Observations of suprapermafrost and intrapermafrost groundwater on Svalbard

Summary

Table S1 presents several recent direct findings and observations of indicators of groundwater on Svalbard that have not been previously reported and analyzed are summarized. Locations of direct findings and observations are presented in Figure S1.1–Figure S1.4. Images and snap shots of videos that document many of the presented results are presented further in this document.

This document consists of the following parts:

S1. Observations of suprapermafrost and intrapermafrost groundwater on Svalbard

Observations of suprapermafrost and intrapermafrost groundwater on Svalbard are presented in Table S1. Locations of the observations are presented in Figure S1–Figure S. Documentation for the observations (see second column in Table S1.) is presented in Part 2.

Table S1. Observations of suprapermafrost and intrapermafrost groundwater on Svalbard

Indicators of groundwater and direct observations, locations of observations	**Documentation: see Part 2**	**Interpretation of indicators and observations**	**Location**	**Observations**
Icings at Longyearelva Numerous small (several meters in diameter) to medium-size (several tens of meters in diameter), and even large (from a hundred meters in diameter) icings were spotted at several locations at the riverbanks, the riverbed of Longyearelva or locations where old river channels used to be.	Figure S1.a1-1 Figure S1.a1-2 Figure S1.a1-3 Figure S1.a1-4 Figure S1.a1-5	Suprapermafrost groundwater of Type II	Figure S1.1, location a1	Small, cracked "mound" icings were observed in April 2008 (Figure S5.a1-1–Figure S5.a1-3) and somewhat bigger icings – in April 2017 (Figure S5.a1-4–Figure S5.a1-5): below the bridge across Road 600 (approximate location). Drilling through the icing revealed water at artesian pressure. The water smelled and tasted like diesel, which may have leaked from the nearby area (Sjøområdet) where many workshops and storage facilities are located. This suggests that this water has a surface origin.
	Figure S1.a2-1 Figure S1.a2-2 Figure S1.a2-3 Figure S1.a2-4 Figure S1.a2-5 Video S1.a2-1 (Sinitsyn, 2023a) Video S1a2-2 (Sinitsyn, 2023a)	Suprapermafrost groundwater of Type II	Figure S1.1, location a2	Small, cracked "mound" icings were observed in April 2017 behind Elvesletta Nord. Ice thickness was found to extend 1 m below the surface of the icing after drilling with a core sampler. After that, through the drilled hole, fresh water with no smell or flavor appeared on the icing's surface.
	Figure S1.a3	Suprapermafrost groundwater of Type II and probably intrapermafrost groundwater	Figure S1.1, location a3	Medium-size, "flat and spread" not cracked icing was observed in June 2017 under the building Nr. 1 and Road 509, Elvesletta Nord. Such icing may be considered as one of the issues which caused deformations of the building (inclined flooring, issues when closing windows, etc.).
	Figure S1.a4	Suprapermafrost groundwater of Type II and/or intrapermafrost groundwater	Figure S1.1, location a4	Medium-size, not cracked icing was observed in April 2017 at the turn of the main pipeline with hot water.

	Figure S1.a5 Video S1.a5 (Sinitsyn, 2023a)	Suprapermafrost groundwater of Type II and/or intrapermafrost groundwater	Figure S1.1, location a5	Large icing (approximately 50–100 m in diameter), "flat and spread" not cracked icing was observed in April 2017 between the districts of Elvesletta Sør and Elvesletta Nord.
	Figure S1.a6 Video S1.a6 (Sinitsyn, 2023a)	Suprapermafrost groundwater of Type II and/or intrapermafrost groundwater	Figure S1, location a6	Medium, mostly "flat and spread" not cracked and cracked icings were observed in May 2017 above the old bridge over Road 503. At least some of the water feeding this icing was coming as seepage from the left-hand riverbank when looking downstream. The icing surface was covered with slush at the area of the seepage.
	Figure S1.a7-1 Figure S1.a7-2 Figure S1.a7-3	Suprapermafrost groundwater of Type II	Figure S1.1, location a7	Small and medium-size, not cracked icings were observed in May 2017 below the bridge over Road 501.
	Figure S1.a8-1 Figure S1.a8-2 Video S1.a8 (Sinitsyn, 2023a)	Suprapermafrost groundwater of Type II	Figure S1.1, location a8	Small, not cracked icings were observed on May 2017 between Nybyen and Sverdrupbyen.
	–	Suprapermafrost groundwater of Type II and/or intrapermafrost groundwater	Figure S1, location a9	Numerous leakages of groundwater and subsequent occurrence of icings were noted under several buildings in the central part of Longyearbyen in wintertime. Those cases took place in the areas where the old river channels used to be. Such events occurred from year to year in the mid-2010s (and most probably still occur), timed with periods of very cold weather (with air temperatures of approximately -20 °C or so). In the cases of such events, inhabitants contacted the local services/authorities and claimed that there was a water leak from piping somewhere under the buildings. The latter, however, was never practically the case (Sinitsyn, 2021a).
Direct observations of groundwater in Longyeardalen Geotechnical investigations and installations of deep pile foundations has revealed several cases of groundwater in the district of Elvesletta and at the riverbed of Vannledningsdalen valley (Norwegian, "the water supply valley").	Figure S1.a10-1 Figure S1.a10-2 Figure S1.a10-3 Figure S1.a10-4	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.1, location a10	Geotechnical field investigations were performed by Ramboll Norge AS (2019a) and conducted for Svalbard Utbygging AS, Elvesletta (2019). Investigations did not identify groundwater in this area. At the same time, soil layers, which may serve as potential aquifers were found. The survey also depicted two icings in the area, which were observed in 2018–2019. Pedersen (Ramboll Norge AS, 2019a) points out that potential aquifers detected on the site (gravel at depths 3–11 m at all drilling locations) are devoted to coarse-grained sediments of former river channels in Longyearelva. Those channels (as pointed out by Pedersen (Ramboll Norge AS, 2019a)) can be seen on the aerial image of Longyearbyen and Longyearelva from 1936 (Figure S1.a10-2). At the present time, most of the old and small river channels are leveled, and Longyearelva is channeled into one large riverbed equipped with rock- protection of

				riverbanks against erosion (Figure S1.a10-1, Figure S1.a10-3, Figure S1.a10-4). The absence of water in identified potential aquifers was explained by a preceding prolonged period without precipitation and mild weather. However, there was an emergence of groundwater beneath some residential buildings in the adjacent sites (2018–2019), which happened in periods of low precipitation and mild weather conditions (Ramboll Norge AS, 2019a). In one of those cases, ice formed around an elevator shaft installed in the basement of the building. It was suggested that the construction of that shaft created a new pathway for groundwater. Similar investigations at adjacent building areas (2018) revealed groundwater and hydraulic conductivity between some of the drilled boreholes (tested via applying air pressure at one borehole and observation of lifted groundwater from the other one). However, hydraulic conductivity between other boreholes at the same site was absent (Ramboll Norge AS, 2019a). Installation of a well equipped with a pump was suggested for tackling the issues with groundwater around the buildings in this area, i.e., such a well would handle possible issues with groundwater in the periods of heavy rainfalls and/or snow melt.
	Figure S1.a11-1 Figure S1.a11-2 Figure S1.a11-3	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.1, location a11	Geotechnical field investigations were performed by Ramboll Norge AS (2018) for Norges arktiske studentsamskipnad (Norwegian Arctic student organization), Elvesletta (April 2018)). Investigations were performed at one of two medium- to large icings in the area using drilling. The icings were up to 1.7 m high. Drilling was performed at three locations across the icing, i.e., on the top, foot, and the "flat" part of the icing. Drilling on the top and foot of the icing revealed loose ground material and pure ice (with a total thickness of approximately 1.5 m) underlain by a 3 m thick aquifer (there was no resistance to drilling in the upper 3 m) at artesian pressure (Figure S5.a-11-3). Drilling revealed frozen soil to the depths of 3–6 m. Drilling on the "flat" part of the icing revealed approximately 1 m of ground ice in the top 2 m of frozen material, which was underlined by a thawed layer to a depth of 6 m. Later, groundwater was detected during the deployment of pile foundations for the student accommodation buildings erected in the area from summer to winter 2020 (Norges arktiske studentsamskipnad, 2020). Groundwater was detected at depths from 4 to 18 m during the installation of some of the piles. After the buildings were constructed, ice formation due to emerging groundwater was noted below the

				buildings (Figure S1.a11-1, S1.a11-2), as predicted by Pedersen (Ramboll Norge AS, 2018).
	–	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.1, location a12	Geotechnical field investigations revealed aquifers at several locations under the riverbed of Vannledningsdalen valley (Ramboll AS, 2019). Aquifers were located under the upper 3–4 m of frozen soil and were mostly aligned with the riverbed. These investigations, performed in February 2019 suggested year-round water flow in the detected aquifers.
	See Table 2 in (Ramboll Norge AS, 2017).	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.1, location a13	Geotechnical investigations of Ramboll Norge AS (2017) were conducted for Longyearbyen Lokalstyre, Elvesletta. Investigations have revealed groundwater at the depths of 1, 4, and 6.8 m in this area. In one case the amount of groundwater was so high that it was not possible to perform a description of ground ice from retrieved soil samples.
Large, continuously growing icings on a sloping terrain, outside of the riverbeds in Longyeardalen	–	Intrapermafrost groundwater	Figure S1.1, location a14	An icing was observed in Longyeardalen, on the slope next to the building of Huset. It was a large (ca. 200 meters in length along the slope, and several tens of meters across the slope) "flat and spread" icing, which was noted during at least some (if not all) winters in 2012–2019. It had a thickness of approximately 0.5 m at the end of the winter season. The icing filled up the drain along the Road 300 and was completely "flooding" a stretch of the road. The latter caused traffic bans on this road during several winters. Also, several springs with artesian pressure were observed on this slope in springtime. The springs disappeared later in the season.
	Video S1.a16 (Sinitsyn, 2023a) Figure S1.a16 Figure S1.a17	Suprapermafrost, and probably intrapermafrost groundwater	Figure S1.1, locations a15–a17	Several springs were observed on the slope above Road 300 on September 9th 2023 (location a15), the springs disappeared few days later. This was preceded by a heavy rain on September 5th–7th. Examples of springs are presented on Video S1.a16 and Figure S1.a16 (location a16) and on Figure S1.a17 (location a17).
Small to medium icings in riverbeds in valleys adjacent to Longyearbyen (Adventdalen, Bolterdalen, Foxdalen, Fardalen).	Figure S1.b2	Suprapermafrost groundwater of Type II	Figure S, location b2	Small, cracked "mound" icing at the middle of Adventdalen, observed by Bourne (Sinitsyn, 2022a) in April 2021.
	Figure S1.b3	Suprapermafrost groundwater of Type II	Figure S, location b3	Small, cracked "mound" icing at the middle of Adventdalen, observed by Bourne (Sinitsyn, 2022a) in April 2021.
	Figure S1.b4-1 Figure S1.b4-2	Intrapermafrost groundwater	Figure S1.2, location b4	Remains of icings (presumable large icings) in Endalen, observed in summer time by Bourne (Sinitsyn, 2022a) in June 2020.
	Figure S1.b5-1 Figure S1.b5-2	Intrapermafrost groundwater	Figure S1.2, location b5	Remains of icings in Adventdalen, observed in summer time by Bourne (Sinitsyn, 2022a) in June 2021.
	Figure S1.b6-1 Figure S1.b6-2	Suprapermafrost groundwater of Type II	Figure S1.2, location b6	Small, cracked icing in Endalen, observed by Bourne, (Sinitsyn, 2022a) in May 2021.
	Figure S1.b7	Suprapermafrost groundwater of Type II	Figure S1.2, location b7	Small, cracked icing in Adventdalen close to the entrance to Eskerdalen, observed by Bourne (Sinitsyn, 2022a) in April 2020.
	Figure S1.b8	Suprapermafrost groundwater of Type II	Figure S1.2, location b8	Small, cracked icing in Adventdalen close to the entrance to Arnicadalen, observed by Bourne (Sinitsyn, 2022a) in April 2021.

	–		33X E509390 N8671358	Medium-size, "mound" icing (2010) observed by Shestov, A. (Sinitsyn, 2021b) in Fardalen (not depicted in Figure S).
Large, continuously growing through the season icings in the Longyearbyen area Large, presumably continuously growing icing was occurring at the bottom area of the small river of Steintippendalen/Gruvedalen (Road Nr. 400).	Figure S1.c-1 Figure S1.c-2 Figure S1.c-3	Intrapermafrost groundwater and suprapermafrost groundwater of Type II Intrapermafrost groundwater	Figure S1.1, location c	Observations of Longyearbyen Lokalstyre and subsequent geotechnical investigations (Ramboll Norge AS, 2019b) revealed large icing at the lower part of Steintippendalen/Gruvedalen. This icing grew annually in the years 2019–2022, creating concern for traffic at the main Road Nr. 400 located nearby. This large icing grew gradually during the winter season of 2019. Geotechnical field investigations (7 boreholes, winter 2019) revealed a large amount of groundwater at depths from 1.3 to 8 m (Ramboll Norge AS, 2019b). Some of the boreholes were hydraulically connected, while others were not. The icing also appeared in the years 2020–2022. A culvert was constructed in the uphill direction from the icing in an attempt to cut off the seepage from the surface layer. Yet, the culvert had no effect on the icing formation (Sinitsyn, 2022b).
	Figure S1.b1	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.2, location b1	Large "mound" icings at the intersection of Adventelva and Bolterelva, observed by Bourne, (Sinitsyn, 2022a) in June 2020. This large icing existed during part of the summer season.
	–	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.2, location b9	Large icing (a hundred meters wide, and several hundred meters long- in the direction along the valley), "flat and spread" in Adventdalen somewhere below the mountains of Arctowskifjellet and Juvdalskampen. This icing was approximately 1–1.5 m thick and largely consisted of slush. The icing was a serious obstacle for snowmobile driving in this area, so that necessary to drive more on the shoulder of the valley to avoid getting stuck in it (one of the springs between 2012 and 2014).
Indicators of the presence of icings in terrain Soil surface with patterns characteristic for icings (as for instance for location c: Figure d-2021-1 to Figure d-2021-3) was spotted in several locations around Isdammen.	Figure S1.d-1 Figure S1.d-2 Figure S1.d-3	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.2, location d	Such patterns were spotted in several places around Isdammem in late August 2021, for example at the sandbanks of the lower part of the Endalselva river.
Other direct observations of ground water Groundwater was revealed during ground investigations in Adventdalen.	–	Intrapermafrost groundwater	Figure S1.2, location e	Unfrozen zones were revealed in April 2021 in Adventdalen (approximately on the opposite side from the intersection of Adventdalen with Todalen) by drilling (Christiansen, 2021).
Evidence of increased permafrost degradation due to thermal impact of rivers	Figure S1.f	Suprapermafrost groundwater of Type II	Figure S1.2, location f	Observations at the valley of Todalen show increased settlement of historical structures (cable post Nr. 10 at Line 6 of the system of cableway posts in Longyearbyen) in the flood zone of Todalselva river.

There is evidence of stronger degradation of permafrost next to small rivers in proximity of Longyearbyen.				
Unknown source feeding Isdammen lake in wintertime Hypothetical source feeding the drinking water lake Isdammen during wintertime remains to be unknown to date.	–	Intrapermafrost groundwater and suprapermafrost groundwater of Type II	Figure S1.2, location g	The Isdammen lake is used for the water supply of Longyearbyen in wintertime. It is an artificial lake, supported by a dam. Previous evaluation (Hilmo, 2007) pointed out that the lake is underlain by permafrost. It is believed that there is an inflow in Isdammen over the winter season, and the variations of water level are small (Sinitsyn). Discharge over the spillway at the dam is absent in winter. There are two sources of water outflow in winter, which are communal use and some leakages from the dam. Hypothetical source feeding the artificial lake Isdammen in wintertime remains unclear (Figure S). Intrapermafrost groundwater and perhaps to a lesser degree, suprapermafrost groundwater of Type II may be suggested as the source of feeding Isdammen during winter. If so, the source of intrapermafrost groundwater may be timed up to some kind of deeper conduits bringing water, which was drained from the plateau areas of surrounding mountains, and a source of subpermafrost groundwater of Type II – to the baseflow of Endalselva river. Perhaps, the establishment of Isdammen might have "activated" or "thermally supported" such an intrapermafrost groundwater system.
Observations of abnormally thick active layer under the riverbeds of shallow rivers in Pyramiden Observations at Odinelva in Pyramiden has revealed abnormally thick active layer, which most probably cannot refreeze in winter and hence may serve as suprapermafrost aquifer. Utilization of such conditions for the needs of water supply was most probably studied already several decades ago in Pyramiden.	Figure S1.h-1 Figure S1.h-2 Figure S1.h-3 Figure S1.h-4 Figure S1.h-5	Suprapermafrost groundwater of Type II	Figure S1.3, location h	Impressive installations were observed in the riverbed of Odinelva in Pyramiden. Deployment of the installations must have taken part earlier than 1998 when the settlement was abandoned. The installation consists of two profiles (one across and one along the river, see Figure S). Boreholes are equipped with steel casings (ca. 20 cm in diameter), which stick out approximately 1.5 m above the bottom of the river. These installations were "discovered" and observed by the authors in late august 2021. At this time, the water depth in the river was approximately 20-50 cm, but the water depth at the boreholes was approximately 3–4 m (measured with rope and a lead) from the bottom of the river. The bottom of the boreholes felt soft (when ticking on it by the lead attached to a rope). This gave the impression that the active layer at the riverbed is at least 3–4 m deep, which is 2 to 3 times thicker than for almost all (see Table 7.1.1. in (Hanssen-Bauer et al., 2019)) terrain settings on Svalbard. This confirms the pronounced thermal influence of the river on the active layer in its riverbed.
Observations of icings in Ny-Ålesund	Figure S1.k-1 Figure S1.k-2 Figure S1.k-3	Intrapermafrost groundwater	Figure S1.4, location k Approximate coordinates: 33X E433980	Remains of a large (at least 10 by 30 m) icing were observed in north-western part of Ny-Ålesund in late June 2023.

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	Figure S1.l	Suprapermafrost or intrapermafrost groundwater	Figure S1.4, location l	The ground floors at Gamle kraftstasjonen (The Old Power Plant) are permanently filled with ice, that points out at the presence of suprapermafrost or/and intrapermafrost groundwater (12.07.2023).
Direct observations of deep thawed zones in Ny-Ålesund Drilling works in Ny-Ålesund has revealed thaw soil below the depth of active layer.	–	Intrapermafrost groundwater	Figure S1.4, location i	In Ny-Ålesund, groundwater was observed at approximately 10 m depth when replacing foundations at the eastern part of Veksthuset building (location i-1) and Vaskerilabben (location i-2) (January–Ferbuary 2018); and at Kunstnerhytta (December 2021) (Sinitsyn, 2022c; Sinitsyn et al., 2022).
Direct observations at the Hovtinden mountain **Springs were observed at the foot of Hovtinden mountain in September 2022.**	Figure S1.j Video S1.j (Sinitsyn, 2023a)	Suprapermafrost or intrapermafrost groundwater	Coordinates: 78.28416 N 13.76040 E	Springs at the Hovtinden mountain were observed in early September 2022, which point out on significantly lengthier period of drainage there compared to the springs at Huset (case a14). Groundwater from such springs contributes to inflow in the Lovénvaknet lake. One may suggest characterizing this groundwater as suprapermafrost or intrapermafrost groundwater.

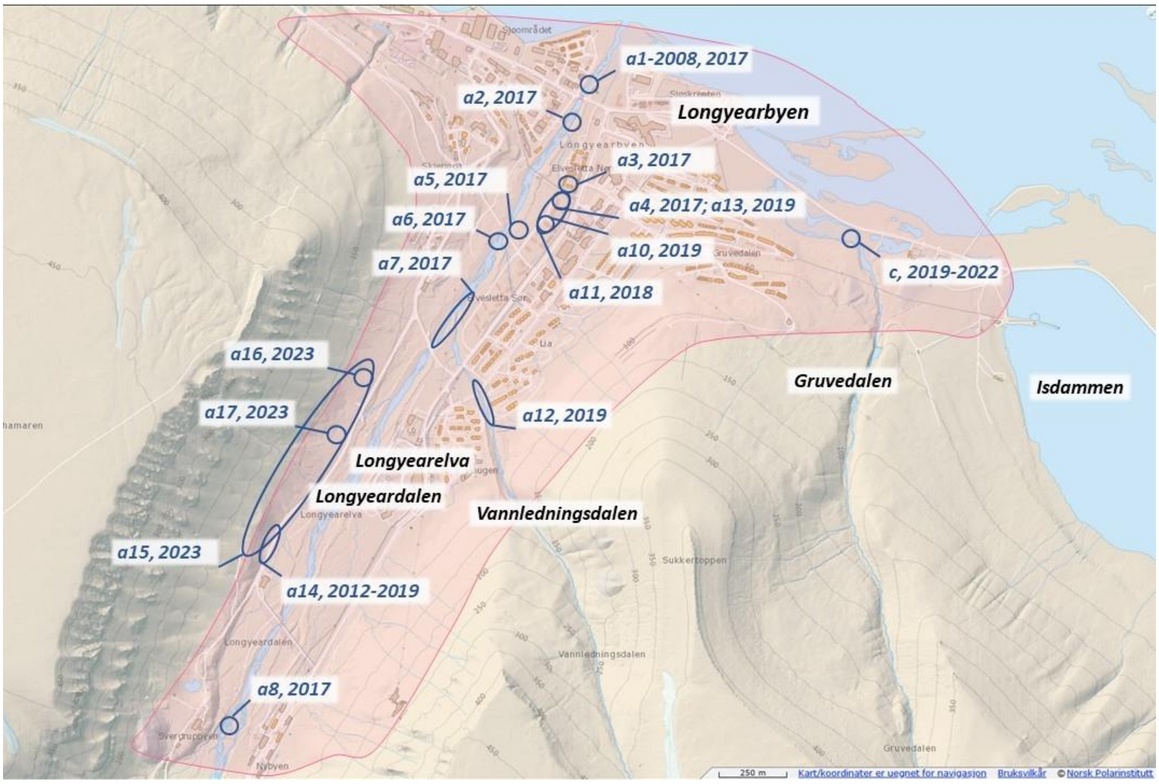

Figure S1.1. Locations of observations in Longyearbyen (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

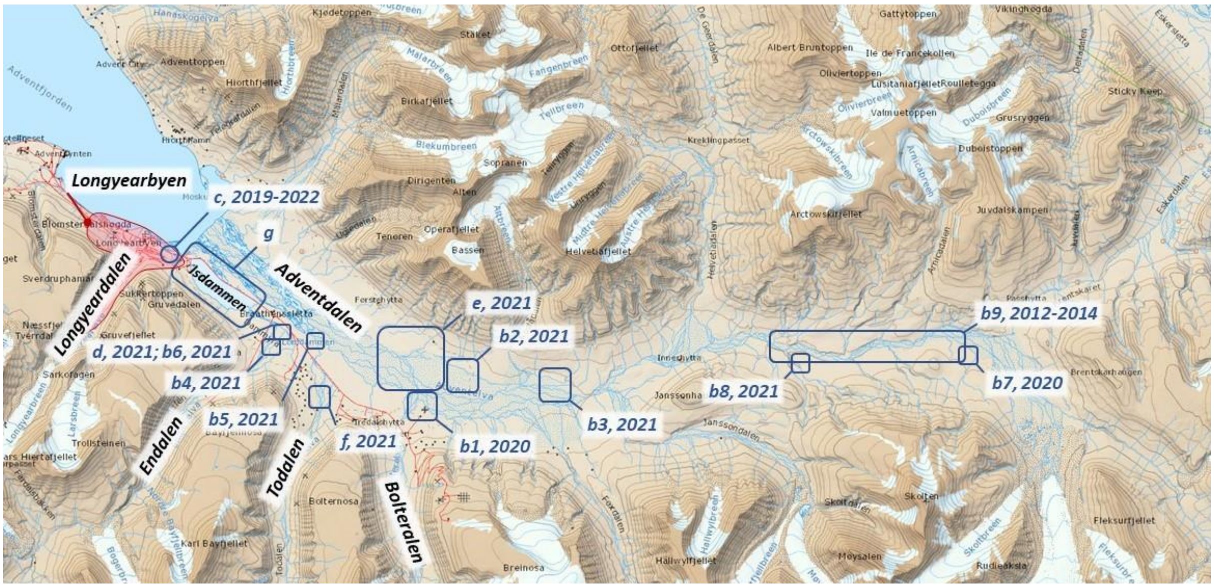

Figure S1.2. Locations of observations in Adventdalen (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

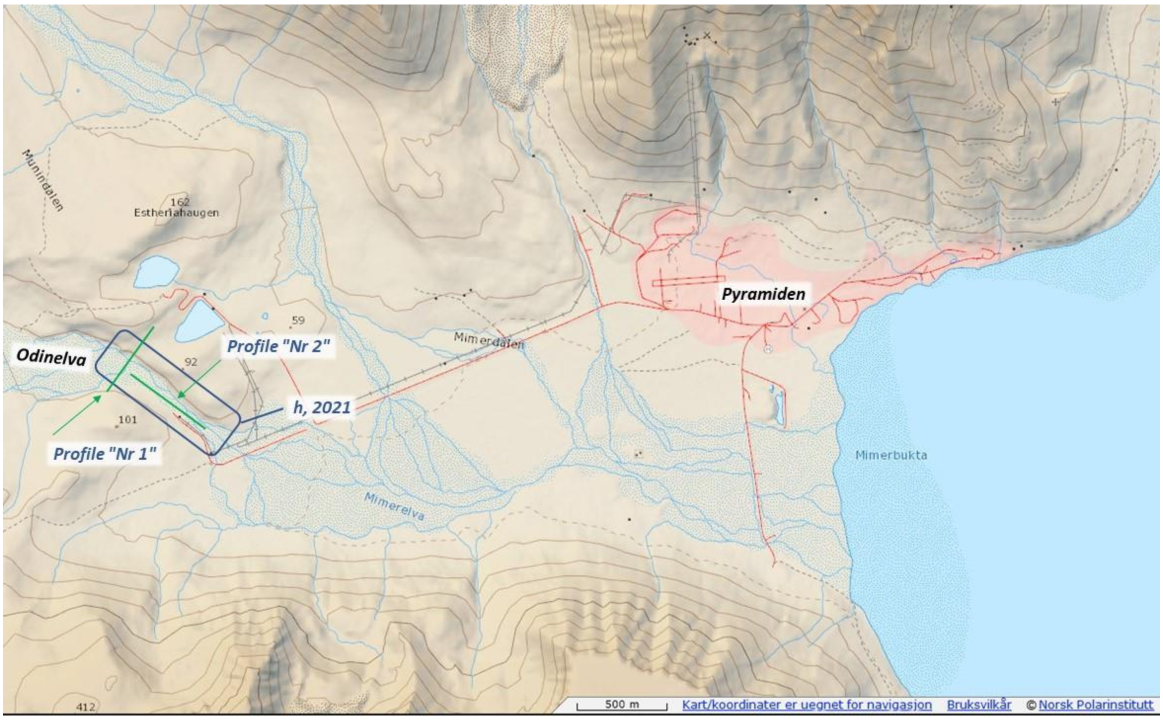

Figure S1.3. Location of observations at Odinelva, Pyramiden (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

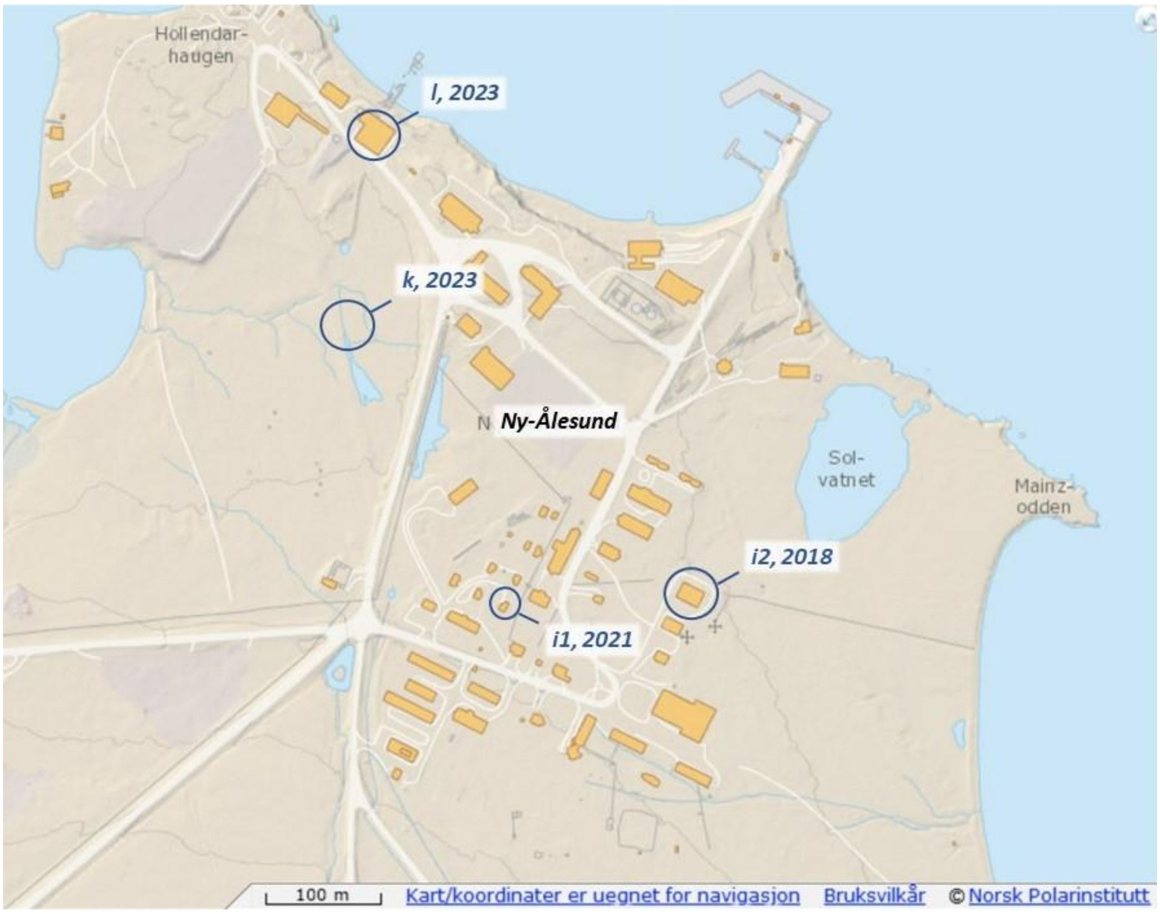

Figure S1.4. Locations of observed groundwater in Ny-Ålesund (Map: TopoSvalbard (2021), © Norwegian Polar Institute).

Figure S1.a1-1. The first, small, cracked "mound" icing at Longyearelva below the bridge across the Road 600 (10.04.2008, location a1 in Table 1). Photo: © Anatoly Sinitsyn.

Figure S1.a1-2. The second, small, cracked "mound" icing at Longyearelva below the bridge across the Road 600 (10.04.2008, location a1 in Table 1). Photo: © Anatoly Sinitsyn.

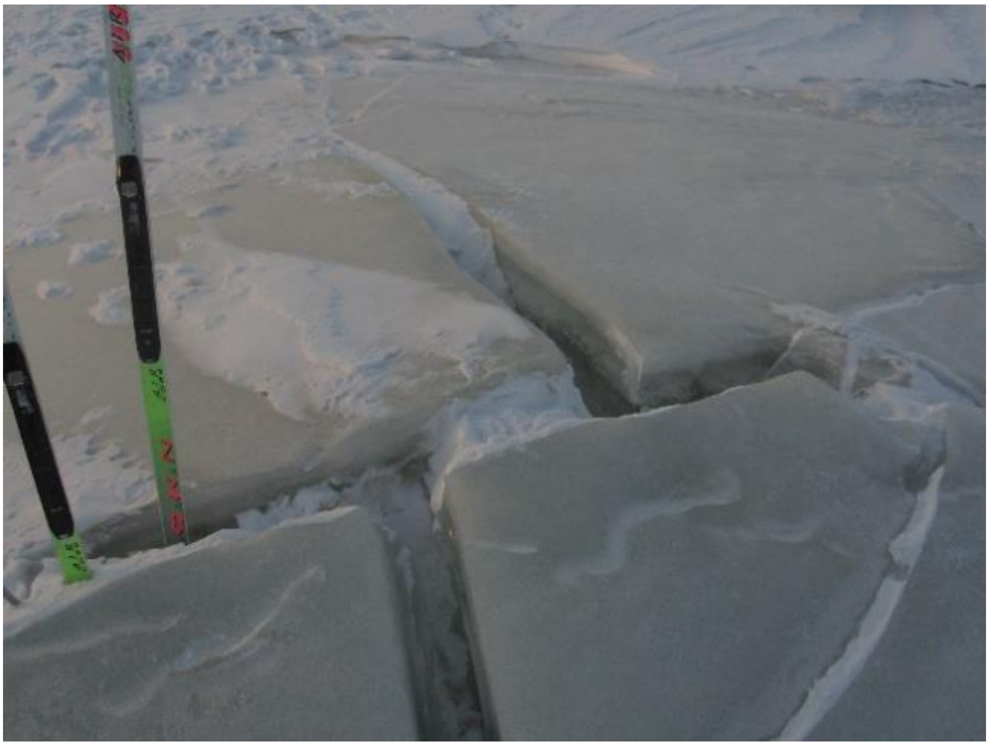

Figure S1.a1-3. Cracks at the first small, cracked "mound" icing at Longyearelva below the bridge across the Road 600 (10.04.2008, location a1 in Table 1). Photo: © Anatoly Sinitsyn.

Figure S1.a1-4. Small, cracked "mound" icing at Longyearelva below the bridge across the Road 600 (18.04.2017, location a1 in Table S1), drilling revealed water at artesian pressure. The water had distinct taste and smell of diesel. Photo: © Anatoly Sinitsyn.

Figure S1.a1-5. General view of small, cracked "mound" icing at Longyearelva below the bridge across the Road 600 (18.04.2017, location a1 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a2-1. Drilling through small, cracked "mound" icing at Longyearelva behind Elvesletta Nord (18.04.2017, location a2 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a2-2. General view at small, cracked "mound" icing at Longyearelva behind Elvesletta Nord (18.04.2017, location a2 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a2-3. Ice core retrieved at the icing at Longyearelva behind Elvesletta Nord (18.04.2017, location a2 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a2-4. Snapshot from Video S1.a2-1 (Sinitsyn, 2023a). Drilling through small, cracked "mound" icing at Longyearelva behind Elvesletta Nord (18.04.2017, location a2 in Table S1). Video: © Anatoly Sinitsyn.

Figure S1.a2-5. Snapshot from Video S1.a2-2 (Sinitsyn, 2023a). Water at artesian pressure, which appeared on the surface of icing at Longyearelva behind Elvesletta Nord (18.04.2017, location a2 in Table S1). Video: © Anatoly Sinitsyn.

Figure S1.a3. Medium-size, "flat and spread" not cracked icing at location under the building Nr.1 and the Road 509, Elvesletta Nord (18.06.2017, location a3 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a4. Medium-size, not cracked icing at Elvesletta affecting supporting structure for pipeline on its turning point (18.04.2017, location a4 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a5-1. Large "flat and spread" not cracked icing at Elvesletta (18.04.2017, location a5 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a5-2. Snapshot from Video S1.a5 (Sinitsyn, 2023a). Large "flat and spread" not cracked icing at Elvesletta (18.04.2017, location a5 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a6. Medium, mostly "flat and spread" not cracked and cracked icings at Longyearelva above old bridge over the Road 503 (03.05.2017, location a6 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a7-1. Small and medium-size, not cracked icings at Longyearelva below the bridge over the Road 501 (03.05.2017, location a7 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a7-2. Small and medium-size, not cracked icings at Longyearelva below the bridge over the Road 501 (03.05.2017, location a7 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a7-3. Small and medium-size, not cracked icings at Longyearelva below the bridge over the Road 501 (03.05.2017, location a7 in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.a8-1. Small, not cracked icings at Longyearelva between Nybyen and Sverdrupbyen (03.05.2017, location a8 in Table 1). Photo: © Anatoly Sinitsyn.

Figure S1.a8-2. Small, not cracked icings at Longyearelva between Nybyen and Sverdrupbyen (03.05.2017, location a8 in Table 1). Photo: © Anatoly Sinitsyn.

Figure S1.a10-1. Longyearelva channelled into one large riverbed equipped with rock- protection of riverbanks against erosion (2017). Blue circle depicts approximate location of Elvesletta. Photo: © A. Skoglund / Norwegian Polar Institute.

Figure S1.a10-2. Longyearbyen and Longyearelva in its natural, unconfined state, running in several channels (1936). Blue circle depicts approximate location of Elvesletta. Photo: © Norwegian Polar Institute, image number S36_3039.

Figure S1.a10-3. Longyearelva running through engineered riverbed below the bridge over the Road 501 (17.08.2021). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.a10-4. Longyearelva running through engineered riverbed above the bridge over the Road 501 (17.08.2021). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.a11-1. Icing below housing for student's accommodation in Elvesletta (09.11.2021, location a11 in Table 1). Photo: © Tove Trondsen/Norges arktiske studentsamskipnad.

Figure S1.a11-2. Icing below housing for student's accommodation in Elvesletta (09.11.2021, location a8 in Table 1). Photo: © Tove Trondsen/Norges arktiske studentsamskipnad.

Figure S1.a11-3. Emergence of water at artesian pressure when drilling through an icing in Elvesletta (23.04.2018, location a11 in Table 1). Photo: © Marit Pedersen/Ramboll AS.

Figure S1.a16. Snapshot from Video S1.a16 (Sinitsyn, 2023a). Spring with artesian pressure on the slope about the Roar 300 (09.09.2023, location a16 in Table 1). Video: © Anatoly Sinitsyn/Sintef.

Figure S1.a17. Water from a spring on the slope above Road 300 (09.09.2023, location a17 in Table 1). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.b1. Large "mound" icings at the intersection of Adventelva and Bolterelva (12.06.2020, location b1 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b2. Small, cracker "mound" icing at the middle of Adventdalen (14.04.2021, location b2 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b3. Small, cracker "mound" icing at the middle of Adventdalen (16.04.2021, location b3 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b4-1. Remains of icings in Endalen (12.06.2020, location b4 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b4-2. Close look-up at the remains of icings in Endalen (12.06.2020, location b4 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b5-1. Remains of icings in Adventdalen (20.06.2021, location b5 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b5-2. Close look-up at the remains of icings in Adventdalen (20.06.2021, location b5 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b6-1. Small, cracked icing in Endalen, (01.05.2021, location b6 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b6-2. Small, cracked icing in Endalen, (01.05.2021, location b6 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b7. Small, cracked icing in Adventdalen close to the entrance to Eskerdalen (13.04.2020, location b7 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b8. Small, cracked icing in Adventdalen close to the entrance to Arnicadalen (14.04.2021, location b7 in Table S1). Photo: © Elizabeth Bourne.

Figure S1.b9. Medium-size, "mound" icing in Fardalen (02.04.2010). Photo: © Aleksey Shestov.

Figure S1.c-1. Large icing at the Road Nr. 400 and Steintippendalen/Gruvedalen (06.04.2018, location c in Table S1). Photo: © Kjersti Olsen Ingerø/Longyearbyen Lokalstyre.

Figure S1.c-2. Ground surface after disappearance of large icing at Road Nr. 400 and Steintippendalen/Gruvedalen (24.07.2018, location c in Table 1). Photo: © Kjersti Olsen Ingerø/Longyearbyen Lokalstyre.

Figure S1.c-3. Ground surface after disappearance of large icing at Road Nr. 400 and Steintippendalen/Gruvedalen (24.07.2018, location c in Table 1). Photo: © Kjersti Olsen Ingerø/Longyearbyen Lokalstyre.

Figure S1.d-1. Soil surface with the characteristic for icings pattern at sandbanks of lower part of the river of Endalselva (late August 2021, location d in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.d-2. Soil surface with the characteristic for icings pattern at sandbanks of lower part of the river of Endalselva (late August 2021, location d in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.d-3. Soil surface with the characteristic for icings pattern at sandbanks of lower part of the river of Endalselva (late August 2021, location d in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.f. Uneven settlement (tilt to the left) of the cable post Nr. 10 at Line 6 (05.09.2021, location f in Table S1), Adventdalen. It is suggested that the settlement occurred due to stronger degradation of permafrost due to warming effect of small river running next to it. Photo: © Anatoly Sinitsyn/Sintef.

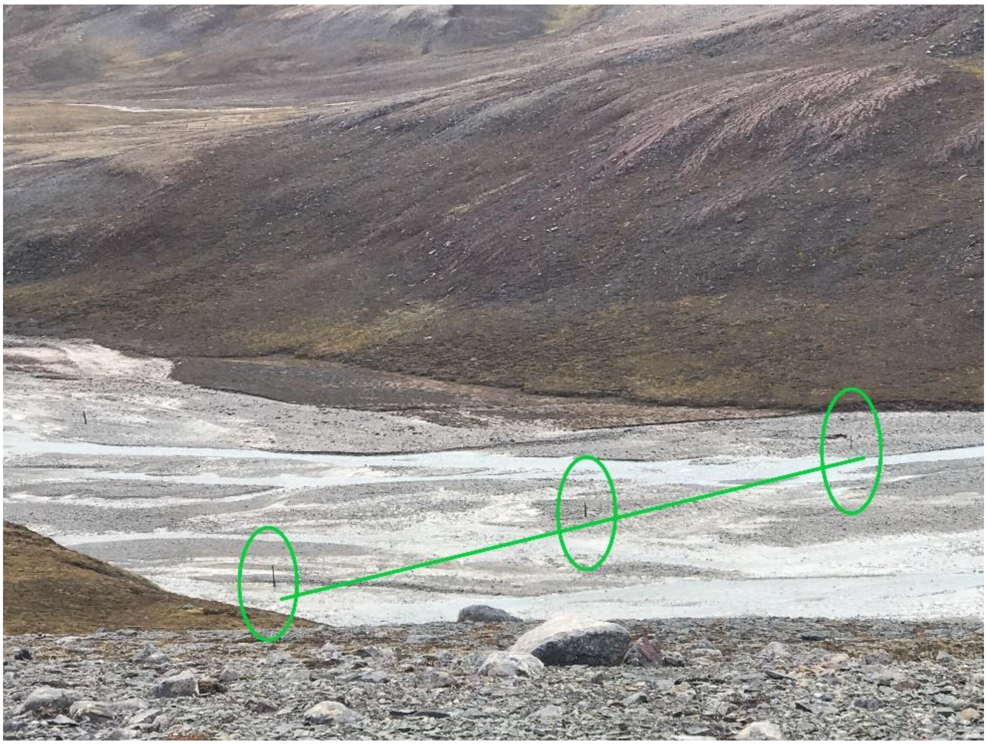

Figure S1.h-1. Profile "Nr.1" with boreholes in the riverbed of Odinelva in Pyramiden (27.08.2021, location h in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.h-2. Profile "Nr.2" boreholes in the riverbed of Odinelva in Pyramiden (27.08.2021, location h in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.h-3. First borehole on profile "Nr.1" in the riverbed of Odinelva in Pyramiden (27.08.2021, location h in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.h-4. Other two boreholes at profile "Nr.1" in the riverbed of Odinelva in Pyramiden (2021, location h in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.h-5. Boreholes in the riverbed of Odinelva in Pyramiden (27.08.2021, location h in Table S1). Photo: © Anatoly Sinitsyn.

Figure S1.j. Snapshot from the Video S1.j (Sinitsyn, 2023a). Spring at the foot of the Hovtinden mountain (10.09.2022, location j in Table S1). Video: © Anatoly Sinitsyn.

Figure S1.k-1. Remains of a large icing, north-western part of Ny-Ålesund (26.06.2023, location k in Table S1). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.k-2. Remains of a large icing, north-western part of Ny-Ålesund (26.06.2023, location k in Table 1). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.k-3. Remains of a large icing, north-western part of Ny-Ålesund (26.06.2023, location k in Table S1). Photo: © Anatoly Sinitsyn/Sintef.

Figure S1.l. Stairs and ground floor at Gamle kraftstasjonen (The Old Power Plant) in Ny-Ålesund, which is permanently filled with ice (12.07.2023, location l in Table S1). Photo: © Ingrid Rekkavik/Kings Bay AS.

S2. Calculated estimation of seasonal ground freezing and thawing in Pyramiden

Seasonal freezing $X_f(m)$ (and thawing depth X_t (*m*), respectively can be estimated based on the Stefan equation (S1):

$$X_f = \left(\frac{2k_f}{L}\int v_s\, dt\right)^{1/2}, \qquad \text{(S1)}$$

where $\int v_s\, dt$ represents the surface freezing index I_{sf} (or, correspondently, the surface thawing index I_{st}), L – latent heat of fusion (kJ/m^3), k_f – average frozen (or correspondently, unfrozen k_u) thermal conductivity of soil. This equation overestimates depths of frost penetration as it neglects the volumetric heat of the frozen and unfrozen soil. Surface freezing index I_{sf} (or, correspondently the surface thawing index I_{st}) is calculated as, (Andersland and Ladanyi, 2004):

$$I_{sf} = n_f\, I_{af}, \qquad \text{(S2)}$$

Where I_{af} is the air freezing index (or, correspondently, air thawing index I_{at}), n_f is the freezing factor (or, correspondently the thawing factor n_t). The air freezing index (I_{af}) is the number of negative ($T < 0$ °C) degree-days between the highest and lowest points on a curve of cumulative degree days versus time (see Figure 3-2 in (Andersland and Ladanyi, 2004)). The air thawing index (I_{at}) is the number of degree-days between the minimum in the spring and the maximum in the next autumn.

For a given soil, latent heat of fusion *L* is calculated as, (Andersland and Ladanyi, 2004):

$$L = \rho_d L' \frac{w - w_u}{100}, \qquad \text{(S3)}$$

where $L' = 333.7$ (kJ/kg) is the mass latent heat for water, ρ_d (kg/m^3) is the dry soil density, w is the total water content, and w_u is the unfrozen water content (percentage dry mass basis) of the frozen soil. For non-saline gravel and sands w_u is assumed to be zero for many practical problems.

Seasonal ground freezing and thawing depths are estimated for gravel/sand based on meteorological data for *Pyramiden* (Herdis et al., 2016), and Longyearbyen airport (Norwegian Centre for Climate Services). The calculations are made to demonstrate approximate seasonal freezing and thawing depths at the riverbeds at *Odinelva* and *Adventelva*. Assumed soil parameters are presented in Table S2.1. Two cases are considered – full saturation (the talik has not dried out during winter), and partial saturation (the talik has partly dried out during winter). Seasonal freezing and thawing depths for 2010–2020 are presented in Table S2.2. For both cases (full and partial saturation), these depth are lesser the thickness of talik (i.e., approximately 4 m), measured in boreholes in *Odinelva* in August 2021, which confirms that this talik is residual, and hence can be classified at suprapermafrost groundwater of Type II according to (van Everdingen, 1990).

Table S2.1. Assumed parameters for soil at riverbed at Odinelva.

Parameter	Value	Reference
Soil type	Gravel or sand	Assumption
w_u	0	Assumption
n_t (gravel and sand)	2.0	Table 3-5 in (Andersland and Ladanyi, 2004)
n_f	0.9	Table 3-5 in (Andersland and Ladanyi, 2004)
ρ_d, kg/m^3	1500	Assumption
Full saturation:		
w	0.3	Assumption
k_u, W/m K	1.75	Figure 2-26 in (Andersland and Ladanyi, 2004)
k_f, W/m K	3.0	Figure 2-26 in (Andersland and Ladanyi, 2004)
Partial saturation (50%):		
w	0.3	Assumption
k_u, W/m K	1.75	Figure 2-26 in (Andersland and Ladanyi, 2004)
k_f, W/m K	3.0	Figure 2-26 in (Andersland and Ladanyi, 2004)

Table S2.2. Estimation of seasonal freezing and thawing depths for gravel/sand in *Pyramiden* and Longyearbyen.

	Full saturation, *w*=0.3				**Partial saturation (50%), *w*=0.15**			
	Pyramiden		**Longyearbyen**		***Pyramiden***		**Longyearbyen**	
Year	X_f, m	X_t, m	X_f, m	X_t, m	X_f, m	X_t, m	X_f, m	X_t, m
2010	2.4	1.5	2.2	1.4	1.8	1.4	1.7	1.3
2011	2.7	1.7	2.6	1.7	2.1	1.6	2.0	1.6
2012	2.1	1.6	2.0	1.5	1.6	1.5	1.5	1.4
2013	2.5	1.6	2.4	1.7	1.9	1.5	1.8	1.5
2014	2.3	1.5	2.1	1.5	1.8	1.4	1.6	1.4
2015	2.4	1.7	2.2	1.7	1.8	1.5	1.7	1.6
2016	1.9	1.8	1.8	1.9	1.5	1.7	1.4	1.7
2017	2.3	1.6	2.1	1.7	1.8	1.5	1.6	1.6
2018	2.2	1.6	2.0	1.6	1.7	1.5	1.5	1.5
2019	2.4	1.7	2.2	1.6	1.8	1.5	1.7	1.5
2020	2.8	1.7	2.7	1.8	2.2	1.6	2.1	1.6
2021	2.2	1.6	2.1	1.5	1.7	1.5	1.6	1.4

S3. Estimation of river talik capacity for water supply in Longyearbyen

Estimation of river talik capacity for water supply in Longyearbyen is presented in Table S3.

Table S3. Estimation of river talik capacity for water supply in Longyearbyen.

	Parameters for assessment	**River**	
		Longyearelva	**Adventelva**
1.	**Dimensions of talik**	**Length:** 2 km – upper part of the river that is not affected by contamination in the ground (from Nybyen to the school). **Width of alluvial river deposits:** 100 m, taken from aerial photos, wider in practice, but part of it hidden by urban developments. **Thickness of river talik that remain unfrozen during winter, *H*:** 2 m, taken by the analogy to observations and calculations for Odinelva in Pyramiden, see location h in Table S1 and Ch 4.4 in the article.	**Length:** 4 km – upper part of the river delta with presumably thick alluvial sediment. This part approximately extends from Todalen valley to Endalen valley. This part is also about the reach of large storms (not driftwood observed), hence is not affected by salt intrusion form the sea. **Width of alluvial river deposits:** 700 m, taken from aerial photos. **Thickness of river talik that remain unfrozen during winter, *H*:** 2 m, taken by the analogy to observations and calculations for Odinelva in Pyramiden, see location h in Table S1 and Ch 4.4 in the article.

2.	**Soil material in taliks**	Silty sand and gravel (based on observations on the ground surface, essentially an assumption when it comes to the soil profile) with porosity *n* of 29% (based on (Andersland and Ladanyi, 2004)).	Well-graded silty sand (based on observations on the ground surface, essentially an assumption when it comes to the soil profile) with porosity *n* of 35% (based on (Andersland and Ladanyi, 2004)).
3.	**Total volume of talik/aquifer** (soil particles and voids) *V*, m^3.	**$4·10^5$**	**$5.6·10^6$**
4.	**Volume of water in talik/aquifer** (full saturation), m^3: $V_v=V·n$	**$1.16 · 10^5$**	**$1.96 · 10^6$**
5.	**Water demands in Longyearbyen:** 1000 m^3/day (Sinitsyn, 2022b). Based on the latter, water demands for 14 days (a short-term emergency situation) V_1: $14·10^3$ m^3; for 200 days (approximate duration of the freezing season) V_2: $2·10^5$ m^3.		
6.	**Water level drop X_1 (m) in talik/aquifer for V_1:** $X_1=(V_v-V_1)·H/V_1$	**0.25**	**0.015**
7.	**Water level drop X_2 (m) in talik/aquifer for V_2:** $X_2=(V_v-V_2)·H/V_2$	**Not assessed as V_2 exceeds size of talik/aquifer**	**0.21**
8.	**Annual precipitation for Longyearbyen (measured), h (mm): 189 (Hanssen-Bauer et al., 2019)**		
9.	**Catchment area *A*, km^2**	**22 (Hanssen-Bauer et al., 2019)**	**500 (Nowak et al., 2021)**
10.	**Fraction of annual precipitation that would be needed for drinking water, %:** $F=V_x/h·A$ V_x – volume of water demand (V_1 or V_2), m^3	***F* for V_1: 0.3** ***F* for V_2: 4.8**	***F* for V_1: 0.02** ***F* for V_2: 0.2**

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