weather precipitation gauge for measuring liquid and solid precipitation. Due to high winds at the site during the winter months, precipitation gauges can underestimate the actual amount of snowfall, necessitating corrections to the raw data to account for wind effects. A full description of the corrections applied to the precipitation data is described in Lemieux et al. (2020).

### 2.4. Groundwater Recharge Estimation

Numerous methods can be used to estimate groundwater recharge (Healy, 2010; Scanlon et al., 2002). The WTF method uses the direct relationship between water table rises and the groundwater recharge for a shallow water table aquifer, such as the superficial aquifer present in the Tasiapik Valley. Groundwater recharge is obtained from the product of the specific yield ( $S_y$ ) and the effective water table rise ( $\Delta h^*$ ) (Healy & Cook, 2002):

$$R = S_y \times \Delta h^*, \quad (1)$$

where  $\Delta h^*$  is directly related to a groundwater recharge event (i.e., no additional effects, such as regional groundwater flow). Delineating  $\Delta h^*$  from time series of water-level measurements can be a subjective process if done by hand; however, any uncertainty associated with  $\Delta h^*$  is negligible compared to the uncertainty associated with  $S_y$  (Delottier et al., 2018). To limit the subjectivity when determining water table rises, the episodic master recession (EMR) method was used to delineate the length of individual recharge events (Nimmo et al., 2015).

As outlined by Lemieux et al. (2020), water content profiles differed between identified groundwater recharge events in Tasiapik Valley. Hence, following the approach of Sophocleous (1991), the event-based WTF was used in conjunction with fillable porosity, which represents the unsaturated fraction of porosity above the water table that fills when the water table rises. Values of fillable porosity are obtained by computing the area between water content profiles before and after a groundwater recharge event (Sophocleous, 1991). The use of fillable porosity helps to avoid the overestimation of recharge that can occur when a constant value of  $S_y$  is used for all recharge events (Lemieux et al., 2020). Furthermore, the use of unsaturated zone data in conjunction with saturated zone data helps make the WTF method suitable for use as a point-scale measurement, as unsaturated zone methods generally provide superior estimates of recharge at local scales (Scanlon et al., 2002).

In order to implement this method, volumetric water content (VWC) probes must be installed across the full extent of the unsaturated zone. Because the VWC probes at all sites other than Site LLS did not span the full extent of the saturated zone, a single set of fillable porosity values were computed using the water content data from Site LLS and were then assumed to approximate the fillable porosity values for the other four sites. A table containing the computed fillable porosity values is provided in the Supporting Information. While

there are a number of studies that use a single refillable porosity value across a number of wells (e.g., Maréchal et al., 2006; Ochoa et al., 2013), this assumption was made here due to the fact that the sample locations are located relatively close together (all sites lie within a 75-m radius from Site LLS) and possess approximately identical hydrogeological settings. Furthermore, with the exception of Site LH, the fluctuations in the water table elevation across all sites occurred below the root zone. Thus, the values of fillable porosity at each site will be driven solely by the soil capillary properties, which are likely similar across all locations. Therefore, while the actual recharge values may be slightly larger or smaller than those presented here due to local differences in fillable porosity, the values computed in this study provide a suitable estimation of how recharge dynamics will shift within the Tasiapik Valley.

To maintain a coherent presentation of results across multiple studies at this location, recharge was evaluated over the course of a hydrological year (HY), which starts on 1 October and ends on 30 September in North America.

### 3. Results and Discussion

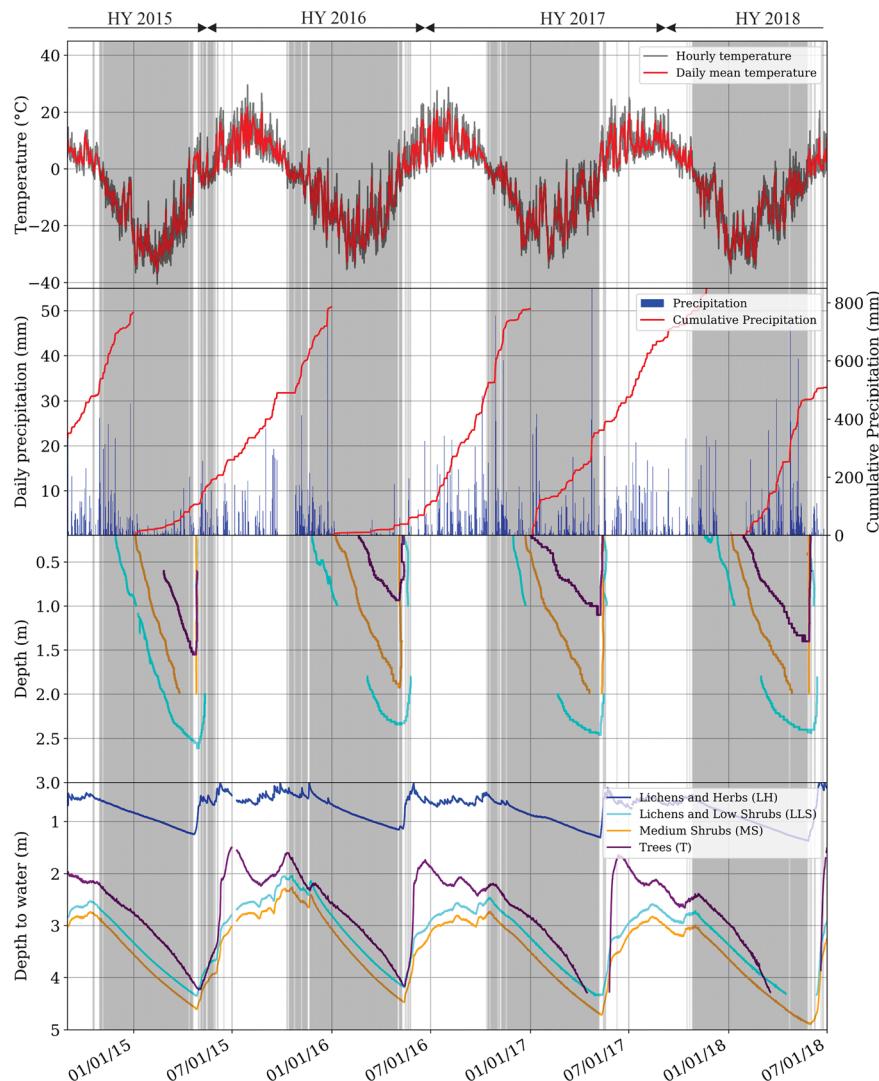
#### 3.1. Subsurface Temperature and Water Levels

Subsurface temperature profiles show that the freezing depth decreases as the height of vegetation increases (Figure 2, panel 4). Additionally, the date of initial freezing occurs progressively later as the height of vegetation increases: the first recorded freezing at Site LLS during HYS 2015–2018 occurs in late November, while the first recorded freezing at Site T generally occurs in mid-February. Despite these differences in the timing of initial freezing, all sites thawed at approximately the same time, with thaw occurring in conjunction with the first period of above-zero-degree days. Water table rises at all sites begin shortly after the thawing of the subsurface.

Water level profiles across the four studied HYS have similar morphologies year to year. However, with the exception of the lichens and low shrubs (LLS) site and the medium shrubs (MS) site, the water level profiles differ from one another in the timing, frequency, and magnitude of water level rises (Figure 2, panel 3). Across all sites, there is a shift in the timing of the first water level rise of each HY. This initial rise coincides with the beginning of the spring snowmelt, which, depending on the height of vegetation, can begin between mid-April and late May (Lemieux et al., 2020).

This temporal shift was more pronounced in the first two HYS studied and displayed a pattern where taller vegetation (i.e., trees) generally saw water tables rise later than sites with shorter vegetation (Figure 2, panel 3). At the site with the shortest vegetation (lichens and herbs, LH), the first water level rise in HY 2015 occurred on 15 April 2015, while the same event did not occur at the site with trees (T) until 16 May 2015—31 days later. The sites with lichens and low shrubs (LLS) and medium shrubs (MS) saw the first water table rise occurring on 25 April 2015, thus earlier than Site T but later than at Site LH. While the offset in water level rises at all sites remained similar in 2016, with a 28-day gap between Sites LH and T, it decreased to 15 days in 2017, before increasing to 18 days in 2018. As suggested from the data interpretation, in the latter two HYS, the beginning of the spring snowmelt may have moved later into the spring for all sites, with water levels at Site LH first rising on 29 May 2018, while Site T did not see water level increases until 8 June 2018. There was no water level observed above the permafrost mound (Site P), suggesting that infiltrated water flowed radially in the unsaturated zone toward the edge of the mound.

For the sites where water level changes were observed, frequency of water level rises tended to decrease, and the magnitude of the rises tended to increase, as vegetation became taller. For example, in the LH and T water level profiles, the former experienced much smaller water table rises, but more of them (evidenced by the high frequency component in the water level signal), while Site T had fewer, larger, rises. The increase in high-frequency water-level fluctuations may also reflect the differences in the depth of the water table between the two sites, as the shallow water table at Site LH is more likely to receive recharge from smaller-scale events, and be more affected by evapotranspiration (ET). Based on the similarities in the profiles between Sites LS and MS, the presence of higher, woodier land cover may be more important than the exact height of the individual shrubs. It may also reflect the shrubs being bent over during burial by snow, therefore homogenizing shrub height after a certain snow thickness (Marsh et al., 2010).



**Figure 2.** Air temperature, precipitation, freezing depth, and depth to water data for all sites for hydrologic years 2015–2018. Shaded regions indicate time periods where the average daily air temperature was below 0°C. Dashed purple line in panel 4 is an interpolation, as the ground was likely frozen during this period, but instrument failure prevented direct measurement of temperature. Note that the permafrost site (P) was not included, as no liquid water was measured in the piezometer during the plotted time period.

### 3.2. Refillable Porosity and Estimated Recharge

Using the method from Sophocleous (1991), refillable porosity values were computed for each recharge event that occurred at Site LLS, as identified by the EMR-WTF method. The values range from 0.00 to 0.20, with a mean value 0.08 and a median value of 0.05. A table containing the computed values can be found in the supplemental materials. Recharge values for the five sites were computed by substituting the fillable porosity values for the  $S_y$  values in the EMR-WTF calculations (Table 1). Because no water level was observed at the permafrost mound site (P), the EMR-WTF method could not be applied to this location. Based on the results of using the EMR-WTF method to compute recharge during HYS 2015–2018, the magnitude of recharge generally increased with the height of vegetation, while the timing of recharge followed the water level rises described in section 3.1. The results further indicate that the largest percentage of total recharge beneath all forms of land cover is a result of spring (~20 March to ~20 June) snowmelt. Thus, the primary mechanism for increased recharge appears to be greater snow entrapment under taller vegetation, occurring as both a result of capture during precipitation events, and the accumulation of blowing snow from areas with shorter, more immature forms of land cover (i.e., lichens and herbs; Essery &

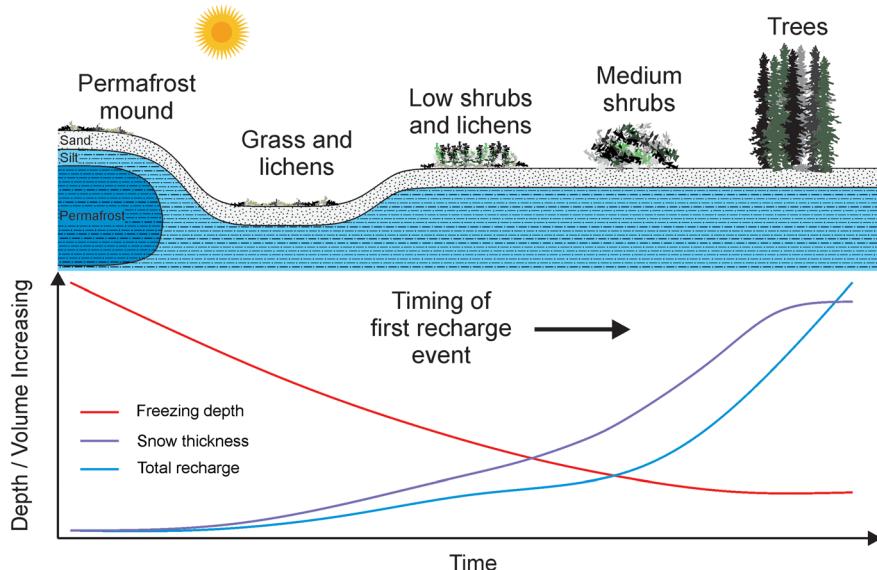
**Table 1**

Recharge Calculations for the Four Sites Where Recharge Could be Calculated with the EMR-WTF Method: Lichens and Herbs (LH), Lichens and Low Shrubs (LLS), Medium Shrubs (MS), and Trees (T) for HYs 2015–2018

	Year/season	Lichens and herbs (LH)	Lichens and low shrubs (LLS)	Medium shrubs (MS)	Trees (T)
Annual recharge (mm)	2015	287	509	441	701
	2016	261	540	429	529
	2017	208	196	183	408
	2018	180	358	477	624
Total recharge 2015–2018 (mm)	-	936	1,603	1,530	2,262
Seasonal totals 2015–2018 (mm)	Spring	576	816	727	1931
	Summer	325	631	662	253
	Fall	35	156	141	78
Seasonal totals 2015–2018 (%)	Spring	62	51	47	85
	Summer	35	39	43	11
	Fall	4	10	9	3

Pomeroy, 2004). This observation is consistent with previous research on snow thickness within the study site, which demonstrated that taller vegetation cover entraps more snow and prevents it from being blown to other parts of the watershed (Busseau et al., 2017). This finding is further supported by the subsurface temperature profiles, where shallower freezing depths at sites with taller vegetation are likely a product of insulation by thicker snowpack (Zhang, 2005). Data further show a large difference in both the timing and magnitude of recharge at Site T, suggesting that forestation, rather than shrubification, causes the most extensive changes to recharge dynamics after the initial thawing of permafrost. This is further evidenced by the similarities in timing as well as the seasonal distribution of recharge events at Sites LH, LLS, and MS (Table 1).

While the other sites studied received an average of 39% of total recharge during the summer months of HYs 2015–2018, the summer months accounted for only 11% of total recharge at Site T during this period. Therefore, it is possible that increased ET at Site T during the summer months is reducing the amount of recharge observed during these months, a finding consistent with other afforestation and ET studies in cold regions (Peel et al., 2010). Furthermore, based on the magnitude and duration of the spring recharge events at Site T, the shading by forest canopy appears to be slowing the rate of spring snowmelt, promoting greater infiltration, as opposed to runoff generation (Varhola et al., 2010).



**Figure 3.** Conceptual model showing the physical changes described in the 90-year chronosequence of Pelletier et al. (2018) (top panel) and corresponding changes in recharge dynamics (bottom panel).

### 3.3. Conceptual Model for Shifting Recharge in Greening Tundra

Pelletier et al. (2018) proposes a conceptual model where the different forms of vegetation within the Tasiapik Valley represent a 90-year chronosequence for the greening of the tundra in the North. In their model, lichens and herbs are the most “immature” landscape, which has not been substantially altered from its prethawed state. High shrubs and trees represent more “mature” landscapes indicative of extensive ecological change. The results of this study allow for the expansion of the conceptual model presented in Pelletier et al. (2018) to include a process-based estimation of how recharge dynamics within the valley will be altered as a result of these ecosystem changes (Figure 3).

The resulting combined conceptual model shows that taller vegetation shifts the timing of recharge from the first to the second half of spring and allows for a greater volume of groundwater recharge. The shift in timing occurs as a result of thicker snowpack melting more slowly due to shading by taller forms of vegetation, particularly in areas that have become forested. Meanwhile, the increase in snow thickness results from greater snow entrapment beneath taller vegetation. As a result, the new, combined conceptual model suggests that increases in recharge volume are likely to be highly localized and will be strongly dependent on the extent of shrubification and forestation within a given catchment.

Locally, the spatial distribution of taller vegetation relative to the position of rechargeable aquifers is also likely to play a large role in whether increased recharge is actually observed. Within the Tasiapik Valley, for instance, the unconfined aquifer only covers two thirds of the watershed. Therefore, a greater volume of snow entrapped by mature land cover located outside of this extent would not contribute to increased recharge. It is also possible that as the landscape matures, snow could be blown from areas with shorter vegetation located over a rechargeable aquifer and then become entrapped beneath taller vegetation located outside the extent of the aquifer—thereby contributing to a decrease in observed recharge.

While the forested areas produced the largest recharge estimates, this increase appears to be driven by an increase in snowpack depth relative to other forms of vegetation resulting from a combination of greater snow entrapment postdeposition, as well as the accumulation of blown snow. This theory is supported by previous snow surveys conducted within the valley, which found that snowpack in forested areas (0.9–1.7 m) was roughly 1.5–2.5 times thicker than in the surrounding tundra areas (0.6–0.7 m) as a result of both processes (Busseau et al., 2017; Pelletier et al., 2018). The presence of warmer subsurface temperatures and longer, larger recharge events that begin later in the spring further supports this theory (Tague & Peng, 2013; Varhola et al., 2010; Zhang, 2005). However, as the landscape continues to mature, the expansion of shrubs and trees will ultimately reduce the extent of open areas that can contribute to blowing snow within the valley, likely reducing the depth of snowpack in forested areas. Without the large spring recharge events afforded by the slow melting of deep, forest-shaded snowpack, it is possible that increased ET generated by forested areas may result in observed recharge values that are similar to those seen in shrub-dominated areas. Thus, while a more mature landscape provides the opportunity for increased recharge, it is not the only factor that determines whether increased recharge actually occurs.

## 4. Conclusions

The chronosequence presented in Pelletier et al. (2018), along with groundwater recharge estimates, were used to create a new, process-based conceptual model that describes the changes in groundwater recharge with continued permafrost thaw and tundra greening. Results from the Tasiapik Valley suggest that with continued maturation of the landscape, the potential for greater groundwater recharge increases due to increased snow entrapment beneath taller vegetation. While the observation of increased snow entrapment by taller vegetation has been documented by several studies, it was not known how this increased snow thickness would alter the timing and volume of recharge beneath different types of land cover within the Tasiapik Valley. Additionally, while this increased snow thickness reduces the depth of seasonal frost penetration, the changes in freezing depth did not appear to have any impact on the timing of recharge.

There are a number of opportunities for continued research that can both further improve the conceptual model proposed here and increase our understanding of recharge in degrading permafrost environments. First, the application of the methods used here to additional sites within the Tasiapik Valley, as well as the discontinuous permafrost region as a whole, will allow for further refinement of the model and

determine its broader applicability outside of the area of study. Additional refinements can be made at smaller scales, such as increasing our understanding of the volume and distribution of blown snow throughout the valley and how changes in land cover will influence them. Finally, numerical modeling of the unsaturated zone could also provide insight into the existence and characteristics of any physical differences in the infiltration process that occur under different types of land cover and further elucidate the role of subsurface temperature in recharge dynamics. While the Sophocleous-WTF method may not provide significant information about changes in unsaturated zone dynamics, it provides a suitable first-cut approximation of how recharge dynamics will shift in the Tasiapik Valley as a result of global warming.

### Acknowledgments

Data used in this study may be accessed on the Nordicana D repository website: water level data (Lemieux, Murray, et al., 2020b), volumetric water content data (Lemieux, Murray, et al., 2020c), subsurface temperature data (Lemieux, Murray, et al., 2020a). Funding for this project was provided by the Université Laval Sentinel North program (funded by Canada First Research Excellence Fund), a Strategic Partnership Grant and Discovery Grant from NSERC, and a grant from the Québec Ministry of the Environment (MELCC). The authors would like to thank Renaud Murray for assistance in installing the instruments used in this project, and Laura Mony for assistance with Python. The authors would also like to thank Drs. Michael Gooseff and Aaron Mohammed, whose insightful reviews greatly improved this manuscript.

### References

- AMAP (2017). Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP). Retrieved from <https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610>
- Baltzer, J. L., Veness, T., Chasmer, L. E., Sniderhan, A. E., & Quinton, W. L. (2014). Forests on thawing permafrost: Fragmentation, edge effects, and net forest loss. *Global Change Biology*, 20(3), 824–834. <https://doi.org/10.1111/gcb.12349>
- Beck, I., Ludwig, R., Bernier, M., Lévesque, E., & Boike, J. (2015). Assessing permafrost degradation and land cover changes (1986–2009) using remote sensing data over Umiujaq, Sub-Arctic Québec. *Permafrost and Periglacial Processes*, 26(2), 129–141. <https://doi.org/10.1002/ppp.1839>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., et al. (2019). Key indicators of Arctic climate change 1971–2017. *Environmental Research Letters*, 14(4). <https://doi.org/10.1088/1748-9326/aafc1b>
- Busseau, B. C., Royer, A., Roy, A., Langlois, A., & Domine, F. (2017). Analysis of snow-vegetation interactions in the low Arctic-Subarctic transition zone (northeastern Canada). *Physical Geography*, 38(2), 159–175. <https://doi.org/10.1080/02723646.2017.1283477>
- Connon, R. F., Quinton, W. L., Craig, J. R., Hanisch, J., & Sonnentag, O. (2015). The hydrology of interconnected bog complexes in discontinuous permafrost terrains. *Hydrological Processes*, 29(18), 3831–3847. <https://doi.org/10.1002/hyp.10604>
- Dagenais, S., Molson, J., Lemieux, J. M., Fortier, R., & Therrien, R. (2020). Coupled cryo-hydrogeological modelling of permafrost dynamics at umiujaq, Nunavik, Canada. *Hydrogeology Journal*, 28(3), 887–904. <https://doi.org/10.1007/s10040-020-02111-3>
- Delottier, H., Priet, A., Lemieux, J. M., & Dupuy, A. (2018). Estimating groundwater recharge uncertainty from joint application of an aquifer test and the water-table fluctuation method. *Hydrogeology Journal*, 26(7), 2495–2505. <https://doi.org/10.1007/s10040-018-1790-6>
- Essery, R., & Pomeroy, J. (2004). Vegetation and topographic control of wind-blown snow distributions in distributed and aggregated simulations for an arctic tundra basin. *Journal of Hydrometeorology*, 5(5), 735–744. [https://doi.org/10.1175/1525-7541\(2004\)005<0735:VATCOW>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0735:VATCOW>2.0.CO;2)
- Fortier, R., Banville, D., Lévesque, R., Lemieux, J. M., Molson, J., Therrien, R., et al. (2020). Development of a 3D cryo-hydrogeological model of a small watershed in a degrading permafrost environment near Umiujaq, Nunavik, Canada. *Hydrogeology Journal*, 28, 813–832.
- Grosse, G., Goetz, S., McGuire, A. D., Romanovsky, V. E., & Schuur, E. A. G. (2016). Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters*, 11(4). <https://doi.org/10.1088/1748-9326/11/4/040201>
- Hayashi, M., Quinton, W. L., Pietroniro, A., & Gibson, J. J. (2004). Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. *Journal of Hydrology*, 296(1–4), 81–97. <https://doi.org/10.1016/j.jhydrol.2004.03.020>
- Healy, R. W. (2010). *Estimating groundwater recharge* (p. 245). Cambridge, United Kingdom: Cambridge University Press. <https://doi.org/10.1017/CBO9780511780745>
- Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, 10(1), 91–109. <https://doi.org/10.1007/s10040-001-0178-0>
- Johnson, E. A., & Miyanishi, K. (2007). Disturbance and succession. In E. A. Johnson, & K. Miyanishi (Eds.), *Plant disturbance ecology: The process and the response* (pp. 1–15). Amsterdam, NL: Elsevier Academic Press. <https://doi.org/10.1016/B978-012088778-1/50003-0>
- Kokelj, S. V., & Jorgenson, M. T. (2013). Advances in thermokarst research. *Permafrost and Periglacial Processes*, 24(2), 108–119. <https://doi.org/10.1002/pp.1779>
- Lafrenière, M. J., & Lamoureux, S. F. (2019). Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. *Earth-Science Reviews*, 191(June 2018), 212–223. <https://doi.org/10.1016/j.earscirev.2019.02.018>
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, 13(8). <https://doi.org/10.1088/1748-9326/aad404>
- Lemay, M.-A., Provencher-Nolet, L., Bernier, M., Lévesque, E., & Boudreau, S. (2018). Spatially explicit modeling and prediction of shrub cover increase near Umiujaq, Nunavik. *Ecological Monographs*, 88(3), 385–407. <https://doi.org/10.1002/ecm.1296>
- Lemieux, J. M., Fortier, R., Murray, R., Dagenais, S., Cochand, M., Therrien, R., et al. (2020). Groundwater dynamics within a watershed in the discontinuous permafrost zone near Umiujaq (Nunavik, Canada). *Hydrogeology Journal*, 1–60. <https://doi.org/10.1007/s10040-020-02110-4>
- Lemieux, J. M., Murray, R., Fortier, R., Dagenais, S., Fortier, P., & Young, N. L. (2020a). Données de température souterraine, vallée de Tasiapik 2014–2019 [Subsurface temperature data, Tasiapik Valley 2014–2019]. *Nordicana D Data Repository*. <https://doi.org/10.5885/45633XX-C5F505FAA5984669>
- Lemieux, J. M., Murray, R., Fortier, R., Dagenais, S., Fortier, P., & Young, N. L. (2020b). Données sur le niveau et la température de l'eau souterraine, vallée de Tasiapik 2014–2019 [Water level and water temperature data, Tasiapik Valley 2014–2019]. *Nordicana D Data Repository*. <https://doi.org/10.5885/45636XX-1ABDEDA4433D46A0>
- Lemieux, J. M., Murray, R., Fortier, R., Dagenais, S., Fortier, P., & Young, N. L. (2020c). Données sur la teneur en eau volumétrique, vallée de Tasiapik 2014–2019 [Volumetric water content data, Tasiapik Valley 2014–2019]. *Nordicana D Data Repository*. <https://doi.org/10.5885/45630XX-D8F2843A4CB04C8A>
- Maréchal, J.-C., Dewandel, B., Ahmed, S., Galeazzi, L., & Zaidi, F. K. (2006). Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *Journal of Hydrology*, 329(1–2), 281–293. <https://doi.org/10.1016/j.jhydrol.2006.02.022>
- Marsh, P., Bartlett, P., MacKay, M., Pohl, S., & Lantz, T. (2010). Snowmelt energetics at a shrub tundra site in the western Canadian Arctic. *Hydrological Processes*, 24(25), 3603–3620. <https://doi.org/10.1002/hyp.7786>

- Murray, R., (2016). Bilan hydrologique d'un bassin versant dans la région d'Umiujaq au Québec nordique. (Master's Thesis). Université Laval, Québec, QC, CA. Retrieved from: Thèses et mémoires: <http://hdl.handle.net/20.500.11794/27364>
- Nimmo, J. R., Horowitz, C., & Mitchell, L. (2015). Discrete-storm water-table fluctuation method to estimate episodic recharge. *Groundwater*, 53(2), 282–292. <https://doi.org/10.1111/gwat.12177>
- Ochoa, C. G., Fernald, A. G., Guldan, S. J., Tidwell, V. C., & Shukla, M. K. (2013). Shallow aquifer recharge from irrigation in a semiarid agricultural valley in New Mexico. *Journal of Hydrologic Engineering*, 18(10), 1219–1230. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000718](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000718)
- Overland, J., Dunlea, E., Box, J. E., Corell, R., Forsius, M., Kattsov, V., et al. (2019). The urgency of Arctic change. *Polar Science*, 21, 6–13. <https://doi.org/10.1016/J.POLAR.2018.11.008>
- Peel, M. C., McMahon, T. A., & Finlayson, F. L. (2010). Vegetation impact on mean annual evapotranspiration at a global catchment scale. *Water Resources Research*, 46, W09508. <https://doi.org/10.1029/2009WR008233>
- Pelletier, M., Allard, M., & Levesque, E. (2018). Ecosystem changes across a gradient of permafrost degradation in subarctic Québec (Tasiapik Valley, Nunavik, Canada). *Arctic Science*, 5(1), 1–26. <https://doi.org/10.1139/as-2016-0049>
- Quinton, W. L., Hayashi, M., & Chasmer, L. E. (2011). Permafrost-thaw-induced land-cover change in the Canadian subarctic: Implications for water resources. *Hydrological Processes*, 25(1), 152–158. <https://doi.org/10.1002/hyp.7894>
- Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10(1), 18–39. <https://doi.org/10.1007/s10040-0010176-2>
- Seguin, M. K., & Allard, M. (1984). Le Pergélisol et les processus thermokarstiques de la région de la rivière Nastapoca, Nouveau-Québec. *Géographie Physique et Quaternaire*, 38(1), 11–25. <https://doi.org/10.7202/032532ar>
- Sophocleous, M. (1991). Combining the soil water balance and water-level fluctuation methods to estimate natural ground-water recharge: Practical aspects. *Journal of Hydrology*, 124(3-4), 229–241. [https://doi.org/10.1016/0022-1694\(91\)90016-B](https://doi.org/10.1016/0022-1694(91)90016-B)
- Tague, C., & Peng, H. (2013). The sensitivity of forest water use to the timing of precipitation and snowmelt recharge in the California Sierra: Implications for a warming climate. *Journal of Geophysical Research: Biogeosciences*, 118, 875–887. <https://doi.org/10.1002/jgrg.20073>
- Tremblay, B., Lévesque, E., & Boudreau, S. (2012). Recent expansion of erect shrubs in the low Arctic: Evidence from eastern Nunavik. *Environmental Research Letters*, 7(3). <https://doi.org/10.1088/1748-9326/7/3/035501>
- Truchon-Savard, A., Jean, M., & Payette, S. (2019). Black spruce (*Picea mariana*) colonization of subarctic snowpatches in response to warmer climate. *Journal of Ecology*, 107(3), 1154–1166. <https://doi.org/10.1111/1365-2745.13123>
- Varhola, A., Coops, N. C., Weiler, M., & Moore, D. A. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3-4), 219–233. <https://doi.org/10.1016/j.jhydrol.2010.08.009>
- Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal*, 15(6). <https://doi.org/10.2136/vzj2016.01.0010>
- Zhang, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43, RG4002. <https://doi.org/10.1029/2004RG000157>