Review of

Role of discrete water recharge from supraglacial drainage systems in modeling patterns of subglacial conduits in Arctic glaciers
by Decaux et al.

General comments

•   <u>Comment from Referee:</u>

This manuscript presents calculated locations and water fluxes through subglacial channels under two Svalbard glaciers. It compares a "spatially uniform recharge" scenario, in which melt and rain water is allowed to enter the subglacial system locally, to a "discrete recharge" scenario, in which the water may only enter at identified moulin or crevasse locations. The study finds better agreement between modeled and observed locations of subglacial outflow when the "discrete recharge" scenario is used.

The result is important and reflects conclusions of other recent work that couples surface hydrologic networks to subglacial hydrology models (e.g., Banwell et al. (2013), Gulley et al. (2012), Bartholomew et al. (2011), to name just a few).

The manuscript too frequently overstates claims, makes assumptions without evidence, lacks presentation of field (or remote sensing) observations that support or refute their predicted subglacial conduit locations and fluxes, and suffers from an imprecise writing style. If these shortcomings can be addressed, it could merit publication in The Cryosphere.

<u>Author's response:</u>

Thanks for endorsing the study like previous reviewer.
We generally agree with your comments and will try to make the article more precise.
Nevertheless, due to harsh condition (polar night, meteorological conditions) and dealing with tidewater glacier it is impossible to have very detail evidences of subglacial channel network.

<u>Author's changes in manuscript:</u>

We answered and changed the article in function of this review.

Speciftc comments

•   <u>Comment from Referee:</u>

P1 L6-8 Most current subglacial hydrology models DO include heterogeneous recharge. Unweighted hydropotential flow accumulation calculations are still regularly performed, but I would no longer consider this the "standard model". I suggest rephrasing this sentence accordingly.

<u>Author's response:</u>

We agree, several studies on the past years state on the importance to consider the supraglacial drainage system. Nevertheless, none of them made a model with complete "real" supraglacial drainage system with locations of glacier moulins and crevasses area as collectors of water and also none made the comparison with and without considering it.

<u>Author's changes in manuscript:</u>

We reformulated accordingly and we removed all "standard model" from the article.

-     Comment from Referee:

P1 L15, 18 The results are generalized to "Arctic tidewater glacierS" and "land-terminating glacierS", yet only one of each type was studied, without placing them into any context of being typical or atypical of other Arctic glaciers. This generalization needs to be either supported or removed.

Author's response:

We agree we need to more support the fact that they are representative of "Svalbard glaciers" and not "Arctic glaciers".

Author's changes in manuscript:

We changed "Arctic glaciers" for "Svalbard glaciers" and we developed more, in the "Study sites" section, the fact that they are both representative of Svalbard glaciers regarding their morphology and hydrothermal structure.

-     Comment from Referee:

P1 L20 The predicted conduits are not compared to observations; therefore, "more realistic results" here is not supported.

Author's response:

The predicted conduits are not compared to direct observations because it is impossible to penetrate and to map the entire englacial and subglacial conduits. Nevertheless it is possible to assess our results thanks to the observed outflow positions and some known subglacial / englacial channels location thanks to Bird Brain and Crystal caves. Also, the fact that they do not display subglacial channels in the accumulation area fit with previous theoretical studies (Fountain and Walder, 1998; Lliboutry, 1971 and other). I fact, they showed that either water in the accumulation area percolate through the snowpack then through the firn to create a layer of saturated water at the interface warm ice / firn to appear supraglacially at the equilibrium line, either it flows englacially, thanks to the presence of crevasses under the snow pack in the accumulation area, to reach the ablation area before to be redirected subglacially. Therefore, there might have some distributed inefficient drainage system below the accumulation area but no a well channelized efficient system.
Finally it could have been possible to make some drillings in order to try to asses our model, but even if we would have the field power it would not be easy due to the national park status of the area. Moreover, hot water drillings have to be very closely spaced to hit a channel and they can easily modify or even spoil natural drainage system.

Author's changes in manuscript:

We better specified in the text.

-     Comment from Referee:

P1 L20-21 The meaning of this sentence is unclear and should be removed or reworded.

Author's response:

We agree.

Author's changes in manuscript:

We removed this sentence and adapt it P1 L14-17.

•   Comment from Referee:

P2 L33-34 "no [model] has used a real representation of the supraglacial drainage system" is patently false. Banwell et al. (2013), Colgan et al. (2011), Mayaud et al. (2014), Bougamont et al. (2014) are studies that have done this.

Author's response:

You are right some works have been done regarding Greenland, on the influence of drainage surface lakes and crevasses areas on local velocity (Bougamont et al. 2014; Colgan et al. 2011). Also some models with discrete moulin input were realized but with moulin's location not based on mapping technics but on localization of depressions areas (Banwell et al. 2013; Mayaud et al. 2014).
All those works show the importance of considering the supraglacial drainage system into the glacial hydrological models. But no assessment of the importance of using discrete or spatially uniform water recharge was realized.

Author's changes in manuscript:

We reformulated this sentence according to previous comments.

•   Comment from Referee:

P3 L1-20 This three-paragraph summary of the manuscript does not belong in the Introduction. If you must outline your paper here, limit yourself to 3-4 sentences at the most.

Author's response:

We had this previous comment from previous referee:
"Introduction consists of three parts. 1) The background knowledge, broad to specific. 2) The gap in knowledge that the paper will address. 3) Your solution to the knowledge gap. Your work should only be discussed in the last paragraph or two, and should summarize what you will do. The description that takes up most of the introduction here does not belong here."

We agree that it is too long but we will not shorten it to 3-4 sentences which is too short to introduce our work. Thus we will keep the format requested by the first reviewer : "work should only be discussed in the last paragraph or two, and should summarize what you will do."

Author's changes in manuscript:

We shorten this last part of the introduction.

•   Comment from Referee:

P3 L23 This statement needs citation.

Author's response:

We agree.

Author's changes in manuscript:

We developed a bit more the statement an added citations:
(Grabiec et al., 2012; Hagen et al., 1993, 2003; Ignatiuk et al., 2014)

•   Comment from Referee:

P3 L32 Ryser et al. (2013) is a natural citation for this statement.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We had Ryser et al. (2013) as a citation.

- <u>Comment from Referee:</u>

  P5 L14-19 This section on the unsuccessful application of automated stream detection algorithm should either be enhanced – stating more detail about the broadband overlap in reflectance, possibly including a comparison of debris-covered and relatively debris-free regions – or removed.

<u>Author's response:</u>

There are more details about the broadband overlap in reflectance in the discussion part P17 L2-11.

<u>Author's changes in manuscript:</u>

We removed this section to only develop it in the discussion part.

- <u>Comment from Referee:</u>

  P7 L1 What is the origin of $\Delta_P = 19\%$? This should be cited and briefly explained.

<u>Author's response:</u>

It is cited: Nowak and Hodson (2013) but we agree the sentence is not clear.

<u>Author's changes in manuscript:</u>

  We reworked the sentence.

- <u>Comment from Referee:</u>

  P7 L4 All the subscript in this equation make it difficult to read. You could consider using Q_0 for the amount of precipitation at your AWS station, since it is sited at roughly 0 meters a.s.l.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We change Q_{pps} for Q_0 in the whole article.

- <u>Comment from Referee:</u>

  P8 L4 Errors in $\Delta_P = 19\%$ are not accounted for here. I suspect these will be larger than errors in h or $Q_{P\,P\,S}$ due to expected substantial meteorological variations between rainfall events. It may be difficult to know and quantify such errors, so at the very least this additional uncertainty should be commented on.

<u>Author's response:</u>

Nowak and Hodson (2013) estimated mean error of calculated runoff as 4% (for $\Delta p = 19\%$). Unfortunately, it is impossible to quantify Δp errors without additional data from Nowak and Hodson (2013) modelling.
We are aware that our errors of the spatial distribution of the precipitation model could be underestimated.
However, our total glacier runoff error is also around 3%.

<u>Author's changes in manuscript:</u>

We added two sentences after P8L7:
"We are aware that the error of precipitation spatial distribution is possibly larger due to expected substantial meteorological variations between rainfall events. However, calculated total glacier runoff error correspond with Nowak and Hodson (2013) estimations."

• <u>Comment from Referee:</u>

  P8 L7 Usually errors are added in quadrature.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We changed the formula and recalculated the errors.

• <u>Comment from Referee:</u>

  P9 L17 - P10 L8 Five scenarios are described, but results from only two scenarios (#2 and #5) are presented. I suggest removing the other three scenarios, which will simplify the presentation.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We changed scenario 2 in 1 and scenario 5 in 2.

We removed the three scenarios 1; 3; 4 and change the rest of the text according to it.

Change scenario 2 and 5 of the figures!!!

• <u>Comment from Referee:</u>

  P9 L22-24 I would not refer to Scenario #2 as "spatially uniform recharge" since water input is allowed to vary spatially according to local production at the surface (Figure 3). Instead, you might call it a "local recharge" scenario, or something like that, to describe the lack of surface meltwater routing.

<u>Author's response:</u>

We agree "spatially uniform recharge" refers better to scenario 1.
"local recharge" was a good idea but after using it seems to be confusing with "discrete recharge" thus we decided to use "spatial recharge".

Author's changes in manuscript:

We change the name in all the text.

-       Comment from Referee:

P10 L16-18 Artesian features (which is a more precise way to say "geyser-like spouts of water") suggest $k > 1$. Although rather nonstandard, you might consider adding $k > 1$ for Werenskioldbreen; Everett et al. (2016) have done this for a Greenland glacier.

Author's response:

We agree we change "geyser-like spouts of water" for "Artesian features".
Regarding the modeling of a scenario k>1, as it is a "non-usual case" (Everett et al. 2016) and that it happen only locally and only on a short period of time (Baranowski 1977) we decided to not implement it.

Author's changes in manuscript:

We changed "geyser-like spouts of water" for "Artesian features".

-       Comment from Referee:

P10 L26-27 Are the locations of the main subglacial channels somehow seeded by the authors in their model? Presumably they originate at locations of concentrated recharge, but this sentence suggests they might be baked into the model. Clarify.

Author's response:

No, no locations of main subglacial channels are seeded. It was just to express that the model involves the channelized system and not distributed system as mentioned below.

Author's changes in manuscript:

We removed this (v) point.

-       Comment from Referee:

P11 A new subsection to include methods of field or remote observations of subglacial conduits needs to be added.

Author's response:

We don't see the point of this new section as we don't use any direct observation of subglacial conduits in the article. While it is question of those ice cave, citations are added and all mapping methods are described in those article.

Author's changes in manuscript:

Nothing.

-       Comment from Referee:

P12 L2 Subsection heading: What does "Changes" refer to – changes over time, space, due to model scenario, etc.? Clarify.

Author's response:

We agree it needs to be clarify

Author's changes in manuscript:

We changed it for "Temporal changes"

• Comment from Referee:

P13 A new subsection discussing the goodness of fit of field observations to the predicted sub-glacial conduit locations and fluxes needs to be added. Relevant parts of the "authors' personal unpublished maps" must be included here.

Author's response:

The personal data collected do not bring more information than the existing data already published and cited in the article. The authors have the opportunity to visit those cave systems several times a year since few years. Those repeated observations just confirm that the data cited are still valid.

Author's changes in manuscript:

P18 L19 we changed "authors' personal unpublished maps" into "authors' personal observations"

• Comment from Referee:

P14 L13 How does the current approach and the results differ from those of Palli et al (2003)?

Author's response:

P2 L16-21 / P3 L16-18 / P8 L18-21 / P9 L18-21: We already explained that Pallis'model is based on hydrological potential gradient, that it does not take into account the supraglacial system and used a spatially uniform recharge of water.

Author's changes in manuscript:

Nothing.

• Comment from Referee:

P17 L21 The assumption that observations from these two glaciers in 1990, 2010, and 2011 can be "extrapolated to the entire Arctic" is terribly overblown.

Author's response:

We agree.

Author's changes in manuscript:

We deleted the sentence P17 L21-22

• Comment from Referee:

P17 L24-26 Here it is noted that "few changes" were found between 1990-2010, yet in the Results section (4.1), "several changes" were noted, grouped into four broad classes. This inconsistency must be addressed before you can claim that your results will be valid on decadal timescales.

Author's response:

We agree it is not consistent.
Our finding shows that there is some supraglacial evolution on decadal timescale but those changes does not represent a complete reorganization of the system (or WIA). The new WIA either stay more or less in the same area (about 300 m² so on a glacier and our model scale it does not change so much) or stay on the same subglacial channel axes. Especially abandoned moulins which see the creation of new upstream moulins.

Author's changes in manuscript:

We explain the situation as above by developing paragraphs in discussion and conclusion sections.

• Comment from Referee:

 P18 L6, L25 These water volumes are very precise. At least one significant figure should be dropped, if not two.

Author's response:

We agree.

Author's changes in manuscript:

We removed one significant number.

• Comment from Referee:

 P18 L18-20 The subglacial channels mentioned here are not generally "well known"; any data used to identify such channels needs to be included in the manuscript.

Author's response:

We agree with "well-known" formulation remark.
Regarding the fact to include more data: we refer to Mankoff 2017 and Benn 2009 maps and say that our subglacial channels modelled match with their orientations. We do not see the need to add those already published maps into the article. In fact, it will overload the article with figures especially that this topic is not the main point of this article.

Author's changes in manuscript:

We removed "well-known" and change it for "well-studied", we also added more citations to show that those systems are studied since a long time.

• Comment from Referee:

 P19 L14-18 Why is this important?

Author's response:

It adds some information on the pattern of the recharge of water on the glacier and show that it is heterogeneous on the glacier surface.

Author's changes in manuscript:

We added one sentence to specify the interest.

- Comment from Referee:

P20 L7-8 This assumption is not adequately supported.

Author's response:

We agree it needs citations.

Author's changes in manuscript:

We added citations [Cogley et al. (2011); Hock (2005); Irvine-Fynn et al. (2011); Jansson et al. (2003)] and developed a bit more the text.

- Comment from Referee:

P20 L15-16 This was not tested or shown in the study. The subglacial flow accumulation algorithm was run on glacier geometry (surface DEM) dating to 2015. Flow accumulation at other time periods was not assessed.

Author's response:

We agree it is not directly tested in the article. Nevertheless during the entire article we insist on the dependency of the subglacial drainage system on the supraglacial one. Also, knowing we have some changes on a decadal timescale implies some changes in the subglacial system.

Author's changes in manuscript:

We reformulated.

- Comment from Referee:

P20 L28 There is no reason that I know of that subglacial channels cannot form underneath an accumulation zone.

Author's response:

Like explain in previous comment and here we cite two articles:
The fact that they do not display subglacial channels in the accumulation area is a more realistic result. In fact, previous studies (Fountain and Walder, 1998; Lliboutry, 1971 and other) show that either water in the accumulation area percolate through the snowpack then through the firn to create a layer of saturated water at the interface warm ice and firn to appear supraglacially at the equilibrium line, either it flows englacially, thanks to the presence of crevasses under the snow pack in the accumulation area, to reach the ablation area before to be redirected subglacially. So from previous theoretical studies, we can only find englacial channels in the accumulation area. Maybe it is possible to have some subglacial channels in the accumulation area if water enters directly subglacially at an interface mountain slope / glacier edge. But we have no observation of such a phenomenon here. Also some subglacial channels in accumulation area can exist due to geothermal or frictional melt but not formed by surface water and they would rather be small and inefficient.

Author's changes in manuscript:

We reformulated the sentence.

- Comment from Referee:

P21 L4-8 This statement directly contradicts that on P20 L15-16 (which, as I noted above, has its own issues). Regardless of which may be true, they are not constrained by this study. If Grabiec et al. (2017) have results that would support one of these statements, they should be described here and then folded into these points.

Author's response:

We agree.
As explain above, the model can be consider as valid for a minimum period of 20 years even if some changes of the supraglacial system were observed on a decadal timescale.

Author's changes in manuscript:

We reformulate both sections in order to be consistent.
Grabiec et al. 2017 was moved in the discussion part.

- Comment from Referee:

P20-21 The conclusion section is far too long. It does not need two paragraphs to restate results, and it certainly should not refer to specific figures. I would start by deleting the first three paragraphs, then winnowing the final three paragraphs into 10-15 lines.

Author's response:

We agree that it does not need two paragraphs to restate our results and that it should not refer to specific figures. We also agree that it is too long, nevertheless only 10-15 lines seems very short for our conclusions.

Author's changes in manuscript:

We removed all references to figures and keep only one reference to article (which is needed).
Also we shorten the whole conclusion.

- Comment from Referee:

Figure 6: The two caves should be noted on these maps as well (red dots would be sufficient).

Author's response:

We agree

Author's changes in manuscript:

We added the caves on Figure 6 with red dots.

- Comment from Referee:

Appendix: I do not think these figures are necessary.

Author's response:

Those figures were asked by the previous referees and were not present before. It allows to show all the scenarios modelled and to justify our decision to not discuss them in the paper.

Author's changes in manuscript:

 Nothing.

Technical corrections

•   <u>Comment from Referee:</u>

P2 L20 Mistakenly written "heterogeneous" instead of "homogeneous"

Author's response:

We agree.

Author's changes in manuscript:

We wrote "homogeneous" instead of "heterogeneous".

•   <u>Comment from Referee:</u>

 P2 L28-30 This is true for temperate glaciers

Author's response:

No, it is also true for polythermal glaciers cf citation P2 L28-30:

- Gulley, J., Benn, D., Müller, D., and Luckman, A.: A cut-and-closure origin for englacial conduits in uncrevassed regions of polythermal glaciers, Journal of Glaciology, 55, 66–80, 2009.
- Irvine-Fynn, T. D., Hodson, A. J., Moorman, B. J., Vatne, G., and Hubbard, A. L.: Polythermal glacier hydrology: A review, Reviews of Geophysics, 49, 2011.

Author's changes in manuscript:

 Nothing.

•   <u>Comment from Referee:</u>

 P2 L31 Smith et al. (2015) would be ideal to cite in support of this sentence

Author's response:

We agree.

Author's changes in manuscript:

We added Smith et al. (2015).

- Comment from Referee:

P6 L15 "spatialized" is not a word

Author's response:

We agree and notice that we used this word several times.

Author's changes in manuscript:

We change the formulation of "spatialized" in the whole article.

- Comment from Referee:

P6 L27 WGMS should be written out and a citation added

Author's response:

We agree.

Author's changes in manuscript:

We added the citation and WGMS has been written out.

- Comment from Referee:

P10 L22 Specify "supraglacial" drainage catchment structure

Author's response:

We agree.

Author's changes in manuscript:

We added "supraglacial".

-     <u>Comment from Referee:</u>

P10 L25 Specify that this refers to *k*.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We added "K".

-     <u>Comment from Referee:</u>

P12 L22 Specify "more" consistent "than the 1990-2010 pair"; they are not fully consistent, just more consistent than the 1990-2010 comparison.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We added "more".

-     <u>Comment from Referee:</u>

P19 L21 Absent a crevasse, moulin, conduit, or hydrofracture, this statement can be true; as written, it is not true

<u>Author's response:</u>

We agree but we will only speak about crevasses and moulins because they are the key elements to the water to penetrate the glacier surface. The conduits are the extension of moulins and crevasses and hydrofracture is one of the formation processes of those features.

<u>Author's changes in manuscript:</u>

We reformulated.

-     <u>Comment from Referee:</u>

P19 L29, P20 L1 Use of the word "satisfying": it is not appropriate to describe emotions associated with obtaining certain results.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We reformulated.

-     <u>Comment from Referee:</u>

P19 L34 If $k \leq 1$, then the subglacial system is never "overpressurized".

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We changed for "higher water pressure".

-     <u>Comment from Referee:</u>

P20 L11 I find a factor of 3 here, not an order of magnitude.

<u>Author's response:</u>

We agree.

<u>Author's changes in manuscript:</u>

We changed for "a factor of three".

-     <u>Comment from Referee:</u>

P21 L9-11 Specify "on these glaciers" at the end of this sentence. The method is not new, but its application to Hansbreen and Werenskioldbreen is.

<u>Author's response:</u>

We agree that the idea of using a discrete recharge is not new. Several studies suggest that it might be important to consider it but none of them asses it. Moreover no study (to our knowledge) modeled the subglacial channels of a glacier using a discrete recharge based on the mapping of the moulins and crevasses areas, for the entire glacier surface, combined with modeled water volumes of each WIAs thanks to the determination of their respective water catchments.

<u>Author's changes in manuscript:</u>

We added "for the entire glacier surface" at the sentence to express our previous explanations.

Role of discrete water recharge from supraglacial drainage systems in modeling patterns of subglacial conduits in ~~Arctic~~ Svalbard glaciers

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Abstract.

As the behavior of subglacial water plays a determining role in glacier dynamics, it requires particular attention, especially in the context of climate warming that is increasing ablation and generating greater amounts of meltwater. Water flowing from the glacier's surface is the main source of supply to the subglacial drainage system. This system is largely influenced by the supraglacial drainage system that collects meltwater and precipitation water and rapidly delivers it to discrete points in the glacier bed via moulins and crevassed areas, called water input areas (WIA). ~~Standard models~~ Models of patterns of subglacial ~~conduit are~~ conduits mainly based on the hydrological potential gradient ~~and do not take~~ without taking into account the supraglacial drainage system ~~into account~~ are still regularly performed. In fact, they consider a ~~spatially uniform~~ spatial water recharge. We modeled the pattern of subglacial channels in two glaciers located in Svalbard, the land-terminating Werenski-oldbreen, and the tidewater Hansbreen during the 2015 melt season. We modeled a ~~spatially uniform~~ spatial and a discrete water recharge in order to compare them. First, supraglacial catchments were determined for each WIA on a high resolution digital elevation model using the standard ~~watershed~~ *watershed* modeling tool in ArcGIS. Then, ~~spatialized~~ interpolated water runoff was calculated for all the main WIAs. Our model also accounts for several water pressure conditions (K). For our two studied glaciers, during the ablation season 2015, 72.5% of total runoff was provided by meltwater and 27.5% by precipitation. Changes in supraglacial drainage on a decadal timescale ~~led to some modifications in the subglacial system in~~ are observed in contrast to its nearly stable state on an annual timescale. Nevertheless, due to the specific nature of those changes, it seems to have a low impact on the subglacial system. Therefore, our models of subglacial channel are assumed to be valid for a minimum period of two decades and depend on changes in the supraglacial drainage system. Results showed that for ~~Arctic~~ Svalbard tidewater glaciers with large crevassed areas, ~~model patterns of theoretical~~ models of subglacial channels that assume ~~spatially uniform~~ spatial water recharge may be somewhat imprecise but are far from being completely incorrect, especially for the ablation zone. On the other hand, it is important to take discrete water recharge into account in the case of land-terminating Svalbard glaciers with limited crevassed areas ~~in the Arctic~~. In all cases, considering a discrete water recharge when modeling patterns of theoretical subglacial channels ~~produces~~ seems to produce more realistic results ~~. Models of subglacial channel are assumed to be valid for a minimum period of two decades and account for changes in the supraglacial drainage system of Arctic glaciers~~ according to current knowledge.

1 Introduction

In the context of global climate change and in particular, the rapid melting of glaciers around the world, it is essential to under-
stand changes in their meltwater drainage system and its consequences for glacier behavior. Today it is even more important
5 to focus on the hydrological system of Arctic glaciers given that the Intergovernmental Panel on Climate Change (IPCC) pre-
dict longer summer seasons (Pachauri et al., 2014) and also knowing that Svalbard glaciers have been shrinking for several
decades already (Błaszczyk et al., 2013; Hagen et al., 2003b). All predictions assume an increase in runoff (meltwater and
precipitation) from Arctic glaciers, ice caps and ice sheets, suggesting intensification of their whole drainage system and con-
sequently of their dynamics and their impact on sea level rise (Hagen et al., 2003a; Hanna et al., 2008; Mair et al., 2002; Nuth
10 et al., 2010; Sundal et al., 2011). Meltwater and precipitation water are directly linked to glacier dynamics by supplying the
subglacial drainage system which lubricate the interface glacier bed/bedrock thereby reducing the basal shear stress resisting
ice flow (Bartholomew et al., 2012; Hoffman et al., 2011; Shepherd et al., 2009). In the case of tidewater glaciers, an increase
in velocity means an increase in calving rate and hence a higher loss of mass thereby contributing even more to sea level rise.
While Greenland and Antarctica are currently considered to be the main future players controlling sea level rise (DeConto and
15 Pollard, 2016; Price et al., 2011; Rignot et al., 2011), it is crucial to understand how supraglacial, englacial and subglacial
drainage systems influence each other in a glacier system, as this knowledge will make it possible to improve ice sheet models.

~~Standard model~~ Nowadays, several models patterns of subglacial conduits are ~~mainly~~ still based on the hydrological poten-
tial gradient and do not take the supraglacial drainage system into account (Fischer et al., 2005; Grabiec et al., 2017; Hagen
et al., 2000; How et al., 2017; Pälli et al., 2003; Sharp et al., 1993; Shreve, 1972; Willis et al., 2009). As a result, they consider
20 a ~~spatially uniform~~ spatial recharge (the term recharge is used here to refer to meltwater and precipitation water entering in the
subglacial drainage system from the surface of the glacier) meaning that the water recharge is ~~heterogeneous~~ homogeneous
or with some local water values over the entire surface of the glacier. This is one of the biggest assumptions that leads to
inaccurate modeling of the locations of subglacial channels (Gulley et al., 2012).
However, due to their direct impact on englacial and subglacial drainage system, studying supraglacial drainage systems is vi-
25 tal. Knowledge of these systems makes it possible to locate where the supraglacial system switches into an englacial and then
subglacial system via moulins, shear fractures or crevasses, called water input areas (WIAs), and hence to better estimate their
water ~~supply~~ recharge (Bartholomew et al., 2011; Benn et al., 2017). Indeed, concentrated surface water streams are necessary
for the formation of a channelized internal drainage system (Mavlyudov, 2006). Likewise, the supraglacial drainage system
largely influences the subglacial system by collecting meltwater and precipitation water and rapidly delivering it to discrete
30 points in the glacier bed via WIAs (Catania and Neumann, 2010; Gulley, 2009; Poinar et al., 2015; Smith et al., 2015). In addi-
tion to being an important source of water for the internal drainage system of glaciers, part of the englacial conduits are formed
by direct incision of supraglacial channels followed by creep closure (Gulley et al., 2009; Irvine-Fynn et al., 2011). Neverthe-
less, the supraglacial drainage system remains one of the least studied hydrologic processes on Earth (Smith et al., 2015).

~~Knowing that spatially uniform recharge does not represent reality~~Spatial recharge is theoretical and is not actually observed on any glacier. Consequently, some models have used discrete recharge ~~(Hewitt, 2013; Werder et al., 2013) but none has used a real~~ but only refer to limited area on a glacier or with randomly placed moulins or even as a model validation method (Hewitt, 2013; Werder et al., 2013). In fact, no precise representation of the entire supraglacial drainage system ~~or studied~~ has been used to constraint a subglacial channels model. Finally, no comparison study on the consequences of assuming ~~spatially uniform recharge~~ spatial recharge has been performed.

Our study focused on the land-terminating glacier Werenskioldbreen and the tidewater glacier Hansbreen, both located in the southern part of the Svalbard archipelago and representative of many ~~Arctic~~ Svalbard glaciers (Fig.1).

The first step consisted in identifying and mapping the supraglacial drainage features of the two glaciers using very high resolution ~~satellite (VHRS) and aerial~~ remote sensing images for the years 1990, 2010, 2011 and 2015. ~~Work combined~~ Combination with field observations ~~. Mapping the supraglacial drainage system~~ allowed us to locate water flows inside the glaciers via moulins and crevasses (Benn et al., 2017, 2009; Holmlund, 1988; Nienow and Hubbard, 2006; Van der Veen, 2007). ~~These WIAs represent the water recharge points of the englacial and (most likely) by extension, of the subglacial drainage system (Bartholomew et al., 2011; Benn et al., 2017). The second step was calculating the~~ In the second step of this study, we calculated the catchment area of each main WIA on ~~the two glaciers~~~~for the year 2015. In order to quantify the amount of water for each WIA, we calculated~~ both glaciers. Subsequently we estimated the total amount of surface water (precipitation and meltwater) ~~of~~ on the whole surface area of the two glaciers together with their surrounding slopes ~~with a spatial resolution of 100 meters,~~ for the entire 2015 ablation season. This allowed us to ~~visualize how subglacial water recharge originating from the glacier's surface is distributed, with absolute water volumes in cubic meters, along with the weight of the outflows on the system. Below, we discuss the implications of precipitation and meltwater for the subglacial drainage system.~~ map WIAs location along with their absolute water recharge volumes. The final step consisted in modeling the pattern of subglacial conduits in the two glaciers using ~~spatially uniform~~ spatial recharge and discrete recharge ~~. This approach~~ for comparison. Our attempt is new and should improve current modeling of the theoretical pattern of subglacial channels~~, more specifically~~. More specifically, we discuss our results with the subglacial conduit models proposed by Pälli et al. (2003) and Grabiec et al. (2017) for our two study glaciers, as these are only based on the hydrological potential gradient (Fischer et al., 2005; Flowers and Clarke, 2002; Sharp et al., 1993; Shreve, 1972). Moreover, contrasting model results with ~~spatially uniform~~ spatial and discrete water recharge enables a better understanding of the influence of this parameter for all glaciers.

2 Study sites and datasets

2.1 Study sites

Two different types of polythermal Svalbard glaciers were chosen because their morphology, surface and subglacial topography, dynamics, thermal state and hydrology are typical for most Svalbard glaciers (Grabiec et al., 2012b; Hagen et al., 1993, 2003a; Ignatiuk et a

. Therefore, together they are representative of the main types of ~~Arctic~~ Svalbard glaciers. Werenskioldbreen is a land-terminating glacier and Hansbreen a tidewater one. They are characterized by two different dynamics that have a direct impact on changes in both the surface topography and the drainage system. Werenskioldbreen is located in south-west Spitsbergen (77°05' N, 15°15' E) (Fig.1), flows from east to west with an average speed of less than 10 m yr^{-1} in two parallel flows divided by a central moraine (Baranowski, 1970; Grabiec et al., 2012a). It is a quite small Svalbard glacier, 6.5 km long, 2.2 km wide, with a surface area of 27.1 km^2 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 is composed of cold ice (below the pressure melting point) overlying a temperate ice layer (at the pressure melting point) ~~(Fig.1(a))~~ (Grabiec et al., 2017), thereby enabling the presence of a well-developed supraglacial drainage system (Ryser et al., 2013). Hansbreen, located at the entrance of Hornsund (77°04' N, 15°38' E) (Fig.1), flows 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 a medium size Svalbard glacier, 15.6 km long, c. 2.5 km wide on average with a surface area of 53 km^2. Its terminus forms a c. 30 m high cliff 1.9 km in width ending directly in the sea (Błaszczyk et al., 2009). Its mean ice thickness is 171 m and its maximum ice thickness is 386 m (Grabiec et al., 2012b). Temperate ice, firn and snow are present in the large accumulation area, allowing water to percolate down to the surface of the temperate ice and preventing the formation of supraglacial channels. The structure of the ablation area is similar to that of Werenskioldbreen with a cold ice layer overlying temperate ice ~~(Fig.1(b))~~ (Grabiec et al., 2017; Navarro et al., 2014), preventing dispersed infiltration of the water ~~over the entire surface of the glacier~~ below the Equilibrium Line Altitude (ELA). However, most of the surface is crevassed, thereby limiting the development of a supraglacial drainage system. Crystal Cave and Bird Brain Cave located on Hansbreen (Fig.1) are the only two ~~well-known~~ well-studied and well mapped intra-glacial drainage systems in our study area (Gulley et al., 2012; Murray et al., 2007; Schroeder, 1998; Turu, 2012).

2.2 Datasets

We used ~~0.5 m resolution VHRS~~ very high resolution (VHRS) WorldView-2 satellite images, with 0.5 m resolution, acquired on 21/08/2015 and Geoeye satellite images acquired on 10/08/2010. We also worked with sets of Norwegian Polar Institute aerial photos from 1990 and 2011. In addition to remote sensing data, field observations and a Global Positioning System (GPS) survey, were necessary to identify control points to calibrate mapping. Maps of the supraglacial drainage system already exist for Werenskioldbreen in 1990 and 2010 (Ignatiuk, 2012; Pulina et al., 1999). Bedrock digital elevation models (DEM) of Hansbreen and Werenskioldbreen at a spatial resolution of 100 m and a vertical resolution estimated at $+/-5$ m, were obtained during a survey conducted in April 2008 by the University of Silesia ~~team~~ and Institute of Geophysics Polish Academy of Sciences teams, combining GPS/GPR (ground penetrating radar) measurements (Grabiec et al., 2012b). We also created a high resolution surface DEM of both glaciers, using WorldView-2 VHRS images for the year 2015. Finally we used a meteorological dataset from the automatic weather station (AWS) located at the Polish Polar Station (PPS) (about 1.5 km from Hansbreen front) to calculate the volume of water produced by melt and precipitation during the 2015 melt season (Fig.1).
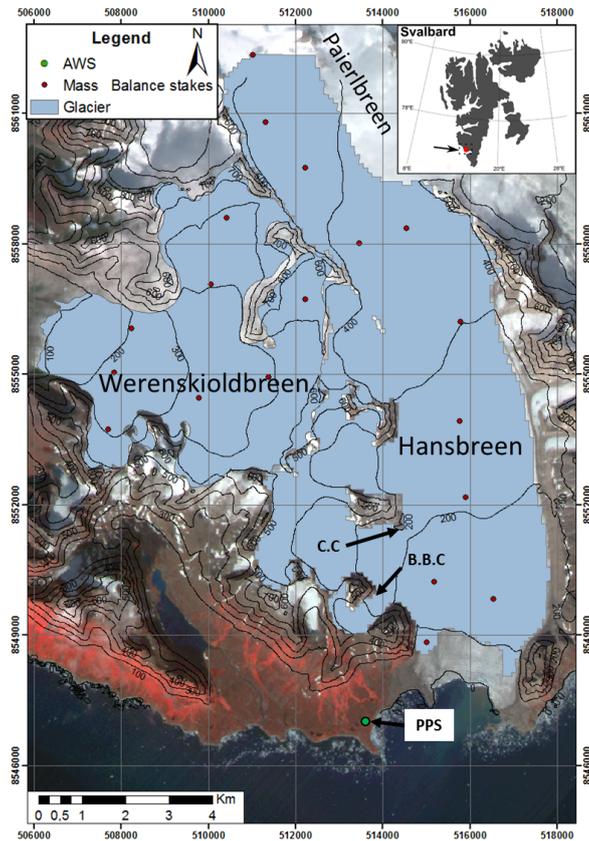
Figure 1. Map showing the location of Hansbreen and Werenskioldbreen, Svalbard, the automatic weather station (AWS), Polish Polar Station (PPS), Mass balance stakes network, Crystal Cave (C.C) and Bird Brain Cave (B.B.C). The background map is a SPOT satellite image acquired on 16/08/1988 and the coordinate system used is WGS 1984 UTM zone 33N.

3 Methods

3.1 Mapping supraglacial drainage

Based on high resolution images, we generated several maps of the supraglacial drainage system of the two glaciers for different years using ArcMap software. ~~We attempted to automate surface stream mapping, as already achieved for Greenland~~
5 ~~by Yang and Smith (2013), using a specific normalized difference water index for the ice surface ($NDWI_{ice}$). $NDWI_{ice}$ uses~~
~~a normalized ratio of blue and red bands that allows each glacier pixel to be classified as either "water" or "non-water". But~~
~~due to the broadband reflection of ice surface and stream-water overlapping each other, it was not possible to use this method~~
~~for our two glaciers.~~

~~Thus we had to map~~ We mapped the surface streams manually, leading to personal choices and naturally to some subjective
10 decisions. We decided to map only active streams with a minimum width of one meter, knowing from field observations that

5

numerous smaller streams are present, along with the limitation due to the spatial resolution of the VHRS images. In addition, we manually mapped crevassed areas and moulins with a diameter greater than one meter, enhanced by direct field observations and GPS measurements.

3.2   Calculation of WIA catchments

5 First, based on the supraglacial maps (section 3.1), we created 2015 WIA maps for both glaciers (Fig.2). WIAs were defined as substantial crevassed areas or crevassed areas intersecting active surface streams and groups of active moulins. In the large accumulation area of Hansbreen, water percolates through the snowpack, then through the firn, to finally create a layer of saturated water at the temperate ice/firn interface (Fountain and Walder, 1998; Lliboutry, 1971). The water flows along this interface, comes to the surface at the ~~equilibrium line~~ ELA or reaches the englacial system of the ablation area thanks to

10 crevasses in the accumulation zone. Because the area situated just below the ~~equilibrium line~~ ELA is considered as a WIA (large crevassed zone), we included the water from the accumulation area in it.

Next, the WorldView-2 stereo pair image from 2015 was processed with Geomatica software to create a surface DEM of our study area. The resulting DEM with a 4 m spatial resolution was delineated for both glaciers thanks to contour files obtained from orthorectified WorldView-2 images with a vertical accuracy of $+/-1.5$ m. We filled in the small sinks on the DEM

15 caused by small imperfections that occurred while we were creating the DEM, giving the impression small lakes formed on the surface which has never been observed in the second part of the ablation season on either glacier. From the corrected DEM, we calculated the flow direction from each pixel to its steepest downslope neighbor.

Finally, using standard ~~watershed~~ *watershed* modeling tool in ArcGIS, we determined the ~~watershed~~ water catchment area of each WIA with 4 m spatial resolution (Fig.2). Some manual adjustments of the catchments delineation were made when

20 necessary. The most common correction was to extend the catchment area where an active stream ending in a WIA was not included in it.

3.3   Estimation of spatially distributed runoff

The main subglacial water source is known to be controlled by runoff water from the surface of the glacier, mainly surface meltwater and precipitation (Flowers and Clarke, 2002; Hodson et al., 1998; Irvine-Fynn et al., 2011). Therefore, to create a

25 quantitative subglacial water flow model, we ~~spatialized~~ extrapolated the amount of meltwater generated by the entire surface of the glacier and the amount of the total precipitation (solid, mixed and liquid) falling on the entire surface of the glacier and on the surrounding slopes for the 2015 melt season (06/06/2015 to 10/10/2015). ~~We considered~~ Considering all types of precipitation ~~by taking~~ allows us to take into account the potential meltwater originating from summer accumulation (due to solid and mixed precipitation)~~in our calculations of total precipitation~~. In fact, we assumed that ~~any~~ all snow deposited during

30 the ablation period ~~melts~~will melt due to positive average temperature over this season. Regarding the large accumulation area of Hansbreen, a large part of the water stored in the firn due to internal accumulation was included in our model. Thanks
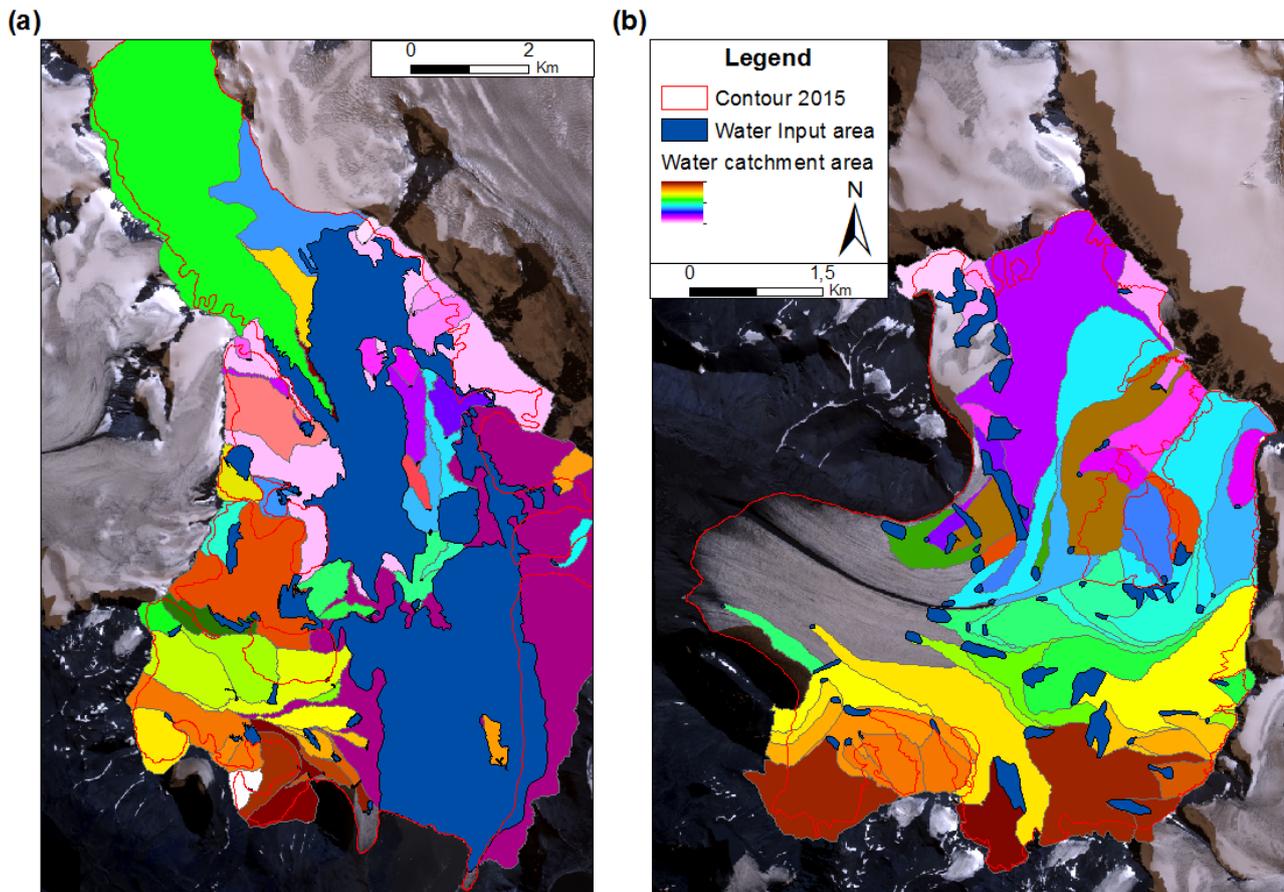
Figure 2. Hansbreen (a) and Werenskioldbreen (b) WIA catchments in 2015. The background of the map is a WorldView-2 VHRS image acquired on 21/08/2015.

to a study by Grabiec et al. (2017), we disposed of an estimation of the refreezing of capillary and percolation meltwater (excluding capillary water that freezes in the fall) in the snow and firn. It was estimated that in season 2007/2008 ~~2.3 10⁶ m³ of~~ 38% of the total meltwater refroze in the snow and firn located above the ~~equilibrium line corresponding to 38% of the total meltwater~~ELA. Therefore, in our calculations, we considered that 38% of the total meltwater in this area was ~~lost~~ trapped within the firn corresponding to $5.5 \cdot 10^6$ m³ ~~.~~ for the year 2015.

Spatial distribution in the surface ablation model was generated based on the summer mass balance ~~measurements~~ data provided by the World Glacier Monitoring Service (WGMS), relying on the mass balance stake network present on both glaciers (Fig 1) (Błaszczyk et al., in press). WGMS provides data about accumulation and ablation points on the glaciers (WGMS, 2017). Surface ablation data combine meltwater produced by the winter snow cover at the beginning of the melt season, and glacier surface melt during the rest of the melting period. The relationship identified between the summer mass

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balance and elevation (R^2 = 0.83) allowed us to model meltwater production (Q_M) for the whole glacier. Surface ablation was approximated by interpolation of stake data over the area (grid 100x100m) at a range of elevations.

In the precipitation model, spatial distribution was calculated as follows. ~~Using~~ Applying a precipitation gradient (Δ_P) of 19% per 100 m ~~and catching error~~(including catching error) calculated by Nowak and Hodson (2013) ~~and knowing the precipitation value measured at the PPS (Q_{PPS}~~ to the precipitation measured at PPS (Q_0), we were able to calculate the amount of precipitation (Q_P) at each altitude (h), in any DEM cell using 1:

$$Q_P = Q_{PPS0} + (\Delta_P Q_{PPS0} h) \tag{1}$$

Therefore, combining the meltwater produced by the whole glacier with the amount of precipitation at each altitude, we were able to calculate the total glacier runoff (Q_H) in any DEM cells following equation 2:

$$Q_H = Q_M + Q_P \tag{2}$$

Surface ablation modeling errors (σ_{Q_M}) were calculated using the standard error of the regression. Errors in the spatial distribution of the precipitation model (σ_{Q_P}) were calculated using the method of total differential function according to equation 3:

$$\sigma_{Q_P} = (\Delta_P h + 1)\sigma_{Q_{PPS} Q_0} + \Delta_P \sigma_h Q_{PPS0} \tag{3}$$

where σ_h is the DEM error and ~~$\sigma_{Q_{PPS}}$~~ σ_{Q_0} the precipitation measurement error at the PPS.

Therefore, we were able to calculate the total glacier runoff error σ_{Q_H} according to equation 4:

$$\sigma_{Q_H} = \underline{\sigma_{Q_M} + \sigma_{Q_P}} \sqrt{\sigma_{Q_M}^2 + \sigma_{Q_P}^2} \tag{4}$$

~~It~~ We are aware that the error of precipitation spatial distribution is possibly larger due to expected substantial meteorological variations between rainfall events. However, calculated total glacier runoff error coincide with Nowak and Hodson (2013) estimations. Moreover, it should be kept in mind that we might have underestimated the total amount of water runoff due to storage of liquid water in the ~~snow pack~~ snowpack and in the firn layer during the winter/spring period which is released during the melt season (Arnold et al., 1998).

3.4 Subglacial modeling

The theoretical pattern of subglacial channels was modeled for the year 2015. This required knowledge of the surface and bedrock topography of the glacier (section 2.2), and of the spatial distribution of ice thickness resulting from them. The spatial resolution of our model was limited by the 100 m resolution of the bedrock DEMs. We consequently had to upscale surface
5   DEMs (section 2.2), WIA catchment maps (section 3.2) and the ~~spatialized~~ spatially distributed water runoff model (section 3.3) in a 100 m grid. Surface and bedrock DEMs had a vertical accuracy of a few meters, which does not have much impact on our results with respect to the resolution of the spatial model (Fischer et al., 2005).

Water is known to circulate on, in and under glaciers in response to the hydraulic potential gradient (Shreve, 1972). ~~Standard~~ Many models, and particularly the latest theoretical pattern of subglacial channels modeled by Grabiec et al. (2017); Pälli
10 et al. (2003), are based on this gradient. We also based our model on this gradient except that we considered water circulation depends not only on the hydraulic potential gradient but also on some glaciological components. Subglacial drainage patterns 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) according to equation 5:

$$K = \frac{P_w}{P_i} \tag{5}$$

15 Therefore, as gridded values of surface and bedrock elevation can be used to model the subglacial drainage pattern from ~~spatialized hydraulic potential~~ calculated hydraulic potential field Φ, we used equation 6:

$$\Phi = \rho_w g z_b + K[\rho_i g(z_s - z_b)] \tag{6}$$

where ρ_w is water density (1000 kg.m^{-3}), ρ_i is 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 elevation.

20 The direction of subglacial water flow was determined based on the hydraulic potential field (Φ calculated for each grid cell). Water flows perpendicularly to the equipotential lines of the hydraulic potential field. We calculated the flow direction in each cell by identifying the neighboring cell with the lowest hydraulic potential value. The next step in the simulation calculates accumulated flow into each grid cell according to our flow direction model. The grid cells with the highest accumulation shape the lines of preferable water flow. ~~At this stagein a standard model,~~ Several models stop at this stage, for which the cell value
25 denotes a cumulative number of cells due to the water inflow to this specific cell. Such a model may be able to successfully predict the location of plumes in front of a tidewater glacier (How et al., 2017). In order to go one step further, knowing the size of the cell, the value can easily be transferred to a drained surface area. In order to quantify the water drained through the system, the total amount of meltwater and precipitation (Q_H) in the 2015 melt season was calculated and assigned to each grid

cell, as described in section 3.3. The cells' values were then accumulated as described above, giving concentrated flow lines and water values through specific cells.

3.5 Model runs

We created ~~five~~ two different simulation scenarios to take some glaciological and meteorological components into account:

1. **~~Standard hydraulic~~ Hydraulic potential ~~model~~(ablation + precipitation input)**

   This model considers a ~~spatially uniform~~ spatial recharge of water, all the grid cells of the model are weighted ~~with a value equal to 1.~~ as a function of the spatially distributed water runoff model values (Q_H) (section 3.3) (Fig.3). It corresponds to the last stage of the theoretical pattern of subglacial channels models achieved in our study area by Grabiec et al. (2017); Pälli et al. (2003) but updated for the year ~~2015.~~ 2015 and with water volume values.

2. **~~Standard hydraulic potential (ablation + precipitation input)~~** ~~This model considers a spatially uniform recharge of water , all the grid cells of the model are weighted as a function of the spatialized water runoff model values(Q_H) (section 3.3) (Fig. 3).~~

3. **WIA (ablation + precipitation input)**

   This model considers a discrete recharge of water, all the grid cells of the model corresponding to a WIA are weighted by the ~~amount of meltwater (Q_M~~total amount of runoff (Q_H) (section 3.3) ~~produced by~~occurring on their particular catchment (section 3.2). All the other grid cells ~~in~~of the model are weighted with a value equal to ~~0.~~

4. **~~WIA (precipitation input)~~** ~~This model considers a discrete recharge of water, all the grid cells of the model corresponding to a WIA are weighted by the amount of precipitation (Q_P)(section 3.3) occurring on their particular catchment (section 3.2). All the other grid cells of the model are weighted with a value equal to 0.~~

5. **~~WIA (ablation + precipitation input)~~** ~~This model 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 (Q_H) (section 3.3) occurring on their particular catchment (section 3.2). All the other grid cells of the model are weighted with a value equal to~~ 0 (Fig.4). (Furthermore, in order to study the proportion of melt and precipitation water, the model has been run considering either the amount of meltwater (Q_M) or the amount of precipitation (Q_P)).

Accordingly for ~~scenarios (3, 4, 5~~scenario (2)), the volume of water reaching each moulin or crevasse area was calculated. It depended not only on the surface topography but also on the surface conditions such as bare ice, firn and snow.

Water pressure in conduits depends directly on discharge (Röthlisberger, 1972) that in turn, relies on recharge. Therefore, water pressure in conduits is directly affected by the available amount of surface water (melt and precipitation) and

Majchrowska et al. (2015) observed marked fluctuations in melt and precipitation rates during the ablation seasons from 2007-2012 on Werenskioldbreen. High pressure events (water pressure at ice overburden pressure) have 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 ~~geyser-like spouts of water~~ artesian features and over pressurized water

5   outflows have been observed on Werenskioldbreen (Baranowski, 1977). Consequently, we modeled the subglacial channels for different K values ($K = 1$; $K = 0.85$; $K = 0.75$; $K = 0.5$; $K = 0.25$; $K = 0$) for ~~all the~~ the two different scenarios for both glaciers~~(resulting in 60 simulationswhich, for obvious reasons, are not all presented here)~~, resulting in 24 simulations.

Therefore, our model considers:

(i) The surface properties of the glacier, and hence the location of runoff and water percolation areas;

10   (ii) The supraglacial drainage catchment structure of the glacier with respect to the WIAs, and hence the volumes of runoff along particular drainage pathways;

(iii) The water volume (meltwater plus precipitation) input to the system throughout the ablation season;

(iv) Several water pressure K scenarios in the channels, mainly to illustrate distinct periods of the melt season~~; (v)The presumed location of the main subglacial channels, to acquire the fundamental knowledge needed to model meltwater~~

15   ~~discharge~~.

In theory, a subglacial drainage system of glaciers involves a distributed and channelized system (Kessler and Anderson, 2004). Because most subglacial water transport occurs in conduits, sustained by the balance between the creep closure effect and melting due to heat released by the water flux (Hewitt, 2011; Nye, 1953; Röthlisberger, 1972), we did not include the distributed part of the subglacial drainage system but focused on the channelized component.
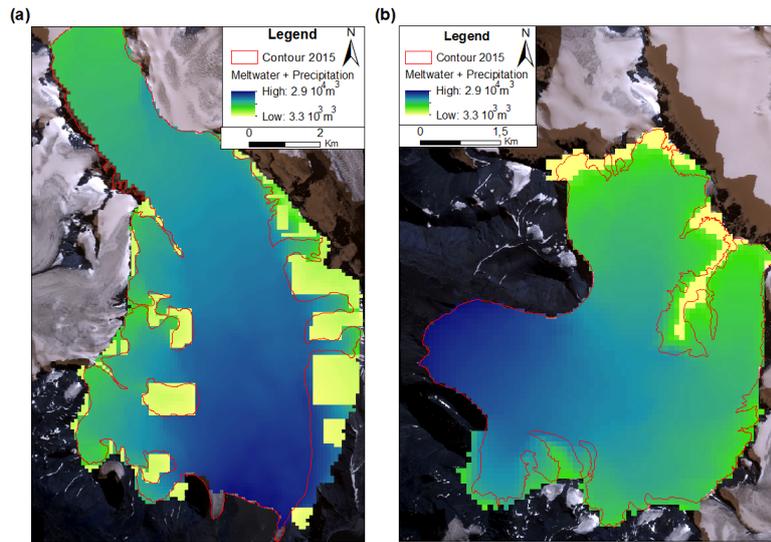
Figure 3. ~~Spatially uniform~~ Spatial water recharge (meltwater + precipitation) for Hansbreen (a) and Werenskioldbreen (b) in 2015. The map background is a WorldView-2 VHRS image acquired on 21/08/2015.
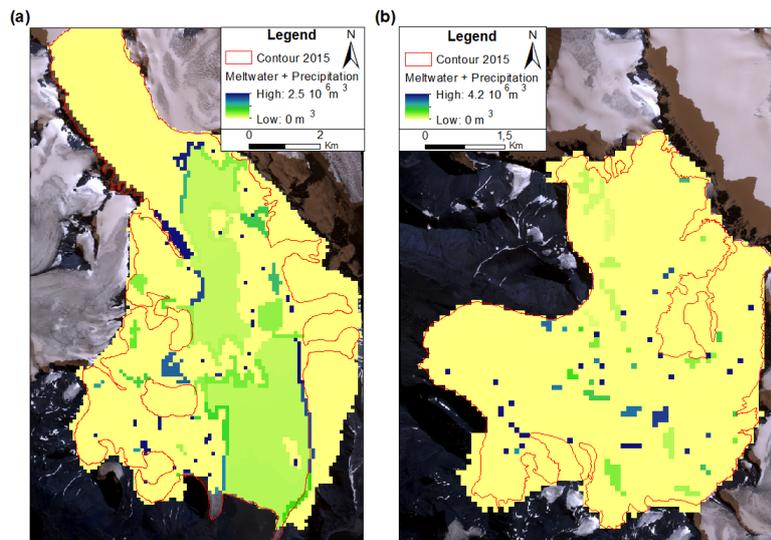
Figure 4. Discrete water recharge (meltwater + precipitation) for Hansbreen (a) and Werenskioldbreen (b) in 2015. The map background is a WorldView-2 VHRS image acquired on 21/08/2015.

4 Results

4.1 ~~Changes~~ Temporal changes in the supraglacial drainage system

The ~~maps~~ mapping of the supraglacial drainage systems of the two glaciers in 2015 only included crevassed areas, moulins, superficial percolation zones and runoff places leading to the WIAs used in our model (Fig.2). However, maps of the whole supraglacial drainage system (including surface streams) for different years were only produced for Werenskioldbreen. In fact unlike Hansbreen, it has limited crevassed areas sustaining a well-developed supraglacial drainage system that allowed us to study the changes it has undergone.

We compared the supraglacial drainage system of Werenskioldbreen at two different timescales, annual (2010-2011) and decadal (1990-2010). Changes in the glacier's geometry were observed in this period (Gajek et al., 2009; Ignatiuk et al., 2014). The supraglacial hydrology of glaciers depends directly on the surface topography (Grabiec et al., 2012b; Nienow and Hubbard, 2006). A change in the supraglacial drainage system would therefore be expected at the decadal timescale, giving us the opportunity to better understand the physical mechanisms controlling it. Figure 5(a) shows the different supraglacial drainage features for the years 1990 (black) and 2010 (blue). First, the fact the surface streams are consistent in the two years is clearly visible, especially on the lower part of the glacier. Then several changes in the system can be observed, identified by numbers in Figure 5(a):

1. Creation of new 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. It was impossible to map the surface drainage features due to a thick snow cover at the end of the 2010 ablation season.

Figure 5(b) shows the different supraglacial features in the years 2010 (blue) and 2011 (green). The two supraglacial drainage systems are more consistent, and some small differences can be distinguished due to the snow cover which made it impossible to map exactly the same areas.

4.2 Modeling the theoretical pattern of subglacial channels

The results of the simulations of scenarios (1)~~and (2)~~, mentioned in section 3.4, ~~logically display the same patterns of subglacial channels as both are based on the spatially uniform water recharge test case. Their difference~~ represents the first improvement to the model of our study area mentioned in this article: we now have a quantitative model ~~(scenario (2)) compared to our scenario (1), which is only qualitative. For this reason, we only discuss the results of scenario (2) (Fig.6(a); 6(b); 6(c) and Fig.7(a); 7(b); 7(c)).~~ compared to the previous models of Grabiec et al. (2017) and Pälli et al. (2003) which are only qualitative.
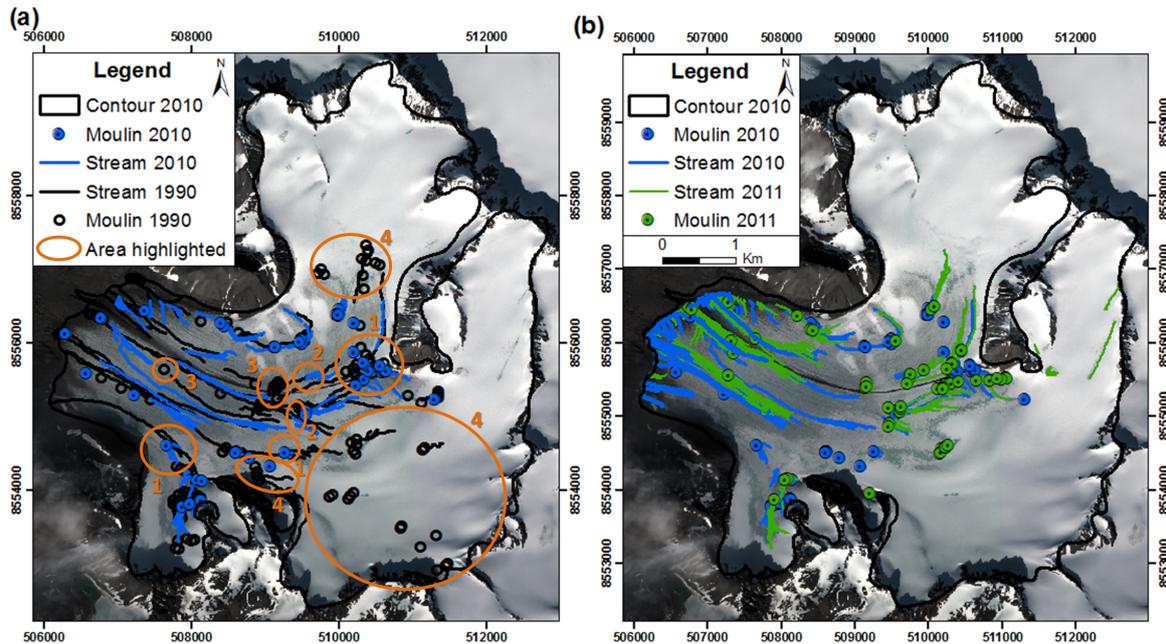
Figure 5. Comparison of the supraglacial drainage system for Werenskioldbreen on a decadal timescale (a) and on an annual timescale (b). Explanations for the numbers are given in in the text. The map background is a GeoEye-1 VHRS image acquired on 10/08/2010 and the coordinate system used is WGS 1984 UTM zone 33N.

~~The results of the simulations of scenarios (3), (4) and (5), mentioned in section 3.4, logically display the same patterns of subglacial channels, since they are all based on the discrete water recharge test case. The fact water recharge is controlled either by meltwater or precipitation, or even by both, does not influence the path of the subglacial conduit due to the predominance of the discrete recharge. Thus, we only discuss the results of the most complete scenario (5) (Fig. 6(d); 6(e); 6(f) and Fig.7(d); 7(e); 7(f)).~~

Because all the simulation 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 water pressure states of simulations in this study, $K = 1$, $K = 0.85$ and $K < 0.85$, represented here by $K = 0$ (Fig.6 and 7). The three other states $K = 0.25$, $K = 0.5$ and $K = 0.75$ are given in the appendix section (Fig.1 and Fig.2).

~~Spatially uniform~~ Spatial and discrete water recharge maps (Fig.6) showed very similar results for Hansbreen except that Crystal Cave and Bird Brain Cave conduits were better represented with a discrete water recharge. In the simulations, no subglacial channels started at these two locations, as is the case in reality when considering a ~~spatially uniform~~ spatial water recharge. In all cases, a general north-west to south-east subglacial water flow exists with one main channel in the eastern part of the glacier. Near the glacier front, the main flow direction changes from north-east to south-west. In the simulations in which $K = 0$ (Fig.6(c) and Fig.6(f)), all the channels are connected to the main channel and have the same outflow at the glacier front.

Simulations in which $K = 0.85$ (Fig.6(b) and Fig.6(e)) and $K = 1$ (Fig.6(a) and Fig.6(d)) show three outflows, the two eastern ones are consistent in the simulations, but the western one is located further west when $K = 1$ than when $K = 0.85$ (Fig.6(a) and Fig.6(d)). In all the scenarios, except scenario (21) with $K = 0$, the main subglacial channel is generated just below the firn line (Fig.6).

5   Concerning Werenskioldbreen, compared to scenario (21) (Fig.7(a); 7(b); 7(c)), scenario (52) (Fig.7(d); 7(e); 7(f)) displays a more dendritic channel network in the central part of the glacier and the conduits start at lower elevations. All the simulations show a main channel flowing in the central part of the glacier, with the same outflows when $K = 1$ (Fig.7(a) and Fig.7(d)) and $K = 0$ (Fig.7(c) and Fig.7(f)), and an outflow located further south when $K = 0.85$ (Fig.7(b) and Fig.7(e)). Scenario (21), in which $K = 1$, shows five outflows (Fig.7(a)) whereas in scenario (52) three outflows are modeled (Fig.7(d)). In the simulations

10   in which $K = 0.85$, three outflows are visible in scenario (21) (Fig.7(b)) and two outflows in scenario (52) (Fig.7(e)). When $K = 0$, both scenarios exhibit only one outflow (Fig.7(c) and Fig.7(f)). Compared to the previous model proposed by Pälli et al. (2003), none of our model scenarios suggest a subglacial flow separated by the medial moraine present on Werenskioldbreen.

      Overall, compared to ~~spatially uniform~~ spatial recharge results, discrete recharge maps exhibit conduits starting at lower elevations with additional subglacial branches, meaning they match the location of the moulins and small crevassed areas

15   better.

15
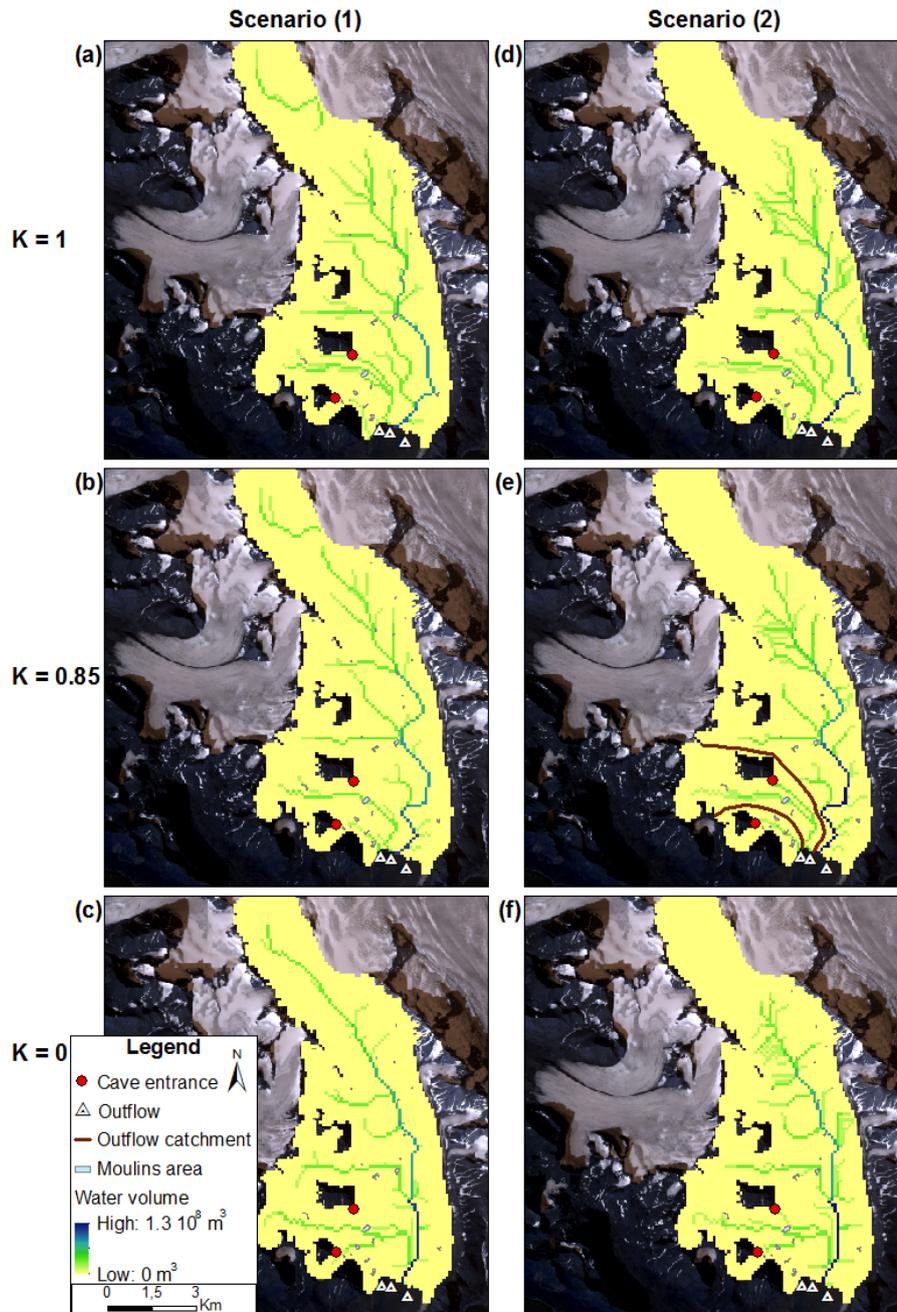
Figure 6. Map of the theoretical pattern of subglacial channels of Hansbreen modeled with scenario (21) ($K = 1$ (a); $K = 0.85$ (b); $K = 0$ (c)) and (52) ($K = 1$ (d); $K = 0.85$ (e); $K = 0$ (f)). The map background is a WorldView-2 VHRS image acquired on 21/08/2015.

16
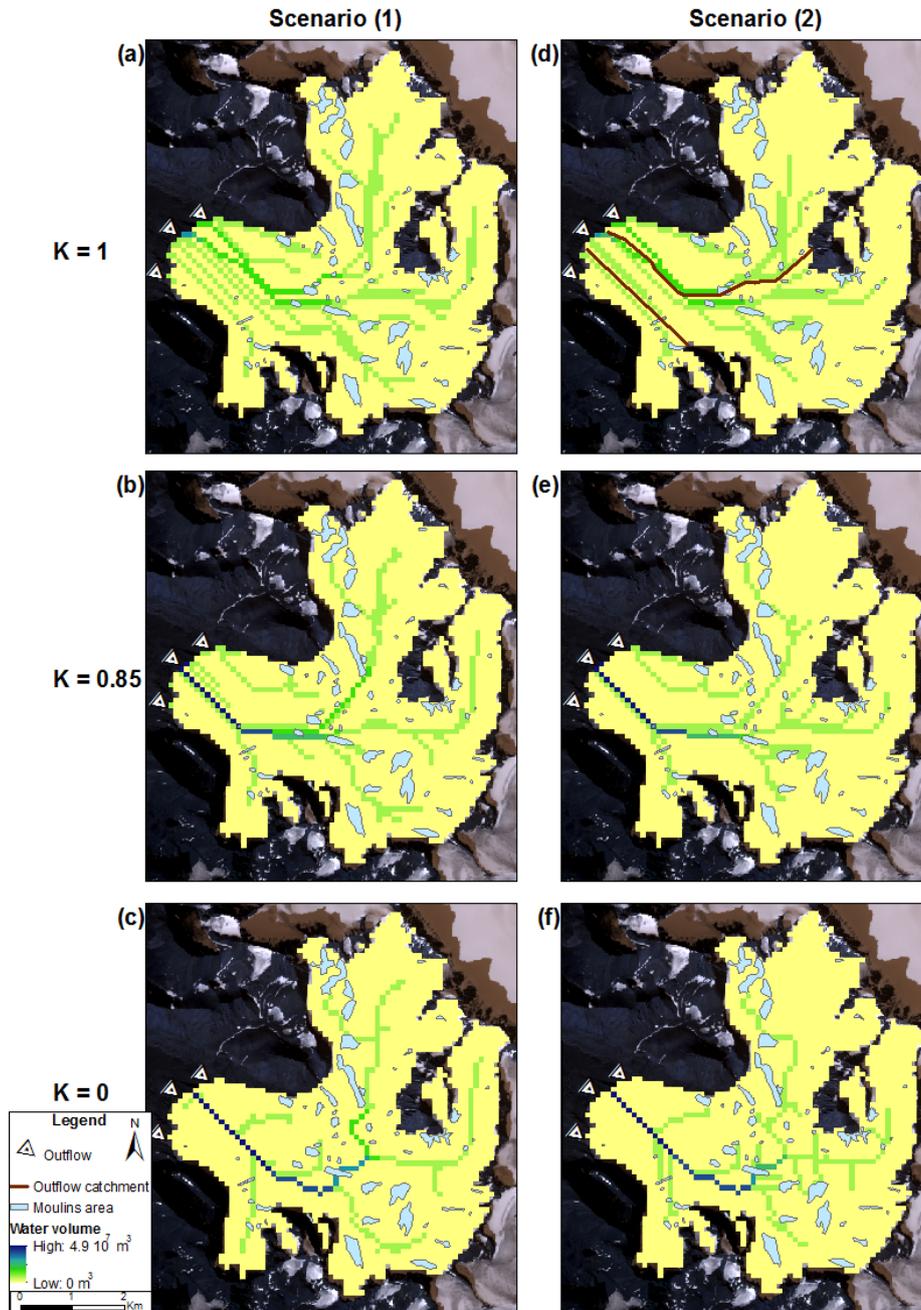
Figure 7. Map of the theoretical pattern of subglacial channels in Werenskioldbreen modeled with scenario (21) ($K = 1$ (a); $K = 0.85$ (b); $K = 0$ (c)) and (52) ($K = 1$ (d); $K = 0.85$ (e); $K = 0$ (f)). The map background is a WorldView-2 VHRS image acquired on 21/08/2015.

5   Discussion

~~The fact that our attempt~~ We attempted to automate surface stream mapping, as already achieved for Greenland by Yang and Smith (2013), using a specific normalized difference water index for the ice surface ~~,~~ $(NDWI_{ice})$. $NDWI_{ice}$ uses a normalized ratio of blue and red bands that allows each glacier pixel to be classified as either "water" or "non-water". The fact that it was not successful has several explanations. First, supraglacial streams in Svalbard glaciers are much smaller than those in ~~Greenlandic~~Greenland. Second, Svalbard glaciers are surrounded by mountains that influence the surface conditions of the glaciers, which is not the case for the Greenland ice sheet. The surfaces of Svalbard glaciers are "dirty", i.e. they contain many small rocks or dust that blows down the mountain slopes and lands on the surface of the glaciers, changing the reflectance properties of the surface's features into a broadband signal rather than a well separated signal specific to each feature. Indeed, looking at optical satellite images, surface streams in Greenland appear as a wide blue line overlying clean ice, which is not the case for Svalbard glacier's streams. Moreover, in Svalbard, there is extensive ice foliation and a network of shear fractures caused by friction with the surrounding mountains that closely resemble surface streams.

The consistency of surface streams on a decadal timescale (Fig.5(a)), especially on the lower part of Werenskioldbreen, could be explained by the weak ~~dynamic~~ dynamics of the front and the fact that the longer a stream remains active and the deeper it carves into the glacier's surface, the more likely it is to survive. Despite these similarities, we observed several changes in the supraglacial drainage system on a decadal timescale in response to changes in geometry caused by climate warming and glacier flow. The occurrence of new moulins and new crevasses has a direct impact on the subglacial drainage system by creating new WIAs followed by potentially new subglacial channels. Abandoned moulins also deactivate the englacial and subglacial conduits they previously supplied with water (Holmlund, 1988; Nienow et al., 1998; Poinar et al., 2015). In the absence of internal water pressure and erosion, such conduits may then be closed by ice deformation. Nevertheless, observed supraglacial changes does not seem to imply a complete reorganization of the subglacial system (e.g. like after a surge event). In fact, new WIAs are either in a relatively close area (about 300 m^2) of the old ones or on the same subglacial channels axes than the pre-existing ones. Especially with abandoned moulins which see the creation of new upstream moulins.

It is therefore crucial to investigate the permanency of the supraglacial drainage system of this glacier because it informs the validity of the duration of our model. ~~Moreover, assuming changes in timescale are the same for all Arctic glaciers makes it possible to extrapolate our results to the entire Arctic.~~ Supraglacial drainage patterns are relatively persistent on an annual timescale (Fig.5(b)) as expected from the study of Nienow and Hubbard (2006). Their study suggests that a subglacial drainage system remains relatively steady from year to year. Finally, considering the ~~few~~ low impact of decadal timescale changes in the supraglacial drainage system ~~on a decadal timescale~~ (Fig.5(a)) on the subglacial system, we can consider that our model is valid, ~~perhaps~~ with some minor 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 by displaying only a few changes regarding the subglacial patterns and the outflows locations.

The three different water pressure states of simulations described in section 4.2 may be representative of two different melt season periods:

- $K = 1$ and $K = 0.85$ may represent the beginning of the melt season when a considerable amount of water is delivered to the hydrological system due to melting of the winter snow mantle. It may also illustrate heavy rainfall and ice melt events. In these conditions, the channels are filled or nearly filled with water, $P_w = P_i$ or $P_w = 0.85P_i$, and water flow may be mainly controlled by the surface topography of the glacier (Flowers and Clarke, 1999).

5   - $K < 0.85$ may represent all the other periods of the melt season. Especially after a high melting event (K value will be close to 0) when the conduits have been extensively enlarged, caused by the walls melting due to the frictional heat released by an intense turbulent water flow, combined with a small water input volume. Under such conditions, the channels are not full of water, $P_w < P_i$ and the water flow may be controlled mainly by the bedrock topography of the glacier (Hagen et al., 2000; Sharp et al., 1993).

10   The total calculated volume of water entering Hansbreen over the whole 2015 melt season is ~~132.73~~ 132.7 10^6 $+/-$ ~~5.40~~ 4.2 10^6 m^3, of which 74% is meltwater and 26% precipitation. Taken together, the theoretical patterns of subglacial channels modelled indicate that most of the water is drained by a main conduit located on the east side of the glacier (Fig.6). ~~Scenarios (2) and (5)~~ Both scenarios exhibit more or less the same subglacial conduits in the ablation area as a result of a heavily crevassed surface. In fact, in scenario (~~5~~2) most of the glacier surface in this area is considered as a WIA (Fig.2(a)) whereas in scenario

15 (~~2~~1) the entire surface is considered as a WIA. Therefore, in scenario (~~5~~2), only 47% of the total water input volume, of the ablation area, is drained in a discrete manner whereas the percentage for Werenskioldbreen is 100% (Fig.4). This is due to the fact that in general, tidewater glaciers are more crevassed than land-terminating glaciers because their greater dynamics are related to the difference in the morphology of their fronts (Larsen et al., 2007; Moon and Joughin, 2008; Van der Veen, 2007) whereas their subglacial hydrology system is very similar. However, scenario (~~2~~1) displays some subglacial channels in

20 the accumulation area while scenario (~~5~~2) does not. This is the main improvement represented by our results, in considering a discrete water recharge for this type of glacier. Scenario (~~5~~2) in which $K = 0.85$ (Fig.6(e)) is most in agreement with field observations. In fact, it is the only scenario that represents the ~~well-known~~ well-studied subglacial channels generated by Crystal Cave and Bird Brain Cave (Gulley et al., 2012; Murray et al., 2007; Schroeder, 1998; Turu, 2012), with a coherent orientation compared to existing maps (Benn et al., 2009; Mankoff et al., 2017) and the authors' personal ~~unpublished maps~~observations,

25 along with the best location of outflows. In fact, the authors visited those two caves systems several times a year since a few years and repeated observations confirmed that the data cited above are still valid. However, the locations of the modeled outflows do not correspond perfectly with our observations and the one made by Grabiec et al. (2017); Pälli et al. (2003) (locations of sediment plumes, turbid water spots and visible R-channel). This is due to a lack of GPR data at the glacier front because of the presence of too many crevasses. The three outflows have their own water catchments and therefore drain different amounts

30 of water (Fig.6(e)). According to our results, the western outflow drained 2.7% of the total water volume, the central outflow 14.8% and the eastern one 82.5%.

    The total calculated volume of water entering Werenskioldbreen over the whole 2015 melt season is ~~43.81~~43.8 10^6 $+/-$ ~~1.96~~ 1.4 10^6 m^3 of which 68.7% meltwater and 31.3% precipitation. The total annual runoff from the Werenskioldbreen basin from

2007 to 2012 measured by Majchrowska et al. (2015) ranged between 56.37 and 98.71 10^6 m^3. First, there is notable variability from year to year. Second, the Werenskioldbreen basin considered in the study by Majchrowska et al. (2015) included the glacier forefield, meaning their study area was larger than ours. Third, we only considered the runoff from 06/06/2015 to 10/10/2015, not for the whole year. Finally, we underestimate the total runoff by only taking the water derived from precipitation and surface melting into account. For these reasons, we can be quite satisfied with our modeled value, which is of about the same order of magnitude as those measured in the preceding years. Regarding our distribution of water sources, we can also be quite satisfied when we compare it with calculations made by Majchrowska et al. (2015). In 2009, total runoff comprised 71% meltwater, 17% precipitation and 9% other sources, and in 2011 it was 63% meltwater, 28% precipitation and 9% other sources. All the model results of the theoretical pattern of subglacial channels indicate that most of the water is drained by a main conduit located in the central part of the glacier whose outflow is located further south of the medial moraine (Fig.7). ~~Scenarios (2) and (5)~~ Both scenarios produce different results because of the low glacier dynamics leading to a poorly crevassed surface resulting in considerable differences in water recharge between the ~~spatially uniform~~ spatial (Fig.3(b)) and the discrete (Fig.4(b)) test cases. Scenario (~~5~~2) in which $K = 1$ (Fig.7(d)), with one outflow located in the northern part of the medial moraine and two outflows in its southern part, best matches field observations. In fact, the modeled locations of the outflows in this simulation fit quite good our observations and the one made by Grabiec et al. (2017); Majchrowska et al. (2015); Pälli et al. (2003) (location of streams in the glacier forefield). The three outflows have their own water catchments and therefore drain different amounts of water (Fig.7(d)). The northern one drained 35% of the total water, the central one 51.6% and the southern one 13.4%. The fact that our model does not appear to be influenced by Werenskioldbreen medial moraine, unlike the model of Pälli et al. (2003), may be due to the new geometry of the glacier in 2015 compared to that in 1999. However, some dye tracing measurements have shown that subglacial water can flow across this medial moraine area during about the same modeling period as that used in the study by Pälli et al. (2003). Regarding Werenskioldbreen's moulins, we observed that those located at higher elevations are supplied by more precipitation than meltwater, contrary to the moulins located at lower elevations e.g. two moulins situated at 420 m a.s.l. are supplied by 69% meltwater and 31% precipitation and one moulin situated at 112 m a.s.l. is supplied by 85.7% meltwater and 14.3% precipitation. Such observation shows that water recharge regarding melt and precipitation water proportion is heterogeneous on the glacier surface. This tendency was not observed on Hansbreen, probably due to its less steep slope and the smaller range of elevation of the cold ice surface compared to Werenskioldbreen.

The fact that discrete recharge models generate subglacial channels starting at lower elevations and prevent any conduits from being generated in the accumulation area may be consistent with reality. In fact, we know that water does not penetrate the bare ice surface of a glacier without the presence of crevasses or moulins, (Fountain and Walder, 1998; Hodgkins, 1997; Lliboutry, 1971; Paterson, 1994; Ryser et al., 2013), and that water percolates through the snowpack and the firn to flow at the temperate ice/firn interface, and also that WIAs are mainly located in the central part of the two glaciers we studied. In some simulations of Hansbreen with scenario (~~2~~1) (Fig.6(a); 6(b) and appendix Fig.1(a)) we observed a subglacial channel in the accumulation area 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 Paierlbreen's drainage system to influence the Hansbreen drainage

system, but not necessarily. In fact, since Paierlbreen surged in 2006, the ice division was drained downslope thereby reducing Paierlbreen's ice pressure on Hansbreen and facilitating the flow of water from the upper part of the Hansbreen system to the Paierlbreen system than the contrary. ~~Moreover, it is satisfying to~~ Therefore, it may fit to the reality to observe this state under high water pressure conditions ($K = 1$, $K = 0.85$ and $K = 0.75$) (Fig.6(a); 6(b) and appendix Fig.1(a)) and not under

5 atmospheric or low water pressure conditions ($K = 0$, $K = 0.25$ and $K = 0.5$) (Fig. 6(c), and appendix Fig.1(b); Fig.1(c)) because of the presence of a bedrock obstacle at this location. Also, a greater number of modeled channels are observed in the simulations in which $K = 1$, than in the simulation in which $K < 1$ (Fig.7). This may be due to the fact that when $K = 1$ new temporary subglacial channels are created due to ~~overpressurized water~~ higher water pressure in the distributed system (Hewitt, 2011). It is ~~quite satisfying to be~~ worth to highlight that we are able to observe these two phenomenons even without

10 the representation of the distributed drainage system in the model.

The volumes of water may be underestimated in the model. Indeed we did not take in account water stored in the ~~snow pack~~ snowpack and in the firn layer during the winter/spring period, which is then released during the melt season, nor subglacial meltwater produced at the glacier bed due to geothermal flux and melting of the subglacial channel walls due to the heat transfer induced by the water circulating within the conduits. Despite these simplifications in our estimations of water volumes,

15 since meltwater is by far the most important source of water recharge in the subglacial system and that precipitation water is included in our model, we can assume that any water sources that are not taken into account in our study can be neglected Cogley et al. (2011); Hock (2005); Irvine-Fynn et al. (2011); Jansson et al. (2003).

6 Conclusions

The supply of water from surface melt is the most influential runoff component ~~(Shreve, 1972)~~, confirmed by the difference of

20 ~~one order of magnitude~~ a factor of three in the amount of water provided by melt (72.5%) and precipitation (27.5%) during the 2015 melt season for Hansbreen and Werenskioldbreen. ~~Water coming from glacier surface is the main source for subglacial drainage, so we decided to identify changes in the supraglacial drainage system before modeling the patterns of theoretical subglacial channels underneath both glaciers.~~

~~Changes~~ We can conclude that changes in the supraglacial drainage system on a decadal timescale resulted in adjustments

25 of the subglacial drainage system in response to the activation or deactivation of WIAs. ~~On the contrary, on~~ Nevertheless, regarding our two study glaciers, the WIAs location is a bit shifted (about 300 m) but generally stay on the same subglacial axes which does not result in a fundamental reorganization of the subglacial system. On an annual timescale, the superficial drainage system of ~~Arctic~~ both glaciers remains spatially consistent, implying similar subglacial drainage systems.

The theoretical pattern of subglacial channels ~~was modeled for the year 2015. First, by considering a spatially uniform~~

30 ~~recharge of water as applied in the standard approach (scenario (1)). Next,~~ under water pressure conditions, ranging from atmospheric to ice overburden, was modeled taking into account local meltwater and precipitation ~~in the melt season (Fig.6(a);~~

~~6(b); 6(c) and Fig.7(a); 7(b); 7(c)), allowed us to progress from a qualitative to a quantitative model. Finally, by~~ and forcing water penetration inside the glacier thanks to identifying the ~~location of WIAs(Fig.2) we achieved more realistic results (Fig.6(d); 6(e); 6(f) and Fig.7(d); 7(e); 7(f)). Therefore, contrary to the standard model based only on hydraulic potential~~

5 ~~gradient and substantiated by the location of active moulins (Fischer et al., 2005), we integrated those moulins along with crevassed areas and the physical properties of the glacier surface in our model. Moreover, knowing that water pressure inside subglacial conduits can vary from atmospheric to ice overburden conditions, all the scenarios were modeled using several different K values ($K = 1$; $K = 0.85$; $K = 0.75$; $K = 0.5$; $K = 0.25$; $K = 0$) (Fig.6; 7 and appendix Fig.1; 2).~~ locations of WIAs, for the melt season 2015.

It can be concluded that, considering a discrete water recharge makes it impossible to display some subglacial channels in
10 the accumulation area ~~which can not be the case~~ formed by surface water supply which is consistent with previous theoretical studies (Fountain and Walder, 1998; Lliboutry, 1971). Concerning Svalbard tidewater glaciers, which have large crevassed areas, modeled patterns of theoretical subglacial channels assuming a ~~spatially uniform~~ spatial water recharge display some imprecisions but are far from being incorrect, especially for the ablation zone~~(Van der Veen, 2007)~~. The same ~~is~~ may be true for badly crevassed glaciers during the active phase of a surge. On the contrary, it is important to consider a discrete water
15 recharge for Svalbard land-terminating glaciers with limited crevassed areas (which is mainly the case in this type of glacier). This ~~is~~ may be also true for long flat Svalbard tidewater glaciers or even glaciers in a quiescent phase of a surge. In any case, considering a discrete water recharge when modeling patterns of theoretical subglacial channels makes it possible to achieve more realistic results.

~~The fact that changes~~ Changes in the location of subglacial channels depend to a great extent on changes at the surface
20 (topography and supraglacial drainage system)~~, in the~~. The permanency of the supraglacial drainage system from year to year ~~(Fig.5(b)) and the limited number of~~ and the lack of major changes on a decadal timescale~~(Fig.5(a)), we can~~, allow us to consider our subglacial channels models ~~of Arctic glaciers are~~ valid, maybe with 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.~~

25 This paper presents a new way of modeling the pattern of subglacial conduits of glaciers~~by taking into account a realistic~~. In fact, it includes a discrete water recharge~~and by considering~~, based on a precise mapping of the entire glacier surface, and the volume of ~~available water from the glacier surface thereby producing~~ water runoff specific to every WIAs. Consequently, it produce more realistic results than was previously possible. Our model results are validated by observed locations of the outflows of subglacial channels at the front of our two studied cases. A more accurate reconstruction of the routes of subglacial
30 water flow 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 systems like permeability or even water pressure, can influence the location of subglacial channels (Hewitt, 2011).~~ Our model also

needs to be compared with a greater amount of field data such as dye tracing measurements and a survey of water discharge from several supraglacial streams sustaining moulins and of glacier outflows.

Code availability. TEXT

Data availability. TEXT

5 *Code and data availability.* TEXT

Author contributions. TEXT

Competing interests. TEXT

Disclaimer. TEXT

Appendix
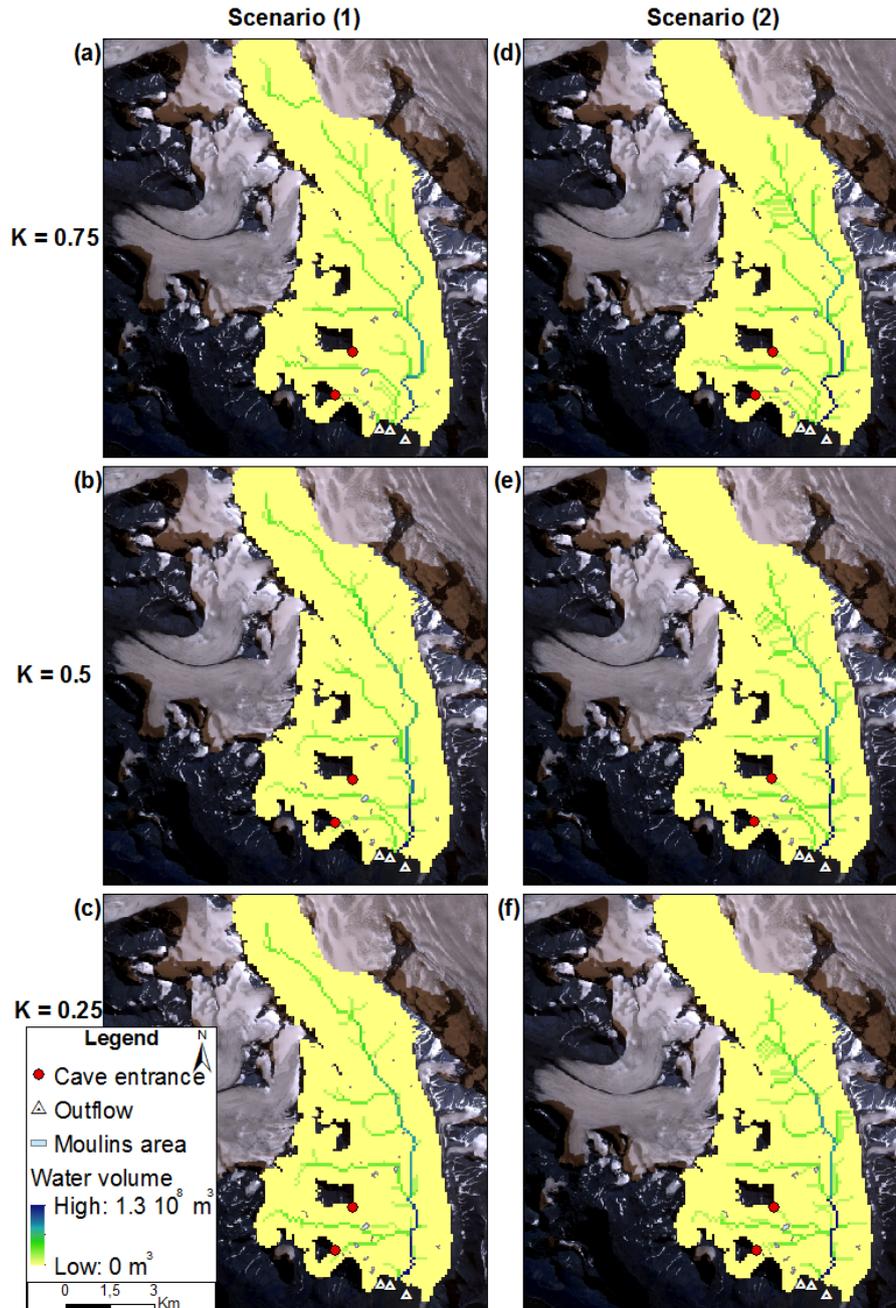
Figure 1. Map of the theoretical pattern of subglacial channels of Hansbreen modeled with scenario (21) ($K = 0.75$ (a); $K = 0.5$ (b); $K = 0.25$ (c)) and (52) ($K = 0.75$ (d); $K = 0.5$ (e); $K = 0.25$ (f)). The map background is a WorldView-2 VHRS image acquired on 21/08/2015.

Figure 2. Map of the theoretical pattern of subglacial channels in Werenskioldbreen modeled with scenario (21) ($K = 0.75$ (a); $K = 0.5$ (b); $K = 0.25$ (c)) and (52) ($K = 0.75$ (d); $K = 0.5$ (e); $K = 0.25$ (f)). The map background is a WorldView-2 VHRS image acquired on 21/08/2015.

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