From land to fjords: The review of Svalbard hydrology from 1970 to 2019 (SvalHydro)

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1. Introduction: A Story of Change

Since the turn of the century, Svalbard has been considered a canary in the coalmine for climate change. Two decades later, the Earth's warning system located in the Norwegian High Arctic experienced irreparable damage, and the title has been passed onto Greenland. Unfortunately, latest research suggests that the new canary has also just reached the point of no return, and its fate might no longer be dependent upon our efforts to limit carbon dioxide emissions (see King et al. 2020). Despite Greenland's record melt-year, the forefront of environmental change affecting Earth's ecosystems continues to be in Svalbard. Here, the warming is two to six times faster than the rest of the world (see Wawrzyniak and Osuch 2020), and the consequences of a shrinking cryosphere have already impacted terrestrial and marine environments.

The magnitude of the climatic changes in the Arctic was evident during the summer melt-season of 2020, when not only Svalbard but also Siberia suffered record-breaking high air temperatures (>21 °C in Svalbard and >38 °C in Siberia). Yet, it is the long-term increase in surface air temperature that is responsible for often irreversible changes associated with the reduction in snow cover, accelerated glacier surface melt and their further recession (AMAP 2017, IPCC 2019). Latest research based on glacier mass balance indicates that in the last 60 years, the above changes, in conjunction with a decrease in glacier refreezing rates, have caused glacier runoff to double, while surface runoff from non-glacierised areas surprisingly remained almost unchanged (van Pelt et al. 2019). In this report, we show that this is not the case for Svalbard catchments when analysing in-situ collected hydrological datasets.

The consequence of hydrological changes in Svalbard is not restricted to local coasts and seas. It is estimated that in the last two decades, melting Arctic glaciers contributed to the global sea level rise at the same rate as the Greenland Ice Sheet. Although climate change predictions vary, depending on the greenhouse gas emissions scenario, there is no doubt that in the High Arctic we can expect further increase in air temperature (by 4–7 °C) and precipitation (by 45–65%) with increased occurrence of heavy rainfall and flood events (NCCS 2019). As a result, total surface discharge is also expected to increase further, although downscaled models and runoff simulations suffer from insufficient data.

Unfortunately, confirmation of the above predictions will be difficult to achieve because:

1. Current long-term hydrological monitoring in Svalbard is sparse, with a clear westward bias (see Figure 1).
2. Monitoring is divided between various institutions and countries, making collaboration limited and data exchange inefficient or often non-existent.
3. Short-term projects performed by various international research teams, that do measure freshwater discharge in easily accessible parts of Svalbard, present mostly partial data from one melting season (generally from July, which is recognized as the month with the highest discharge), or at most, two seasons only (due to funding restrictions). In consequence, they produce an incomplete representation of surface hydrology, while the data are often difficult to access.

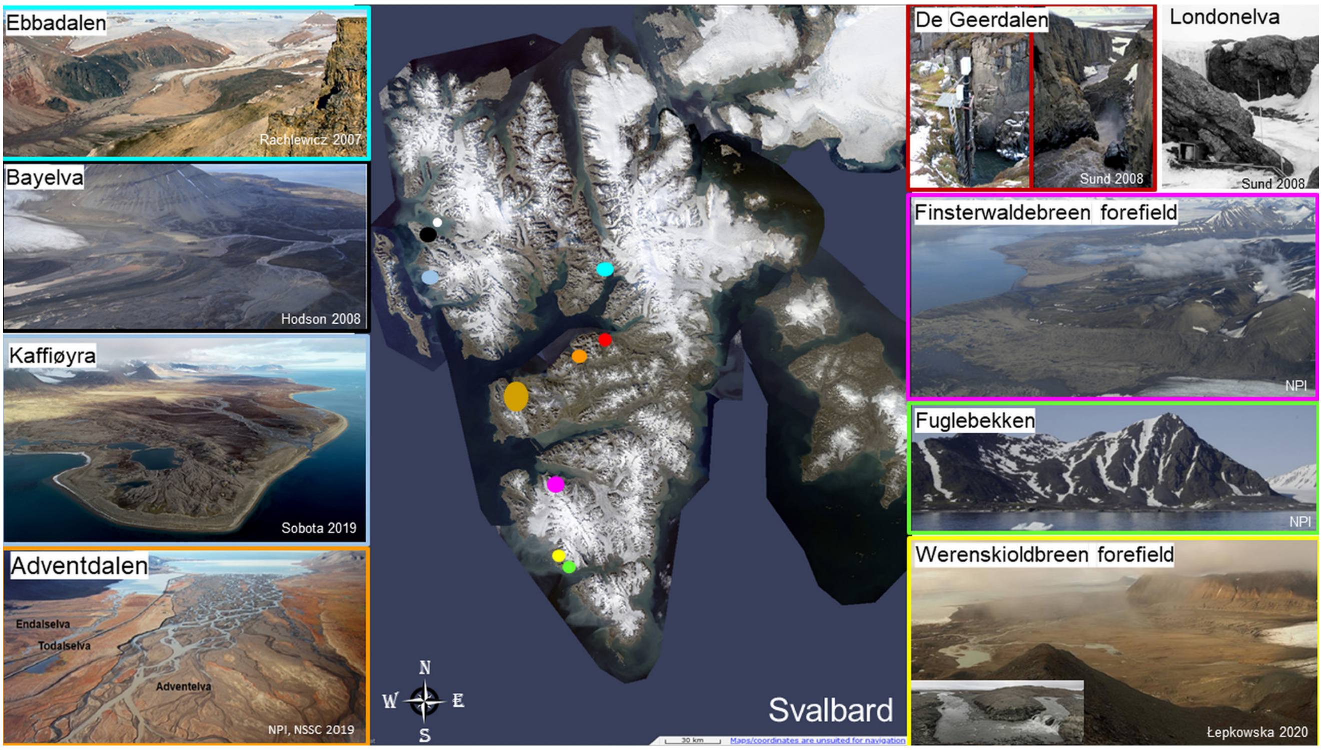

Figure 1: Map of catchments with long-term hydrological monitoring also showing a westward bias for Svalbard research. From south to north: (green) Hornsund – Fuglebekken, (yellow) Nottinghambukta – Werenskioldbreen, (pink) Van Keulenfjorden – Finsterwalderbreen, (brown) Grønfjorden - Grøndalen, Grønfjordbreen, Aldegondabreen, Kongressdalen; (orange) Adventfjorden – Adventdalen; (red) Sassenfjorden – DeGeerdalen, (turquoise) Petuniabukta – Bartilelva, Ferdinandelva, Ebbaelva, Elsaelva; (blue) Kaffiøyra - Waldemarbreen, Kongsfjorden – (black) Bayelva and (white) Londonelva. Not all monitoring sites are represented in the pictures. See Appendix 1 for details on all sites

As a result, the most widely available and used dataset for producing estimates and predictions of surface runoff from glacierised areas across the entire Svalbard usually come from state-run monitoring programs of the Norwegian Water Resources and Energy Directorate (NVE) and/or the Norwegian Polar Institute (NPI).

The above means that the observations and projections of hydrological changes for the Norwegian High Arctic are based on just two catchments: Bayelva transferring water into Kongsfjorden, and De Geerelva flowing into Sassenfjorden (e.g. NCCS 2019). These monitoring stations are located in the central part of the island, with the former being more northward (see Figure 1, Appendix 1).

However, research shows that meteorological conditions vary greatly across Svalbard (e.g. Førland et al. 2011, Nordli et al. 2014, Osuch and Wawrzyniak 2017a), as does the surface runoff. This is because local conditions influence air temperature, precipitation, evaporation, occurrence of winter rainfall, capacity for groundwater storage and the length of melting season. Yet, the influence of the above on surface runoff and consequently water balance is rarely mentioned in the literature (Nowak and Hodson 2013).

We already know that polar regions of the future will be very different to what we can see today, but given the heterogeneity of the Arctic environment, the level of that change will depend on general and local variables intrinsically linked to the air temperature, precipitation and changes in the cryosphere's capacity for storage or release of water.

Given the above, it is unsurprising that hydrological response to undergoing environmental revolution has been named one of the most important research needs in the High Arctic (NCCS 2019; Retelle et al. 2019).

Therefore, through this report we:

4. Present the first ever comprehensive hydrological dataset from all institutions performing long-term hydrological monitoring in Svalbard, in order to **depict the magnitude and direction of hydrological changes**, as well as to highlight the heterogeneity of the environment.
5. Seed the **SvalHydro** initiative to create a long-term hydrological observatory across Svalbard. The aim is to establish and strengthen collaboration between all institutions performing long-term monitoring on the island.
6. **Indicate gaps in knowledge that require our immediate attention**, and in some cases, necessity for new investments. This is to produce more accurate hydrological predictions and recommend actions that need to be taken for environmental protection.

2. Overview of Existing Knowledge

2.1. Water balance, the High Arctic problem

A water balance (or water cycle) is the movement of water from the atmosphere (through condensation and precipitation) to the ground (in the form of snow, ice and runoff) and its return to the atmosphere (through evaporation, see Figure 2).

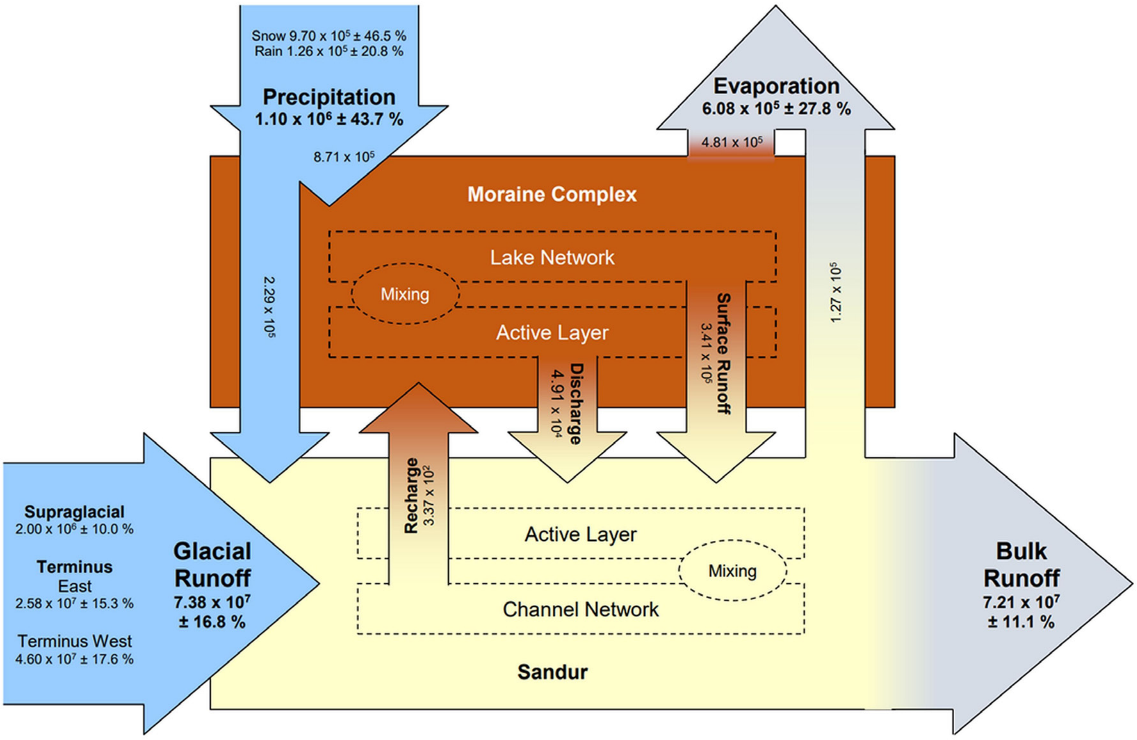

Figure 2: An example of a water cycle in a glacierised catchment in the High Arctic (Finsterwalderbreen watershed). Blue arrows: water inputs; grey arrows: water outputs; other arrows: internal transfers; dashed lines: minor multi-directional, stores/exchanges that cannot be quantified from the data available. All the water fluxes are in m^3, with estimates of probable error, except for channel recharge, active-layer discharge and surface runoff, these fluxes must be viewed as first-order estimates. The determination of errors in all other water fluxes are described in detail in Hodgkins et al. 2009. Modified from Cooper et al. 2011.

To describe those movements during a hydrological year (i.e. water inputs and outputs from 1st October to 30th September), a water balance equation was created (see Eq 1).

$$P+C-Q-Q_g-E_a \pm \Delta S= \epsilon \qquad \text{(Eq 1)}$$

Where P is precipitation [mm/y], C is condensation [mm/y], Q is surface runoff [mm/y], Q_g is groundwater runoff [mm/y], E_a is evaporation [mm/y], ΔS is change in storage [mm/y] and ϵ [mm/y] is a residual error term representing water that is not properly accounted for (as the inputs and outputs in the equation should be in balance).

While many forms of this equation exist with different levels of complexity, a study by Nowak and Hodson (2013) modified the most-used versions of it [described in Hagen and Lefauconnier (1995) and Killingtveit et al. (2003)] for providing accurate results in glacierised catchments of the changing High Arctic (see Eq 2).

$$P_{winter(ngs)} + (P_{JJAS}+P_Q) + B_s + C - E_a \pm \Delta S= \epsilon \text{ (Eq 2)}$$

Where $P_{winter(ngs)}$ is areal winter snowfall from non-glacierised areas [mm/y], P_{JJAS} is areal precipitation during June–September [mm/y], P_Q is daily winter precipitation causing discharge [mm], B_s is summer mass balance of glaciers occupying a catchment [mm/y], C is condensation [mm/y] and E_a is evaporation [mm/y].

Although Eq 2 renders the smallest errors in the water balance due to its appreciation of High Arctic conditions, the equation is far from perfect.

For example, some of its components such as condensation (C) and evaporation (E_a) are still based on artificial assumptions and constants created from sparse measurements performed over 30 years ago (C =9.38 mm/y, E_a=46.88mm/y Killingtveit et al. 1994). Although using those constants had merits, we now know that meteorological conditions vary greatly across Svalbard, and even small differences between locations of measuring sites may cause substantial changes in the obtained results (Wawrzyniak and Osuch 2020). Therefore, a constant created for a catchment in the north where the climate is colder and more continental will not reflect conditions in the south where the climate is much warmer and maritime. In addition, the rapidly warming Arctic that observes **dramatic increase in precipitation and air temperature leaves three-decade-old measurements outdated**.

Likewise, measurements of precipitation in the High Arctic are sparse, and gauging stations are located at the sea level. However, majority of the catchments in Svalbard contain mountainous areas, so calculation of the total precipitation needs to include a correction for the elevation gradient. In Eq 2, the assumption was made – based on the results of old measurements and hydrological modelling – that a 19% per 100 m increase of snowfall and rainfall alike will yield the best results. Yet, since **no active measurements of precipitation at various elevations are currently made in Svalbard**, it is another approximation of the conditions that could be close to reality but may not reflect the true values.

Another source of uncertainty in the water balance calculations, and in some cases a source of large errors, come from the change in water storage term (ΔS). It is still commonly accepted that the Arctic conditions allow for the assumption that ΔS is negligible. This is because catchments are underlined by continuous permafrost, while glaciers covering the surface undergo little changes. In addition, the duration of hydrological monitoring used in calculations is usually long, so small annual changes should not, in theory, influence the results in a significant way. However, Nowak and Hodson (2013) also indicated that the **water storage term can no longer be considered negligible** due to changes that follow warming of the High Arctic climate (i.e. thawing of the permafrost, thickening of the active layer, rapid retreat of glaciers coupled with their thermal regime change, or most importantly, increased occurrence of extreme winter rainfall events, causing ground icings).

The final problem that the Arctic hydrology is facing is a change in the boundaries of the hydrological year. The artificial dates of 1st October until 30th September were established based upon data indicating that all precipitation that falls in the form of rain or snowfall from October will stay on the ground until the melt season begins in May. However, there is increasing amount of evidence that extreme rainfall events following climatically driven changes now cause river discharge to happen well into October, November or in some cases December (see for e.g. Majchrowska et al. 2015). **Shifting** the **theoretical boundaries of the hydrological year is therefore necessary in view of the changing climate**.

Therefore, in this report, we present the evidence that the hydrological research in the High Arctic is in dire need of a 'facelift' that will take into consideration dramatic changes following climate warming. We also demonstrate the importance of long-term hydrological datasets by showing that while freshwater discharge from non-glacierised catchments and catchments with large glacier cover continues to increase, **water fluxes from catchments with smaller glaciers, where ice has already retreated markedly, have been in fact decreasing for one or more decades**.

Rethinking the water balance equation is a crucial step towards achieving understanding of the current hydrological conditions in the Arctic, as well as being able to accurately predict its contribution to the global water cycle. Especially, when every record-breaking measurement is a painful reminder that the changes we are facing here are beyond the point of no return.

2.2. Air temperature, a winter problem

In the mountainous catchments of Svalbard, snow and ice significantly affect water circulation by temporarily storing and releasing water on various time scales. Many studies have revealed that increase in melt and hydrological activity are directly proportional to increase in air temperature (see Hock 2003). Furthermore, air temperature is also responsible for distinct variability in annual and diurnal discharge.

Data collected from monitoring stations across Svalbard (Hornsund, Longyearbyen and Ny-Ålesund) show that in the last 40 years, the number of positive degree days (days with air temperature above 0°C) almost doubled. We also observe a latitudinal difference in the speed of that warming as the most southward located Hornsund experienced much more positive degree days than central Longyearbyen and the most northward Ny-Ålesund, This is also the case when we look at the length of the period where temperatures continuously stay above 0°C (Figure 3). In addition, melt season across Svalbard continues to start earlier while the freeze-up, marking the beginning of winter, continues to start later (Figure 3b, c). **The summer season is getting longer**, but research also indicates that **it is the winter that sees the most severe consequences of the warming** (see Nowak and Hodson 2013). Increasing number of warm weather episodes that result in intense rainfall almost immediately create extensive icings and ground ice. The former two prevent reindeer from grazing, lead to vegetation browning and impact soil temperatures (Vikhamar-Schuler et al. 2016), while the latter can alter water balance in affected catchments for more than one hydrological year (Nowak and Hodson 2013).

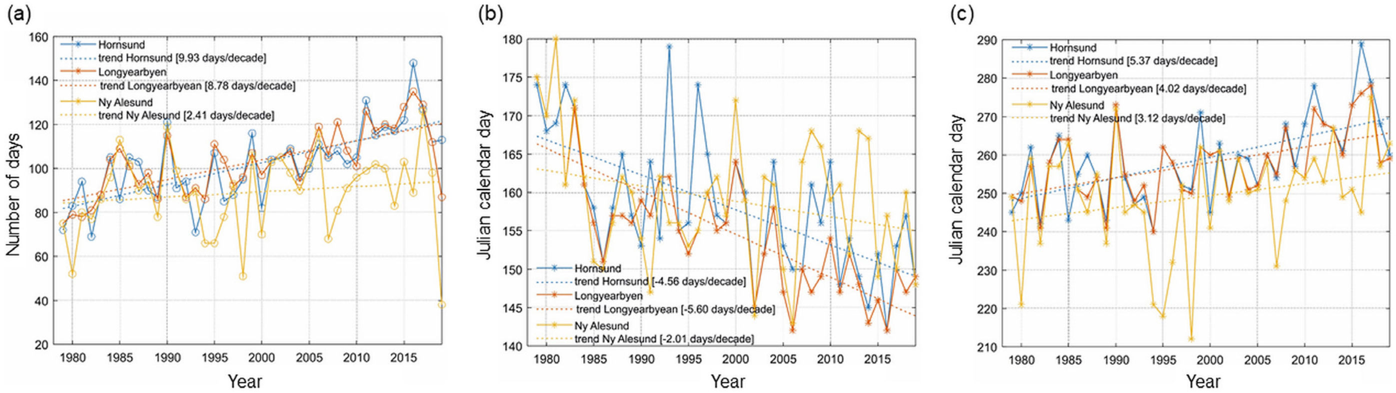

Figure 3: Variability of (a) the length of the longest period with positive air temperature, (b) start date and (c) end date of the continuous period with positive air temperature at Hornsund, Longyearbyen and Ny-Ålesund in the period 1979–2019. Trends were estimated by the modified Mann-Kendall test. The slope of the trend was estimated using Sen's method (Sen 1968).

2.3. Precipitation, the end of season dilemma

An immediate consequence of continuous increase in air temperature is the increase in precipitation. The trends we see do not follow increase in air temperature exactly, as local climate alters the magnitude of observed rainfall. For example, the maritime location of Hornsund is responsible for the largest decadal increase in rainfall and decrease in snowfall (see Figure 4). However, Longyearbyen – which is located in the central part of the island where climate is more continental – observed the smallest decadal changes, although the trends are in the same direction. Finally, in the most northward located Ny-Ålesund, both summertime rainfall and wintertime snowfall continue to increase.

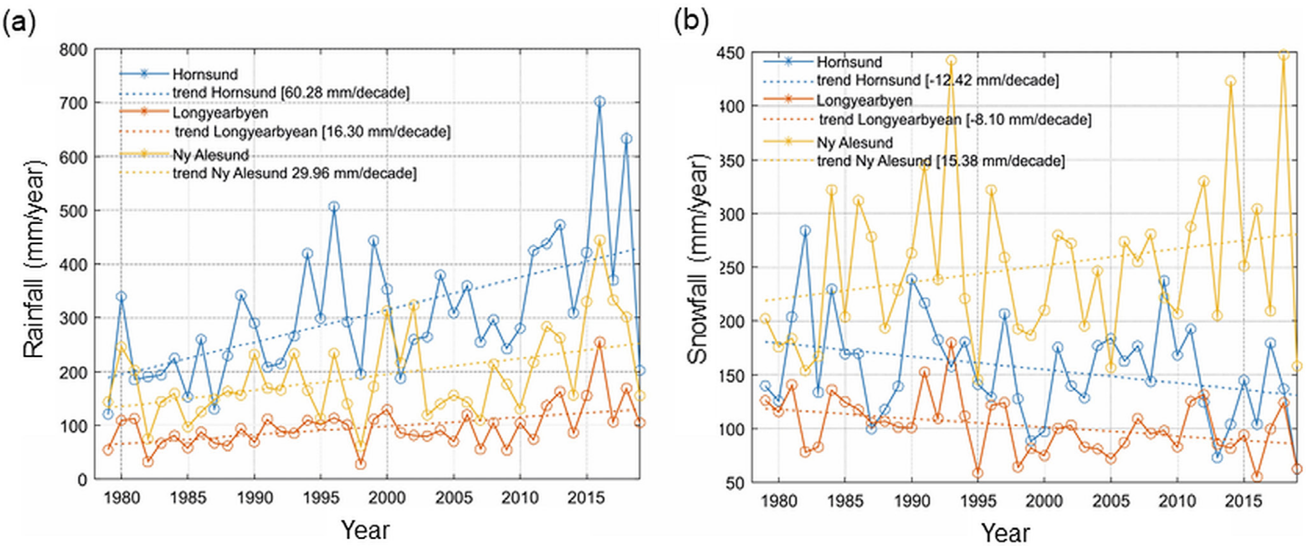

Figure 4: Variability of annual (a) sum of rainfall, (b) sum of snowfall at Hornsund, Longyearbyen, and Ny-Ålesund in the period 1979–2019. It was assumed that rainfall occurred during positive degree days (>0°C)

Nonetheless, the consequences of the above changes have an influence upon water balance in all catchments across the archipelago. Increased rainfall is followed by increased occurrence of slushflows (Jaedicke et al. 2008), landslides and rockfalls (Lewkowicz and Way 2019). The changes are most noticeable in the shoulder seasons. While March and April are most affected by the increase in air temperatures shifting the beginning of snowmelt season earlier, September and October have also been getting wetter. The change is **prolonging the melting season and freshwater flux from terrestrial environments well outside the assumed boundaries of a hydrological year**.

The measurements of snowfall and rainfall are however sparse and not without errors. Available studies indicate that Arctic catchments often exhibit a pattern in which runoff appears to significantly exceed precipitation (Killingtveit et al. 2003). This can be attributed to a combination of measurement errors, non-representative locations of precipitation stations, net glacial ablation as well as knowledge gaps caused by insufficient monitoring.

Measurements are often underestimated in upland areas as rain gauges are only located at the sea level (Førland et al. 1997). Measurements of the end-of-winter, snowpack water–equivalent flux also remain challenging for hydrological studies. Sources of potential error in estimates relate to snow-depth measurements and the fact that the snow depth is often interpolated or extrapolated using a regression on elevation. The spatial variation of accumulation seems to contribute by far the most to overall error, being greater, for instance, than the inter-annual variability (Hodgkins et al. 2005). The probable error range for the snowpack water flux can be as high as ±44% (Hodgkins et al. 2009).

Killingtveit et al. (2003) made the same point in suggesting that residual error in water balance calculations (‘ϵ’ in Eq 1 and Eq 2) is probably related to problems of precipitation correction. However, a study by Nowak and Hodson (2013) discovered that if the residue (ϵ) is considerably large, this theoretical surplus of water in a catchment cannot be construed as an error and is in fact a result of extreme winter rainfall events. This is because such unaccounted **rainfall can be stored in the active layer for the duration of one or two hydrological years**.

2.4. Glacier mass balance, a change in storage

Glaciers of Svalbard have been losing mass for the last half of the century, although the tendency to a more negative balance has been observed for the last twenty years (-8±6 Gt/y, Schuler et al. 2020, also see Figure 5). This year (2020) is no different. Although glacier mass balance measurements for 2020 are underway at the time of writing of this report, preliminary results already suggest that 2020 will be another year of very negative mass balance, particularly due to the record low snow water equivalent measured in spring (JC Gallet and J Kohler, personal communication. Also observed by A Nowak, I Sobota and A Hodson on Bogerbreen, Waldemarbreen and Foxfonna, personal communication).

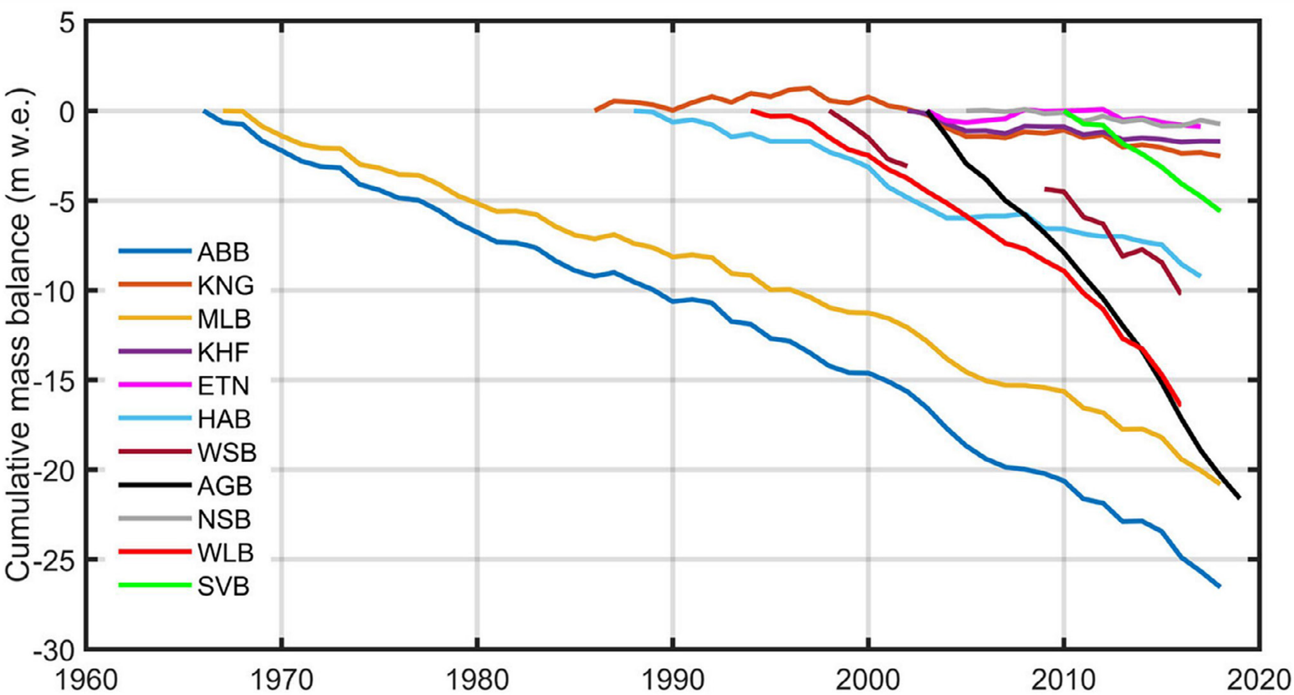

Figure 5: Cumulative surface mass balance of selected Svalbard glaciers. ABB – Austre Broggerbreen, KNG – Kongsvegen, MLB – Midtre Lovenbreen, KHF – Kronebreen/Holtedahlfonna, ETN – Etonbreen, HAB – Hansbreen, WSB – Werenskioldbreen, AGB – Austre Grønfjordbreen, NSB – Nordenskioldbreen, SVB - Svenbreen (Source: Schuler et al 2020)

In Svalbard, smaller and thinner glaciers with modest snow accumulation area respond to the warming (i.e. retreat) much faster than larger ones where the accumulation zones are sizeable (Schuler et al. 2020). The former can be found in the central and southern part of the island, where the climate is milder, while the latter are mostly in the northern part of the island where the climate is much colder and drier. The type of Svalbard glaciers varies from cirque to valley glaciers, ice caps and ice fields, and so does their thermal regime. Smaller glaciers with thickness below 100m are typically cold-based, with the entire ice temperature below the pressure melting point (except for summer surface ice). They are frozen to their beds and their internal water storage freezes during winter. In contrast, larger and thicker glaciers are polythermal, which means that they consist of both cold and temperate ice (see Figure 6). The latter is at the pressure melting point (i.e. warmer) and permits the presence of liquid water. As a result, polythermal glaciers can transport, store and release water from subglacial and/or englacial channels even during winter. According to a study from 1993 by Hagen et al., the majority of glaciers in Svalbard are of the latter type.

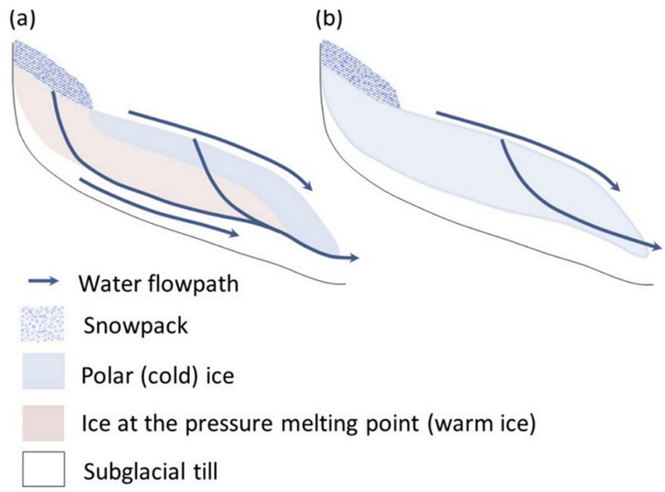

Figure 6: Simplified diagram of (a) polythermal glacier; (b) cold-based (polar) glacier thermal regime and drainage system (Source: Nowak-Zwierz 2013)

However, if we consider that the marked warming of the High Arctic in recent decades has resulted in continuous glacier thinning as well as their rapid recession, we also need to be aware that since 1993, many polythermal glaciers have transformed, or are in the process of transformation, into cold-based (e.g. Austre Brøggerbreen, Bogerbreen, Tellbreen, and Scott Turnerbreen). Such thermal regime change has a significant effect upon fluxes of water, suspended sediments as well as transport of major ions and nutrients into downstream environments (see Nowak and Hodson 2014).

Suddenly, subglacial drainage ceases, and glacial storage – a contribution of winter discharge into a catchment's water budget – is replaced by an increased summer meltwater delivery from rapidly receding glaciers. Fluxes of ions into coastal waters are enriched due to intensified chemical weathering of freshly released suspended sediments.

Transformation of glaciers' thermal regime and their subsequent recession presents a challenge for calculations of the water balance, as it influences the change in storage term (ΔS) of the water balance equation **in more than one way**. Receding glaciers also uncover ground that is now subjected to cold Arctic conditions. As a result, those areas undergo a slow transformation from unfrozen ground (that used to be protected from harsh temperatures by the glacier ice) into permafrost (Szafraniec and Dobinski 2020). Although changes in the ground thermal regime of deglaciating catchments are marked, they still need to be included in the hydrogeological models. These so far only consider changes in a catchment's hydrology due to permafrost degradation (e.g. Bense et al 2009; Bense et al 2012).

2.5. Surface discharge, dire need for long term monitoring

Cryospheric changes that occur in Arctic catchments have, and will continue to have, a marked effect on hydrology in glacierised watersheds. A study by Huss and Hock (2018) indicated that globally, even in large-scale basins where the ice cover fraction is minimal, downstream hydrological effects of glacier recession can be substantial. If we consider that freshwater discharge in some catchments in Svalbard consists of 50–70% of glacial meltwater (Majchrowska et al. 2015; Sobota et al. 2016), marked glacial recession observed in recent years in various watersheds will carry major consequences for the entire downstream ecosystems, terrestrial or coastal, that are dependent upon freshwater supply. Water fluxes, sediment, nutrient and major ion transports, drinking water supply or in some cases hydropower are and will continue to be affected.

In order to prepare for the above we need to be aware of the current hydrological conditions in catchments across the Arctic. Yet, research in high-latitude hydrology continues to be challenging despite technological advancements. The infrastructure remains very limited, and the extreme seasonality reduces the utility of many standard techniques, e.g. even where weir structures have been built, they typically fail to capture early-season runoff adequately because of snow- and ice-blocking of channels at the beginning of the melting season (e.g. Sund 2008). Significant challenges persist in measuring precipitation reliably and representatively; this not only hinders process analysis and water resources management, but also makes climate change detection difficult (e.g. Førland and Hanssen-Bauer 2003).

Measuring and monitoring the discharge of even moderately sized, glacially fed rivers is a demanding task because of the temporal and spatial instability of their flow regimes (see examples in Figure 7), particularly if continuous, complete time series are required. Furthermore, the majority of rivers are extremely braided, (see Figure 1 for an example), and there is no certainty which braid will be active for the entire summer. Therefore, long-term monitoring remains restricted to easily accessible places where local geology allows for collection of all discharge in one channel.

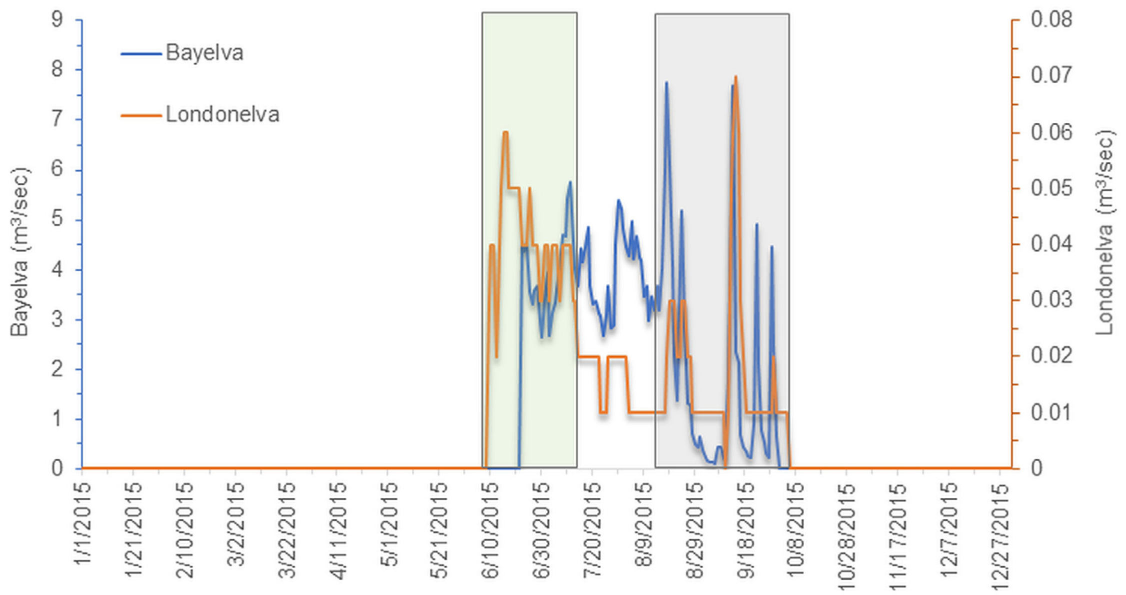

Figure 7: An example of a seasonal hydrograph from a glacierised catchment (Bayelva) and a non-glacierised catchment (Londonelva). Grey rectangle on the hydrograph covers rainfall-dominated discharge. Green rectangle indicates snowmelt-dominated discharge. White area in between corresponds to discharge dominated by glacier ice-melt.

2.5.1. Have we passed 'peak water'?

Despite the above, measurements undertaken at sparse hydrological monitoring stations on the west coast of Svalbard indicate that freshwater fluxes from glacierised and non-glacierised watersheds are changing.

In case of the former, rapid glacier recession opens water stores previously locked in the long-term storage (glacier ice). Thus, in catchments dominated by glaciers, we should observe an increase in annual glacier runoff until 'peak water' (or a maximum) is reached. After that, a decline in water discharge is expected due to reduced glacier area that cannot support a steady increase in discharge anymore (Huss and Hock 2018, see Figure 8). However, since glacier coverage, and therefore meltwater contribution to total surface discharge, will vary between different catchments, so will their water fluxes and the timing of peak water.

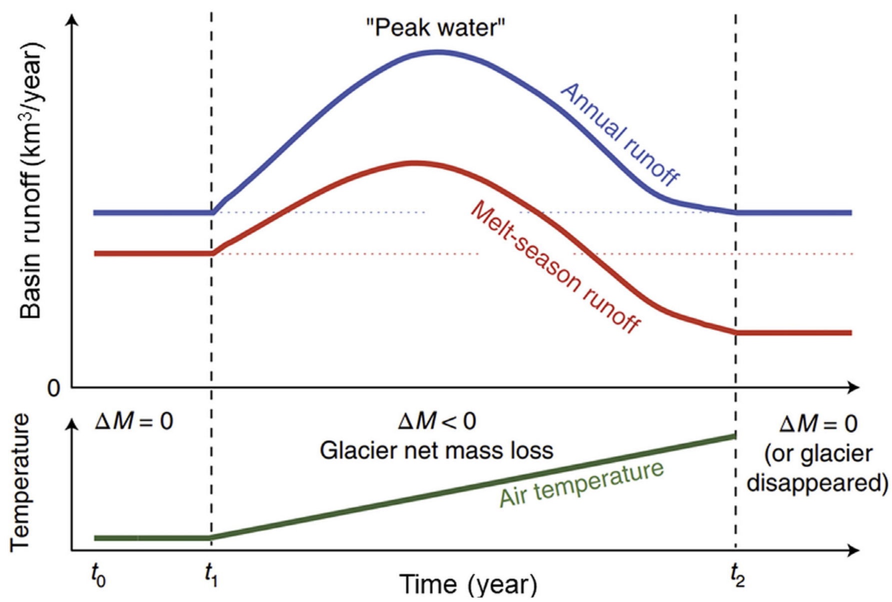

Figure 8: Changes in runoff from a glacierised catchment as a result of continuous climate warming (after Huss and Hock 2018)

Table 1: Average decadal freshwater fluxes (Qavg) into marine environment from three types of catchments (non-glacierised, lacustrine, and glacierised) and watersheds with various level of glaciation. See catchments' description in Appendix 1.

Catchment type	Site name	Qavg 1970-1980	Qavg 1980-1990	Qavg 1991-2000	Qavg 2001-2010	Qavg 2011-2019
		x103 m3/year				
Non-glacierised	Fuglebekken[1]	162	362	453	421	534
	Londonelva	-	-	271	-	647
	Dynamiskbekken	-	-	-	241	-
	Elsaelva (almost non-gl)	-	-	-	-	1,106
Non-glacierised lacustrine	Kongresselva 2017–2019	-	-	-	-	10,695
Glacierised	Werenskioldbreen[2]	57,000	52,000	65,000	74,000	83,000
	Adventelva[3]	-	-	286,836	313,737	376,143
	Bayelva – started in 1989	-	25,696	27,533	33,683	30,889
	De Geerelva	-	-	42,290	41,953	38,156
	Aldegondabreen 2017–2019	-	-	-	-	23,699
	Finsterwalderbreen1999–2000	-	-	73,800	-	-
	Ferdinandelva	-	-	-	-	3,190
	Ragnarelva 2001–2003	-	-	-	19,777	-
	Horbyeelva 2001–2003	-	-	-	44,243	-
	Ebbaelva	-	-	-	47,508	-
	Bertilelva	-	-	-	-	7,260
	Waldemarelva			6,904	5,587	5,231
	Grøndalselva 2017–2019	-	-	-	-	45,618

[1]Simulated discharge using the Nordic-HBV model calibrated on discharge observations from the period 2014–2019 and validated on archival flow observations; discharge;

[2]unpublished data based on 21 hydrologically active seasons between 1970 and 2019;

[3]data based on the Nordic-HBV model calibrated on the De Geerelva discharge observations from 1991 to 2019

Table 1 indicates that in Svalbard, catchments with **smaller glaciers that have receded markedly have already achieved 'peak water'** and are on the falling limb of the runoff curve (see Bayelva, De Geerelva, Waldemarelva). In contrast, those **watersheds with larger glaciers** and perhaps higher percentage of non-glacierised area (e.g. Adventelva, Werenskioldbreen) **are still on the rising limb.** Similarly, **non-glacierised catchments** (e.g. Fuglebekken, or Bratteggbekken, an 8 km^2 watershed south of Werenskioldbreen; personal communication with E Łepkowska) **see an increase in discharge, most likely due to increase in precipitation** (and ground ice melt within the freshly thawed active layer).

Lack of long-term monitoring data precludes us from accurate estimation of the current and future freshwater fluxes from partially glacierised terrestrial environments into the coastal waters of the Arctic**.**

Hydrological data also show that **we can no longer rely on Arctic freshwater forecasting based solely on changes in glacier mass balance** as glacier cover in watersheds vary greatly (from 10% to 70%). In addition, glacier recession does have an influence on subsurface water stores which now more than ever needs to be acknowledged in surface water hydrology.

2.6. Groundwater contribution, the holy grail of Arctic hydrology

Studies of sub-surface hydrology in Svalbard tend to focus on sub-permafrost groundwater with relatively little attention paid to water flow within the active layer. We know that the groundwater flowpath in areas of continuous permafrost depends on location (geology), type of recharge (glaciers, rainfall, lakes, rivers) hydraulic gradients and water quality (temperature and chemical composition). Water transfers are restricted by ground ice, and the most visible outflows are pingos and springs, with the latter being the most obvious during winter when all other surface discharge is frozen (Orvin 1944; Vtyurin 1994). The two best known groundwater systems in Svalbard are located in Grøndalen (see Demidov et al. 2019) and Adventdalen (see e.g. Hodson et al. 2019, Hodson et al. 2020). Yet, still little is known about the sub-permafrost water fluxes, even though the direction of the movement has been studied (e.g. Booij et al. 1998 or Haldorsen and Heim 1999).

For example, if a catchment has a direct connection to a fjord, seawater intrusions into land can reach even a few kilometres into the land. These intrusions then form saline sub-permafrost aquifers that can result in surface discharge (Demidov et al. unpublished; Hodson et al. 2020). Such cryopegs (or taliks, lenses of salt or brine over cooled water) were encountered under both the Grøndalselva and Adventelva estuaries. Sub-permafrost aquifers are also fed by glacier meltwaters (see Figure 9). These aquifers, however, have a very different chemical signature, as firstly they were created by diluted ice melt and then altered by subsurface migration though valley deposits and saturated by chemical weathering or cryogenic metamorphism (Woo 2012; Demidov et al. 2019; Hodson et al. 2019). Although the chemical signature of groundwater within and under permafrost is relatively easy to study via their surface outflows (see a review of the Arctic region groundwaters by Lecher 2017), using it to estimate water flux produces large errors and uncertainties. Therefore, research usually focuses upon identifying groundwater discharge and their chemical characteristics, while the only continuous discharge measurements of such water in Svalbard were performed by Hodson et al. (2020).

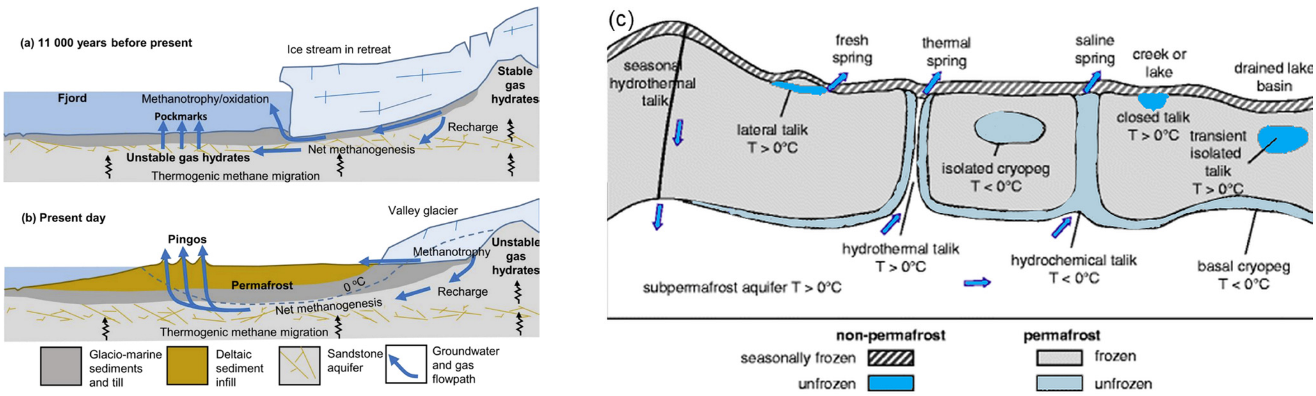

Figure 9: A schematic of sub-permafrost water flowpath in (a, b) glacierised catchments (Hodson et al. 2020) (c) non-glacierised catchments (Woo 2012)

The hydrology of aquifers residing on top of permafrost (in the seasonally frozen active layer) to date has received even less attention (see Cooper et al. 2011), though we know that water from the active layer can discharge in the form of spring or small water seeps anywhere in a valley, estuarine area and beneath the slopes. Surface discharge is usually easier to spot at the end of summer, when all the snow has thawed, glaciers have reduced their melt and the ground has not started freezing yet. As with sub-permafrost groundwaters, active layer hydrology is identified mostly with hydrochemical studies. Its chemical composition is variable, reflecting properties of the sediments it drains.

Even though **we do not directly measure groundwater fluxes in Svalbard**, hydrochemical research shows that **groundwater plays a role in surface runoff** (Figure 10) and the annual formation of the active layer is hydrologically significant (Stäblein 1971). Downward-thawing rates are initially high, although variations in microtopography and the persistence of patchy snow cover may result in the development of an irregular permafrost table with thawed troughs and frozen ridges, though this irregularity tends to subside as the melt season progresses. The potential for sub-surface water storage and flow in the active layer increases in line with the gradual increase in the depth of the permafrost table, which constitutes the lower boundary layer for water movement (Pecher 1994; Osuch et al. 2019). Sub-surface flow in the active layer may increasingly contribute to proglacial throughputs of runoff, as larger fluxes of water are observed at the surface due to increased glacier melt and increased precipitation. Increased precipitation in the autumn that is following the changing climate also coincides with the deepest active layer, influencing recharge and throughput of the shallow groundwater fluxes. **Yet we know next to nothing about the hydrology of this rapidly changing groundwater system**.

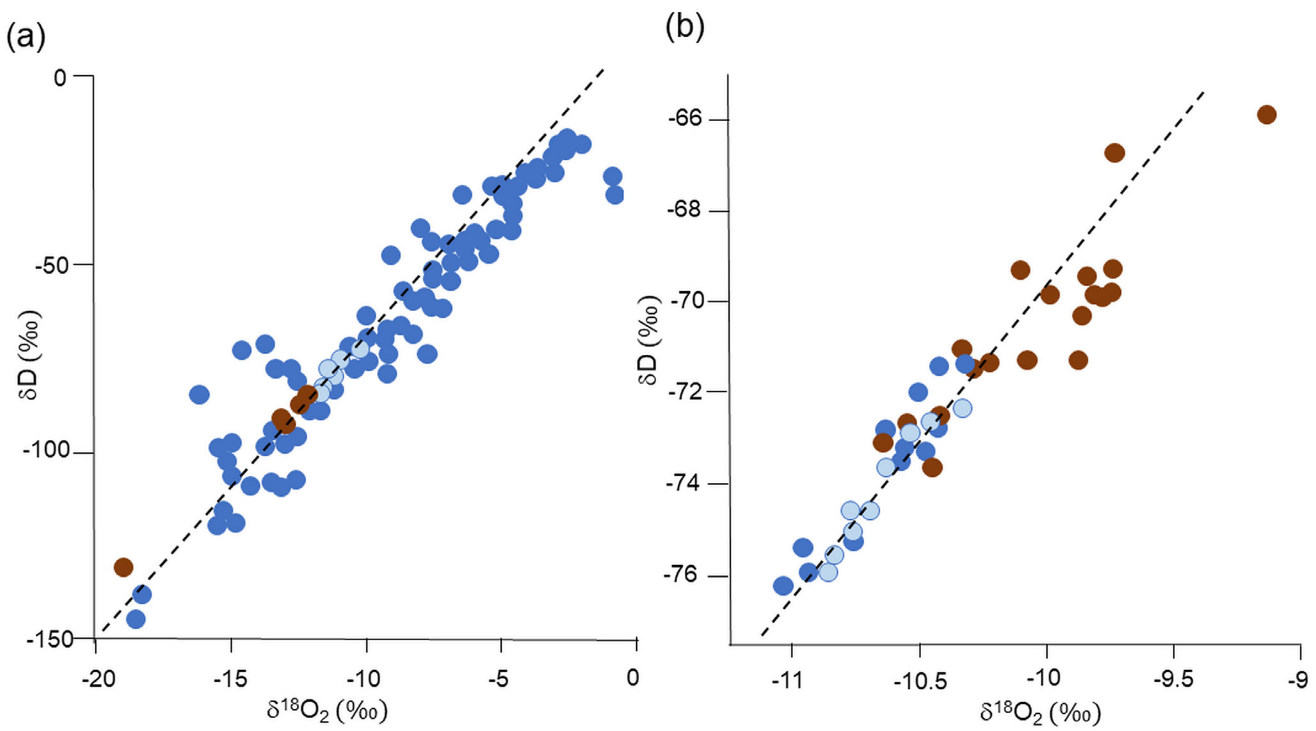

Figure 10 Groundwater contribution to surface runoff. An example of isotopic signature of rainfall (dark blue), river water (light blue) and groundwater (brown) in (a) Grøndalen and (b) Kongressdalen. Dashed lines represent global meteoric water in (a) Barentsburg and meteoric water in (b) (Demidov et al. 2019, Skakun et al. 2020)

3. Connections and synergies with other SESS report chapters

Water is the link that connects all environments; therefore, any changes within those environments (whether atmospheric, terrestrial or marine) will immediately be reflected in changes in the water cycle (i.e. water budget). Hydrological research in the Arctic is challenging, lacks investments and long-term monitoring, yet it is a fantastic bridge that allows us to connect interdisciplinary studies.

For example, this report also includes chapters dedicated to improving our knowledge on snow cover distribution and enhancing snow cover date collection, thus contributing to minimising errors in the water budget calculations. PASSES (Salzano et al. 2021) provides a picture of terrestrial photography applications, while SvalSCESIE (Killie et al. 2021) compares an existing satellite-based, long-term climate data record with the model output for snow water equivalent and in-situ measurements. Lastly, SATMODSNOW (Malnes et al. 2021) studies the relationships between satellite observations and hydrological snow models and quantifies the difference.

4. Unanswered questions

4.1. Precipitation

As indicated above, one of the most urgent questions concerning Arctic hydrology in the changing climate is related to precipitation. Current observations, as well as most recent predictions, indicate that the amount of rainfall in Svalbard will continue to increase. However, despite the general consensus on the direction of the change, we still do not know the following:

1. How much of that precipitation can be accounted for as snowfall and how much as rainfall?
2. What is the precipitation gradient change with elevation?
3. How we can reliably quantify and monitor winter rainfall (i.e. rain on snow) to provide information on slush flows, as well as water infiltration into ground for rockslides and landslides?
4. How will glacierised catchments across Svalbard respond to increasing precipitation, especially when considering variability in local climate?
5. How flash floods caused by extreme rainfall events will change sediment transport from Arctic catchments? What will be the sediment transport from glacierised and deglaciating catchments after such events? Focus should be given to changes in bank erosion and increased occurrence of debris slides and debris flows

4.2. Evaporation & Condensation

The rate of evaporation begins to assume significance following the recession of the snowpack, reflecting the increase in air temperatures and the abundance of surface water available for evaporation. However, as the melt season proceeds, the rate of evaporation gradually declines, reflecting the progressive drying out of the ground surface. Observed changes in air temperature and precipitation as well as length of the melting season mean that there is also a dire need for up-to-date measurements of evaporation and condensation. These should be performed across the Arctic following the example from Hornsund, with appreciation of heterogeneity of the meteorological conditions and vegetation across the island.

4.3. Water Storage

Rapid changes in ground temperature, thickening of the active layer and thawing of the permafrost yield several unanswered questions that need to be addressed before we can confidently describe the Arctic's contribution to the freshening of the Arctic ocean.

What is the glacial contribution to the groundwater system? The linkages between two frozen bodies that are rapidly changing need to be explored. A coupled glacier–groundwater model needs to be developed to investigate the effects of different climate scenarios on freshwater transport into marine environments

What is the capacity of the thickening active layer for water storage and water transfer? Measurements need to be undertaken to help answer questions on groundwater contribution to surface discharge, nutrient flux into terrestrial and coastal areas, and to help answer questions related to risk management of geohazards, such as landslides, erosion or debris flow. In addition, changes to the waterlogged active layer will have an indirect influence upon fluxes of gasses such as carbon dioxide (CO_2) and methane (CH_4)

Finally, we should start addressing the lack of appreciation for modelling of permafrost changes in glacierised catchments, which also needs to include permafrost aggradation due to glacier recession.

4.4. Rethinking water balance in the High Arctic

Given the above, it is unsurprising that the **Arctic hydrology is in a desperate need of a 'facelift'**. Rapid warming shifting the timing of onset of snowmelt and prolonging the meltwater season means that the hydrological year should be redefined. Dramatic changes in precipitation patterns also need to be addressed, and precipitation measurements across a range of elevations should be performed to provide data that correspond to the current climatic conditions. Change in freshwater storage can no longer be assumed negligible, even in glacierised catchments with continuous permafrost. This is because glaciers in Svalbard change their thermal regime from polythermal to cold-based, and so their internal water storage and interaction with groundwaters also change. Furthermore, active layer depth is rapidly increasing as permafrost is thawing. This creates possibilities for new water flowpaths as well as water storage to the next hydrological year. All this has a profound effect upon surface hydrology and all downstream environments, whether terrestrial or marine.

This report shows a **steady decrease in freshwater fluxes from some glacierised catchments of the High Arctic for one or more decades**. However, water fluxes from rainfall-dominated watersheds have been increasing. In order to know the aerial extent of that transition, we must improve hydrological research in Svalbard.

5. Recommendations for the future

We recommend a series of actions deemed necessary to close the water budget for the Norwegian High Arctic. To do so, we suggest the **development of existing sites and the establishment of new supersites for hydrological research**. The main action points are:

Return of long-term hydrological monitoring projects delivering data that are easy to access, as these are vital for providing information on consequences and the speed of changes occurring as a result of climate warming. The data are also crucial for hydrological modelling in glacierised and deglaciating catchments across the Arctic.

Set up of autonomous meteorological and hydrological monitoring on:

The East coast of Svalbard. Possible locations include catchments advecting water into Agardhbukta (e.g. Væringsdalen or Eistradalen). Locations were chosen based on the relative ease of access and short distance from Longyearbyen.

In addition, autonomous monitoring should be established in the North of Svalbard (e.g. Svartdalen (Wijdefjorden) or Mosselhalvøya).

A permanent hydrological monitoring station should be re-established in (partially glacierised) Endalen and (non-glacierised) Gruvedalen, as these are the only catchments supplying drinking water to neighbouring Longyearbyen.

Establish a **network of meteorological stations across a range of elevations** at key locations in Svalbard (e.g. Longyeardalen, Hornsund, Ny-Ålesund, as well as the East coast)

Set up time-lapse cameras in the catchments under hydrological monitoring (see above) to allow for discharge monitoring during the beginning of snowmelt season, when hydro stations are still frozen over and do not provide reliable water discharge data.

Perform measurements of water fluxes **in the active layer** (e.g. via boreholes) in conjunction with already established research on active layer thermal regime changes. These should ideally be undertaken in catchments where long-term hydrological monitoring is already (or will be) established

Conduct **multi-sensor remote sensing studies** in locations that are difficult to access. The versatility of remote sensing means that remote research can now provide information on surface moisture content, ground dynamics, snow water equivalent, ice freeze/thaw cycles and vegetation mapping, thereby delivering new data. It can also improve spatial coverage in catchments that are already under in-situ monitoring.

6. Data availability

Due to a large number of partners and available data, information is provided in the Appendix 2.

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References

AMAP (2017) Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. ISBN 978-82-7971-101-8

Bense V, Ferguson G, Kooi H (2009) Evolution of shallow groundwater flow systems in areas of degrading permafrost. Geophys Res Lett 36 (22), 1-6. https://doi.org/10.1029/2009GL039225

Bense V, Kooi H, Ferguson G, Read T (2012) Permafrost degradation as a control on hydrogeological regime shifts in a warming climate. J Geophys Res Earth Surf 117 (Issue F3), 1-18. https://doi.org/10.1029/2011JF002143

Booij M, Leijnse A, Haldorsen S, Heim M, Rueslåtten H. (1998) Subpermafrost groundwater modelling in Ny-Ålesund. Nord Hydrol 29:385–396.

Brázdil R., Chmal H., Kida J., Klementowski J., Konečný, M., Pereyma J., Piasecki J., Prošek P., Sobik M., Szczepankiewicz-Szmyrka A. (eds.), 1988. Results of investigations of the Geographical Research Expedition, Spitsbergen 1985. Univerzita Purkyně, Brno: 337 pp.

Cooper R, Hodgkins R, Wadham J, Tranter M (2002) The hydrology of the proglacial zone of a High Arctic glacier (Finsterwalderbreen, Svalbard): Sub-surface water fluxes and complete water budget. J Hydrol 406:88–96.

Demidov N, Wetterich S, Verkulich S, Ekaykin A, Meyer H, Anisimov M, Shirrmeister L, Demidov V, Hodson AJ (2019) Geochemical signatures of pingo ice and its origin in Grøndalen, west Spitsbergen. The Cryosphere 13(11): 3155–3169. https://doi.org/10.5194/tc-13-3155-2019

Elvevold S, Dallmann W, Blomeier D (2007) Geology of Svalbard. Norwegian Polar Institute: Grafisk Nord AS, 37.

Førland EJ, Hanssen-Bauer I, Nordli PØ (1997) Climate statistics and long-term series of temperature and precipitation at Svalbard and Jan Mayen. Klima 21/97. Oslo, Norwegian Meteorological Institute.

Førland EJ, Hanssen-Bauer I (2003) Past and future climate variations in the Norwegian Arctic: Overview and novel analyses. Polar Res 22(2):113–124.

Førland E J, Benestad R, Hanssen-Bauer I, Haugen J E, Skaugen T E (2011) Temperature and precipitation development at Svalbard 1900–2100. Adv Meteorol 893790. https://doi.org/10.1155/2011/893790

Geological map Svalbard 1:100 000 (1991) Spitsbergen Norsk Polarinstitutt Temakart nr. 16.

Hagen JO, Lefauconnier B (1995) Reconstructed runoff from the High Arctic basin Bayelva in Svalbard based on mass balance measurements. Nord Hydrol 26:285–296.

Hagen JO, Liestøl O, Roland E, Jørgensen T (1993) Glacier atlas of Svalbard and Jan Mayen. Nor Polarinst Medd 129. Oslo, Norwegian Polar Institute

Haldorsen S, Heim M (1999) An arctic groundwater system and its dependence upon climatic change: an example from Svalbard. Permafr Periglac Process 10:137–149.

Hanssen-Bauer I, Kristensen Solås M, Steffensen EL (1990) The climate of Spitsbergen. Oslo, Norsk Meteorologiske Institutt Rapport, 39/90

Harland WB (1997) The geology of Svalbard. The Geological Society, London, ISBN 1-897799-93-4

Hjelle A (1993) The geology of Svalbard. Polarhåndbook 7. Oslo, Norwegian Polar Institute ISBN 13: 9788276660579

Hock R (2003) Temperature index melt modelling in mountain areas. J Hydrol 282:104–115, doi:10.1016/S0022-1694(03)00257-9.

Hodgkins R, Cooper R, Wadham J, Tranter M (2005) Inter-annual variability in the spatial distribution of winter accumulation at a high-Arctic glacier (Finsterwalderbreen, Svalbard), and its relationship with topography. Ann Glaciol 42:243–248.

Hodgkins R, Cooper R, Wadham J, Tranter M (2009) The hydrology of the proglacial zone of a High Arctic glacier (Finsterwalderbreen, Svalbard): atmospheric and surface water fluxes. J Hydrol 378:150–160.

Hodson A, Nowak A, Redeker K, Holmlund ES, Christiansen HH, Turchyn AV (2019) Seasonal dynamics of methane and carbon dioxide evasion from an open system pingo: Lagoon pingo, Svalbard. Front Earth Sci 7:30 https://doi.org/10.3389/feart.2019.00030

Hodson A, Nowak A, Senger K, Redeker K, Christanses HH, Jessen S, Hornum T, Betlem P, Thornton SF, Turchyn AV, Olaussen S, Marca A (2020) Open system pingos as hotspots for sub-permafrost methane emission in Svalbard. Cryosphere Discuss. 14, 3829–3842 https://doi.org/10.5194/tc-2020-11

Hodson A, Tranter M, Gurnell A. Clark M, Hagen JO (2002) The hydrochemistry of Bayelva, a High Arctic proglacial stream in Svalbard. J Hydrol 257:91114

Humlum O, Instanes A, Sollid JL (2003) Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. Pol Res 22(2):191–215.

Huss M, Hock R (2018) Global-scale hydrological response to future glacier mass loss. Nat Clim Change Lett 8:135–140. doi: 10.1038/s41558-017-0049-x

Ignatiuk D, Migała K (2013) Werenskiold glacier. In: Zwolinski Z, Kostrzewski A, Pulina M (eds) Ancient and modern geoecosystems of Spitsbergen. Poznan, Poland: Association of Polish Geomorphologists, 96–99.

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds) In press

Jaedicke C, Kern MA, Gauer P, Baillifard MA, Platzer K (2008) Chute experiments on slushflow dynamics. Cold Reg Sci Technol 51(2–3):156–167. https:doi.org/10.1016/j.coldregions.2007.03.011

Killie MA, Aaboe S, Isaksen K, Van Pelt W, Pedersen ÅØ, Luks B (2021) Svalbard snow and sea-ice cover: comparing satellite data, on-site measurements, and modelling results In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard. Integrated Arctic Earth Observing System, Longyearbyen, pp 220-235. https://doi.org/10.5281/zenodo.4293804

Killingtveit Å, Pettersson LE, Sand K (1994) Water balance studies at Spitsbergen, Svalbard. In: Sand K, Killingtveit Å (eds) Proceedings of the 10th International Northern Research Basins Symposium and Workshop, Norway. SINTEF Rep. 22 A96415. Trondheim, Norwegian Institute of Technology, 77-94

Killingtveit Å, Pettersson LE, Sand K (2003) Water balance investigations in Svalbard. Polar Res 22:161174

King MD, Howat IM, Candela SG, Noh MJ, Jeong S, Noel MR, van den Broeke MR, Wouters B, Negrete A (2020) Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. Commun Earth Environ 1:1. https://doi.org/10.1038/s43247-020-0001-2

Lecher A (2017) Groundwater discharge in the Arctic: A review of studies and implications for biogeochemistry. Hydrology 4:41. https://doi.org/10.3390/hydrology4030041

Lewkowicz AG, Way RG (2019) Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nature Comm 10:1329. https://doi.org/10.1038/s41467-019-09314-7

Majchrowska E, Ignatiuk D, Jania J, Marszałek H, Wasik M (2015) Seasonal and interannual variability in runoff from the Werenskioldbreen catchment, Spitsbergen. Pol Polar Res 36:197–224.

Malnes E, Vickers H, Karlsen SR, Saloranta T, Killie MA, Van Pelt W, Pohjola V, Zhang J, Stendardi L, Notarnicola C (2021) Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 202-219. https://doi.org/10.5281/zenodo.4294072

NCCS 2019 Hanssen-Bauer I E, Førland J, Hisdal H, Mayer S, Sandø AB, Sorteberg A. (eds), 2019. Climate in Svalbard 2100 - A knowledge base for climate adaptation. Rapport 1/2019, Norwegian Environment Agency (Miljødirektoratet). ISSN 2387-3027

Nordli Ø, Przybylak R, Ogilvie, AE, Isaksen K 2014. Long-term temperature trends and variability on Spitsbergen: The extended Svalbard airport temperature series, 1898–2012. Polar Res 33:21349, https://doi.org/10.3402/polar.v33.21349

Nowak-Zwierz A (2013) Hydrological and biogeochemical response of a High Arctic glacierised catchment to climate change. A long-term study from Bayelva watershed, Svalbard. PhD thesis, University of Sheffield. UK

Nowak A, Hodson A (2013) Hydrological response of a High Arctic catchment to changing climate over the past 35 years: a case study of Bayelva watershed, Svalbard. Polar Res 2013(32):19691. https://doi.org/10.3402/polar.v32i0.19691

Nowak A, Hodson A (2014) Changes in meltwater chemistry over a 20-year period following a thermal regime switch from polythermal to cold-based glaciation at Austre Brøggerbreen, Svalbard. Polar Res 33:1. https://doi.org/10.3402/polar.v33.22779

Orvin AK (1934) Geology of the Kings Bay region, Spitsbergen. Skrifter om Svalbard og Ishavet 57. Oslo, Norway's Svalbard and Arctic Ocean Survey (Norwegian Polar Institute).

Orvin AK (1944) Litt om kilder på Svalbard. Norsk Geografisk Tidsskrifft 1:16–38.

Osuch M, Wawrzyniak T (2017a) Inter- and intra-annual changes of air temperature and precipitation in western Spitsbergen. Int J Climatol 37:3082–3097. https://doi.org/10.1002/joc.4901.

Osuch M, Wawrzyniak T (2017b) Variations and changes in snow depth at meteorological stations Barentsburg and Hornsund (Spitsbergen). Ann Glaciol 58 (75), 11–20.

Osuch M, Wawrzyniak T, Nawrot A. 2019. Diagnosis of the hydrology of a small Arctic permafrost catchment using HBV conceptual rainfall-runoff model. Hydrol Res 50.2, 459–478.

Pecher K (1994) Hydrochemical analysis of spatial and temporal variations of solute composition in surface and subsurface waters of a high arctic catchment. Catena 21:305–327

Romashova KV, Chernov RA, Vasilevich II (2019) Study of the glacial flow of rivers in the Grønfjord bay basin (Western Svalbard). Arct Antarct Res 65(1):34–45. (in Russian) https://doi.org/10.30758/0555-2648-2019-65-1-34-45

Salzano R, Aalstad K, Boldrini E, Gallet JC, Kępski D, Luks B, Nilsen L, Salvatori R, Westermann S (2021 a) Terrestrial photography applications on snow cover in Svalbard. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-251. https://doi.org/10.5281/zenodo.4294084

Schuler TV, Kohler J, Elagina N, Hagen JOM, Hodson AJ, Jania JA, Kääb AM, Luks B, Małecki J, Moholdt G, Pohjola VA, Sobota I, Van Pelt WJJ (2020) Reconciling Svalbard glacier mass balance. Front Earth Sci 8:156. https://doi.org/10.3389/feart.2020.00156

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389. https://doi.org/10.2307/2285891.

Retelle M, Christiansen HH, Hodson A, Nikulina A, Osuch M, Poleshuk K, Romashova K, Roof S, Rouyet L, Strand SM, Vasilevich I, Wawrzyniak T (2020) Environmental Monitoring in the Kapp-Line- Grønfjorden region. In: Van den Heuvel et al (eds) SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 84-107. https://sios-svalbard.org/SESS_Issue2

Sobota I, Nowak M, Weckwerth P, 2016. Long-term changes of glaciers in northwestern Spitsbergen. Glob Planet Change 144:182–197.

Sobota I, Araźny A, Barcikowski A, Birkenmajer K, Grześ M, Gugnacka-Fiedor W, Lankauf RK, Plichta W, Przybylak J, Zubel P (2013) Geographical environment in the vicinity of the Nicolaus Copernicus University Polar Station – Kaffiøyra. In: Zwoliński Z, Kostrzewski A, Pulina M (eds.). Dawne i współczesne geoekosystemy Spitsbergenu: polskie badania geomorfologiczne = Ancient and modern geoecosystems of Spitsbergen: Polish geomorphological research. Bogucki Wydawnictwo Naukowe, Poznań:181–204.

Stäblein G (1971) Der polare Permafrost und die Auftauschicht in Svalbard. Polarforschung 41:112–120.

Skakun AA, Chikhachev KB, Ekaykin AA, Kozachek AV, Vladimirova DO, Veres AN, Verkulich SR, Sidorova OR, Demidov NE (2020) Stable isotopic composition of atmospheric precipitation and natural waters in the vicinity of Barentsburg (Svalbard). Ice and Snow 60(3):379–394. (In Russian). https://doi.org/10.31857/S2076673420030046

Sidorova OR, Tarasov GV, Verkulich SR, Chernov RA (2019) Surface ablation variability of mountain glaciers of West Spitsbergen. Arct Antarct Res 65(4):438–448. https://doi.org/10.30758/0555-2648-2019-65-4-438-448

Sund M (2008) Polar hydrology. Norwegian water resources and Energy Directorate's work in Svalbard. NVE Report 2. Oslo, Norwegian Water Resources and Energy Directorate.

Szafraniec E, Dobinski W (2020) Deglaciation rate of selected nunataks in Spitsbergen, Svalbard – Potential for permafrost expansion above the glacial environment. Geosciences 10(5):202. https://doi.org/10.3390/geosciences10050202

Terekhov AV, Tarasov GV, Sidorova OR, Demidov VE Anisimov MA, Verkulich SR (2020) Estimation of mass balance of Aldegondabreen (Spitsbergen) in 2015–2018 based on ArcticDEM, geodetic and glaciological measurements. Ice and Snow 60(2):192–200. https://doi.org/10.31857/S2076673420020003

Van Pelt W, Pohjola V, Pettersson R, Marchenko S, Kohler J, Luks B, Hagen JO, Schuler T, Dunse T, Noel B, Reijmer C (2019) A long-term dataset of climatic mass balance, snow conditions, and runoff in Svalbard (1957–2018). The Cryosphere, 13, 2259–2280. https://doi.org/10.5194/tc-13-2259-2019

Vikhamar-Schuler D, Isaksen K, Haugen JE, Tømmervik H, Luks B, Schuler TV, Bjerke JW (2016) Changes in winter warming events in the Nordic Arctic region. J Climat 29:6223–6244. https://doi.org/10.1175/JCLI-D-15-0763.1

Verkulich S, Zazovskaya E, Pushina Z, Savelieva L, Soloveva D, Demidov N, Shishkov V, Dercon G (2018) The postglacial environmental changes in vicinity of the Barentsburg settlement (West Spitsbergen). EGU General Assembly, Vienna, Austria, 8-13 April 2018. EGU 2018-7729.

Vtyurin B I (1994) The contemporary periglacial environment in the polar regions. Polar Geogr 18(1):44-62. https://doi.org/10.1080/10889379409377530

Wawrzyniak T, Osuch M, Nawrot A, Napiórkowski JJ (2017) Run-off modelling in an Arctic unglaciated catchment (Fuglebekken, Spitsbergen). Ann Glaciol doi: 10.1017/aog.2017.8.

Wawrzyniak T, Osuch M (2020) 40 years High Arctic climatological dataset of the Polish Polar Station Hornsund (SW Spitsbergen, Svalbard). Earth Syst Sci Data 12:805–815, https://doi.org/10.5194/essd-12-805-2020

Woo M-K (2012) Permafrost hydrology. Springer, Berlin, Heidelberg. ISBN: 978-3-642-23461-3. https://doi.org/10.1007/978-3-642-23462-0

Ødegård RS, Hagen JO, Hamran S (1997) Comparison of radio echosounding (30 MHz–1000 MHz) and high-resolution borehole temperature measurements at Finsterwalderbreen, southern Spitsbergen, Svalbard. Ann Glaciol 24:262–267.

Appendix 1

Description of sites where hydrological monitoring is taking place on long-term or semi long–term basis. See Figure 1 for locations.

Site	Site description	Hydrological regime	Institute performing monitoring
Hornsund - Fuglebeken	A deglaciated catchment with an area of 1.27 km^2. Heterogenous land cover and topography. Elevation range 4–522 m a.s.l. Slopes covered with washed rubble sediments, solifluction tongues, rock streams, alluvial cones and bare solid rock of Hecla Hoek geological formation (Harland 1997). Below the slopes, marine terraces covered with sea gravel are covered by diverse tundra vegetation. Close to the eastern boundary of the catchment is the lateral moraine of Hansbreen. The ground has a continuous permafrost layer down to more than 100 m depth (Humlum et al. 2003). Mean annual air temp: −3.7 °C (1979–2019), the warmest month: July (avg. 4.6 °C); the coldest month: March (avg. −10.2 °C). The highest air temperature recorded: 16.5 °C on 25th July 2020. Mean annual precipitation: 463 mm. Snow cover is present approx. 250 days/year. Snow depth 0.3-2.0 m (Wawrzyniak and Osuch 2020).	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	Institute of Geophysics, Polish Academy of Science, Poland
Nottinghambukta - Werenskioldbreen	Werenskioldbreen is a land-terminating valley-type polythermal glacier situated in the Wedel-Jarlsberg Land. The glacier has a catchment area of 44.1 km^2 (glacierised in 61%). Maximum elevation of the firn field is 650 m a.s.l., (Ignatiuk and Migała 2013). Outflows from the Werenskioldbreen take the form of karst springs, geysers and a type Röthlisberberger (R) subglacial outflow channel. The main outflow, located in the northern part of the glacier, originates in an ice gate and creates the Kvislaelva (~80% of the total water yield). In the proglacial zone, tributary rivers originating from the glacier front join and form Breelva, which drains into the Greenland Sea. The average annual runoff is approx. 80±14x10^6 m^3, which is equivalent to an 1800 mm layer of water from the catchment surface (Majchrowska et al. 2015).	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	University of Silesia and University of Wrocław, Poland
Van Keulenfjorden - Finsterwalderbreen	Finsterwalderbreen, is located at 77° 31' N, 15° 19' E on the southern shore of Van Keulenfjorden, southern Spitsbergen. The glacier itself is 12 km long, north facing and flows to the coast from a maximum elevation of 1065 m a.s.l. It is up to 200 m thick, and has a polythermal temperature structure, with a 25–170 m thick cold surface layer, a warm firn accumulation zone and a bed that is mostly temperate, apart from limited areas at the margins (Ødegård et al. 1997). The catchment is mostly devoid of vegetation, except above the most recent glacial trimline and on terminal moraines delimiting the proglacial zone, where a sparse Arctic flora survives. The bedrock geology is diverse, comprising Precambrian basement and Carboniferous through Cretaceous sedimentary units (Hjelle 1993). The mean annual air temperature at 35 m a.s.l. is -3.9 °C, and mean monthly air temperatures are only positive during the summer, although even then they remain <6.0 °C; annual precipitation is in the 180–440 mm w.e. range, with the bulk being delivered as snow during the winter months (Hanssen-Bauer et al. 1990).	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	Loughborough University, The United Kingdom

Grønfjorden - Grøndalselva	Glacierised catchment with an area of 98 km^2, (glacier area–7.4 km^2). Elevation range 0–840 m a.s.l. Grøndalen is a trough valley with the main river Grøndalselva, which has 23.5 km. The river has a flat wide valley. Cretaceous deposits protrude on the surface in the delta part of the river. A group of seven large pingos have developed in the central part of the valley (Demidov et al. 2019). Grøndalselva is fed by many tributaries, which collect meltwater discharge from small hanging glaciers. Two larger glaciers, Tavlebreen and Passfjellbreen, as well as their terminal moraines lie in the upper valley part. Glacier runoff made up to 24% of total river discharge in 2017–2018 (Romashova et al. 2019). The permafrost thickness exceeds 100 m (Demidov et al. 2019). Snow cover height (2002–2019) 10–194 cm (mean 58 cm). 50% of total annual runoff falls in June.	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt, groundwater	The Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia
Grønfjorden - Aldegondabreen	Glacierised catchment with an area of 9.4 km^2, (glacier area–5.7 km^2). River length–2.6 km. Elevation range 0–720 m. Over the last decades, Aldegondabreen lost more than a half of its ice volume. (Terekhov et al. 2020). Average annual ablation rate on Aldegondabreen was 1.947 m w. e. (or 10.2 million m^3) in 2016–2018 (Sidorova et al. 2019), which comprised 47% of the water discharge of the river (Romashova et al. 2019). The drainage system of the Aldegondabreen consists of three tributaries. The streams form a braided system in the moraine area and merge into Aldegondaelva, discharging into Grønfjorden. The river flows through a valley formed by moraine deposits and sandstones with coal seams, shales and some limestones (Elvevold et al. 2007). A small delta with unstable position is formed by the deposited sediments. There are several small lakes (less than 100 m^2) in the catchment area formed by the icemelt groundwater (Romashova et al. 2019). Snow depth on the glacier (2002–2019) was 78–238 cm (mean 157 cm). 30% of annual runoff falls in July.	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	
Grønfjorden - Kongresselva	Non-glacierised catchment area 10.5 km^2. River length–3.9 km. Elevation range 0–500m. The river flows out of the karst lake Kongress. The catchment area is composed of ancient metamorphosed and sedimentary rocks of the Precambrian, Upper Paleozoic and Mesozoic ages. Ice-wedged polygons and rock streams are common features of the hill slopes in the valley, while the vegetation is sparse on the slopes of bare rock or rocks covered by algae and lichen crusts and develops mostly in depressions. Several tributaries fed by precipitation and underground water contribute to the river flow (Skakun et al. 2020). Snow depth (2016–2019) 10 cm–196 cm (mean 66 cm). 30% of annual runoff falls in June.	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	
Adventfjorden - Adventdalen	Partially glacierised catchment with an area of 500 km^2. Elevation range 0–1130m a.s.l. Adventdalen is a large U-shaped valley approx. 30 km long and approx. 4 km wide. The main river flowing through it, Adventelva, is extremely braided and flows into Adventfjorden that then connects to Isfjorden. Adventelva collects runoff from several glacierised valleys with different types of thermal regime. Glacially derived freshwater carries a high sediment load. Some of the sediment is also deposited at the valley bottom, creating a fluvially active region. During winter, the river freezes to the bottom, and the valley is covered in a thin layer of snow due to prevailing strong easterly winds. The area is underlain by a continuous permafrost ranging from 100 m to 500 m (Humlum et al. 2003). The valley also contains alluvial fans, extensive aeolian deposits in the central part of the valley, marine terraces, pingos (both open and closed system) and rock glaciers. The geomorphology around the valley is dominated by mountain plateaus covered in extensive blockfields and ice wedge polygons and other periglacial features in the valley bottom. The bedrock geology of the catchment mainly consists of sedimentary rocks, while the unconsolidated sediments are dominated by different slope deposits and glacio-fluvial deposits (personal communication with L Rubensdotter).	Restricted to melt season only (usually May–October). Snowmelt, rainfall, ground ice melt	The University Centre in Svalbard (UNIS), Department of Arctic Geology, Norway
Sassenfjorden – De Geerdalen	Glacierized catchment, area–79.1 km^2, of which 10% is glacier covered. Includes several glaciers. The monitoring station is located in a narrow gorge in part of a waterfall with a stable rock profile. Meteorological measurements were carried out for a few years in the early 1990's as part of the first water balance studies used to estimate precipitation-elevation gradients (Killingtveit et al. 1994)	Restricted to melt season only (usually May–October). Snowmelt, rainfall, ground ice melt	The Norwegian Water Resources and Energy Directorate (NVE), Norway

Petuniabukta	Small scale catchments with different level of glacier cover from 0 to approx. 60%. Elevation ranges from 0 to 935 m a.s.l. The highest point is the Pyramiden mountain. The region is characterised by rather continental climate with low winter temperatures and high summer temperatures and generally low precipitation (around 400 mm per year). Local climate is also affected by long duration of sea ice (usually November–June). This has resulted in low level of glacier coverage, especially in the western part (Dickson land), where even large catchments do not have glaciers.	Restricted to melt season only (usually May–October). Snowmelt, rainfall, ground ice melt	The Polar Geo-Lab, Masaryk University, Czech Republic and Adam Mickiewicz University, Poland
Kaffiøyra - Waldemarbreen	A glacierised catchment, area approx. 16km^2, 16% of which is occupied by a polythermal valley glacier Waldemarbreen. Elevation range 0–770 m a.s.l. In the north and east, it borders the Prins Heinrichfjella ridge (500–770 m a.s.l.) and in the south Gråfjellet (300–350 m). The hydrological network in the region consists of multiple glacier-fed braided rivers covering up to 40 km^2. The monitoring station on Waldemarelva (approx. 5.5 km long) is in the upper section of the river, close to the moraines, where the water flows onto the outwash plain. Between 1997 and 2019, the average discharge was 0.9 m^3/s and ranged from 0.5 to 1.4 m^3/s. Waldemarbreen consists of two distinct parts, separated by a medial moraine. It is approximately 1 km long and 600 m wide with an area of 2.4 km^2. The mean annual mass balance of Waldemarbreen in 1996–2019 was -0.84 m w.e. The only positive year was 1996 (+0.02 m w.e.). From the time of the maximum advance, Waldemarbreen decreased by c. 35% (Sobota et al. 2013)	Restricted to melt season only (usually May–October). Glacier melt, Snowmelt, Rainfall, Ground ice melt	The Nicolaus Copernicus University in Torun, Faculty of Earth Sciences and Spatial Management, Polar Research Center, Poland
Kongsfjorden-Bayelva	A glacierised catchment, area–approx.32 km^2, 50% of which is occupied by cold-based valley glaciers. Elevation range 4–742 m a.s.l. The southern and eastern part of the watershed is underlain by red sandstones, quartzite and phyllite, while the northern and western areas are underlain by sedimentary rocks, such as sandstone, shale, dolomite and limestone (Orvin 1934; Hjelle 1993). The area of the catchment is almost entirely underlain by permafrost with a seasonal active layer measuring from 0.5 to 1.5 m (Killingtveit 2004).	Restricted to melt season only (usually May–October). Glacier melt, Snowmelt, Rainfall, Ground ice melt	The Norwegian Water Resources and Energy Directorate (NVE), Norway
Kongsfjorden-Londonelva	A small de-glacierised catchment, area–0.7 km^2, located on Blomstrandøya (a small island in Kongsfjorden) The elevation ranges from 15 to 149 m a.s.l. It is the only catchment under long-term monitoring that is entirely underlain by carbonate rocks (karst).	Restricted to melt season only (usually May–October). Snowmelt rainfall, ground ice melt	

Appendix 2

Data Sources

Dataset	Parameters	Period	Location or area	Metadata / Data access (URL, doi)	Data provider, reference
1.Meteorological 2. Hydrological	1. Mean daily air temperature, daily sum of precipitation and PET 2. Water discharge	1. 1979–2019 2. 2014–2019 (measured)	Hornsund	SIOS data access portal: https://bit.ly/3mn1WAI SIOS data access portal: https://bit.ly/2Kw49fV	IG PAS, Tomasz Wawrzyniak tomasz@igf.edu.pl
Hydro-meteorological	Mean daily air temperature, daily sum of precipitation and mean daily flow	1970–1974, 1979, 1980, 1983, 1986, 1988, 1998, 2007–2013, 2017–2020	Nottinghambukta (Werenskioldbreen)	Polish Polar DataBase of the Centre for Polar Studies, University of Silesia, http://ppdb.us.edu.pl/geonetwork/ SIOS data access portal: https://bit.ly/2KA2dTJ	University of Silesia, Centre for Polar Studies, Poland, Elżbieta Łepkowska elzbieta.majchrowska@us.edu.pl
Hydro-meteorological	Winter balance, summer balance, air temperature, relative humidity, wind speed, global and net radiation, precipitation, runoff and flow and hydraulic head in proglacial subsurface	1999–2000	Van Keulenfjorden	SIOS data access portal: https://bit.ly/37c0AU7	Richard Hodgkins, Loughborough University, United Kingdom r.hodgkins@lboro.ac.uk
Hydrological model	Flow-recession analyses and linear-reservoir simulation of runoff time series	1999–2000	Van Keulenfjorden	SIOS data access portal: https://bit.ly/2KKDgFn	Richard Hodgkins, Loughborough University, United Kingdom r.hodgkins@lboro.ac.uk
Hydrological	Mean snow cover depth, density of the snow cover, snow water equivalent, mean daily discharge, and chemical composition	2002–2019	Grønfjorden	Submitted to the PANGAEA repository	Arctic and Antarctic Research Institute, Russia Rae-s@aari.ru, hydrology2@aari.ru
Hydrological model and meteorological data	1 Water discharge 2.Air temperature and precipitation 3. Active layer temp. 4. Permafrost temp.	1. 1991–2019 2.1989–ongoing 3. 2000–ongoing 4. 2008–ongoing	Adventdalen	1. Metadata will be made available in the SIOS data portal in Q1 of 2021 2. Adventdalen: SIOS data access portal: https://bit.ly/37gFLb4 Svalbard Airport https://www.eklima.met.no 3. https://www2.gwu.edu/~calm/data/north.htm 4. http://gtnpdatabase.org/boreholes and https://geo.ngu.no/kart/permafrost_svalbard/	Hydrological data: Aga Nowak, the University Centre in Svalbard aga.nowak@unis.no Active layer: CALM Permafrost: Global Terrestrial Network for Permafrost (GTN-P)

Dataset	Parameters	Period	Location or area	Metadata / Data access (URL, doi)	Data provider, reference
Hydrological	Water discharge	1.1992–ongoing 2.1991–ongoing	1.Londonelva 2.De Geerdalen	Personal communication	The Norwegian Water Resources and Energy Directorate
Hydrological	Daily discharge	1. 2011–2014 2. 2001–2014	Petuniabukta	1. SIOS data access portal: https://bit.ly/2KLZ5V5 2. Personal communication	1. Polar Geo-Lab, Masaryk University,Czech Republic 2. Adam Mickiewicz University, Poznan, Poland
Hydrological and meteorological	1. Meteorological conditions 2. Glacier mass balance (part of WGMS) 3. Water discharge 4. Permafrost and active layer thickness (part of CALM program)	1.1975–ongoing 2.1996–ongoing 3.1970's (sporadic), 1996–ongoing 4.1996–ongoing	Kaffiøyra	1. Personal communication 2. https://wgms.ch/data_exploration/ 3. Personal communication 4. https://www2.gwu.edu/~calm/data/north.htm	The Polar Research Center, Nicolaus Copernicus University, Ireneusz Sobota irso@umk.pl CALM
Hydrological	1. Glaciological 2. Hydrological 3. Water temp. 4. Conductivity: 5. Sediments	1.1963–ongoing 2.1974–1978, 1989–ongoing 3.1991–ongoing 4.2004–ongoing 5.1989–ongoing	Bayelva	1. https://data.npolar.no/dataset/ad6c4c5a-e926-11e2-b06b-005056ad0004 2-5. Personal communication	1. The Norwegian Polar Institute 2-5. The Norwegian Water Resources and Energy Directorate
Meteorological	Mean daily air temperature and precipitation	1967–ongoing	Kongsfjorden Svalbard Airport	https:/www.eklima.met.no	The Norwegian Meteorological Institute