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Role of discrete recharge from the supraglacial drainage system for modelling of subglacial conduits pattern of Svalbard polythermal glaciers

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Abstract. Being a determinant factor of the glacier's dynamic, subglacial water behavior needs a special attention. Water flowing from the glacier's surface is the principal source supplying the subglacial drainage system. Therefore, insight into the state and evolution of the supraglacial drainage system is crucial for recognition of recharge pattern of the englacial and subglacial drainage pathways. Climate warming causes increased ablation generating higher amount of meltwater and thinning of glacier. Decadal timescale evolution of the supraglacial drainage leads to some modifications of the system in opposition to its nearly stable state on an annual timescale. For two studied glaciers Hansbreen and Werenskioldbreen in southern Svalbard surface meltwater is the main runoff component. During the ablation season 2015, 72.5 % of the total amount was provided by meltwater and 27.5 % by precipitations. Supraglacial catchments were determined on the high resolution digital elevation model using standard watershed modelling tool in ArcGIS, for each water-input area (WIA). Spatialized water runoff calculations for all the main WIAs have been done. Having data on the water sources from catchments delimited on glacier's surface, modelling of a theoretical pattern of subglacial conduits was done considering discrete water recharge via moulins, shear fractures or crevasses. Classical modelling with an assumption of homogeneous water supply was done for comparison. Several water pressure conditions have been taken into account as well. Results show that models of subglacial drainage system with homogeneous water recharge are more realistic for tidewater glaciers with rather broad permeable firn areas and creased frontal zones, while discrete water recharge models are better for land-terminating glaciers with almost continuous impermeable superficial cold ice layer. Subglacial channel models are assumed to be valid for a minimum period of two decades taking into account evolution of supraglacial drainage system and ice thickness changes of Svalbard polythermal glaciers.

Copyright statement.

1 Introduction

In the context of global climate change and, in particular, rapid melting of glaciers around the world, it is important to understand the evolution of their meltwater drainage system and its consequences on glaciers behavior. Due to its direct impact on englacial and subglacial drainage system, supraglacial drainage system studies are the first crucial step. It allows to locate where the supraglacial system switches into an englacial and then subglacial system via moulins, shear fractures or crevasses and to better estimate their water supply. Indeed, concentrated surface water streams are necessary for the formation of a channelized internal drainage system (Mavlyudov, 2006). Moreover, in addition of being an important source of water for the internal drainage system of glaciers, a part of englacial conduits are formed by direct incision of supraglacial channels followed by creep closure (Gulley et al., 2009; Irvine-Fynn et al., 2011) (Gulley et al., 2009; Irvine-Fynn et al., 2011). However, it remains one of the least-studied hydrologic processes on Earth.

Our study focus on the land-terminating glacier Werenskioldbreen and the tidewater glacier Hansbreen, representative of many Svalbard glaciers, both located in the southern part of the Svalbard archipelago (Fig.1). It is even more important to focus on the hydrological system of Arctic glaciers nowadays, having in mind predictions of the Intergovernmental Panel on Climate Change (IPCC) suggesting longer summer (Pachauri et al., 2014) seasons and also knowing that Svalbard glaciers are shrinking since several decades (Błaszczyk et al., 2013; Hagen et al., 2003b). In fact, all prognosis suggest an increase in runoff (meltwater and precipitations) of Arctic glaciers, ice caps and ice sheets which suggests an intensification of their whole drainage system and therefore of their dynamics and impact on sea-level rise (Hagen et al., 2003a; Hanna et al., 2008; Mair et al., 2002; Nuth et al., 2010; Sundal, 2011).

The first step of our study consists in the recognition of supraglacial drainage features of our two study glaciers by using Very High Resolution Satellite (VHRS) and aerial remote sensing images combined with field observations, for the years 1990, 2010, 2011 and 2015. During this period changes in glacier's geometry have been observed (Gajek et al., 2009; Ignatiuk et al., 2014). Supraglacial hydrology of glaciers directly depends on the surface topography (Grabiec et al., 2012; Nienow and Hubbard, 2006). Therefore, it is expected to observe an evolution of the supraglacial drainage system on this decadal timescale giving us the opportunity to better understand the physical mechanisms controlling it. Mapping the supraglacial drainage system allows us to locate where water is flowing inside the glaciers via moulins and crevasses (Benn et al., 2017, 2009; Holmlund, 1988; Nienow and Hubbard, 2006; Van der Veen, 2007). Those WIAs represent the water recharge points of the englacial and, (with a high probability) by extension, of the subglacial drainage system (Bartholomew et al., 2011; Benn et al., 2017).

This leads to the second step of our study, which consists in catchment areas' calculation of all the main WIA of the two glaciers for the year 2015. In order to quantify dedicated amount of water for each WIA, we calculated the total amount of surface water (precipitations and meltwater) of the whole glaciers' surfaces together with their surrounding slopes with a spatial resolution of 100 meters, for the entire ablation season 2015. It allows us to visualize how subglacial water recharge coming from the glacier's surface is distributed, having absolute water volume values in cubic meter, and the outflows' weight on the system. Besides, we are also able to discuss about precipitations and meltwater implications in the subglacial drainage system.

The final step of our study aims to improve the actual way of modelling the theoretical pattern of subglacial channels, more specifically last subglacial conducts models realized by Pälli et al. (2003) and Grabiec et al. (2017) on our two studied glaciers, which are exclusively based on the hydrological potential theory (Fischer et al., 2005; Flowers and Clarke, 2002; Sharp et al., 1993; Shreve, 1972). In fact, current subglacial models are based on important assumptions which lead to inaccurate modelled subglacial channels locations. One of the biggest assumption used asserts, water recharge into glacier is spatially and temporally uniform (Gulley et al., 2012). Thus contrasting model's results with homogeneous and discrete water recharge will allow us to better understand the influence of this parameter. Moreover, we are discussing about the different water pressure conditions existing in a subglacial drainage system. That is why our model considers:

(i) thermal structure and surface properties of the glacier, and so location of runoff and water percolation areas;

(ii) drainage catchment structure of the glacier regarding WIA, and so the runoff volumes following particular drainage pathways;

(iii) water volume (meltwater plus precipitations) input to the system for the entire ablation season;

(iv) several water pressure scenarios within the channels, essential to illustrate distinct periods of the melt season;

(v) presumed location of main subglacial channels, giving a fundamental knowledge for modelling meltwater discharge.

In theory, subglacial drainage system of glaciers involves distributed and channelized system (Kessler and Anderson, 2004). Because most of the subglacial water transport occurs in the conduits, sustained by the balance between creep closure effect and melting due to heat released by water flux (Hewitt, 2011; Nye, 1953; Röthlisberger, 1972), we are not considering the distributed part of the subglacial drainage system; we only focus on the channelized component. Also, seeing bedrock topography as constant through the years, glacier's surface geometry as a slow changing process (several years) and knowing that those two parameters largely control the equilibrium drainage structure of the glacier (Fischer et al., 2005; Flowers and Clarke, 2002), we can consider our subglacial channels modelled valid for several years.

2 Study area

This study is focus on two polythermal Svalbard glaciers. They have been chosen because they represent the main types of polythermal glacier in Svalbard. Werenskioldbreen is a land-terminating glacier and Hansbreen a tidewater one. Thus both of them are characterized by two different dynamics which directly impact the evolution of the surface topography and drainage system. Werenskioldbreen, located in the south-west Spitsbergen (77°05' N, 15°15' E) (Fig.1), is flowing from east to west with an average speed less than 10 m yr^{-1} in two parallel flows divided by a central moraine (Baranowski, 1970). It is considered as a quite small Svalbard glacier of 6.5 km long, 2.2 km wide, with a surface of 27.1 km^2 located between 40 and 650 m a.s.l (Ignatiuk et al., 2014; Majchrowska et al., 2015). It has a maximum thickness of about 275 m and a cold ice snout less than 50 m thick frozen to the bedrock up to 700 m upstream from the front line (Navarro et al., 2014; Pälli et al., 2003). Its entire surface composed by cold ice (below the pressure melting point) overlying on a temperate ice layer (at the pressure melting point) (Fig.1(a)) (Grabiec et al., 2017), allows the presence of a well-developed supraglacial drainage system. Hansbreen, located at the entrance of Hornsund (77°04' N, 15°38' E) (Fig.1), is flowing from north to south with a velocity of c. 150 m yr^{-1} at the front and of 55-70 m yr^{-1} 3.7 km upstream (Błaszczyk et al., 2009). Situated between 0-664 m a.s.l, it is considered as a medium size Svalbard glacier of 15.6 km long, c. 2.5 km wide in average and an area of 53 km^2. Its terminus forms c. 30 m heigh cliff of 1.9 km wide ending directly into the sea (Błaszczyk et al., 2009). It has 171 m of mean ice thickness with a maximum ice thickness of 386 m (Grabiec et al., 2012). In the accumulation area temperate ice and firn are present, allowing water percolation through the glacier body while the structure of the ablation area is similar to Werenskioldbreen with a cold ice layer overlying temperate ice (Fig.1(b)) (Grabiec et al., 2017; Navarro et al., 2014), preventing a disperse infiltration of the water directly inside the glacier.

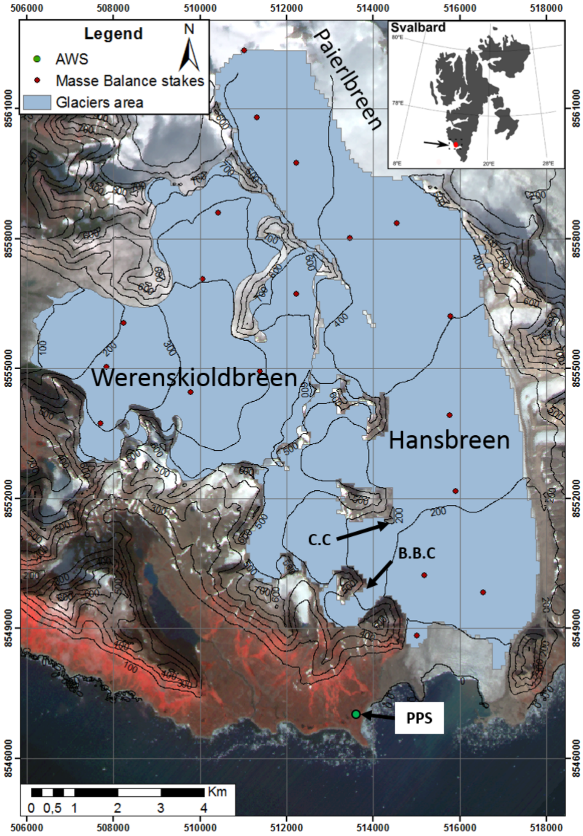

Figure 1. Location map of Hansbreen and Werenskioldbreen, Svalbard, showing location of Automatic Weather station (AWS), Polish Polar Station (PPS), Mass balance stakes network, Crystal Cave (C.C) and Bird Brain Cave (B.B.C). Map's background is the SPOT satellite image acquired on 16/08/1988 and the coordinate system used is WGS 1984 UTM zone 33N.

Those two glaciers are characterized by the most common Svalbard polythermal structure which implies that the majority of the bare ice surface is composed by cold ice (Fig.2) (Grabiec et al., 2017; Navarro et al., 2014; Pälli et al., 2003). Thus the superficial part is composed by an impermeable layer which results to the development of a well channelized dendritic supraglacial drainage system (Irvine-Fynn et al., 2011).

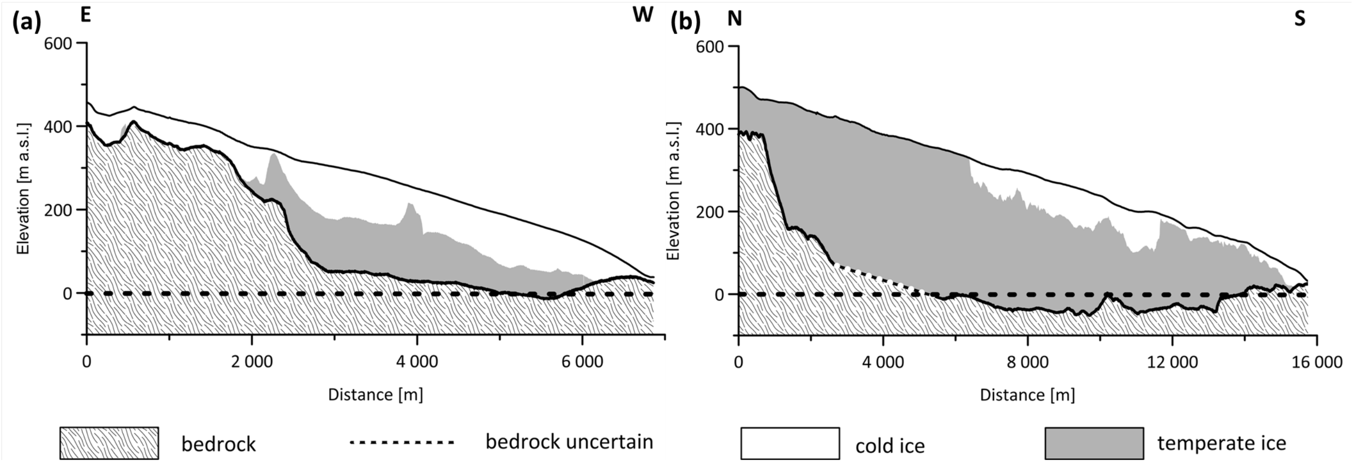

Figure 2. Thermal structure of Werenskioldbreen (a) and Hansbreen (b) after (Grabiec et al., 2017).

3 Methods and dataset

3.1 Dataset

Polar glaciers are large and located in remote areas, so it is difficult or even impossible to be able to locate all the supraglacial hydrological features existing on their surfaces without remote sensing data. Compare to Greenland drainage elements, the ones on Svalbard glaciers are quite small, it is therefore essential to use very high resolution images to be able to distinguish them. For some years it can be difficult to obtain reliable data. Because we have to use optical images, they should be acquired during a cloud free period. Moreover they have to be generated at about the end of the ablation season when most of the glacier's surfaces are snow free and the hydrological system is well developed. During this study we used VHRS images of 0.5 m resolution from WorldView-2 satellite acquired on 21/08/2015 and from Geoeye satellite taken on 10/08/2010. We also worked with sets of Norwegian Polar Institute (NPI) aerial photos from 1990 and 2011. In addition to remote sensing data, field observations and Global Positioning System (GPS) survey, in order to mark control points, have been necessary to calibrate our mapping. Maps of the supraglacial drainage system already exist for Werenskioldbreen in 1990 and 2010 (Ignatiuk, 2012; Pulina et al., 1999). Bedrock Digital Elevation Model (DEM) of Hansbreen and Werenskioldbreen, with a spatial resolution of 100 m and a vertical resolution estimated at +/−5 m, were obtained during a survey mission performed in April 2008 by the University of Silesia team, combining GPS/GPR (Ground Penetrating Radar) measurements (Grabiec et al., 2012). Also we created a high resolution surface DEM of both glaciers, using VHRS images from WorldView-2 for the year 2015. Finally we used meteorological dataset, in order to calculate water volume produced by melt and precipitations, from the Automatic Weather Station (AWS) located at the Polish Polar Station (PPS) (about 1.5 km from Hansbreen front) during the melt season 2015 (Fig.1).

3.2 Supraglacial drainage mapping

Based on high resolution images, we generated several maps of the supraglacial drainage system of the two studied glaciers for different years thanks to ArcMap software. An attempt to automatize the surface stream mapping, as succeed by Yang and Smith (2013) for Greenland, using a Normalized Difference Water Index specific for the ice surface ($NDWI_{ice}$) has been done. $NDWI_{ice}$ uses normalized ratio of blue and red bands allowing the classification of each glacier pixel into either "water" or "non-water" surface. But due to the broadband reflection of ice surface and stream-water overlapping each other, it was not possible to apply this method on our two glaciers. It can be explain by several factors. First of all supraglacial streams of Svalbard glaciers are much smaller than Greenlandic ones. Then Svalbard glaciers are surrounding by mountains influencing glacier's surface conditions which is not the case for Greenland ice sheet. In fact Svalbard glacier's surfaces are “dirty”, they contain a lot of small rocks or event dust blowing away from mountain's slopes to glacier's surfaces changing reflectance properties of the surface's features into a broadband signal rather than a well separate one specific to each feature. Indeed, looking at optical satellite images, Greenlandic surface streams appear as wide blue line overlying on a clean ice surface, which is not the case for Svalbard glacier's streams. Moreover, a well developed ice foliation and shear fractures network, due to the friction with surrounding mountains and looking very similar to surface streams is present.

Thus we had to come down to map the surface streams manually, leading to personal choices and naturally to some subjective decisions. We decided to map only the active streams of about 1 meter wide minimum, knowing from field observations that numerous smaller streams are present, along with the limitation due to the spatial resolution of the VHRS images. Additionally, we manually mapped crevassed areas and moulins, with a diameter greater than 1 meter, enhance by direct field observations and GPS measurements.

3.3 WIA's catchments calculation

First of all, based on the supraglacial mapping (section3.2) we created 2015 WIA maps for both glaciers (Fig.3). WIA were defined as substantial crevasses areas or crevasses areas intersecting active surface streams, groups of active moulins and firn or temperate ice zones.

Then WorldView-2 stereo pair image from 2015 was processed with Geomatica software in order to create a surface DEM of our study area. Achieve DEM of 4 m spatial resolution was delineated for both glaciers thanks to contour files obtained from orthorectify WorldView-2 images and achieve a vertical accuracy of $+/-1.5$ m. We fill the small sinks present on the DEM, due to small imperfections occurring during the DEM creation, in order to avoid the formation of small lakes on the surface which has never been observed in the second part of the ablation season on those two glaciers. From the corrected DEM, we calculated the flow direction from each pixel to its steepest downslope neighbour.

Finally, using standard watershed modelling tool in ArcGIS, we determined the catchment area of each WIA with a 4 m spatial resolution (Fig.3). Some manual adjustments of the catchments delineation have been realized, when necessary. The most common correction was to extend the catchment areas where an active stream ending in a WIA was not included into it.

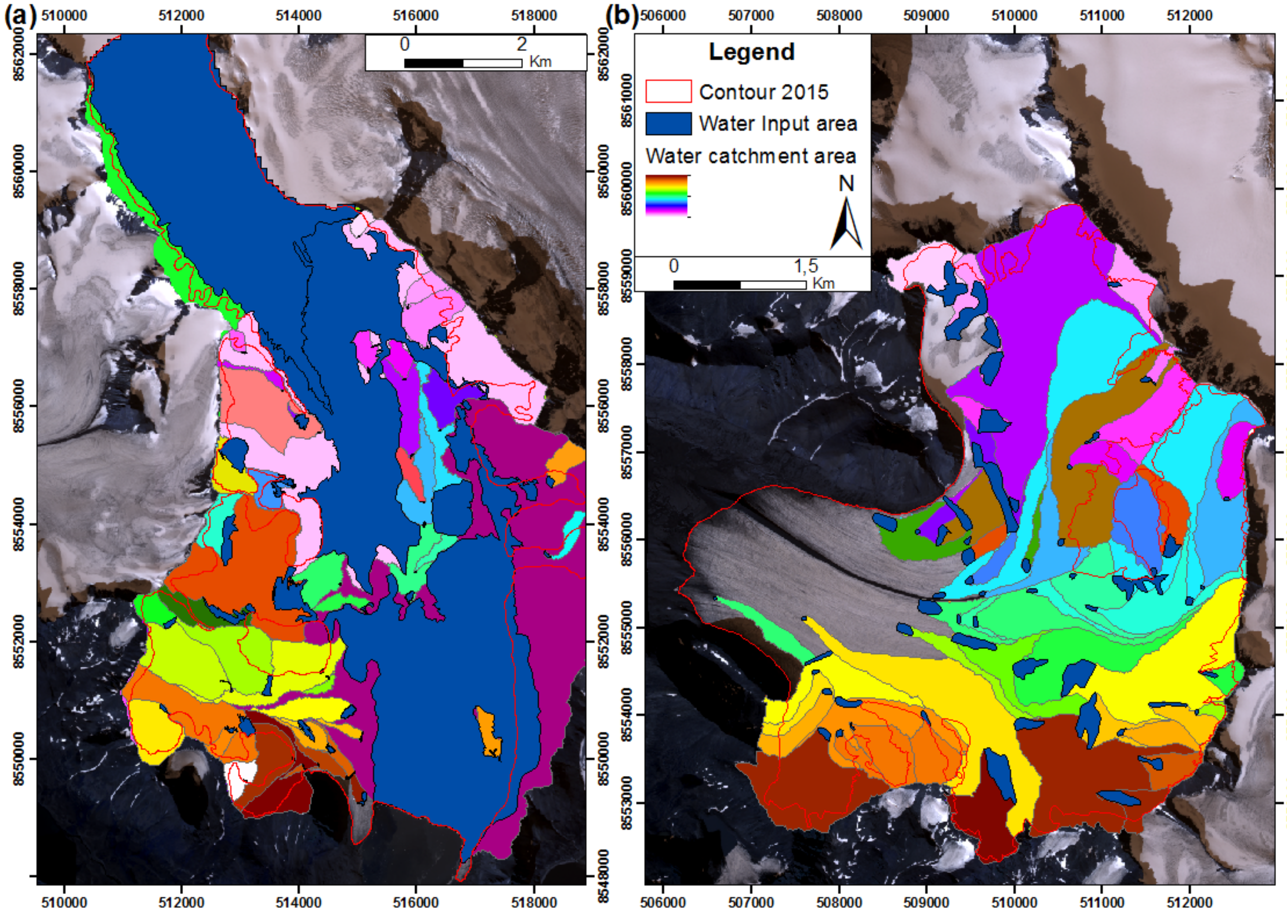

Figure 3. WIA's catchments of Hansbreen (a) and Werenskioldbreen (b) in 2015. Map's background is the WorldView-2 VHRS image acquired on 21/08/2015 and the coordinate system used is WGS 1984 UTM zone 33N.

3.4 Spatialized water runoff calculation

Main subglacial water source is known to be controlled by water runoff on the glacier's surface essentially characterized by surface meltwater and precipitations (Flowers and Clarke, 2002; Hodson et al., 1998; Irvine-Fynn et al., 2011). Therefore, in order to create a quantitative subglacial water flow model, we spatialized the amount of meltwater generated on the entire glacier's surfaces and the amount of the total precipitations (solid, mixed and liquid) on the whole glacier's surfaces and the surrounding slopes for the determined melt season 2015 (06/06/2015 to 10/10/2015).

Spatial distribution of surface ablation model has been generated based on the summer mass balance measurements (WGMS), relying on mass balance stake network present on both studied glaciers (Fig 1). It combines meltwater produced by winter snow cover, at the beginning of the melt season, and glacier's surface melt, during the rest of the melting period. The relationship found between summer mass balance and elevation (R^2= 0.83) allows us to model the meltwater production for the entire glacier.

Spatial distribution of precipitation model has been calculated with the following process. Using the precipitation gradient (Δ_P) of 19 % per 100 m and catching error calculated by Nowak and Hodson (2013) and knowing the precipitation value measured at the PPS (Q_P), we were able to calculate the amount of precipitation at each altitude (h), for any DEM cell (Q_h) following equation 1. Also, potential meltwater from the summer accumulation has been taken into account in calculations of the total precipitation.

$$Q_h = Q_{PPS} + (\Delta_P Q_{PPS} h) \tag{1}$$

We have to keep in mind the fact that we might under-estimate the total amount of water runoff due to liquid water storage in the snow pack and in the firn layer during the winter/spring period and then released during the melt season (Arnold et al., 1998).

3.5 Subglacial modelling

Theoretical pattern of subglacial channels model has been completed for the year 2015. It requires knowledge of surface and bedrock topography of the glacier (section 3.1), and of the spatial distribution of ice thickness obtained from them. Spatial resolution of our model is limited by the bedrock DEMs resolution of 100 m. Therefore we had to upscale surface DEMs (section 3.1), WIA's catchments maps (section 3.3) and spatialized water runoff model (section 3.4) into a 100 m grid. Surface and bedrock DEMs have a vertical accuracy of few meters which does not impact much our results regarding the spatial model resolution (Fischer et al., 2005).

Water is known to circulate on, in and under glaciers in response to hydraulic potential gradients (Shreve, 1972). Classical models, and particularly last theoretical pattern of subglacial channels models realized on our study area by Grabiec et al. (2017); Pälli et al. (2003), are based on this theory. We also based our model on this theory with the difference that we consider that water circulation depends not only on hydraulic potential gradient but also on some glaciological components. Subglacial drainage pattern can be modelled by assuming a spatially uniform flotation fraction K which is the ratio between water pressure (P_w) and ice overburden pressure (P_i) (Flowers and Clarke, 1999) following equation 2:

$$K = \frac{P_w}{P_i} \tag{2}$$

Therefore, as gridded values of surface and bedrock elevation can be used to model the subglacial drainage pattern from spatialized hydraulic potential Φ, we used the following equation 3:

$$\Phi = \rho_w g z_b + K[\rho_i g(z_s - z_b)] \tag{3}$$

where ρ_w is the water density (1000 kg.m^{-3}), ρ_i is the ice density (917 kg.m^{-3}), g is the acceleration due to gravity (9.81 m.s^{-2}), z_b and z_s are respectively bed and surface's elevation.

In order to take into account some glaciological and meteorological components, we created five different simulation scenarios:

1. **Standard hydraulic potential model**
   It considers a homogeneous recharge of water, all the grid cells of the model are weighted with a value equal to 1. It corresponds to the last stage of theoretical pattern of subglacial channels models achieved on our study area by Grabiec et al. (2017); Pälli et al. (2003) but updated to the year 2015.

2. **Standard hydraulic potential (ablation + precipitation input)**
   It considers a homogeneous recharge of water, all the grid cells of the model are weighted in function of the spatialize water runoff model values (section 3.4) (Fig.4).

3. **WIA (ablation input)**
   It considers a discrete recharge of water, all the grid cells of the model corresponding to a WIA are weighted by the amount of meltwater (section 3.4) produced on their particular catchment (section 3.3). All the other grid cells of the model are weighted with a value equal to 0.

4. **WIA (precipitation input)**
   It considers a discrete recharge of water, all the grid cells of the model corresponding to a WIA are weighted by the amount of precipitation (section 3.4) occurring on their particular catchment (section 3.3). All the other grid cells of the model are weighted with a value equal to 0.

5. **WIA (ablation + precipitation input)**
   It considers a discrete recharge of water, all the grid cells of the model corresponding to a WIA are weighted by the total amount of runoff (section 3.4) occurring on their particular catchment (section 3.3). All the other grid cells of the model are weighted with a value equal to 0 (Fig.5).

Accordingly for the scenarios (3,4,5), water volume reaching each moulins or crevasses area is calculated and depends not only on the surface topography but also on the surface conditions such as cold ice, temperate ice, firn and snow.

Water pressure in conducts depends directly on available amount of surface water (melt and precipitation) (Röthlisberger, 1972; Weertman, 1972) and Majchrowska et al. (2015) observed important fluctuations of melt and precipitation rates during the ablation seasons from 2007-2012 on Werenskioldbreen. Moreover, high pressure event (water pressure at ice overburden pressure) has been observed in the internal drainage system of Hansbreen at the beginning of intense melting periods (mainly in June and July) (Benn et al., 2009; Pälli et al., 2003; Schroeder, 1998; Vieli et al., 2004). And also, geyser-like spouts of water and over pressurized water outflows have been observed for Werenskioldbreen (Baranowski, 1977). Thus we modelled the subglacial channels for different K values ($K = 1$; $K = 0.85$; $K = 0.75$; $K = 0.5$; $K = 0.25$; $K = 0$) for the whole different scenarios for both glaciers (resulting in 60 simulations which are not presented here for obvious reasons).

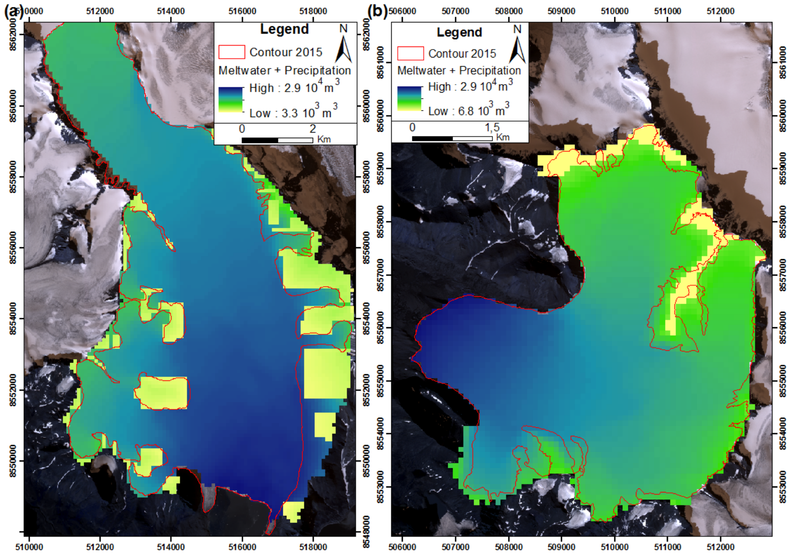

Figure 4. Homogeneous water recharge (meltwater + precipitations) for Hansbreen (a) and Werenskioldbreen (b) in 2015. Map's background is the WorldView-2 VHRS image acquired on 21/08/2015 and the coordinate system used is WGS 1984 UTM zone 33N.

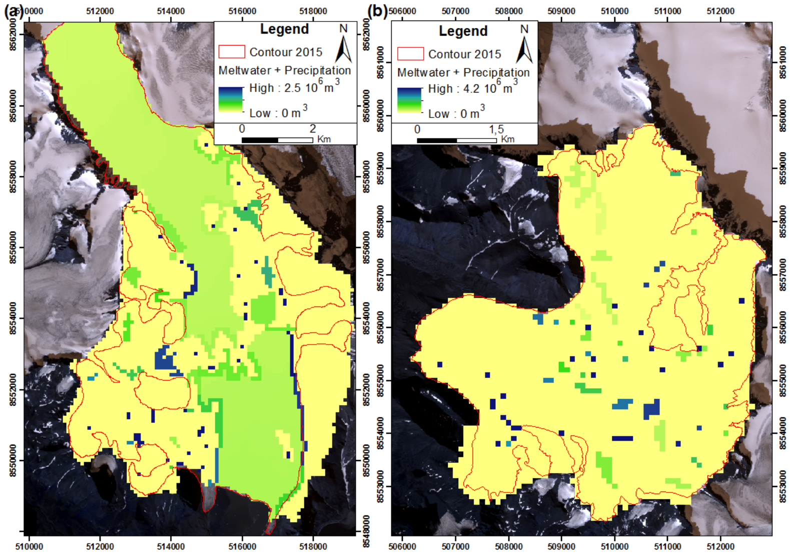

Figure 5. Discrete water recharge (meltwater + precipitations) for Hansbreen (a) and Werenskioldbreen (b) in 2015. Map's background is the WorldView-2 VHRS image acquired on 21/08/2015 and the coordinate system used is WGS 1984 UTM zone 33N.

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4 Results

4.1 Supraglacial drainage system evolution

Supraglacial drainage system mapping have been realized for both studied glaciers in 2015 regarding only crevassed areas, moulins and percolation zones leading to WIA determinations used in our model (Fig.3). However, mapping of the whole supraglacial drainage system (including surface streams) for different years was performed only for Werenskioldbreen. In fact contrary to Hansbreen, having its entire surface composed by cold ice, Werenskioldbreen exhibits a well-developed supraglacial drainage system allowing us to study its evolution.

We compared the supraglacial drainage system of Werenskioldbreen on two different timescales, annual (2010-2011) and decadal (1990-2010). Figure 6(a) shows the different supraglacial drainage features for the years 1990 (black color) and 2010 (blue color). First of all we can notice a clear consistency of the surface streams between those two years, especially on the lower part of the glacier. Then several evolution of the system, pointed with numbers on Figure 6(a), can be observed:

1. Creation of news moulins deactivating downstream surface streams.
2. Occurrence of new crevasses or shear fractures deactivating downstream surface streams.
3. Abandoned moulins due to their flowing out of a depression area, because of glacier's motion, or due to the deactivation of upstream surface streams.
4. Impossibility of mapping the surface drainage features due to an important snow cover at the end of the ablation season 2010.

Figure 6(b) shows the different supraglacial features for the years 2010 (blue color) and 2011 (green color). Both supraglacial drainage system are consistent, we can distinguish some small differences due to the snow cover which restrain to map exactly the same areas.

4.2 Theoretical pattern of subglacial channels model

Resulting simulations of scenarios (1) and (2), mentioned in section 3.5, logically display the same subglacial channel patterns, being both based on the homogeneous water recharge theory. Their difference mark the first model improvement for our study area in this article. In fact we now have a quantitative model (scenarios (2)) compare to our scenario (1) which is only qualitative. For this reason, we will only discuss results of scenario (2) (Fig.7(a); 7(b); 7(c) and Fig.8(a); 8(b); 8(c)).

Resulting simulations of scenarios (3), (4) and (5), mentioned in section 3.5, logically display the same subglacial channel patterns, being all based on the discrete water recharge theory. The fact we have water recharge controlled either by meltwater or precipitation, or even by both, does not influence subglacial conduct path due to the predominance of the discrete recharge aspect. Thus, we will only discuss results of the most complete scenario (5) (Fig.7(d); 7(e); 7(f) and Fig.8(d); 8(e); 8(f)).

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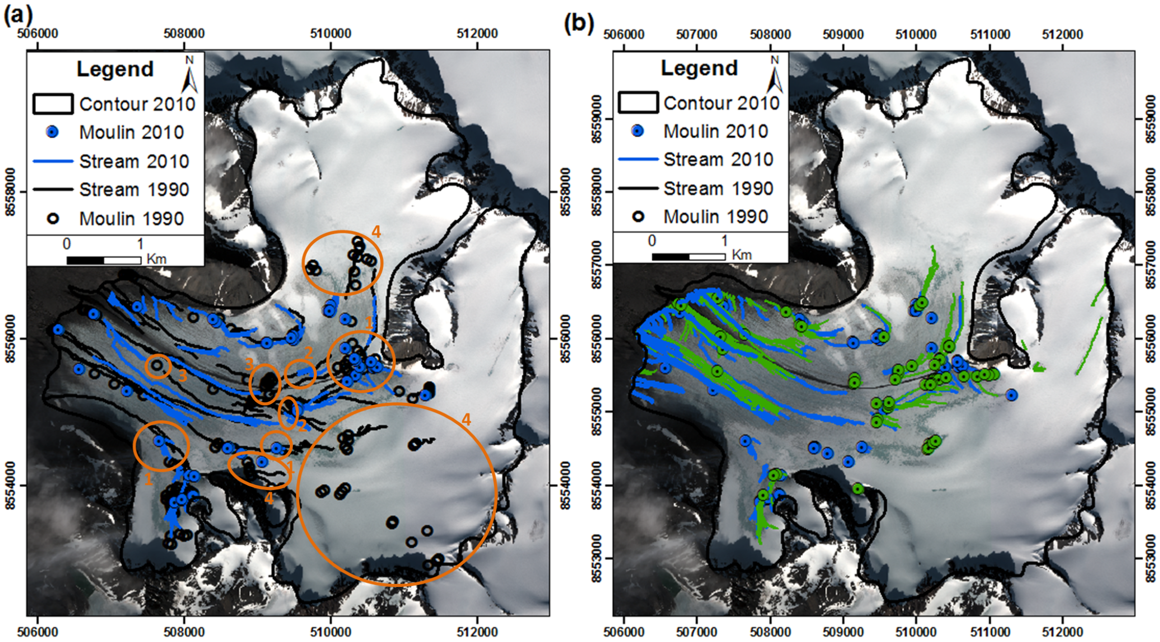

Figure 6. Comparison of the supraglacial drainage system for Werenskioldbreen on a decadal timescale (a) and on a annual timescale (b). Explanations of numbers in the text. Map's background is the GeoEye-1 VHRS image acquired on 10/08/2010 and the coordinate system used is WGS 1984 UTM zone 33N.

Because all simulation's results for $K < 0.85$ display almost the same subglacial conduits pattern and clear differences are visible between results for $K = 0.85$ and $K = 1$, we only consider three states of simulations in this study, $K = 1$, $K = 0.85$ and $K < 0.85$:

- $K = 1$ and $K = 0.85$ might represent the beginning of the melt season when an extensive amount of water is delivered to the hydrological system due to winter snow mantle melting. It might also illustrate the stage of heavy rainfalls and ice melt events. Under such conditions, channels are filled or nearly filled with water, $P_w = P_i$ or $P_w = 0.85P_i$, and water flow might be controlled mainly by the surface topography of the glacier (Flowers and Clarke, 1999).
- $K < 0.85$ might represent all the other periods of the melt season. Especially after a high melting event (K value will be close to 0) when conducts have been extensively enlarge, due to the wall melting generated by frictional heat released by an intense turbulent water flow, combined with a small water volume input. Under such conditions, the channels are not full of water, $P_w < P_i$ and water flow might be controlled mainly by the bedrock topography of the glacier (Hagen et al., 2000; Sharp et al., 1993).

Homogeneous and discrete water recharge maps (Fig.7) show very similar results for Hansbreen except that Crystal Cave and Bird Brain Cave conducts are better represented with a discrete water recharge. In all cases, we observe a general subglacial water flow from north-west to south-east with one principal channel running on the eastern part of the glacier. Main flow direction changes near the glacier front to flow from north-east to south-west. Regarding simulations with $K = 0$ (Fig.7(c) and Fig.7(f)), all channels are connected with the principal one and display one unique outflow at the glacier front. Simulations with $K = 0.85$ (Fig.7(b) and Fig.7(e)) and $K = 1$ (Fig.7(a) and Fig.7(d)) exhibit three outflows, the two eastern one are consistent on those simulations, but the western one is further west for $K = 1$ compare to $K = 0.85$ cases (Fig.7(a) and Fig.7(d)). The main subglacial channel is generated just below the firn line except for $K = 0$ state (Fig.7(c) and Fig.7(f)).

Concerning Werenskioldbreen, compare to scenario (2) (Fig.8(a); 8(b); 8(c)), scenario (5) (Fig.8(d); 8(e); 8(f)) displays a more dendritic channel network in the center part of the glacier and conducts start at lower elevations. All simulations show a main channel flowing in the center part of the glacier, with the same outflow position for $K = 1$ (Fig.8(a) and Fig.8(d)) and $K = 0$ (Fig.8(c) and Fig.8(f)) situations, and an outflow located further south for $K = 0.85$ conditions (Fig.8(b) and Fig.8(e)). Regarding cases where $K = 1$, scenario (2) exhibit five outflows (Fig.8(a)) while three outflows are modelled in scenario (5) (Fig.8(d)). Situations with $K = 0.85$, three outflows are visible for scenario (2) (Fig.8(b)) whereas two outflows are display by scenario (5) (Fig.8(e)). For $K = 0$, both scenarios exhibit only one outflow (Fig.8(c) and Fig.8(f)). Compare to the previous model of Pälli et al. (2003), none of the scenarios of our model suggest a subglacial flow separated by the medial moraine present on Werenskioldbreen.

Overall, compared to homogeneous recharge results, discrete recharge maps exhibit conducts starting at lower elevations with additional subglacial branches making them better match the location of moulins and small crevasses areas.

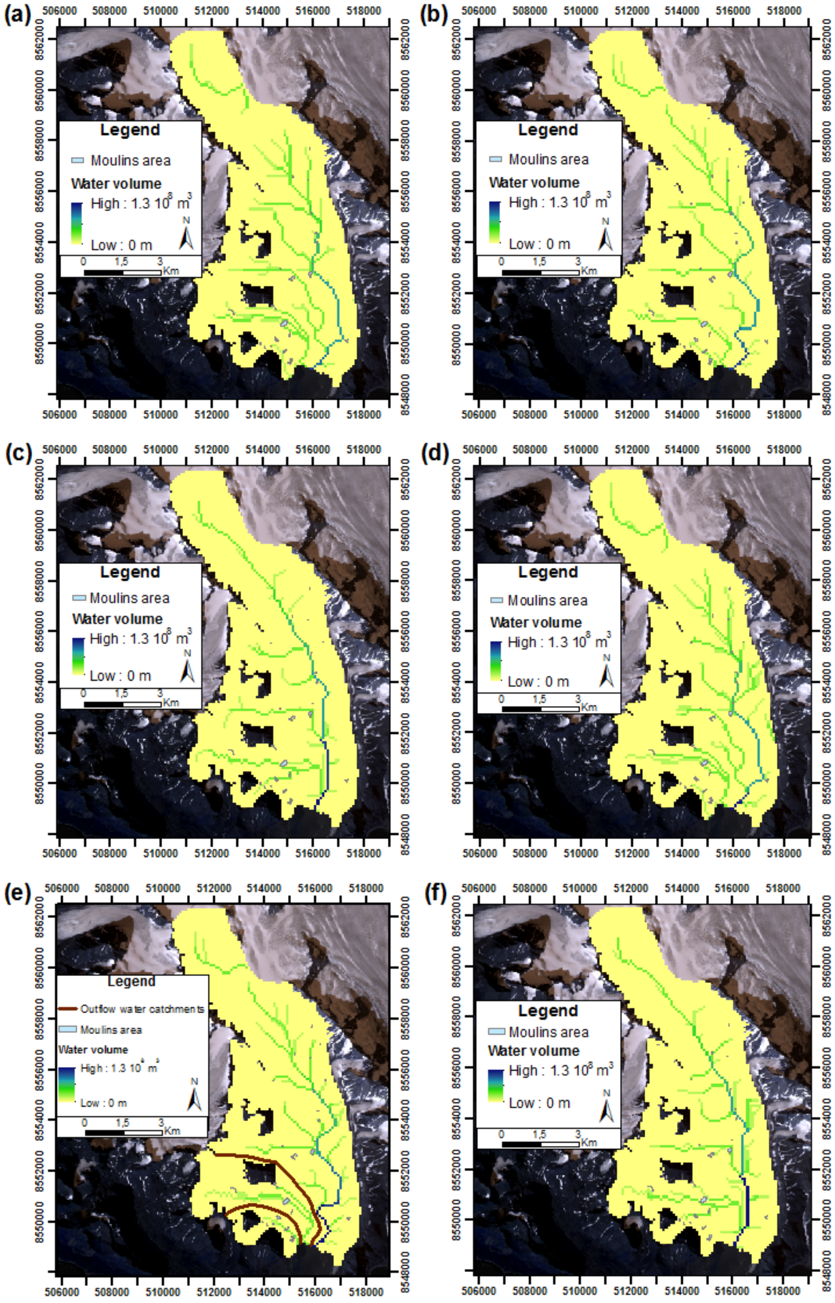

Figure 7. Map of the theoretical pattern of subglacial channels of Hansbreen modelled with scenario (2) ($K = 1$ (a); $K = 0.85$ (b); $K = 0$ (c)) and (5) ($K = 1$ (d); $K = 0.85$ (e); $K = 0$ (f)). Map's background is the WorldView-2 VHRS image acquired on 21/08/2015 and the coordinate system used is WGS 1984 UTM zone 33N.

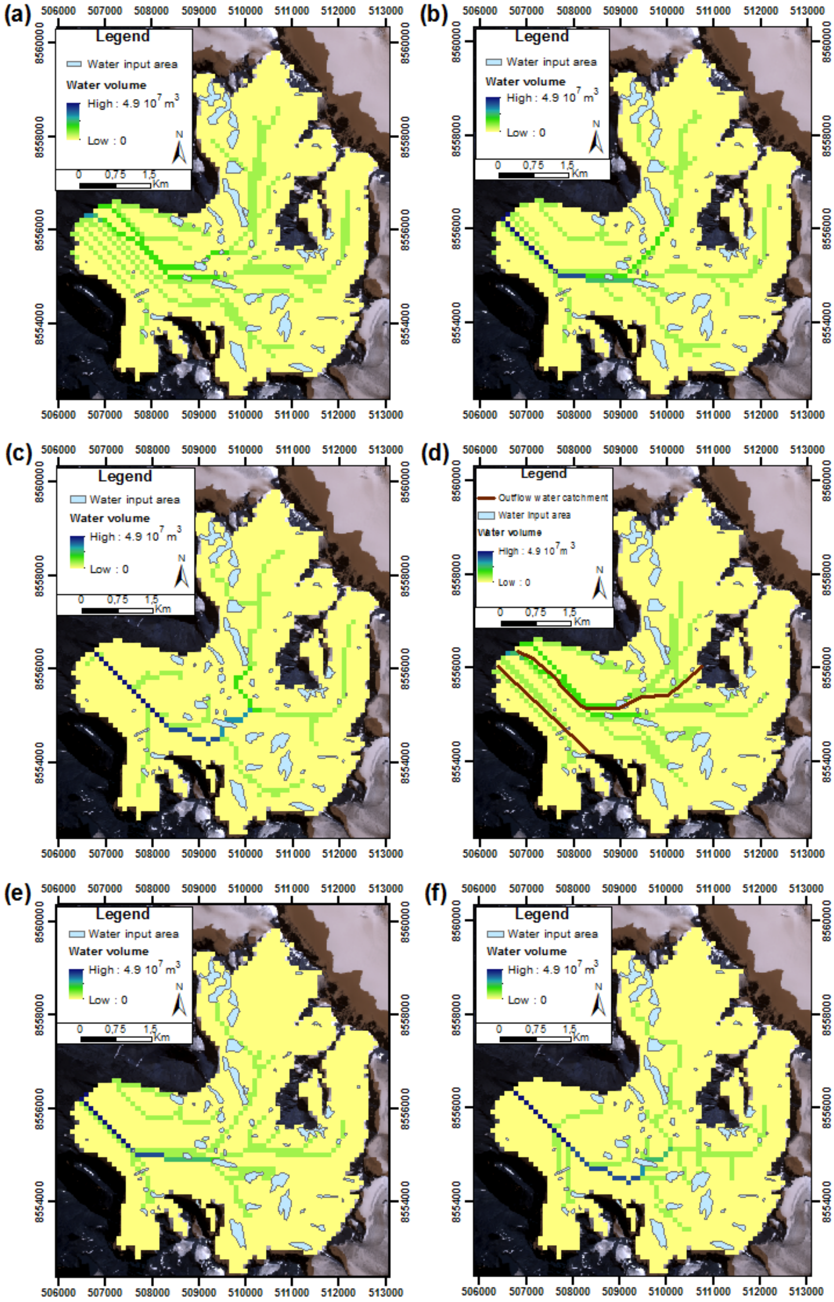

Figure 8. Map of the theoretical pattern of subglacial channels of Werenskioldbreen modelled with scenario (2) ($K = 1$ (a); $K = 0.85$ (b); $K = 0$ (c)) and (5) ($K = 1$ (d); $K = 0.85$ (e); $K = 0$ (f)). Map's background is the WorldView-2 VHRS image acquired on 21/08/2015 and the coordinate system used is WGS 1984 UTM zone 33N.

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5 Discussion

Consistency of surface streams on a decadal timescale (Fig.6(a)), especially on the lower part of Werenskioldbreen, might be explained by a weak front's dynamic and the fact that the longer time a stream remains active and the deepest it will carve its way into the glacier's surface sustaining even more its duration. Despite those similarities, we observed several evolutions of the supraglacial drainage system on a decadal timescale in response to the geometry changes induced by climate warming and glacier's flow. Occurrence of new moulins and new crevasses has a direct impact on subglacial drainage system by creating new WIA and then potentially new subglacial channels. Also abandoned moulins deactivate englacial and subglacial conducts that they supplied with water. Those conducts might then be closed up by ice deformation, having no water pressure and erosion within anymore.
Supraglacial drainage patterns are relatively persistent on annual timescale (Fig.6(b)) as expected from the study of Nienow and Hubbard (2006). It suggests that subglacial drainage system is rather steady from year to year.

Hansbreen's total water input volume calculated is 132 730 167 +/- 5 403 817 m^3 for the whole melt season 2015, consisting of 74 % meltwater and 26 % precipitations. Theoretical pattern of subglacial channels modelled results indicate altogether that most of the water is drained by a main conduct located on the east side of the glacier system (Fig.7). Scenarios (2) and (5) exhibit more or less the same subglacial conducts as a result of a heavily crevassed surface and an accumulation area composed by a firn layer overlying on temperate ice, both draining 42.8 % of the total water input volume. In fact, for scenario (5) most of the glacier's surface is considered as a WIA (Fig.3(a)) where scenario (2) considers the entire surface as a WIA.Therefore, regarding scenario (5), only 57.2 % of the total water input volume is drained in a discrete manner where it is 100 % for Werenskioldbreen (Fig.5). Scenario (5) with $K = 0.85$ (Fig.7(e)) is the more consistent regarding field observations. In fact, it is the only one which represents the well-known subglacial channels generated by Crystal Cave and Bird Brain Cave, with a coherent orientation compare to existing maps (Benn et al., 2009; Mankoff et al., 2017) and personal unpublished mapping, along with the best outflows location. However, modelled outflows locations do not correspond perfectly with our observations (locations of sediment plumes, turbid water spots and visible R-channel). This is due to a lack of GPR data at the glacier's front because of the presence of too many crevasses. The three outflows have their own water catchments and therefore drained different amount of water (Fig.7(e)). According to our results, the western one drained 2.7 % of the total water volume, the central outflow 14.8 % and the eastern one 82.5 %.

Werenskioldbreen's total water input volume calculated is 43 808 061 +/- 1 962 880 m^3 for the whole melt season 2015, consisting of 68.7 % meltwater and 31.3 % precipitations. Theoretical pattern of subglacial channels modelled results indicate altogether that most of the water is drained by a main conduct located on the center part of the glacier with an ouflow further south to the medial moraine (Fig.8). Scenarios (2) and (5) display different results because of a low glacier's dynamic leading to a poor crevassed surface, and also of its entire surface composed by an impermeable layer of cold ice, resulting in considerable water recharge differences between the homogeneous (Fig.4(b)) and the discrete (Fig.5(b)) theories. Scenario (5) for $K = 1$ (Fig.8(d)), with one outflow in the northern part of the medial moraine and two outflows in its southern part, is the most appropriate regarding field observations. In fact, modelled outflows locations of this simulation fit the best with our outflows observations. The three outflows have their own water catchments and therefore drained different amount of water (Fig.8(d)). The northern one drained 35 % of the total water volume, the central one 51.6 % and the southern one 13.4 %. The fact that our model does not seem to be influenced by Werenskioldbreen medial moraine, compare to Pälli et al. (2003) model, might be due to the new geometry of the glacier in 2015 compare to 1999. However, some dye tracing measurements have shown that subglacial water can flow across this medial moraine area, during about the same modelling period of Pälli et al. (2003) study. Regarding Werenskioldbreen's moulins, we noticed that the ones located in higher elevation are mainly supplied by water from precipitations than meltwater contrary to the ones located in lower elevations e.g. two moulins situated at 420 m a.s.l. are supplied with 69 % of meltwater and 31 % by precipitations and one moulin situated at 112 m a.s.l. is supply with 85.7 % of meltwater and 14.3 % by precipitations. Such tendency has not been observed on Hansbreen, probably due to its less steep slope and the smaller elevation range of the cold ice surface compare to Werenskioldbreen.

The fact that discrete recharge models generate subglacial channels starting at lower elevations might be consistent with the reality. In fact, we know from observations that water does not penetrate the glaciers' body in its upper part where cold ice surface exist and also that WIA are particularly located in the middle part studied glaciers. This clearly does not concern the firn zone in the accumulation area of Hansbreen where we observe a subglacial channel flowing outside the glacier in an eastern glacier system belonging to Paierlbreen. This could be an artefact due to the boundary of our model which does not allow any influences of Paierlbreen's drainage system on Hansbreen drainage system, but not necessarily. In fact, since Paierlbreen surged in 2006, the ice division was drained down-slope reducing Paierlbreen's ice pressure on Hansbreen making the water flow easier from the upper part of the Hansbreen's system to Paierlbreen's system than the contrary. Moreover, it is fulfilling to observe this state under high water pressure conditions ($K = 1$ and $K = 0.85$) (Fig.7(a); 7(b); 7(d) and 7(e)) and not under atmospheric water pressure conditions ($K = 0$) (Fig. 7(c) and 7(f)) because of the presence of a bedrock obstacle in this location. Also, a greater number of modelled channels are observed in the simulations with $K = 1$, than in the simulation with $K < 1$ (Fig.8). This might be due to the fact that when $K = 1$ new temporary subglacial channels are created due to overpressurized water in the distributed system (Hewitt, 2011). It is quite satisfying to be able to observe this phenomenon even without the representation of the distributed drainage system in the model.

Water volume values of the model might be under-estimating. Indeed we do not take in account water storage in the snow pack and in the firn layer during the winter/spring period, which is then released during the melt season, but also subglacial meltwater produced at the glacier bed due to geothermal flux and melting of the subglacial channel walls due to the heat transfer induce by the water circulation within the conducts. Despite those simplifications in our water volumes estimations, meltwater being, from far, the predominant source of water recharge in the subglacial system, we can assume that water sources which are not considered here in our study can be neglected.

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6 Conclusions

Water supply from surface melt is the principal influential runoff component (Shreve, 1972), confirmed by the difference of one order of magnitude in the amount of water provided by melt (72.5 %) and precipitations (27.5 %) during the melt season 2015 for Hansbreen and Werenskioldbreen. Water coming from glacier's surface is the main source for subglacial drainage, thus we decided first, to characterize supraglacial drainage system changes before modelling the theoretical subglacial channel patterns underneath both glaciers.

Evolution of the supraglacial drainage system on a decadal timescale initiates adjustments of the subglacial drainage system in response to the activation or deactivation of WIAs. On the contrary, on an annual timescale the superficial drainage system of Svalbard glaciers is spatially consistent implying similar subglacial drainage system.

Theoretical pattern of subglacial channels has been modelled for the year 2015. First, by considering an homogeneous recharge of water as apply in the classical method (scenario (1)). Then, by taking into account meltwater and precipitations melt season values (Fig.7(a); 7(b); 7(c) and Fig.8(a); 8(b); 8(c)), allowing us to pass from a qualitative to a quantitative model. Finally, by forcing water penetration inside the glacier thanks to the determination of WIA (Fig.3) we achieved more realistic results (Fig.7(d); 7(e); 7(f) and Fig.8(d); 8(e); 8(f)). Therefore, contrary to classical model based only on hydraulic potential theory and substantiate by the location of active moulins (Fischer et al., 2005), we integrated those moulins along with crevasses areas and physical properties of glacier's surface into our model. Moreover, knowing that water pressure within subglacial conducts can vary from atmospheric to ice overburden conditions, all scenarios have been modelled for several K values ($K = 1$; $K = 0.85$; $K = 0.75$; $K = 0.5$; $K = 0.25$; $K = 0$).

It can be concluded that, concerning Svalbard tidewater glaciers, having large crevassed areas and still vast permeable firn zones, models of theoretical subglacial channel pattern can assume a homogeneous water recharge. Similarly for badly crevassed glaciers during the active phase of a surge. On the contrary, it is important to consider a discrete water recharge for Svalbard land-terminating glaciers with an impermeable layer of cold ice over almost their entire surface.This is also valid for long and flat tidewater glaciers or even glaciers in a quiescent phase of a surge, both having limited crevassed areas.

The fact that evolution of subglacial channels position is highly dependent on surface changes (topography and supraglacial drainage system), regarding the permanency of the supraglacial drainage system from year to year (Fig.6(b)) and its few changes on decadal timescale (Fig.6(a)), we can consider subglacial channels models of Svalbard glaciers valid, with maybe some slight changes, for a minimum period of 20 years. Results of the subglacial drainage system modelled for the year 1936 and the period 2005-2008 by Grabiec et al. (2017) reinforced our statement.

This study introduce a new way of modelling the subglacial conduct pattern of polythermal glaciers by taking into account a discrete water recharge and by considering the volume of available water from the glacier's surface giving more realistic results than before. They are confirmed by observed locations of subglacial channels' outflows at the front of land-terminating Werenskioldbreen. Nevertheless, a more accurate reconstruction of subglacial water-flow routing would require a model including englacial water transport and storage, drainage through a subglacial water sheet (distributed drainage system) and subsurface groundwater flow. In fact, physical parameters of distributed drainage system like permeability or even water pressure, can influence subglacial channels' location (Hewitt, 2011). Moreover our model would need to be compared with a greater amount of field data such as dye tracing measurements and water discharge survey of several supraglacial streams sustaining moulins and of glaciers' outflows.

Code availability.

Data availability.

Code and data availability.

Author contributions.

Competing interests.

Disclaimer.

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