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Development of multiple taliks near settlements on Svalbard – a new source of drinking water for the High Arctic?

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Abstract

This article presents a comprehensive documentation and analysis of long-term observations of year-round groundwater occurrences in rivers and various types of taliks under continuous permafrost conditions on Svalbard. Previously thought to be nonexistent, the existence of these taliks has been confirmed through rigorous field observations, geotechnical investigations, and extensive data collection. This discovery holds pivotal implications for our current understanding of permafrost conditions in central Svalbard. The research reveals the presence of several year-round taliks in close proximity to the settlements in Longyearbyen, Pyramiden, and Ny-Ålesund. Importantly, these findings open up opportunities for using these taliks as groundwater reservoirs for extraction of drinking water, either in their natural state or with appropriate engineering modifications. Furthermore, climate change may enhance the possibilities in future by expanding the size of these talik reservoirs due to rising air temperatures and increased inflow of fresh water over prolonged summer thaw periods. The results underscore the importance of including river taliks in continuous permafrost areas in water management strategies for Svalbard and similar Arctic regions. This research not only challenges prior assumptions but also offers valuable insights for sustainable water resource utilization in a changing climate context.

Keywords: talik, water security, groundwater, permafrost, Arctic, Svalbard, climate change.

Running head: Groundwater taliks near settlements in Svalbard – identification and future perspectives.

1 Introduction

For the convenience of the readers, a glossary with several definitions that were used in the article is presented in the Appendix 1. Such terms are marked with asterisk (*) when they appear in the text for the first time.

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1.1 Water security in small remote Arctic communities

Livelihoods in the Arctic are heavily entangled with the existence of permafrost*. Approximately 5 million people in the Arctic inhabit areas where permafrost is prevalent (Ramage et al., 2021), highlighting the crucial role of permafrost in the northernmost regions. Access to sustainable, high-quality freshwater sources for drinking water supply is of growing concern in the Arctic, where rivers and lakes are the most common drinking water sources (Lemieux et al., 2016; White, 2007). However, these surface water sources typically freeze during winter and often exhibit a low water quality due to high suspended sediment loads from glacier meltwater and land use contaminants (Nowak and Hodson, 2013). The challenge of water security* is especially acute in small remote Arctic communities, where large numbers of indigenous residents live (Cassivi et al., 2023).

In temperate regions, groundwater is considered a safer drinking water resource than surface water, as it requires little or no treatment to be suitable for drinking due to natural water filtration (Stenstrøm, 1994). These advantages may apply to Arctic conditions as well, provided that groundwater is accessible. In addition, in cold regions, groundwater has more consistent and higher water temperatures (compared to surface water), which eases treatment processes and renders the engineering constructions of water intakes more manageable. In the Arctic, groundwater has traditionally been overlooked as a potential source of potable water due to the common belief that it is not readily available (Lemieux et al., 2016). Recent research, however, has revealed the presence of unfrozen groundwater resources in Arctic environments with conditions ranging from discontinuous* to continuous* permafrost (e.g. (Lemieux et al., 2016)). Despite a few exceptions (Lemieux et al., 2020; Lemieux et al., 2016; Smith, 1996; Mckenzie et al., 2021; Alter, 1969; Liu et al., 2022), little attention has been given to the potential use of groundwater as a future drinking water source, with only a few studies covering groundwater extraction in cold regions (Alter, 1969; UFC 3-130-05, 2004; Buttle and Smith, 2004).

Groundwater may exist in the active layer* (i.e., the ground layer that is subject to annual thawing and freezing, typically 1–2 m thick, in areas underlain by permafrost (van Everdingen, 2005)), but its extent is usually limited and insufficient for water supply (Zastruzny et al., 2017). Therefore, in the continuous permafrost zone, aquifers* in taliks* (talik being a layer or body of unfrozen ground within a permafrost area due to local thermal, hydrological, hydrogeological, or hydrochemical anomalies (van Everdingen, 2005)) beneath rivers might be the only source of drinking water (Lemieux et al., 2016; Kane et al., 1973). Taliks beneath rivers are defined as river taliks*, depending on the permafrost thickness and the size of the river, such taliks may be either open or closed (van Everdingen, 2005). Groundwater or taliks beneath large rivers and lakes are, when present, considered the most reliable and economical groundwater sources in the Arctic (UFC 3-130-05, 2004). Depending on the size of the river or lake, such taliks may provide an adequate quantity and quality of water to meet a community's water demand (Smith, 1996; Instanes et al., 2016).

Kane et al. (2013) pointed out the potential of using groundwater from river taliks* in continuous permafrost. Even dry, inactive stream channels can have thawed zones below, offering a suitable water source if the appropriate type of soil is present (UFC 3-130-05, 2004). However, practical criteria for water use connecting ground thermal conditions, hydrological parameters of a river and the possible existence of taliks are lacking. Notably, Liu et al. (2022) conducted pioneering research combining numerical modeling and field investigations to describe the dynamics of river-talik systems in continuous permafrost. They observed that during winter, as the riverbed water dries up and the riverbed freezes, the river talik transforms into a confined tube-like system hydraulically isolated from the riverbed, potentially creating icings because the hydraulic head in such taliks may fracture the overlying ice cover.

Buttle and Smith (2004) advocate constructing infiltration galleries (i.e., subsurface structures in form of horizontal drains placed below the water table to collect groundwater) at wide gravelly rivers or small rivers and streams in permafrost regions. This approach solves the necessity to locate the flow under ice and may allow for water extraction from subsurface flow when the surface flow ceases completely. The galleries must be situated in thawed zones and use permeable materials.

Subpermafrost wells are technically feasible when the permafrost extends to a maximum depth of a few hundred meters. However, the drilling and maintenance costs for such wells are high, as they require special well casings or grouting methods to protect water from freezing while maintaining permafrost around the well (Alter, 1969). Furthermore, subpermafrost water (i.e., water occurring in the noncryotic ground below the permafrost (van Everdingen, 2005)) often contains high amounts of dissolved minerals due to the long residence time (UFC 3-130-05, 2004). Unconventional water supply enhancement, such as desalination of seawater or saline groundwater, have been suggested as options for producing potable water in the Arctic (UFC 3-130-05, 2004). It is, however, energy demanding technology and discharging hypersaline concentrate, known as "brine", poses disposal challenges, which is costly and associated with negative environmental impacts (Jones et al., 2019).

The uncertainty surrounding water management in the High Arctic is compounded by insufficient data on water consumption, flow rates, and purification practices, leaving the risk of irreversible changes that could jeopardize the sustainability of Arctic water supply in the future. The growing water demand in Arctic communities, driven by urbanization and modernization, further strains freshwater resources. Hence, there is a need to compile and generate new data to assess the nexus between permafrost degradation, groundwater recharge, and subsequent discharge into High Arctic streams.

1.2 Predictability in utilizing groundwater in the Arctic

The potential for using groundwater as a future source of potable water in Arctic communities may increase as permafrost transitions from continuous to discontinuous. At the same time, permafrost degradation could impact both water quantity and quality due to changes in the water cycle and an increased risk of contamination from former and present industrial and municipal activities. Hence, the Arctic water cycle is subject to multiple natural and anthropogenic stresses, threatening future water safety and security of the many Arctic communities using shallow rivers and lakes as sources of drinking water (Lemieux et al., 2016; White, 2007; CliC/AMAP/IASC, 2016).

An assessment of the potential for groundwater use is only feasible with reliable model predictions of future hydrological changes caused by permafrost degradation (and other factors, such as glacier retreat if glaciers are present). The impact of permafrost degradation on the water cycle remains elusive and is not sufficiently

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represented in models, meaning predictive capabilities for impact assessments are lacking (Walvoord and Kulrylyk, 2016).

Lamontagne-Hallé et al. (2020) provide guidelines for numerical modeling of groundwater in cold regions. Moreover, recent review articles on groundwater flow in cold regions (Walvoord and Kulrylyk, 2016; Lemieux et al., 2020) call for integrated, data-driven modeling approaches to better understand and predict the impacts of climate change on permafrost degradation and the ensuing effects on water sources in permafrost areas. Such modeling may incorporate climate projections, hydrological modeling in river basins, permafrost and subsurface hydrological modeling. Meteorological data are used in simulations to estimate ground temperatures through surface energy balance models (such as 1D-CryoGrid, NEST, and SHAW), which are coupled with subsurface simulations (Sjöberg et al., 2013; Kurylyk et al., 2014; Atchley et al., 2015; Orgogozo, 2019). Surface hydrology modeling in permafrost provides calculations of seasonal freeze-thaw penetration via analytical or numerical solutions. Groundwater modeling in permafrost is based on coupling a three-dimensional Richards-type equation for water flow to a three-dimensional heat transfer equation considering heat conduction, heat advection, thermal dispersion, and pore water phase change (Kurylyk et al., 2014). These subsurface simulations provide information on permafrost temperatures and preferential groundwater flow paths, and the interactions between thermal and hydrologic regimes. To obtain a more realistic depiction of local hydrological responses to global warming through empirical-statistical downscaling (ESD) (Benestad et al., 2016) the dependency of local climatic conditions on the large-scale state and local geography should be considered (Benestad et al., 2016). However, these model-based predictions require validation through detailed field observations.

Reliable predictions on future water cycle changes caused by permafrost degradation could have considerable implications for managing Arctic freshwater resources. To date, our knowledge of climate change impacts on the quantity and quality of surface and groundwater resources remains insufficient (CliC/AMAP/IASC, 2016).

1.3 Permafrost hydrology

1.3.1 Terminology for permafrost hydrology

Permafrost controls the hydrology (quantity and quality) of Arctic water sources (Sjöberg et al., 2013) by acting as an impermeable layer, limiting the recharge of underlying aquifers and confining groundwater flow to the seasonally thawed active layer above permafrost (i.e., suprapermafrost aquifers), to intrapermafrost, or to subpermafrost aquifers (Figure 1).

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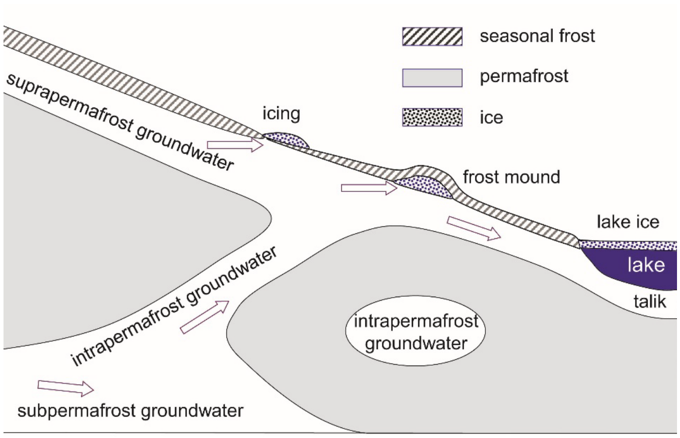

Figure 1: Ground water in permafrost (Figure: Woo (2012), © Springer).

To quantify the available groundwater, it is essential to sum up the different types of aquifers. Suprapermafrost aquifers can be categorized into three types (Haldersen et al., 1996; van Everdingen, 1990a) those that freeze entirely during winter (Type I), those that partially freeze (Type II), and those that never freeze (Type III) (Figure 2). Aquifers of Type I correspond to the active layer; aquifers of Type II are located between the active layer and the permafrost table (convective heat transport in permeable soils may contribute to the development of this type), and aquifers of Type III are not influenced by seasonal frost and are normally found in closed taliks beneath major waterbodies such as rivers and lakes (Lemieux et al., 2016). Intrapermafrost aquifers do not experience seasonal freezing (Lemieux et al., 2016) while subpermafrost aquifers correspond to groundwater located beneath the permafrost base. It is important to acknowledge that "taliks associated with rivers and lakes may occur in the continuous permafrost zone" (van Everdingen, 2005).

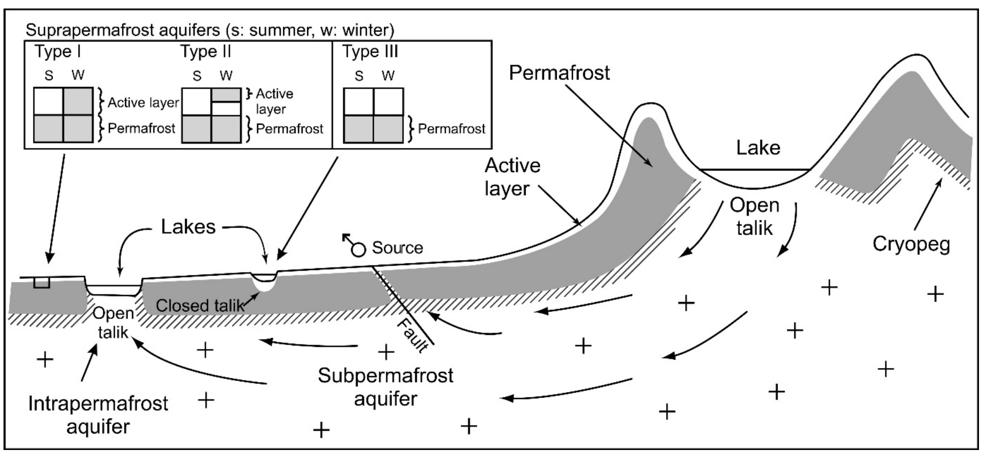

Figure 2: Suprapermafrost groundwater (Figure: Lemieux et al. (2016) adapted from Haldersen et al. (1996) and van Everdingen (1990b), © Springer).

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Icings* and observations of ground surface modified by icings can provide valuable indicators of river taliks, or suprapermafrost groundwater of Type II and intrapermafrost groundwater. This is based on van Everdingen (1990a), according to which "essentially all icings to some extent are related to the discharge of ground water". The growth of icings, fed by the discharge of suprapermafrost water, ceases long before the end of the freezing season due to the depletion of reserves or the freezing of conduits. In contrast, icings nourished by subpermafrost or intrapermafrost water continue to grow until the end of the freezing season (van Everdingen, 1990b). These distinctions and indicators play a crucial role in understanding the various groundwater types and their behavior within permafrost regions.

1.3.2 Effects of permafrost degradation on the hydrology in the continuous permafrost zone

Previous field studies investigating the effects of permafrost degradation on the hydrology of large Arctic rivers and the formation of taliks have primarily focused on the Low Arctic (Figure 3). This area is dominated by sporadic to discontinuous permafrost zones (e.g., (Lemieux et al., 2020)). However, "there is no sharp distinction, or boundary, between the continuous and discontinuous permafrost zones" (van Everdingen, 2005) and field data from the High Arctic, where permafrost is continuous, remain sparse and are usually related to perennial surface springs and open-system pingos (e.g., (Liestøl, 1977; Hornum et al., 2020)). This scarcity of data underscores the need for more extensive and accurate observations, a point emphasized by the Arctic Monitoring and Assessment Programme (AMAP) (2017) are vital for calibrating and validating models and improving the predictive capabilities of existing models. Concerning the size of the rivers, most previous studies on permafrost degradation and its impacts for the hydrological cycle have been restricted to surface water monitoring of large rivers. Unfortunately, the many small Arctic rivers and catchments remain poorly understood (CliC/AMAP/IASC, 2016). Likewise, very few studies have incorporated field observations and subsurface geo-hydrological field monitoring data in their predominantly modelling-based research (Liu et al., 2022). This lack of field data hampers our ability to predict how the hydrological cycle in small Arctic catchments will respond to future climate changes, both in the broader Arctic region (CliC/AMAP/IASC, 2016) and particularly in the High Arctic (Figure 3).

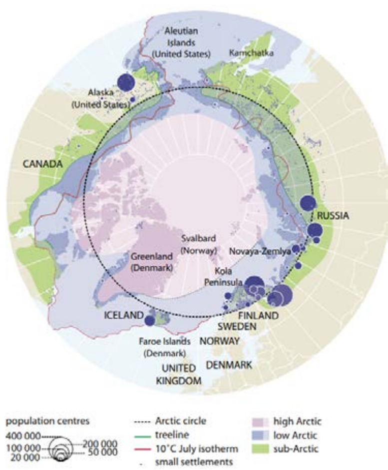

Figure 3: Overview for high-, low-, and sub-Arctic regions (Corell et al. (2013), © GRID-Arendal).

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1.3.3 Impacts of climate warming on groundwater in the Arctic

During the last 50 years, the Arctic has experienced a severe warming trend that is more than twice the global average due to Arctic amplification (Arctic Monitoring and Assessment Programme (AMAP), 2017). This warming has contributed to the ongoing well-documented degradation of permafrost (Walvoord and Kulrylyk, 2016; Bojinski et al., 2014). This degradation is characterized by a significant reduction in both the extent and thickness of permafrost zones, which in turn has intensely altered the Arctic water cycle (Corell et al., 2013). The degradation of permafrost leads to an increase in groundwater recharge and enhanced connectivity with surface water bodies (Walvoord and Kulrylyk, 2016) (Figure 4). This shift in the hydrologic regime may lead to a more groundwater-driven water cycle and stronger links between surface water bodies and aquifers. The recharge of groundwater is also dependent on precipitation, including rainfall, falling over the Arctic. There are indications that precipitation has increased by 9% between 1971 and 2019 (Arctic Monitoring and Assessment Programme (AMAP), 2021). This increase can partly be attributed to the retreat of sea ice, which changes moisture sources. In addition, a general (Bintanja and Selten, 2014; Vihma et al., 2016) increase in evaporation (Bintanja and Selten, 2014; Vihma et al., 2016) must be considered when evaluating the water balance and, thus, the recharge of groundwater storage in the Arctic.

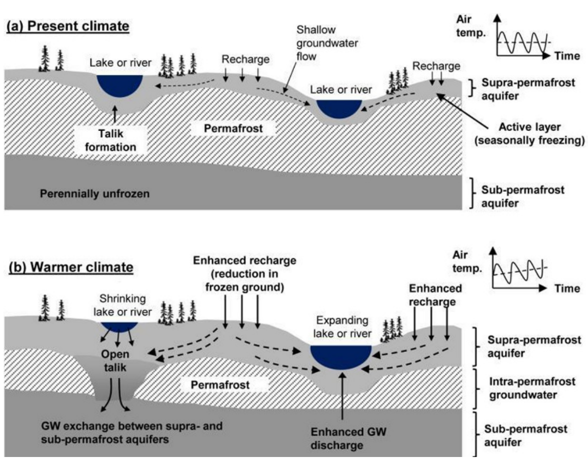

Figure 4: Transformation from a surface-dominated hydrological system to a groundwater dominated system under global warming (Figure: from Walvoord and Kulrylyk (2016), used under a Creative Commons CC—BY-NC-ND license).

As permafrost gradually thaws, isolated taliks* (a talik entirely surrounded by perennially frozen ground (van Everdingen, 2005)) can be formed (Kurylyk et al., 2016). The formation of taliks is a critical stage in permafrost degradation, and this process can be further accelerated by subsurface water flow through the taliks, delivering heat (Atchley et al., 2015). The emergence of lateral taliks* (a talik overlain and underlain by perennially frozen ground (van Everdingen, 2005)) can be considered as an initial condition leading to year-round streamflow, driven

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by increased baseflow in the rivers. It is also known that water bodies have a large thermal impact on permafrost. For example, migrating river meanders can lead to the degradation of underlying permafrost (Crampton, 1979).

1.4 Study site

1.4.1 Geographical location

Svalbard is an archipelago located in the Arctic Ocean between the Norwegian mainland and the North Pole, as depicted in Figure 5. Administered by Norway, this unique region is home to a variety of permanent settlements and research stations. These include Longyearbyen and Barentsburg, both permanent communities, as well as the permanent research settlement of Ny-Ålesund, the Hornsund research station, and the recently decommissioned coal-mining settlement of Svea. Additionally, several abandoned mining settlements, including Pyramiden, Grumant and Coles Bay, can be found on the archipelago. Longyearbyen is the largest settlement on Svalbard with approximately 3000 inhabitants.

Figure 5: Overview map of Svalbard (© OpenStreetMap Contributors (2017)). Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

1.4.2 Climate, permafrost and hydrology

Over the past four decades, Svalbard has witnessed an exceptional increase in air temperatures, surpassing Arctic and global warming averages by a significant margin, with temperatures corresponding to 2 to 2.5 times the Arctic average and 5 to 7 times the global average (Isaksen et al., 2022) This warming trend has also extended the summer thaw periods (Stocker et al., 2013). Observations show that the air temperature increase has followed the RCP 8.5 scenario during the last decades. Climate projections predict increasing air temperatures and precipitation on

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Svalbard for the 21st century (Benestad et al., 2016; Hanssen-Bauer et al., 2019; Nordli et al., 2020; Rongved et al., 2018).

Svalbard, located in the continuous permafrost zone of the Northern Hemisphere, features permafrost of varying thickness, ranging from less than 150 m close to the coast to more than 450 m in the mountain areas (Liestøl, 1977; Humlum et al., 2003). Permafrost temperatures are relatively warm when compared to Svalbard's latitude, and temperatures at or close to the depth of zero-annual amplitude (MGT) vary from -2.6 °C to -5.2 °C at different observation sites (Hanssen-Bauer et al., 2019). The active layer thickness (ALT) is generally in the range of 100 to 200 cm (Christiansen et al., 2019). The ALT can be estimated by direct observations (probing with a steel rod and borehole monitoring, e.g. CALM 2021 Circumpolar Active Layer Monitoring (CALM Program, 2021)) or by geophysical investigation (e.g., (Bazin et al., 2021)). Observations ranging from one decade to several decades show a warming of permafrost and an increase in the ALT (Hanssen-Bauer et al., 2019). Models project the near-surface permafrost to thaw on Svalbard by the end of the 21st century (Hanssen-Bauer et al., 2019). However, these models do not account for crucial processes like lateral water flow, which is known to accelerate permafrost thaw, suggesting that the actual thawing rate may be faster than predicted.

Following the classification of Church (1974), the hydrological regime in the study area encompassing the watersheds of Longyearelva, Adventelva and Odinelva can be classified as proglacial. In this regime, snowmelt produces a spring peak in discharge, while the highest flow occurs in summer due to glacial runoff.

For 1979–2019, Nowak et al. (2021) depict a steady decrease in freshwater fluxes, especially from smaller glacierized watersheds, while water fluxes from rainfall-dominated watersheds have been increasing. The length of flow season showed a clear upward trend, with the Longyearbyen area experiencing an average increase of nine days per decade during the same period. Climate projections suggest an increase in mean annual precipitation and runoff for the total land area of Svalbard during the 21st century, with increased occurrence of heavy rainfall and flood events (Hanssen-Bauer et al., 2019). At the same time, a decrease in the runoff is projected for some rivers after the year 2050 (Hanssen-Bauer et al., 2019) a trend supported by Nowak et al. (2021) In the future, one may anticipate an increase in annual glacier runoff in glacier-dominated catchments until it reaches a maximum. Currently, the majority of runoff occurs in summer, but instances of runoff after winter rain events have been observed in some rivers on Svalbard (Longyearelva), a trend that has become more frequent in recent decades (Hansen et al., 2014; Vikhamar-Schuler et al., 2016). The predicted rise in winter air temperatures, which may result in an increased fraction of liquid precipitation during winter, is likely to further increase runoff (Hanssen-Bauer et al., 2019).

1.4.3 Groundwater in Svalbard

On Svalbard, groundwater primarily occurs in two forms: subpermafrost water and suprapermafrost water in the active layer in summer. Liestøl (1977) relates subpermafrost groundwater to the existence of thawed zones below the accumulation part of polythermal glaciers (where the glacier bed is at pressure-melting point) and describes the significance of this zone for groundwater supply. Liestøl (1977) points out that the conditions of pressure-melting point at the glacier bed "cause openings in the continuous permafrost layer, through which water will sink

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into the ground below the glacier bed and cause a groundwater stream to flow downwards under the permafrost layer and out to the coast and sea". Furthermore, while flowing under the permafrost base down to the coast, the groundwater can be at artesian pressure due to the overlying impermeable permafrost layer. In some places, impermeable layers will force groundwater to deeper layers where geothermal heat is absorbed and later such water can be seen on the ground surface as warm springs. In other cases, expelling of groundwater under artesian pressure will lead to the formation of pingos* (pingo – a perennial frost mound consisting of a core of massive ice, produced primarily by injection of water, and covered with soil and vegetation (van Everdingen, 2005)) of the Greenland type (characterized by "the hydrostatic pressure from below the permafrost together with the freezing expansion is blowing up strata into mounds", Liestøl (1977)). Springs and pingos in Svalbard were reported in several publications since the mid-20th century (Orvin, 1944; Liestøl, 1977; Salvigsen et al., 1983; Yoshikawa and Harada, 1995; Yoshikawa and Nakamura, 1996; Haldorsen and Heim, 1999; Humlum et al., 2003; Woo, 2012; Hodson et al., 2020).

In winter, water draining from underneath polythermal glaciers can form massive icing in front of them. The principal processes associated with subpermafrost water in Svalbard are presented in Figure 6.

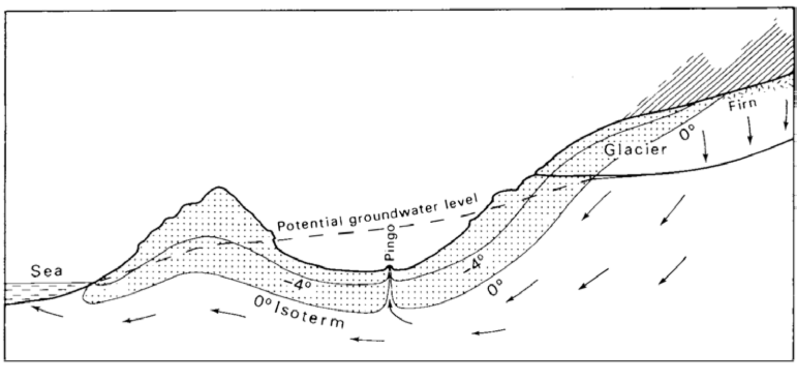

Figure 6: Vertical profile of the permafrost (grey area) and groundwater movement from the glacier accumulation to the coast from Liestøl (1977) © Norwegian Polar Institute.

Suprapermafrost groundwater in the active layer is monitored in Ny-Ålesund (Noregs vassdrags- og energidirektorat (NVE), 2023). There are also other types of subpermafrost water on Svalbard, i.e., "old sub-permafrost water" that was pushed down by the advancing freeze front during permafrost aggradation (Weinstein et al., 2021).

According to Petterson (1994), all rivers on Svalbard freeze over entirely in the fall, except for a few rivers fed by springs (groundwater under artesian pressure) or in front of some glaciers. The presence of river taliks and intrapermafrost water in riverbeds has not been reported in scientific literature for Svalbard to date. This lack of data may partly be explained by the fact that most boreholes established for scientific purposes on Svalbard were installed in "normal" terrain settings rather than in riverbeds, where such installations are technically challenging. Publicly available data on monitoring permafrost temperatures on Svalbard do not indicate the existence of taliks. Yet, without explicitly mentioning river taliks, Liestøl (1977) notes that "water left in the riverbed after the summer

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drainage, represents local heat reservoirs", this may delay seasonal freezing. One of the objectives of this study is to document field observations of river taliks.

1.4.4 Water security in Svalbard

Arctic regions, including Svalbard, are facing a growing concern regarding water security due to permafrost conditions. Drinking water in Longyearbyen is derived from a meltwater/river water intake in Gruvedalen during summer (June to September), with an artificial dam (Isdammen) as the reserve water source (Figure 7). The Gruvedalen water consists of snow melt in the first part of the summer-season and to increasing degree of thaw-water from the developing active layer in later season. During fall and winter, the Gruvedalen river freezes, and the water supply from the valley is temporarily shut down. Hence, during the long winter season, the water supply to Longyearbyen is fully dependent on the Isdammen reservoir. A burst of the water pipe or dam construction may have severe consequences for the local community (Longyearbyen Lokalstyre/COWI, 2018). In addition, the raw water source has water quality issues related to high levels of suspended sediment loads and contaminants originating from acid mine drainage (Nowak and Hodson, 2013). This is a vulnerable situation for the Arctic society of Longyearbyen, including residents, visitors (on-shore and off-shore tourism), business/industry, power supply, and heating plants (Longyearbyen Lokalstyre/COWI, 2018; Ording, 2007). In Barentsburg, Ny-Ålesund, Pyramiden and Svea, drinking water is or was, in the case of abandoned settlements, mostly derived from lakes. There is no alternative source of drinking water in Barentsburg (as far as we understand) and Ny-Ålesund in wintertime, which makes the situation in those settlements also vulnerable. Pyramiden had a comprehensive system for water management, which included several artificially dammed lakes, in addition to water intake from a river.

2 Methods

This study aims to contribute to cryo-hydrogeology in continuous permafrost regions, using multiple examples from Svalbard. The results are useful for long-term management strategies for water security both on Svalbard and in other Artic locations with comparable geo-cryological conditions. The results may help to identify priority areas for field surveys aimed at assessing aquifers potentially suitable for water supply on Svalbard. In particular, this study

(1) documents field observations of river taliks, taliks in "normal" terrestrial settings, and intrapermafrost groundwater within relatively small rivers and at the foothills of mountain slopes on Svalbard. These locations serve as representative sites situated within continuous permafrost in the High Arctic.

(2) presents detailed observations of icings and of the modifications they cause to the ground surface. These observations are instrumental in identifying river taliks or suprapermafrost groundwater of Type II. We differentiate between small icings (less than 10–20 m in diameter), whose growth ceases long before the end of the freezing season, and medium to large icings (larger than approximately 20 m in diameter), whose growth continues until the end of the freezing season.

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(3) evaluates the results of geotechnical field observations ("datamining" in geotechnical reports provided by consultant companies), used by the industry to characterize site conditions for the needs of infrastructure development. These reports usually provide data on soil profile (including lithology and stratigraphy), soil state (thawed or frozen), water content in the ground, and, in some cases, ground temperatures.

(4) presents observations of springs that may originate from intrapermafrost sources (conduits, when active, are characterized as probable intrapermafrost groundwater).

(5) compiles additional insights gained from local residents and their experiences. This input may provide data regarding the timing of icing growth and other qualitative information on the study objects.

(6) presents a comprehensive discussion on the findings in cryo-hydrogeology in the light of water security on Svalbard and other polar regions.

The collected data is presented in detail in the Supplement, which offers detailed observations from 30 cases in Longyearbyen (48 photographs, six videos (Sinitsyn, 2023a), and three personal communications), four cases in Ny-Ålesund (4 photographs and one personal communication), one case in Pyramiden (4 photographs and one personal communication), and one case at Hovtinden mountain (one photograph and one video (Sinitsyn, 2023a). The designations of observation locations (location c) remain consistent in the figures presented in the manuscript and the Supplement.

3 Observations and interpretation

3.1 Icing observations

3.1.1 Icings at riverbeds, riverbanks, and former river channels of Longyearelva

Between 2008 and 2017, within the Longyeardalen valley, which encompasses Longyearbyen and the Longyearelva river, numerous icings were observed in the riverbed, riverbanks, and areas of former river channels during the winter months (locations a1–a9 and a11 in Figure 7, Table S1, and corresponding figures in the Supplement, and videos (Sinitsyn, 2023a). The size of the icings ranges from small (< 10 m in diameter) and medium (several tens of meters in diameter) to large (a hundred of meters in diameter) (Figure S1.a5, Video S1.a5-3 (Sinitsyn, 2023a)). These icings are shaped either like a mound (Figure 8 a and Figure 8 b; Figure S1.a1-1–Figure S1.a1-5) or as more spread and flat ice features (Figure S1.a5, Video S1.a5-3 (Sinitsyn, 2023a)). Drilling through the "mound" icings normally revealed water at artesian pressure (locations a1, a2, and a11; Videos S1.a2-1–S1.a2-2 (Sinitsyn, 2023a); Figure S1.a11). The surfaces of the "flat and spread" icings were sometimes covered with a wet surface (slush) (as observed in location a6). A more uniform and laterally extensive seepage of groundwater is probably the reason for the formation of these "flat and spread" icings with slush. Note that only a few icings were observed in the riverbed of Longyearelva in April 2008 (Figure S1.a1-1–Figure S1.a1-3), but a significantly higher number appeared in April 2017 (Figure S1.a1-4 and Figure S1.a1-5). This difference may indicate an increase in groundwater flow over the last decade or the expansion of a river talik, coinciding with the

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warming trend witnessed in Longyearbyen during the same period. Similar icings were observed at Longyearelva in other years within the 2008–2019 timeframe, although we have not documented these cases. The growth of some of the icings slowed down significantly towards the end of the winter season in some years (Ramboll Norge AS, 2019b). The formation of these icings is believed to be influenced by the infiltration of surface water during warm periods in wintertime (Ramboll Norge AS, 2019a), yet some observations indicate that icing growth occurred in periods without liquid precipitation. This suggests that groundwater originating from suprapermafrost Type II and intrapermafrost aquifers may serve as the source feeding these icings (Figure 9). The discharge of groundwater at the ground surface (leading to the formation of icings) is likely determined by a sequence of warm and cold periods during winter: discharge takes place during cold periods (when air temperatures are colder than -10 °C), especially when they follow mild weather conditions with a time-gap of a few weeks (Ramboll Norge AS, 2019a; Sinitsyn, 2021). The groundwater beneath the observed icings is often artesian. Pedersen (Ramboll Norge AS, 2019a) suggests two factors influencing the artesian pressure. Firstly, it builds up due to the freezing of the active layer from the top, in combination with impermeable permafrost below the aquifers. Secondly, mild winters may facilitate the infiltration of surface water, enabling the replenishment of intrapermafrost groundwater and subsequently raising pressure within the aquifers. The latter is supported by observations made at location a1 (Figure 7) in April 2017 when water sampled from the icing displayed distinct traces of diesel, most probably originating surface water drainage from the nearby semi-industrial area (commonly referred to as Sjøområdet).

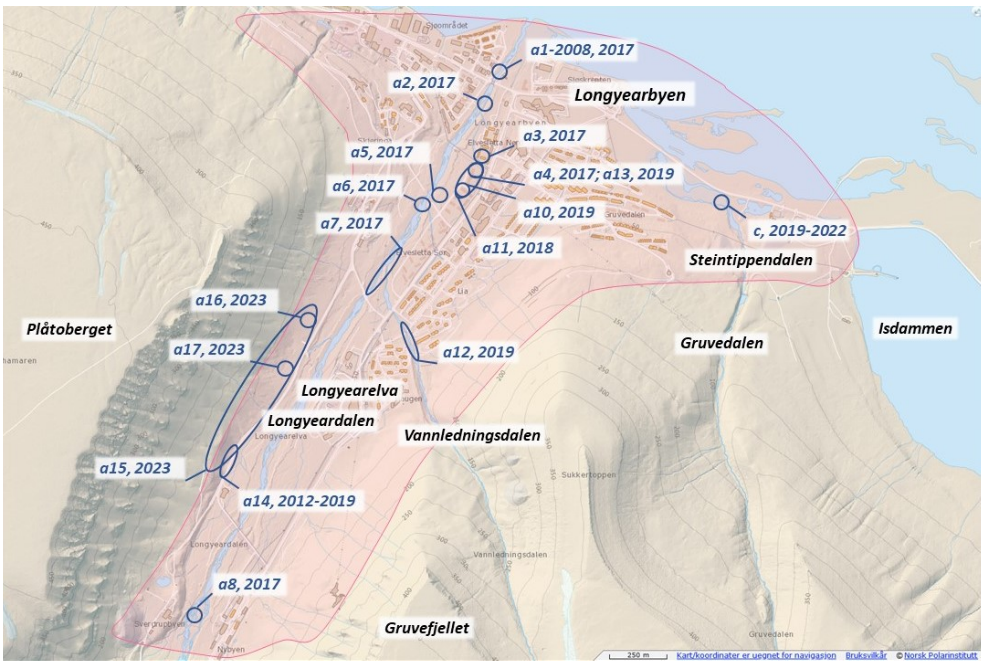

Figure 7: Locations of observations in Longyearbyen (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

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Figure 8. Some of the observations of indicators of groundwater (full list of observation is presented in the Supplement): a. – small, cracked "mound" icing at Longyearelva below the bridge across the Road 600, location a1 (10.04.2008, Figure S1.a1-1 in the Supplement); b. – small, cracked "mound" icing at Longyearelva below the bridge across the Road 600, drilling revealed water at artesian pressure, location a1 (18.04.2017, Figure S1.a1-4); c. – remains of a large icing, north-western part of Ny-Ålesund (26.06.2023, Figure S1.k-2.); d. – emergence of water at artesian pressure when drilling through an icing in Elvesletta, location a11, photo: © Marit Pedersen/Ramboll AS (23.04.2018, Figure S1.a11); e – Longyearbyen and Longyearelva in its natural, unconfined state, running in several channels, blue circle depicts approximate location of Elvesletta, location a10, photo: © Norwegian Polar Institute, image number S36_3039 (1936, S1.a10-2); f – Longyearelva channelled into one large riverbed equipped with rock- protection of riverbanks against erosion, blue circle depicts approximate location of Elvesletta, location a10, photo: © A. Skoglund/Norwegian Polar Institute (2017, S1.a10-1); g – large "mound" icings at the intersection of Adventelva and Bolterelva, location b1, photo: © Elizabeth Bourne (12.06.2020, S1.b1); h – first borehole on profile "Nr.1" in the riverbed of Odinelva in Pyramiden, location h (27.08.2021, S1.h-3).

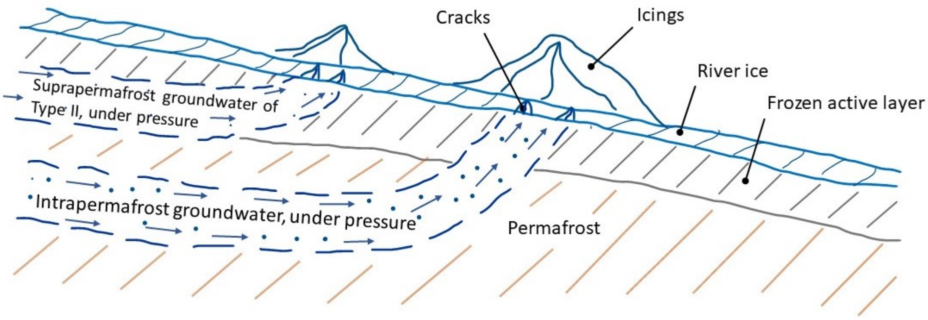

Figure 9: Illustration of suggested suprapermafrost groundwater of Type II and intrapermafrost groundwater in Longyearelva/Longyeardalen (sketch N1).

The presence of icings at location a1 (Figure 7) in the Longyearelva river, approximately 200 meters from the shoreline, suggests that there might be no river talik with suprapermafrost groundwater of Type II within this particular 200-meter stretch towards the sea. However, this observation may not necessarily be indicative of the whole area of the old delta of Longyearelva, which has been consolidated into a single engineered channel (Sjøområdet). In fact, there are suspicions that the (6-meter deep) pile foundations supporting some of the houses in this area were lifted by groundwater, i.e., some flow of subpermafrost groundwater of Type II or/and intrapermafrost groundwater in the sea cannot be ruled out for this area.

3.1.2 Icings on sloping terrain in Longyeardalen

Icings in the Longyeardalen valley (Figure 7) also occur in other settings, e.g., at the foot of sloping terrain. One such icing was observed repeatedly during several winters within the 2012–2019 period, situated on the slope next to the Huset building (location a14). This particular icing extended approximately 200 meters along the slope, spanning several tens of meters in width, and exhibited the characteristic "flat and spread" shape. Its thickness reached approximately 0.5 m or more by the end of each winter season. This icing filled the drainage ditch along the road and was completely flooding a stretch of Road Nr. 300 in several winters, causing road closures. While the growth dynamics of the icing were not continuously monitored, it was observed that the icing expanded, at least during the first part of the winter season. Additionally, several springs with artesian pressure were observed on the same slope during the spring months (approximately May–June), disappearing later in the summer. The spring points are not visible when inactive, in that they lack any morphological signature in the surface (i.e. depression), but only appeared as small fountains on vegetated ground surface or direct out of surficial rock debris. Observations of temporary reactivation of the same springs were made after a heavy rain event from the 5th to the 7th of September 2023, where several springs under artesian pressure were observed over the course of a few days (Video S1.a16 (Sinitsyn, 2023a), Figure S1.a16, Figure S1.a17). These observations point to the presence of subsurface water conduits that are episodically active in this area. In early September 2022, similar, but larger springs were documented on the lower slopes of the Hovtinden mountain in the Trollheimen area on Svalbard (see Sect. 3.5).

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It is possible that both the observed icing and the springs were fed by water draining from the above Platåberget plateau (Figure 7). This drainage may occur through fractured sandstone or through pores in unfractured sandstone on the slope above (marked as Pattern I in Figure 10). We suggest that this icing points to intrapermafrost groundwater. In addition, it is plausible to suggest that there might be deeper conduits carrying groundwater that feeds the icings in the Longyearelva river, centrally in the valley bottom (marked as Pattern II in Figure 10). This scenario, if accurate, shares to some extend similarities with the discharge of groundwater from the base of the Vestre Lovénbreen glacier in Ny-Ålesund (Haldersen et al., 1996). In that case, water is discharged through limestone dolomite and sandstone into subpermafrost aquifers.

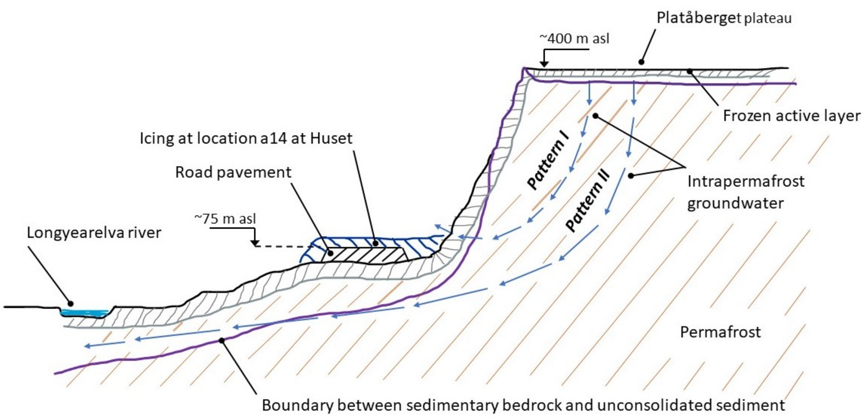

Figure 10: Illustration of suggested intrapermafrost groundwater at Huset (location a14) in winter and spring season.

3.1.3 Icings in Adventdalen

The observations made along the Adventdalen valley, with the Adventelva river being the largest river in the area of Longyearbyen, in 2020–2021 reveal the presence of numerous icings in the riverbed (locations b2, b3, b5, b7-b9 in Figure 11). Icings were also observed along other rivers in the proximity of Adventdalen valley (b1, b4, b6, c, d, f in Figure 11). These icings are likely linked to the valley floors of smaller tributary valleys where they converge with the larger Adventdalen valley.

The icings along the riverbed of Adventelva can be categorized into two different types: 1) mound-like features, these are characterized by several meters in diameter and typically one to two meters in height; and 2) widespread features, these are considerably larger, ranging from several tens of meters to a few hundred meters in diameter and approximately one meter in height (Figure 11, location b9). We interpret the smaller icings as indicators of suprapermafrost Type II, based on the description of river talik occurrences as outlined by Liu et al. (2022) (Figure 9). The larger icings, on the other hand, are interpreted as intrapermafrost groundwater., This interpretation stems from the requirement of large amounts of water with a continuous discharge during winter, indicating that such groundwater must be part of a deeper and more extensive groundwater system that can provide a continuous water supply throughout the winter.

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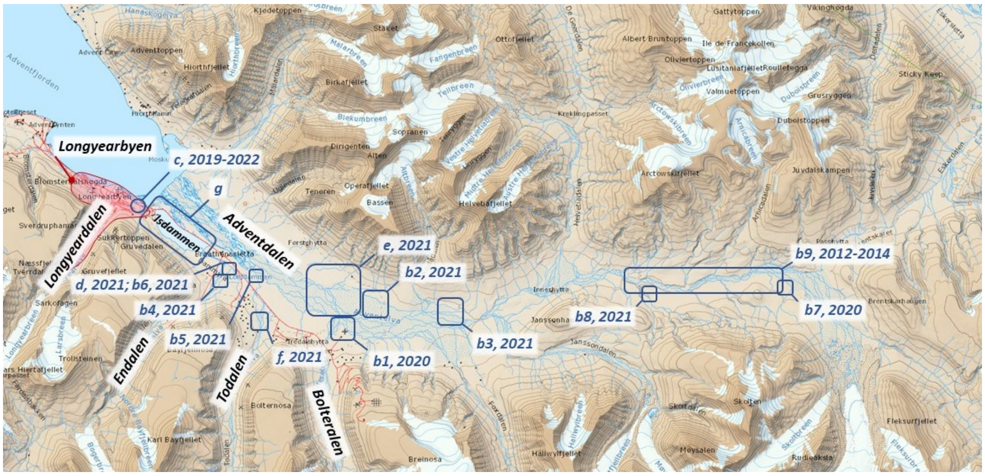

Figure 11: Locations of observations in Adventdalen (Map: TopoSvalbard (2021), © Norwegian Polar Institute)

Interestingly, no icings are observed in the delta of Adventelva, even though this river has a much larger discharge than Longyearelva. This absence of icings could indicate unconstrained (by permafrost) flow of groundwater within a hypothetical river talik in Adventelva leading into the sea (Figure 12). This potential talik may encompass both suprapermafrost groundwater of Type II and intrapermafrost groundwater. A similar, but smaller, talik could be suggested for Endalselva (Figure 12).

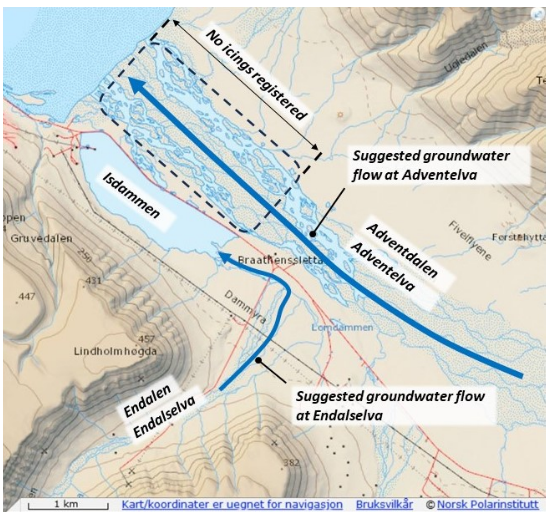

Figure 12: Proposed flow of groundwater from Adventdalen into the sea (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

The icings related to the valley floors of smaller tributary valleys (all locations in Figure 11 and Table S1 in the Supplement), such as Steintippendalen (location c), Endalen (location d, b4, b6), and Bolterdalen (location b1), exhibit the same variations in size as discussed above. The interpretation for smaller icing features along Adventelva presented above is also applicable to the small features within these smaller valleys (location b6).

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However, the larger icings in these valleys (locations c, d, b1, and b4) appear more like mound-like features (Figure 8 g; Figures S1.b1 and S1.c-1). A detailed description and discussion of the larger icings on the valley floors of these smaller tributary valley is presented in Sect. 4.2.3.

3.2 Direct observations of groundwater

3.2.1 Longyeardalen

There are a number of direct observations of groundwater in Longyeardalen, particularly at Elvesletta (locations a10, a11, and a13), and in the Vannledningsdalen valley ("the water supply valley") (location a12). These observations were made during several geotechnical investigations (performed with rotary drilling) and the installation of deep pile foundations (reaching depths of down to 24 m). The investigations were performed in depths of down to approximately 30 m and delivered the soil type, the depth to bedrock, the presence of ice lenses, and observations of groundwater. These investigations included drilling to describe the soil profile and drilling of the icings. They also revealed groundwater at different levels. For instance, one campaign conducted in March 2017 revealed water at depths ranging from 1 m to 6.8 m (Ramboll Norge AS, 2017). In contrast, a campaign in March 2019, located a few hundred meters to the south, did not detect groundwater, but rather encountered ground conditions at depths of 3–11 m that "may be suitable to host groundwater" (Ramboll Norge AS, 2019a). These conditions typically consisted of a mixture of gravel and silt, or just gravel. Another campaign specifically focused on investigating conditions beneath the icings (a11). This campaign revealed an aquifer under artesian pressure beneath the icing (Figure 8 g, Figure S1.a11). The icing was underlain by a thawed zone reaching depths of 3–6 m below the ground surface (Ramboll Norge AS, 2018). In addition, during the deployment operations for deep pile foundations, ground water was encountered at depths ranging from 4 m to 18 m (Norges arktiske studentsamskipnad, 2020). These observations (i.e. (Ramboll Norge AS, 2017, 2019a, 2018; Norges arktiske studentsamskipnad, 2020)) were made in areas that were formerly river channels of Longyearelva. Although the river currently flows through a single engineered channel (Figure 8 e, Figures S1.a10-1, S1.a10-3–S1.a10-4), historical images clearly display the presence of these former river channels (Figure 8 f, Figure S1.a10-2). Hence, it is highly likely that the occurrence of groundwater is linked to these old river channels (Ramboll Norge AS, 2019a, 2018). Furthermore, the observations of Pedersen [59] point out the existence of both suprapermafrost groundwater of Type II, which is "mobilized" by seasonal freezing and evidenced as surface icings, and intrapermafrost groundwater, some of which exhibit a somewhat stable discharge. Aquifers were also found beneath the riverbed of the Vannledningsdalen valley (Ramboll AS, 2019), located under the upper 3–4 m of frozen soil and largely aligned with the riverbed. These aquifers were suggested to have year-round water flow (Ramboll AS, 2019). It is conceivable that this flow may contribute to the flow in aquifers, as indicated by the icings downstream in Longyearelva (locations a1– a7, a9–a10), and hence to be the reason that many of the icings in Longyearelva are located below its intersection with Vannledningsdalen. The source of these aquifers is unknown, and perhaps may be attributed to water drained from the watershed of Vannledningsdalen valley (Figure 7), which occupies part of the Gruvefjellet plateau (Figure 7). This suggests similar drainage patterns as presented in Figure 10.

We suggest that these direct observations reveal groundwater that can be classified as suprapermafrost groundwater of Type II and intrapermafrost groundwater, respectively. Furthermore, we suggest that some of the

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sources supplying intrapermafrost groundwater may be connected to water with longer residence times, such as water draining from surrounding plateaus through fractured sandstone (as outlined in Figure 10). Additionally, intrapermafrost groundwater may be hydrologically linked to the sea, potentially forming a year-round flow of this water into the sea. This may especially apply to groundwater located deeper in the soil profile, as observed in the case reported by Norges arktiske studentsamskipnad (2020), where water was observed at depth of 4–18 m. These conclusions call for a modification of Figure 9 to incorporate a deeper layer of intrapermafrost groundwater, resulting in Figure 13.

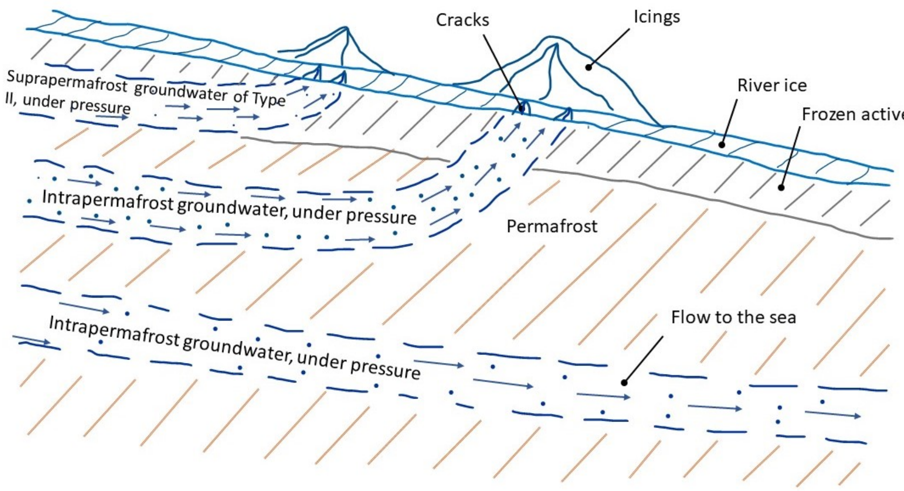

Figure 13. Illustration of suggested suprapermafrost groundwater of Type II and intrapermafrost groundwater in Longyearelva/Longyeardalen (sketch N2).

3.2.2 Adventdalen

In Adventdalen, unfrozen zones were revealed through drilling in April 2021, approximately situated on the opposite side of the valley from the point where Adventdalen meets Todalen (Christiansen, 2021) (location e in Figure 11). In addition, there are numerous indications of increased permafrost degradation in Adventdalen, primarily attributed to the thermal impact of the rivers. For example, the increased settlement of historical cableway posts within the flood zone of the Todalselva river (location f in Figure 11, Figure S1.f) implies a relatively higher rate of permafrost degradation in comparison to the nearby areas that remain unaffected by river stream/flood plain. This phenomenon is interpreted as the result of the riverine flow influence on permafrost (Sinitsyn et al., 2022).

3.2.3 Large continuous growing icings in the Longyearbyen area

From 2019 to 2022, a large (several meters in height) and continuously growing icing formation developed at the foot of the small Steintippendalen valley (lower part of the Gruvedalen valley, see Figure 7). Steintippendalen valley leads into the Adventdalen valley (location c and Figure S1.c-1). There is a seasonal river in this valley,

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active only during the snowmelt period in the summer. The icing partly occupied the riverbed and partly the adjacent sandbank/riverbank. The water from this seasonal river serves as a source for Longyearbyen's drinking water supply during the summertime. However, in the autumn, the surface water in the river dries up and the community shifts its water intake to the Isdammen lake. This recurring icing has been observed annually at least during the winters from 2019 to 2022 and has posed an imminent threat to a nearby road, nearly blocking it. We assume that a relatively constant discharge of groundwater contributes to this case. In February 2019, geotechnical field investigations revealed large amounts of groundwater beneath (depths from 1.3 to 8 m) this icing (Ramboll Norge AS, 2019b). In an attempt to cut off the seepage from the surface layer, a culvert was constructed uphill from the icing formation. Yet, this culvert did not affect the icing formation (Sinitsyn, 2022b). Thus, it is reasonable to conclude that the formation of this icing may be linked to a deep conduit of intrapermafrost groundwater. Although this icing disappears during the summer, it leaves behind a characteristic pattern of "reworked soil" on the ground surface (Figures S1.c-2–S1.c-3). Similar patterns were also observed in the sandbanks of the lower part of the Endalselva river, which feeds the artificial Isdammen lake (Figure 11 location d; Figures S1.d-1–S1.d-3; location b4). Warmer and wetter years in the past decade may have facilitated the emergence of this intrapermafrost conduit, providing enough water within its watershed to support the icing formation during the winter (Figure 14). In June 2020 similar large, and probably continuously growing icing was observed at the junction of Adventelva and Bolterelva rivers (Sinitsyn, 2022a) (Figure 8 g; Figure 11 location b1; Figure S1.b1). This large icing persisted during a portion of the summer season.

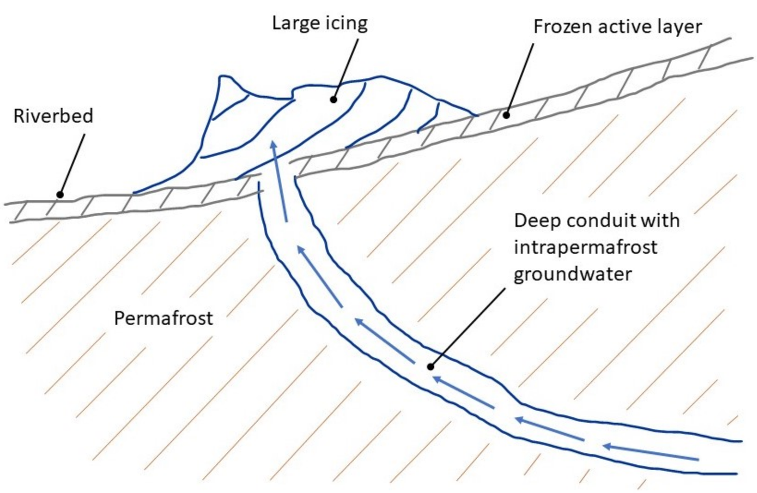

Figure 14: Illustration of suggested intrapermafrost groundwater at Steintippendalen/Gruvedalen (Figure 7 location c).

3.2.4 Observations in Ny-Ålesund

The observations of icings in Ny-Ålesund include: an icing beneath a small building at the foot of the Zeppelinfjellet mountain (Sinitsyn, 2022c) and remains of a substantial icing (measuring approximately 10 by 30

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meters) in late June 2023 (Figure 8 c, Figures S1.k-1–S1.k-3). Additionally, it is noteworthy that the ground floors of Gamle kraftstasjonen (the old power plant) are permanently filled with ice, a clear indicator of the presence of suprapermafrost or/and intrapermafrost groundwater (Figure S1.4). Moreover, recently, thaw zones were revealed in Ny-Ålesund during the installation of pile foundations for two buildings (Sinitsyn, 2022c) (cases i1 and i2 in Table S1 and in Figure S1.4). These thaw zones were found at a depth of approximately 10 m, strongly implying the existence of intrapermafrost groundwater.

3.3 Other considerations for the Longyearbyen area

The Isdammen lake serves as the primary source for water supply in Longyearbyen during winter. It is an artificial lake, held in place by a dam. A previous evaluation conducted by Hilmo (2007) confirmed the presence of permafrost underlying the lake. It is generally believed that there is an inflow of water into Isdammen throughout the winter season, and water level fluctuations during this period are small (Sinitsyn, 2023b). Importantly, there is no discharge over the spillway at the dam during winter. There are two sources of water outflow from Isdammen in winter: the water consumption of the community and some leakages from the dam itself. The sources feeding Isdammen during the winter months remain unclear (location g in Figure 11). Intrapermafrost groundwater and, perhaps to a lesser degree, suprapermafrost groundwater of Type II may be contributing to this water source during the winter. If this is indeed the case, the source of intrapermafrost groundwater may be linked to some kind of deeper conduits that transport water drained from the plateau areas of the surrounding mountains (Figure 15; this situation is similar to the one presented in Figure 10). Additionally, the source of subpermafrost groundwater of Type II could be connected to the baseflow of Endalselva river (Figure 16). It is conceivable that the establishment of Isdammen might have "activated" or "thermally supported" such an intrapermafrost groundwater system. However, the exploration of other alternatives, such as the supply of water from subpermafrost groundwater, falls largely outside of the scope of this study.

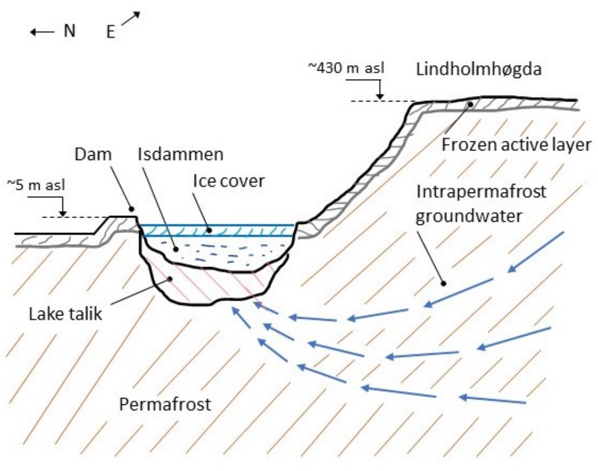

Figure 15. Illustration of suggested intrapermafrost groundwater feeding Isdammen.

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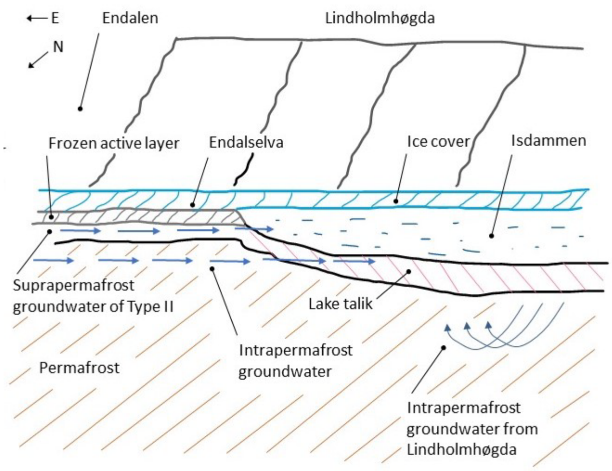

Figure 16: Illustration of suggested suprapermafrost groundwater of Type II and intrapermafrost groundwater at Endalselva/Isdammen.

3.4 Observations in Pyramiden

An intriguing installation is situated within the riverbed of Odinelva in Pyramiden (location h in Figure S1.3). In addition, there is evidence to suggest the presence of another facility installed within the riverbed of Odinelva. The installation consists of two profiles – one extending across and the other running parallel to the river, see Figure S1.3. Each borehole is equipped with steel casings/filters (ca. 20 cm in diameter) sticking out approximately 1.5 m above the bottom of the river. These filters were used to collect water from the river aquifer. We do not know whether the system was in operation during the winter. However, it was phased out prior to the 1990s and partly dismantled when artificial lakes were established for water supply (Sinitsyn, 2022b).

These installations were "discovered" and observed by the authors in late August 2021 (Figure 8 h, Figures S1.h-1–S1.h-5). At that time, the water level in the river ranged from around 20 to around 50 cm, while the water depth within the boreholes measured about 3–4 m (determined using a rope and a lead weight) from the river's bottom. The borehole bottoms felt soft when tapped with the lead attached to a rope. This gave the impression that the talik at the riverbed was at least 3–4 m deep, which is two to three times thicker than the ALT observed (Hanssen-Bauer et al., 2019) in terrain settings or calculated based on theoretical approaches (Sect. S2). This observation confirms the pronounced thermal influence of the river on the active layer in its riverbed. Calculations based on the Stefan solution (Table S2.2) suggest that this talik, if fully saturated, cannot entirely refreeze (freezing down to a depth of 2.8 m) during winter in the coldest year within the 2010–2021 period (Figure 17). This points to the likely presence of suprapermafrost groundwater of Type II beneath the riverbed at Odinelva. Another plausible explanation could be that this aquifer dries out during the winter months due to a lack of inflow, a situation also reported by (Liu et al., 2022). However, even for partially saturated cases, full refreezing of a talik in winter would not occur either (with an estimated freezing depth of approximately 2.2 m; Table S2.2).

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The installations at Odinelva suggest that the concept of using groundwater from aquifers beneath shallow rivers in areas with continuous permafrost on Svalbard, at least during summer, was put into practice already several decades ago. If the facility at Odinelva provided water during the winter, the seasonally frozen layer acted as a barrier, protecting the talik beneath against potential contamination from the terrain surface.

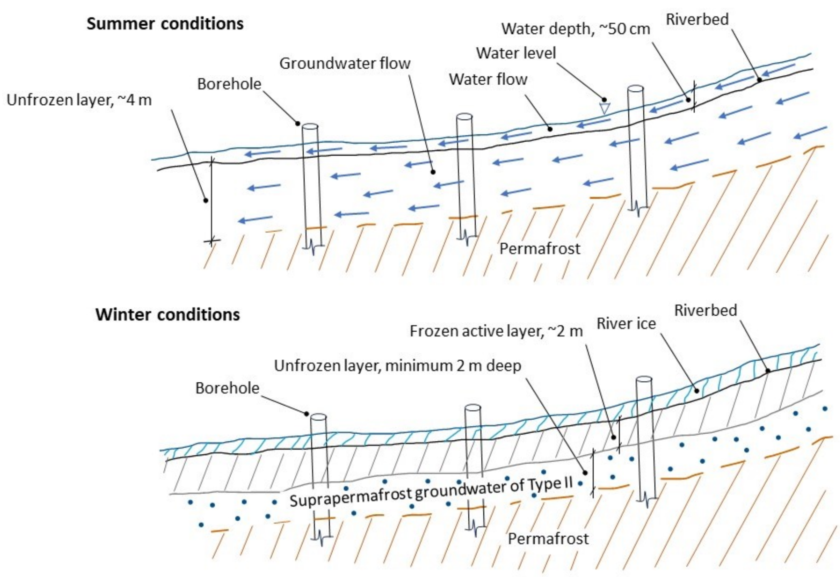

Figure 17: Illustration of suggested suprapermafrost groundwater Type II at Odinelva in Pyramiden during summer (top) and during winter (bottom).

3.5 Other observations in Svalbard

The majority of observations is concentrated in the vicinity of Longyearbyen, with additional data collected in Pyramiden and Ny-Ålesund. While these observations are most likely relevant to other parts of Svalbard as well, and vice versa (as demonstrated in case j), most of them have been documented in Longyearbyen. This concentration is due to the numerous infrastructural projects and research activities taking place in this area, which provide occasional observations of indicators or direct findings of groundwater.

A spring was observed at the Hovtinden mountain (Trollheimen area) on September 10, 2022, (location j, Video S1.j (Sinitsyn, 2023a), Figure S1.j). Note that the night before the video was taken, there was heavy rainfall (11 mm of precipitation in 24 hours), which probably contributed to the heightened spring activity. The morphology of the Hovtinden spring-site is, however, distinctive from the one observed at Huset (Sect. 4.1.2): this spring-point is situated within a small, bowl-like depression. This depression, along with the accumulation of sandy sediments within it, indicates a more or less permanent water seepage, which may slowly erode the surface soil. This suggests a significantly longer period of groundwater activity compared to the springs at Huset (see Sect. 4.1.2). It is reasonable to assume that more consistent groundwater activity associated with such more continuous springs also

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contributes to the downslope Lovénvatnet lake through subsurface inflow. Consequently, these subsurface flows would then also be characterized as supra- or intrapermafrost groundwater.

3.6 River taliks as potential drinking water

Different alternative water sources for Longyearbyen have previously been discussed, including energy-demanding desalination of seawater. However, from multiple perspectives, the extraction of recently emerging groundwater sources is regarded a more sustainable approach of water supply (Ording, 2007). Utilizing aquifers represents a "purely natural" solution for water supply (WWAP (United Nations World Water Assessment Programme)/UN-Water, 2018). From a technical point of view, aquifers serve as natural storages. Further, a solution based on groundwater may have lower initial investment and maintenance costs compared to alternative methods. Additionally, groundwater solutions have a significantly reduced carbon footprint compared to most other technologies. Since groundwater is less susceptible to surface contamination, its water quality typically surpasses that of surface water. Thus, harnessing groundwater as a resilient source of drinking water will likely enhance the sustainability of Longyearbyen. In particular, groundwater use can improve the living conditions in the harsh Arctic environment and support the development of local businesses. For instance, supplying cruise ships with local potable water can strengthen local businesses and boost the sustainability of Arctic tourism. Although uncertainties exist regarding the presence of adequate groundwater resources in the Longyearbyen area, the benefits of discovering a viable groundwater source could be immense, underscoring the need for prioritizing further hydrogeological investigations (Ording, 2007). In this regard, establishing at least a pilot or smaller facility to provide emergency water supply or serve as a secondary/backup solution would enhance the resilience of the town's water supply. The development of groundwater as a drinking water source for Longyearbyen may require technological advancements such as the design of infiltration galleries or the adaptation of managed aquifer recharge (MAR) practices to suit the demands of the cold climate. MAR technologies are aquifer-centric nature-based solutions providing unique opportunities to overcome the fluctuation of natural water supply by utilizing aquifers as buffers (WWAP (United Nations World Water Assessment Programme)/UN-Water, 2018)). In such cases, the technological solution may be influenced by factors such as talik size, sediment permeability, and the hydrological regime of the talik (isolated or hydraulically connected) during wintertime, including parameters of water quantity and discharge throughout the year. Nevertheless, MAR work can also influence the size of the talik around it due to the thermal impact of water flow on permafrost. This issue should be considered if MAR is to be implemented.

The current water demand in Longyearbyen stands at approximately 1000 m^3 per day (Sinitsyn, 2022b) Thus, for a short-term emergency lasting 14 days, 14 000 m^3 of water is required, while 200 000 m^3 are needed for the approximate 200 days of the freezing season. Without MAR technology, a talik/aquifer with a thickness of 2 m at Longyearelva could hold 116 000 m^3, and 1 960 000 m^3 at Adventelva (conservative assumptions, see Sect. S3). For a short-term emergency, the corresponding water level drop would be around 25 cm for Longyearelva and 1.5 cm for Adventelva, respectively. For a 200-day period, the water level would decrease by 21 cm for Adventelva, but the capacity of a natural talik at Longyearelva, as defined by conservative assumptions, would not suffice to cover a 200-day period of water supply. The fraction of annual precipitation required to meet these water demands

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is negligible (less than 1%, see Sect. S3). This clearly demonstrates that, in principle, such taliks could serve as suitable drinking water resources for settlements like Longyearbyen.

Prior to making substantial long-term investments in alternative solutions for Longyearbyen's water supply, comprehensive groundwater field investigations are imperative. These investigations should be based on geophysics, followed by ground truthing. Further, to safeguard potential catchment areas from pollution, the mentioned factors must be taken into account in the areal planning of Arctic settlements. Again, these suggestions could apply to other communities facing similar conditions in the Arctic. Due to the rapid warming rates and the well-established infrastructure on Svalbard, the region is well-suited for pilot projects focused on supplying drinking water from emerging taliks. These projects can then serve as models for other Arctic communities.

The objectives of future studies should aim to enhance our understanding of global warming impacts (temperature and precipitation changes) on permafrost degradation and the future groundwater resources in the High Arctic. An advance in empirical data (i.e., field observations and monitoring) of cryo-hydrogeology in regions with continuous permafrost may improve predictive capabilities for assessing the role of permafrost degradation on groundwater recharge and discharge. This could contribute to the fundamental scientific basis for the management of drinking water resources in Arctic communities in the coming decades, with the findings intended for dissemination to policymakers and water resource managers in the Arctic region.

4 Conclusions

In this study we present groundbreaking permafrost data from Svalbard. The first ever direct and indirect observations of suprapermafrost groundwater of Type II, which is linked to a network of small and shallow rivers in central Svalbard, including Longyearelva, Adventelva, and Vannledningsdalen. We also prove the existence of river taliks in areas characterized by continuous permafrost conditions. Importantly, our observations reveal that these groundwater systems are also active during winters, giving evidence of year-round groundwater flow in continuous permafrost and marking a significant milestone in the understanding of continuous permafrost dynamics on Svalbard.

Our findings extend beyond the identification of suprapermafrost groundwater and point towards the existence of intrapermafrost groundwater, which at times appears to be linked to river systems (e.g., Longyearelva, Steintippendalen, Endalselva), and at other times exhibits an independent existence (e.g., icing at Huset, taliks in Ny-Ålesund). This intrapermafrost groundwater is suggested as a probable source feeding the Isdammen lake during the winter months. The influence of global warming emerges as a factor contributing to the activation of these groundwater systems, underscoring the far-reaching impact of climate change on Arctic hydrology. The observed taliks may also contribute to a shift from continuous to discontinuous permafrost.

However, despite these groundbreaking discoveries, the detailed characteristics of the observed taliks on Svalbard remain largely unknown. Critical information such as their dimensions (i.e., spreading and common depth), discharge dynamics throughout the year, water head, water quality, sources of winter replenishment, conduit patterns, lithology (in many cases), and ground temperatures (in most of the cases) remain elusive. Additionally,

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the potential impacts of a changing cryosphere on these taliks, including alterations in snowpacks and glacier recession, are yet to be fully understood. These knowledge gaps highlight the imperative need for comprehensive site characterization of river taliks not only in Longyearbyen but also at other sites in the Arctic with comparable geo-cryological conditions and climate profiles. Such characterizations will not only improve our understanding of these systems but may also prove invaluable in assessments of potential contaminations trapped within the permafrost, including the active layer.

To conclude, our research challenges the conventional knowledge that no river taliks persist during winter beneath rivers in the continuous permafrost zone of Svalbard. Instead, we show that such taliks already exist and highlight the potential for their amplification under the influence of global warming. We identify the taliks we found under rivers on Svalbard as Type II suprapermafrost groundwater and intrapermafrost groundwater. Further, we claim that we found intrapermafrost taliks that may be linked to sandstone drainage from plateau areas to lower valley slopes. Additionally, we are convinced that our findings extend to comparable conditions in other High Arctic continuous permafrost regions of similar setting. Thus, we advocate for further investigations into the potential of river taliks as resources to meet the pressing demand for water supply in Arctic communities. These considerations and investigations should be incorporated into the long-term management plans of Arctic authorities to ensure the sustainability of vital water resources in these regions.

Author contribution

Sinitsyn, A.O: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft preparation of the article; Bazin, S. contributed to the scientific discussion from a geophysical perspective and to the manuscript revision; Benestad, R., Isaksen, K. and Lutz, J. contributed to methodology, writing, the scientific discussion from a meteorological point of view and to the manuscript revision, in addition Lutz, J. contributed to visualization; Etzelmüller, B. and Westermann, S. contributed to conceptualization, methodology, writing, scientific discussion from the geo-cryological point of view and the manuscript revision; Kvitsand, H. contributed to methodology, writing, scientific discussion from the perspective of water security; Popp, A. contributed to methodology, writing, scientific discussion from geo-cryological and hydrological points of view and to the manuscript revision; Rubensdotter, L. contributed to the scientific discussion from a geological perspective and to the manuscript revision.

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Appendix 1. Glossary

Active layer – the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost (van Everdingen, 2005).

Aquifer (from Latin aqua water and ferre to bear, to carry) – a layer or a layered sequence of rock or sediment, comprising one or more geological formations that can store and transmit significant quantities of water under an ordinary hydraulic gradient. Aquifer also includes the unsaturated part of the permeable material, that is, the part above the water table, as well as the saturated part. The sole saturated part of an aquifer, or the part from the aquifer bottom to the water table is referred to as the “effective” aquifer (Price, 1996).

Continuous permafrost – permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the thermal regime of the ground, causing the development of continuous permafrost (van Everdingen, 2005).

Discontinuous permafrost – permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost (van Everdingen, 2005).

Icings – sheetlike masses of layered ice formed on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring or emerge from below river or lake ice through fractures (van Everdingen, 2005).

Isolated talik – a talik entirely surrounded by perennially frozen ground (Van Everdingen, 2005).

Lateral talik – a talik overlain and underlain by perennially frozen ground (Van Everdingen, 2005).

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Permafrost – earth materials that remain frozen for more than two subsequent years (van Everdingen, 2005).

Water security – the capacity of a population to safeguard sustainable access to adequate quantities of water of acceptable quality for sustaining livelihoods, human well-being, and socio-economic development, for protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability (UNITED NATIONS. UN WATER, 2013).

Pingo – a perennial frost mound consisting of a core of massive ice, produced primarily by injection of water, and covered with soil and vegetation (van Everdingen, 2005).

River talik – a layer or body of unfrozen ground occupying a depression in the permafrost table beneath a river (van Everdingen, 2005).

Talik – a layer or body of unfrozen ground occurring in a permafrost area due to a local anomaly in thermal, hydrological, hydrogeological, or hydrochemical conditions (van Everdingen, 2005).