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RECEIVED
18 September 2020

REVISED
18 February 2021

ACCEPTED FOR PUBLICATION
19 February 2021

PUBLISHED
30 March 2021

TOPICAL REVIEW

What conditions favor the influence of seasonally frozen ground on hydrological partitioning? A systematic review

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Keywords: seasonally frozen ground, hydrology, infiltration, frozen soils, snowmelt runoff, soil water

Supplementary material for this article is available online

Abstract

The influence of seasonally frozen ground (SFG) on water, energy, and solute fluxes is important in cold climate regions. The hydrological role of permafrost is now being actively researched, but the influence of SFG has received less attention. Intuitively, SFG restricts (snowmelt) infiltration, thereby enhancing surface runoff and decreasing soil water replenishment and groundwater recharge. However, the reported hydrological effects of SFG remain contradictory and appear to be highly site- and event-specific. There is a clear knowledge gap concerning under what physiographical and climate conditions SFG is more likely to influence hydrological fluxes. We addressed this knowledge gap by systematically reviewing published work examining the role of SFG in hydrological partitioning. We collected data on environmental variables influencing the SFG regime across different climates, land covers, and measurement scales, along with the main conclusion about the SFG influence on the studied hydrological flux. The compiled dataset allowed us to draw conclusions that extended beyond individual site investigations. Our key findings were: (a) an obvious hydrological influence of SFG at small-scale, but a more variable hydrological response with increasing scale of measurement, and (b) indication that cold climate with deep snow and forest land cover may be related to reduced importance of SFG in hydrological partitioning. It is thus increasingly important to understand the hydrological repercussions of SFG in a warming climate, where permafrost is transitioning to seasonally frozen conditions.

1. Introduction

Seasonally frozen ground (SFG) has a major influence on land surface energy and water balance, and thereby on all ecological, hydrological, pedological, and biological activities at the Earth's regions with seasonal below-freezing ground surface temperatures. Soils and sediments in cold regions can freeze and thaw seasonally, or stay frozen perennially for two or more consecutive years, a condition defined as permafrost (Dobinski 2011). Seasonal ground freeze and thaw occurs both in permafrost zones and permafrost free zones (Lemke *et al* 2007). Ground overlying the permafrost layer that freezes and thaws seasonally is called the active layer. The incidence of seasonal freezing is wide, with around 25% of the Northern Hemisphere's land surface currently being subject to seasonal freezing of the ground outside the permafrost zone, and 25% within the permafrost zone (Zhang *et al* 2003). This has major ramifications for nutrient and carbon fluxes (Goulden *et al* 1998, Wagner-Riddle *et al* 2017), soil erosion (Edwards and Burney 1989, Sharratt *et al* 2000), vegetation dynamics (Hayashi 2013, Bjerke *et al* 2015), heat exchange between atmosphere and ground surface (Hagemann *et al* 2016), and land-use practices (Christensen *et al* 2013, Yanai *et al* 2017).

Climate change will alter the frozen ground regime and extent (Chadburn *et al* 2017, Biskaborn *et al* 2019, Wang *et al* 2019). The predicted warming of cold regions is likely to increase the frequency of freeze-thaw events (Venäläinen *et al* 2001). This could significantly affect the biogeochemistry of rivers and alter ecosystem functioning, increasing the transport of organic matter, inorganic nutrients, and major ions to oceans, e.g. the Arctic Ocean (Arctic Climate Impact Assessment 2004, Frey and McClelland 2009, Ala-Aho *et al* 2018, Box *et al* 2019). Furthermore, a rise in temperature could cause the carbon-rich frozen ground to release carbon and other greenhouse gases into the atmosphere, as positive feedback to climate change (Schaefer *et al* 2014, Koven *et al* 2015, Serikova *et al* 2018). The hydrological repercussions of thawing permafrost and changes in the active layer have been actively researched in the past 10 years, whereas the hydrological influence of permafrost free SFG has received less attention (but with a recent acceleration in research interest, see supplementary material figure S9 (available online at stacks.iop.org/ERL/16/043008/mmedia)). We focused our review on permafrost free but SFG, and consequently from hereon use the term SFG to refer to SFG in permafrost free conditions.

Long-term observations and records of seasonal frost penetration depths are important for detecting spatiotemporal variability and trends in SFG, and therefore instrumental in understanding the past and future hydrological regime of cold regions. These data suggest that the SFG regime is already under considerable change, with decreasing maximum frost depth penetration and duration in the late part of the 19th century (Frauenfeld *et al* 2004, Zhao *et al* 2004, Sinha *et al* 2010). Simulations based on climate change scenarios suggest that the trend is likely to continue (Venäläinen *et al* 2001, Wang *et al* 2019). However, it is unclear how the already recorded, and further anticipated, changes in SFG are reflected in the hydrological regime, an issue that was the scope of this review.

The fundamental reason why ground freezing is important for hydrological processes is that when the ground freezes, ice blocks a part of the previously water-filled soil pores and prevents water flow through these pores. It is typically perceived that frozen ground, whether seasonal or permafrost, limits the degree by which different parts of the landscape interact through the exchange of water, i.e. are hydrologically connected. However, regions with permafrost differ in their hydrological response to regions where only the top ground layer freezes seasonally (for which we use the term SFG). Permafrost penetrates deep into subsurface layers (meters to hundreds of meters) and thereby affects the hydraulic properties of the ground over significant depths. Many studies indicate that permafrost impedes or fully prevents deep groundwater flow (Beilman *et al* 2001, Woo *et al* 2008, Walvoord *et al* 2012). During snowmelt when the active layer is not yet thawed, shallow subsurface flow and rapid surface runoff generation occur because of limited storage capacity in the topsoil (Hinzman *et al* 1991, Kane *et al* 1991). In contrast, the influence of SFG extends to relatively shallow depth (typically less than a meter), and insulating effect of the snowpack may reduce or even fully prevent the development of ground frost even in below-freezing air temperatures (Hardy *et al* 2001, Lindström *et al* 2002, Iwata *et al* 2018). However, if the ground is frozen during the onset of snowmelt, it is commonly assumed that SFG affects partitioning of snowmelt water through increasing surface runoff and decreasing groundwater recharge (Dunne and Black 1971, Okkonen and Kløve 2011, Ireson *et al* 2013). This means that in winter and spring, SFG seasonally promotes shallow water flow paths and reduces deep flow paths. In other words, SFG is considered to decrease the hydrological connectivity from ground surface to subsurface water reservoirs, but to increase the connectivity between hillslopes and channels (Covino 2017).

Rain and snowmelt on frozen ground can cause major flooding events and erosion. Examples of ground frost-induced floods were documented in the interior Pacific Northwest USA in 1973 (Johnson and McArthur 1973) and 1996 (Halpert and Bell 1997) and around the Rhine River in Germany 1993 and 1995 (Barredo 2007). In addition to floods, there are examples of more subtle hydrological influences of SFG. Lack of ground frost intensifies groundwater recharge, especially during winter months, which can result in increased base flow to rivers and streams (Peterson *et al* 2002, Ploum *et al* 2019).

There are several existing review papers with merits in synthesizing the hydrology of SFG. Ireson *et al* (2013) prepared an overview of the physical processes taking place in frozen ground using numerous field studies as examples. Based on this, they developed a conceptual model of surface and subsurface hydrological processes in semi-arid seasonally frozen regions. Hayashi (2013) reviewed the hydrological processes in frozen ground with special emphasis on the implications of SFG on ecological functions and nutrient cycling. Kurylyk and Watanabe (2013) performed a comprehensive review of mathematical representations of ground freezing and thawing processes and suggested ways of advancing hydrological modeling in frozen ground. Lundberg *et al* (2016a) reviewed the spatiotemporal interactions between snow cover and SFG, and their hydrological repercussions, and concluded that groundwater models consider snow and frozen ground processes in an overly simplistic manner. Mohammed *et al* (2018) focused on the process and hydrological importance of macroporosity in frozen ground and developed a strong argument for taking soil macroporosity better into account in both conceptual understanding and numerical modeling of water flow in frozen ground. Despite the documented evidence of the influence of SFG on hydrology, the universal hydrological responses to SFG remain controversial and contradictory. A collective finding from previous work is that the hydrological influence of SFG is site- and event-specific (Laudon *et al* 2007, Appels *et al* 2018). Laboratory studies typically show a distinct effect of ground frost on the infiltration capacity at small scale (Burt and Williams 1976, Iwata *et al* 2010a, Watanabe and Kugisaki 2017), whereas catchment-scale studies show considerable variability, with sometimes little or no evidence of SFG influencing hydrology (Granger *et al* 1984, Cherkauer and Lettenmaier 2003, Stähli 2017). Individual investigations are always defined by: (a) a region's prevailing 'static' physiographical conditions, such as soil type and surface topography; and (b) temporally varying environmental conditions, such as air temperature, snow conditions, and vegetation cover. For this reason, each individual study encompasses only a small subset of the environmental conditions in seasonally frozen regions, and the conclusions reached on SFG influence are necessarily tied to the context and conditions of the study site, obscuring the generalization of the results.

To further complicate matters, the hydrological influence of SFG cannot be measured and reported with a well-defined universal metric. Instead, interpretation relies on observing changes in a selected hydrological flux variable brought about by the frozen state of the ground. Therefore, the conclusion on whether a given study site is influenced by SFG is based on the interpretation of each dataset, with a degree of subjectivity by the investigators. Furthermore, past research on ground freezing and thawing was fragmented over time and performed within different scientific fields, including forestry, civil engineering, soil science, climate sciences, hydrology, and hydrogeology. This led to a variety of research methods being used in both field-based observations and numerical modeling, resulting in varied practices in acknowledging and reporting hydrological fluxes.

The problems of variable site environmental conditions and non-comparability of data make it difficult to synthesize the information on the hydrological influence of SFG that has so far remained 'frozen' in the literature. Thus, there has been no comprehensive analysis of the reasons why SFG influences hydrology at one site but not at another, or in 1 year but not in another. Inconsistent conclusions based on site investigations are typical of hydrological studies, so a wider perspective needs to be gained through a review of the literature, summarizing the findings at many individual sites (Evaristo and McDonnell 2017). There is a clear knowledge gap concerning under what physiographical and climate conditions SFG is more likely to influence hydrological fluxes.

Therefore, we conducted a systematic review of scientific publications providing data-based answers to the question 'To what degree does SFG influence hydrological fluxes?'. Extracting the conclusions reached, together with information on the physiographical and environmental conditions of a given study, allowed us to explore another question: 'Under what conditions does SFG influence hydrological fluxes?'. Our systematic review adds to the existing literature by not only reviewing current knowledge, but also establishing a new dataset to explore the importance of SFG on hydrological partitioning. By compiling a dataset with global coverage, we can draw conclusions that extend beyond individual site investigations. Our findings are of wide interest to earth science researchers striving to understand the environmental repercussions of climate change for water resources in seasonally frozen regions.

The remainder of this paper is organized as follows: In section 2, we review the observational field methods and numerical modeling techniques used to study the hydrology of SFG. In section 3, we describe our systematic reviewing methodology, which produced a dataset we used to analyze why some studies report SFG to be more hydrologically relevant than others. In section 4, we review key factors reported to determine the hydrological response in SFG, e.g. climate conditions such as air temperature and snow amount, land use, soil characteristics, and scale of measurement in observing the hydrological response. After describing each factor, we discuss its influence on SFG hydrology in light of the findings in our systematic review of published data. In section 5, we discuss expected changes in the hydrology of SFG. In section 6, we highlight critical future research needed to better understand the role of SFG in cold region hydrology, and finish with conclusion in section 7.

2. Determining the hydrological influence of SFG: observational techniques and numerical modeling

2.1. Observational techniques to study the hydrological influence of SFG

In studying the hydrological influence of SFG, two main questions must be considered: (a) what is the extent of frozen ground; and (b) how does the frozen state of the ground alter the flow of water? Existing measurement techniques to study SFG processes primarily answer different versions of the question (a), i.e. What is the freeze/thaw status of the ground? How deep is the frost penetration? and, less commonly, What is the volumetric ice content in the ground? A wide set of tools, such as frost tubes filled with methylene blue solution, temperature sensors, soil moisture sensors, and geophysical techniques like ground penetrating radar, have been used to determine ground frost penetration depth (Steelman and Endres 2009, Steelman *et al* 2010, Butnor *et al* 2014, Ma *et al* 2015). Frost tubes and temperature sensors use temperature as a proxy to estimate whether water

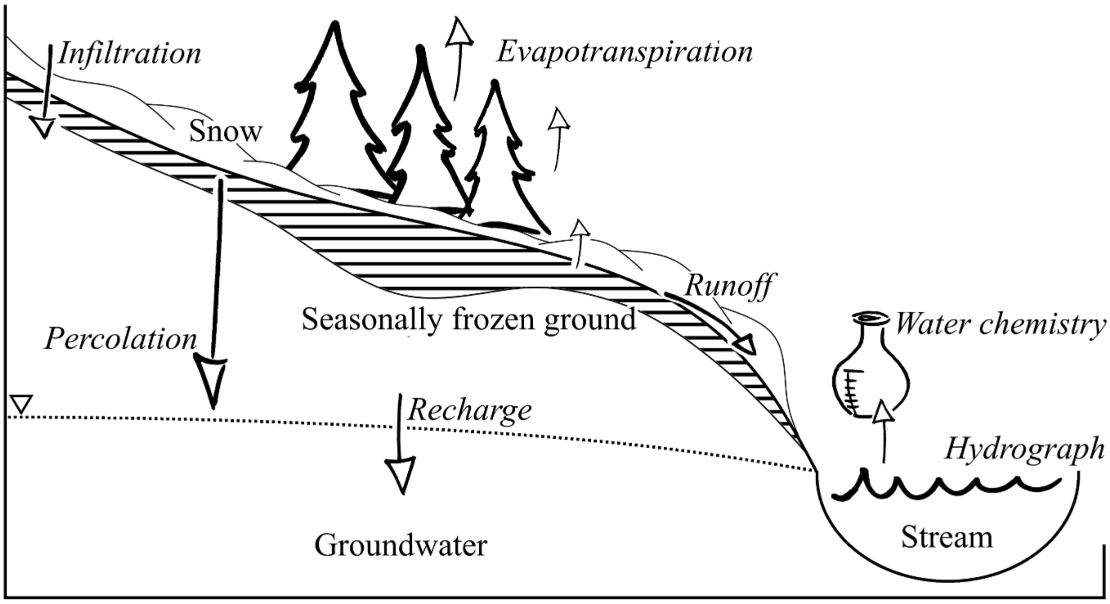

Figure 1. Key hydrological fluxes and water quality parameters (in italic) where the influence of SFG on the hydrological cycle can be seen. Our review focused on studies observing SFG-induced changes in the fluxes of infiltration, percolation, evapotranspiration, groundwater recharge, runoff (surface or near surface), hydrograph (stream response), and water chemistry using tracer techniques .

in ground is frozen. On comparing the results with direct observations Iwata *et al* (2012) found satisfactory agreement, with root mean square error of about 3 cm for both frost tubes and temperature sensors. Determination of the temporal changes in soil moisture or liquid water content (LWC) has been used to measure ground freezing with time domain reflectometry (Stähli and Stadler 1997). This technique is based on the dielectric change in the ground as the LWC decreases with freezing. A comprehensive review of ground-based techniques for measuring and monitoring ground frost depth was performed by Lundberg *et al* (2016b).

However, measuring the presence or properties of ground frost is not sufficient to evaluate the hydrological influence of SFG, i.e. answer the question (b) above. To address this, other techniques are needed to observe changes in the hydrological system caused by SFG. However, there is no commonly recognized and standardized method for measuring and determining the influence of SFG on hydrology. Ideally, the hydrological influence of frozen ground should be observed by measuring a specific hydrological flux when the ground is in frozen and unfrozen state, and comparing the results. For example, hydraulic conductivity is typically determined by measuring fluid flux through the soil matrix under a given hydraulic gradient in laboratory conditions. If this flux is smaller for frozen than unfrozen soil samples, while other factors remain unchanged, this leads to an indirect conclusion that frozen water in the soil matrix has hydrological repercussions (Burt and Williams 1976). As a field study example, the ground frost penetration depth and ice content can be changed by snow cover manipulations. Measurement and comparison of infiltration or runoff fluxes in different frost regimes, while other factors remain identical, allows a direct conclusion on the influence of SFG on hydrological partitioning (Iwata *et al* 2011). The hydrological influence of SFG has been studied by observing changes SFG brings about in the following hydrological fluxes or variables: infiltration, percolation, evapotranspiration, groundwater recharge, runoff (surface or near surface), stream response (hydrograph), and water chemistry using tracer techniques (figure 1). In this systematic review, we identified and analyzed previous experimental data on the hydrological influence of SFG on these variables.

The influence of SFG on infiltration can be determined as the difference between frozen and unfrozen infiltration rates at the ground surface. The research methods primarily used to date to quantify the difference have been small-scale experimental setups in field conditions, e.g. infiltration rings (Kane and Stein 1983b, Hayashi *et al* 2003). Percolation, i.e. water movement through the soil matrix, has typically been measured in the context of determining soil hydraulic conductivity. Hydraulic conductivity measurements have usually been conducted in a laboratory environment, in small-scale experiments using soil cores or monoliths in which hydraulic conductivity has been determined with and without the presence of frost (Wiggert *et al* 1997, Watanabe and Kugisaki 2017). The influence of SFG on groundwater recharge has been studied using field-based techniques measuring groundwater level or groundwater–surface water interactions and numerical modeling of the groundwater system (Thorne *et al* 1998, Daniel and

Staricka 2000, Okkonen and Kløve 2011). Observed or simulated changes in groundwater recharge flux have provided indirect evidence of the hydrological influence of SFG. In the present review, we considered runoff flux to be measured (or simulated) near-horizontal water flow on the ground surface or in surficial soil layers. Runoff studies have typically been performed in hillslope-scale plots with constructed runoff water collection systems to evaluate surface and/or near-surface runoff generation under different ground frost conditions and in different soil horizons (Willis *et al* 1961, Dunne and Black 1971, Bayard *et al* 2005). Hydrograph responses to rainfall or snowmelt have been used to study whether stream discharge differs in frozen and unfrozen catchments. Hydrographs integrate the response of the whole hydrological system, and the scale of measurement is the catchment above the stream gauging point. A typical assumption is that stream response is more pronounced when the ground is frozen, which has been reported e.g. as runoff coefficient (Granger *et al* 1984, Stähli 2017) or changes in hydrograph recession (Ploum *et al* 2019). To further analyze the streamflow response, modeling approaches have been used to evaluate the influence of SFG on catchment hydrology and stream runoff generation (Prévost *et al* 1990, Sterte *et al* 2018). A typical modeling study introduces a mathematical representation of frozen ground into the model and tests whether the new model demonstrates better performance in simulating the hydrological flux of interest, most typically a stream hydrograph. More unconventional study variables to evaluate SFG influence on water fluxes have also been tested. SFG may reduce water availability for evapotranspiration, which has been quantified through measurements or simulations (Mellander *et al* 2004, Wu *et al* 2016, Miao *et al* 2017). Water chemistry (Fuss *et al* 2016) and environmental tracers such as stable water isotopes (δ^2H and δ^{18}O), have been used to separate hydrological flow paths in different ground frost conditions (Laudon *et al* 2007, Smith *et al* 2019), allowing a conclusion on SFG influence on hydrology.

2.2. Representation of SFG in numerical hydrogeological and land surface modeling

We categorized the existing SFG modeling approaches into: (a) hydrological conceptual models; (b) thermo-hydrogeological models; and (c) land-surface models (table 1). Although these categories are not well-defined and many models could fall into several categories, we considered this categorization useful in providing context for the history and present state of SFG model applications in hydrological research.

2.2.1. Hydrological conceptual modeling

Various methodologies have been used to simulate ground freeze/thaw processes and the movement of water in or at the surface of a frozen soil matrix. The first physically-based thermo-hydrological models emerged in the early 1970s, but their applicability was not in line with the needs of hydrologists and hydrogeologists of the era. Computational techniques and resources were not sufficient to solve the complex differential equations for spatially extensive study areas of interest and management, i.e. catchments and aquifers. The need to simulate streamflow from snowmelt for operational applications has led to the development of conceptual approaches to deal with the hydrological influence of SFG.

The first implementations were carried out by Gray *et al* (1985) and Anderson and Neuman (1984). Gray *et al* (1985) modeled SFG influence on a small catchment in Saskatchewan, Canada. Their approach was based on the concept that infiltration into frozen ground can be categorized into three distinct classes: restricted, unlimited, and limited. They defined the limited (winter) category of infiltration as a simple function of pre-winter soil water content and snow water equivalent (SWE), and integrated it into their bucket-type rainfall-runoff model. This modification significantly improved model performance, demonstrating that conceptual ground frost models can be successfully applied for operational purposes in hydrograph simulations. Similar improvements in simulations were obtained by Anderson and Neuman (1984) for larger river basins in Minnesota, USA. They developed an empirical 'Frost Index' based on meteorological variables and snow and soil moisture conditions. The calculated frost index was used to regulate water percolation rates in a hydrological model.

Instead of fully conceptual SFG formulations, mixed approaches combining hydrological bucket-type models with a simplified version of the heat transport equation, pioneered by Koren (1980), have been developed (Pomeroy *et al* 2007, Mohammed *et al* 2013, Koren *et al* 2014, Gao *et al* 2018). Such mixed approaches allow more data on soil properties and state variables, such as soil water content or ground temperature, to be used in the model calibration and validation, potentially reducing model uncertainty. Another mixed approach type, which combines a conceptual frozen ground representation with physically-based models, has been proposed and applied for SFG sites (Mahmood *et al* 2017, Sterte *et al* 2018).

2.2.2. Thermo-hydrogeological modeling

The first efforts to create physically-based models by coupling thermal energy transport and water flow were made in the early 1970s (Harlan 1973, Guymon and Luthin 1974, Motovilov 1977). These models were developed to assist with cold region infrastructure and were based on the analogy between Darcian fluid flow in unsaturated unfrozen porous media and flow in saturated partially frozen ground. At the time, computational technology restricted model

Table 1. Overview of available models for simulating the hydrological influence of SFG categorized to their scope and applications.

Model category	Hydrological	Land surface	Thermo-hydrogeological
Typical frozen ground formulation to model equations	Conceptual	Mixed conceptual and physical	Physical
Main variable of interest affected by frozen ground	Stream runoff	Soil moisture status	Subsurface water fluxes
Primary simulation cases	Hydrological field studies	Large-scale domain with point field verification	Theoretical, idealized examples
Typical scale of application	Catchment	Continental	Hillslope or soil profile
Typical ground freezing regime simulated	Permafrost or SFG (not both in the same scheme)	Permafrost and SFG (both in the same scheme)	Permafrost (increasingly also SFG)
Key advantages	Low data requirements	Able to utilize data at different scales	Model equations and parameters physically based
Key disadvantages	Empirical model parameterization	Limited model validation using hydrological fluxes	High data requirements

development models to one dimension and comparisons to soil column laboratory experiments (Jame 1977, Taylor and Luthin 1978), although the principles described in the literature of the time have served as the base for current thermo-hydrogeological models. These models couple the Richards equation (Richards 1931) of groundwater flow with the energy balance equation of heat transport (equations (1) and (2) in supplementary material S2), which can still be considered the state-of-the-art representation of the physics of ground freeze-thaw.

Building on this pioneering work, 1D models like SHAW (Flerchinger and Saxton 1989), COUP (Jansson 2004), and HYDRUS-1D (Hansson *et al* 2004) have been used to couple thermal energy and water flow in hydrological simulations of SFG. The key attraction of existing 1D models is their ability to couple above-ground energy balance to subsurface process in their model domain without a great increase in computational burden. This has allowed ecohydrological simulations of plant influence on water and energy partitioning (Ala-aho *et al* 2015a, Metzger *et al* 2016), and very importantly for SFG hydrology, of good simulations of snow accumulation and melt (Stähli *et al* 2001, Assefa and Woodbury 2013, Okkonen *et al* 2017). Capturing snow cover dynamics is essential both in estimating ground surface temperature over winter as frost layer builds, and in estimating water input on SFG during spring snowmelt, where SFG influence on hydrology is greatest. 1D models have also been used to provide boundary conditions for groundwater models in SFG regions (Okkonen and Kløve 2011, Ala-aho *et al* 2015b) and 3D thermo-hydrogeological models in permafrost regions (Langford *et al* 2019), because of more complete above-ground process description and better numerical efficiency than with 3D models.

In the past decade, there has been growing interest in hydrological research on ground freezing and thawing, and development of 3D physically-based models to simulate these processes. Although there are differences in the hydrological responses of perennially and SFG, the physical principles producing the responses are the same. For this reason, the physically-based models developed to simulate thawing of permafrost are suitable for application to SFG regions. Most of the currently available 3D thermo-hydrogeological models, e.g. SUTRA (Voss and Provost 2002), HGS (Aquanty 2015), and FEFLOW (Diersch 2013), have been developed from a groundwater modeling perspective, as an extension of the current hydrogeological and fully integrated groundwater–surface water simulators. A wide range of mathematical representations is currently used in thermo-hydrogeological codes. These models differ in their numerical, coupling, and discretization schemes, and also in the form of the Clapeyron equation applied (equations (3) in supplementary material S2), soil freezing curve derivations, and frozen hydraulic conductivity functions (Kurylyk and Watanabe 2013). Including state-of-the-art, physically-based freezing-thawing processes for surface and subsurface domains involves highly non-linear relationships and is numerically challenging, requiring the application of advanced solution schemes and leading to long running times and parameterization issues. It should be also noted that, despite their physical basis, many 3D physically-based models employ a simplified representation of surface hydrology and/or snow accumulation and melt.

Development and refinement of thermo-hydrogeological models has continued and more 3D computer codes integrating surface and subsurface thermal hydrology have emerged, e.g. GeoTOP 2.0 (Endrizzi *et al* 2013) and ATS (Painter *et al* 2016). Simplified, physically-based modeling approaches based on analytical solutions of energy balance equations have also been proposed or used for large-scale modeling (Hayashi *et al* 2007, Semenova *et al* 2014, Kurylyk and Hayashi 2016). One such approach is Stefan's formula (Stefan 1891), a simple algorithm utilizing the analytical solution of the conduction equation for calculating frost/thaw depth penetration (equation (4) in supplementary material S2). The analytical model requires data on land surface temperatures, which are often not available, leading to the development of empirical and quasi-empirical factors relating to meteorological variables and land surface temperature (Kurylyk and Hayashi 2016).

In terms of field applicability, the physically-based thermo-hydrogeological models are in their infancy. Test cases are at the stage of intercomparisons of idealized test cases for permafrost thawing, e.g. the Interfrost project (Grenier *et al* 2018). Most existing catchment-scale applications deal with permafrost regions, typically with an outlook on hydrological change due to permafrost thaw (Bense *et al* 2009, McKenzie and Voss 2013, Krogh *et al* 2017, Rawlins *et al* 2019). At the moment, catchment-scale applications of state-of-the-art, physically-based thermo-hydrogeological models that focus on permafrost free SFG regions are basically non-existent. Two-dimensional applications for hillslope-scale studies are rare and almost exclusively performed with SUTRA code (McKenzie *et al* 2007, Kurylyk *et al* 2014, Evans and Ge 2017, Evans *et al* 2018), with the exception of recent work by Schilling *et al* (2019) who integrated SFG processes into a fully integrated groundwater–surface water model, HydroGeoSphere. Overall, the lack of field-scale applications of thermo-hydrogeological models has been attributed to poor data availability and challenges in monitoring ground freeze-thaw processes (Hayashi 2013, Ireson *et al* 2013).

2.2.3. Land-surface modeling

Land surface models (LSMs), also referred to as Earth system models, couple water and energy fluxes with biogeochemical and ecological processes at the interface of the Earth surface and the lower atmosphere (Overgaard *et al* 2006, Best *et al* 2011). Good simulation of soil moisture conditions is crucial in LSMs, but for a long time, the influence of freezing on soil moisture reservoirs received little attention in the LSM modeling community (Slater *et al* 1998, Maxwell and Miller 2005). This is surprising, given the spatial coverage and importance of permafrost and SFG in the Northern Hemisphere. Inclusion of ground freeze/thaw routines has recently been deemed particularly important in permafrost regions, because of positive feedback between the climate system and organic soil carbon sources exposed by permafrost thaw (Schuur *et al* 2015). In recognition of this, recent state-of-the-art LSMs account for the thermo-hydrological processes of ground freeze/thaw both in permafrost and seasonally frozen condition (Lawrence *et al* 2012, Chadburn *et al* 2015, Guimberteau *et al* 2018, Yang *et al* 2018, Melton *et al* 2019).

The mathematical approach employed to date to represent the hydrology of frozen ground in LSMs has been a mix of physically-based and empirical approaches. Ground freeze-thaw status has typically been simulated using physically-based 1D heat transport equations (Gouttevin *et al* 2012), or simplified to the Stefan equation only accounting for latent heat requirements to freeze or thaw the ground (Hagemann *et al* 2016). Storage and flow of water in the ground has typically been solved in the vertical dimension, using the Richards equation (Clark *et al* 2015). In principle, this approach has been similar to that in thermo-hydrogeological models, but the dimensionality has been reduced to vertical and the model equations have been solved in a more simplified, computationally inexpensive manner. A typical approach to account for SFG influence on hydrology has been to reduce the bulk hydraulic conductivity of frozen ground, with a physically- or empirically-based approach, and incorporate the temporarily modified parameter value in a 1D Richards equation to solve for water flow (e.g. Cherkauer and Lettenmaier 1999, Koren *et al* 1999).

Slater *et al* (1998) explicitly solved ice content in the ground as part of Richards equation formulation, which decreased the soil hydraulic conductivity in their LSM. Luo *et al* (2003) found that including ground freeze/thaw improved the simulation of ground temperature and its variability at seasonal and interannual scales in multiple land-surface parameterization schemes. Niu and Yang (2006) made several advances in SFG representation in LSMs by bringing in a physical process understanding, where the ground was assumed to retain some permeability when frozen, to LSM SFG parameterization. They: (a) allowed unfrozen water to coexist with ice in the ground over a wide range of temperatures below 0 °C by using a modified form of the Clapeyron equation (Flerchinger and Saxton 1989); (b) computed vertical water fluxes by introducing the concept of a fractional permeable area, which partitioned the model grid into an impermeable part (no vertical water flow) and a permeable part; and (c) used the total soil moisture (liquid water and ice) to calculate soil matric potential and hydraulic conductivity. Comparisons between the original and modified frozen ground schemes, with data from a small catchment and from the six largest cold region river basins, showed that the modified scheme produced better estimates of monthly runoff and terrestrial water storage change (Niu and Yang 2006).

Gouttevin *et al* (2012) specifically simulated the hydrology of SFG with their LSM, and reported improved runoff simulations at both catchment and continental river basin scale. Ekici *et al* (2014) used a physically-based formulation that coupled the heat transfer and Richards equation in one dimension, and incorporated the co-existence of ice and unfrozen water according to Niu and Yang (2006). Hagemann *et al* (2016) used the same model formulation and reported large improvements in simulated snowmelt peak runoff due to frozen ground in spring in the SFG-influenced Baltic Sea basin.

Recent thermo-hydrological schemes in LSMs largely remain adopted from Koren *et al* (1999), Niu and Yang (2006), Gouttevin *et al* (2012), except for improvements to water phase change equations and parameterization suggested by Yang *et al* (2018) and hydraulic conductivity and matric potential formulations by Ganji *et al* (2017). Other recent advances that are not strictly related to conceptualizing energy transport and water flow, but still have hydrological importance, are done on improving land surface parameterization and soil profile representation. Deeper soil profiles (tens of meters instead of 3–5 m) have been found important in correctly simulating active layer thaw in the permafrost region due to heat sink in deep cold permafrost (Chadburn *et al* 2015, Melton *et al* 2019), but not tested or proven important in SFG regions because this deep heat sink is missing. Another advance in improving thermo-hydrological simulations has been including a layer of moss and/or organic soil that increases insulation properties of the top soil (Guimberteau *et al* 2018, Melton *et al* 2019). Again, LSMs have demonstrated the importance of mosses only in simulating the active layer in the permafrost. From a physical perspective mosses, lichens, or organic soil layers are equally important in SFG regions by causing more insulating (less freezing) and water interception before entering the mineral soil (lower water and ice content) (Ala-aho *et al* 2015a).

3. Systematic review of hydrological influence on SFG

3.1. Systematic review methodology

Our systematic review process consisted of three main steps: (a) study identification (screening by title); (b) screening the selected studies for applicability in the analysis (screening by scope); and (c) double-blind review (by two people) of the studies to extract data for further analysis. The workflow of the literature identification, screening, and review process is presented in supplementary material (figure S1).

3.1.1. Step (a): screening by title

We identified a total of 379 studies in which frozen ground was an essential part of the study set-up. Studies applying a range of research methods, from laboratory and field experiments to numerical simulations, were included in the review. Papers relevant to our research topic were identified through three pathways: (a) a title word search in Scopus and Web of Science, (b) reference crawling: incorporating relevant work cited in other reviewed papers, and (c) miscellaneous sources, including primarily papers known/suspected to be relevant from past experience of the writing team, or recent work through publication alerts. Details on the title word search and other screening steps are given in supplementary material S1.

3.1.2. Step (b): screening by scope

From the set of identified papers, we further screened those included in the analysis by applying two criteria. For a study to be included, it had to have:

(a) An explicit conclusion, result, or data-based speculation that SFG has (or does not have) an *influence on hydrological fluxes*, i.e. the partitioning of water to infiltration, runoff, percolation, groundwater recharge, or evapotranspiration.
(b) Conclusion/s based on *original measurements* or hydrological simulations calibrated/validated with original measurements presented in the paper.

The first criterion made our scope unique, as much of the SFG-related literature focuses on frost penetration depth or ground temperature change. Our interest was in determining whether the frozen state of ground has hydrological consequences. The second criterion, to account only for studies that founded their conclusions on original measurements, excluded studies that developed hydrological modeling algorithms but did not validate the models against measured data (Kulik 1977, e.g. Flerchinger and Saxton 1989, Tao and Gray 1993). Even though our title word search (see supplementary material S1) attempted to exclude work done in permafrost regions, at this point we did a second screening to ensure the original research was done on SFG by reviewing the study site description.

Screening in step (b) revealed that 143 of the 379 publications identified in step (a) contained data-based conclusions (or discussions) on whether 'the frozen state of ground influences hydrological fluxes'. However, some of these 143 studies produced multiple entries in our analysis (i.e. multiple study sites or methods yielded multiple individual conclusions from one study), which resulted in a total of 162 analyzed entries in our dataset. Although this dataset is extensive in coverage, we cannot claim to have included all studies conducted to date, because of limited availability, language barriers, or failure to identify all relevant work in the literature search, particularly in the case of early research in the Soviet Union.

3.1.3. Step (c): double-blind review

The most important piece of information extracted from each study was the nature of the conclusion/s reached about the influence of SFG on hydrological partitioning, in terms of the observed or simulated flux of water infiltration, surface runoff, percolation through soil matrix, groundwater recharge, or transpiration. In our analysis, we categorized the influence of SFG into four classes:

(a) EVIDENT: the data show indisputable evidence of SFG influence in all hydrological events/years studied.
(b) OCCASIONAL: the data show clear evidence of SFG influence in some, but not all, hydrological events/years studied.
(c) UNCERTAIN: the data suggest that SFG can explain some aspects of the hydrological response, but the data/conclusions are not definitive.
(d) ABSENT: the data show no evidence of SFG influence on hydrological fluxes.

Quotation or summary of the decisive argument(s) in each paper, on which our conclusion category is based, is included in our dataset. Below we give examples for studies and conclusions in each category. EVIDENT: Kane (1980) evaluated how ground ice and moisture content was related to infiltration rates using infiltration test in the field. They found that: 'the greater the moisture content, the greater the ice present in the frozen soil; thus the infiltration rate and the saturated hydraulic conductivity were reduced'. OCCASIONAL: Stähli *et al* (2004) used a dye tracer in an excavated vertical soil profile to examine the infiltration pathways in alpine soils. They found that 'Soil frost conditions varied between winters…During the first winter the water infiltration showed a pronounced preferential behavior…During the second winter the impeding impact of soil frost was clearly seen.' UNCERTAIN: Komiskey *et al* (2011) studied nutrient and sediment loading runoff from frozen agricultural fields by monitoring runoff volumes, meteorological variables, and ground frost regime. They concluded that '…it appeared that runoff amounts were more related to the timing and type (snow/ sleet/rain) of precipitation, intensity of precipitation (rainfall), air temperatures, and snowpack properties such as depth, water equivalent, ice layers, and temperature, rather than soil temperatures or frost depth alone'. ABSENT: Nyberg *et al* (2001) studied the influence of ground frost on water flow paths along a hillslope by monitoring ground moisture and frost regime and runoff. They stated: '…there was no clear frost effect on runoff during the three investigated winters'.

In addition to the reported conclusion on SFG hydrological influence, we extracted data that could explain why some site investigations or laboratory/modeling studies show a more evident hydrological response to frozen ground than others. The data included spatial and temporal scale of measurement, soil physical properties, climate characteristics, land cover, frost penetration depth, and other relevant attributes either reported directly in the studies reviewed, or extracted from global datasets based on the location of the study site (for full description, see table S1). The global datasets we used were Köppen–Geiger climate classification based on data for the period 1976–2000 (Kottek *et al* 2006), mean and annual maximum SWE for the period 1980–2014 (Luojus *et al* 2013), and mean air temperature of the coldest quarter in the years 1970–2000 (Fick and Hijmans 2017). The variables were selected to encompass physiographical and environmental conditions that previous studies have found to be important for explaining the hydrological response in frozen ground.

3.2. Hydrological influence of SFG is common, but not universal

Most of the SFG influences reported in the studies fell into the EVIDENT or OCCASIONAL categories (75.9%), implying that the frozen state of ground has hydrological repercussions in most experimental or simulation settings (table 2). However, it is important to point out that the majority of studies reviewed suggested that even if SFG influences water movement, it rarely completely blocks it. The remaining 24.1% of studies reviewed reported that SFG has only vague or non-existent impacts on hydrological fluxes (UNCERTAIN or ABSENT categories), confirming the assumption underlying our initial hypotheses that the influence of SFG on hydrological fluxes is not universal. The differences in reported SFG influence allowed us to explore the experimental settings or environmental conditions in which SFG is hydrologically less important.

The field studies reviewed spanned the Northern Hemisphere and mostly fell between the seasonal frost boundary in the south and the continuous permafrost boundary in the north (figure 2), demonstrating a successful screening to exclude hydrological studies in permafrost settings. A majority (58%) of the field studies were conducted in Canada and the USA (figures 2 and 3). Other regions with high numbers of studies were Scandinavia, Alpine Central Europe, Japan, and western parts of the Tibetan Plateau. Interestingly, studies from Europe reported the smallest percentage of EVIDENT hydrological influence of SFG and, conversely, the highest percentage of ABSENT influence. The ABSENT reports of SFG influence were clustered in Fennoscandia (figure 2). The earliest reviewed studies dated from the 1950s, since when the number of studies on the topic has been steadily increasing (figure 3). This increase may be related to the higher numbers of scientific papers published overall and to our better access to more recent literature, rather than to growing interest in the research topic. However, it is worth noting that relatively fewer studies reported an EVIDENT influence after 1990 than before.

Table 2. The reviewed literature grouped to study method (columns) and the conclusion about the influence of soil frost on hydrological partitioning made in the study (rows). For full details of the conclusions and data extracted from each study see Ala-aho *et al* (2020).

SFG influence	Laboratory	Field	Simulation
Evident	(Benoit and Bornstein 1970, Burt and Williams 1976, Rudra *et al* 1986, Engelmark 1988, Edwards and Burney 1989, Andersland *et al* 1996, Seyfried and Murdock 1997, Wiggert *et al* 1997, Stadler *et al* 2000, McCauley *et al* 2002, Weigert and Schmidt 2005, Fouli *et al* 2013, Watanabe *et al* 2013, Zhao *et al* 2013b, Campbell *et al* 2014, Sutinen *et al* 2014, Ban *et al* 2017, Watanabe and Kugisaki 2017, Watanabe and Osada 2017, Appels *et al* 2018, Wu *et al* 2018)	(Diebold 1938, Garstka 1944, Stoeckeler and Weitzman 1960, Kuznik and Bezmenov 1963, Larin 1963, Haupt 1967, Dunne and Black 1971, Murray and Gillies 1971, Harris 1972, Alexeev *et al* 1973, Romanov *et al* 1974, Kane 1980, 1981, Zuzel *et al* 1982, Kane and Stein 1983a, 1983b, 1987, Granger *et al* 1984, Price and Woo 1988, Byrne 1989, Thunholm *et al* 1989, Blackburn *et al* 1990, Seyfried *et al* 1990, Pikul *et al* 1992, Tao and Gray 1994, Auckenthaler 1995, Seyfried and Wilcox 1995, Stadler *et al* 1996, Derby and Kinighton 1997, Pikul and Aase 1998, Radke and Berry 1998, Thorne *et al* 1998, Pitman *et al* 1999, Daniel and Staricka 2000, Sharratt *et al* 2000, Jones and Pomeroy 2001, Xiuqing and Flerchinger 2001, Xiuqing *et al* 2001, Hayashi *et al* 2003, Laudon *et al* 2004, Hejduk and Kasprzak 2010, Iwata *et al* 2010a, 2013, Redding and Devito 2011, Zhang *et al* 2013, Zhao *et al* 2013a, Anis and Rode 2015, Coles *et al* 2016, Eskelinen *et al* 2016, Wu *et al* 2016, Coles and McDonnell 2018)	(Molnau and Bissell 1983, Anderson and Neuman 1984, Gray *et al* 1985, Sand and Kane 1986, Barry *et al* 1990, Molnau *et al* 1990, Prévost *et al* 1990, Johnsson and Lundin 1991, Koren *et al* 1995, 2014, Cherkauer and Lettenmaier 1999, 2003, Li and Simonovic 2002, Zhao *et al* 2002, Koren 2006, Niu and Yang 2006, Okkonen and Kløve 2011, Hagemann *et al* 2016, Qin *et al* 2017, Sterte *et al* 2018)
Occasional	(Hess 2017)	(Baker and Mace 1976, Blackburn and Wood 1990, Baker and Spaans 1997, Pomeroy *et al* 1997, Stähli *et al* 1999, 2004, Bayard *et al* 2005, Orradottir *et al* 2008, Sutinen *et al* 2009, Iwata *et al* 2011, Christensen *et al* 2013, He *et al* 2015, Miao *et al* 2017, Pan *et al* 2017, Starkloff *et al* 2017)	(Mohammed *et al* 2013, Mahmood *et al* 2017)
Uncertain		(Hale 1951, Willis *et al* 1961, Mace 1968, Kapotov 1990, Bengtsson *et al* 1992, Woo and Rowsell 1993, Stein *et al* 1994, Shanley and Chalmers 1999, Hardy *et al* 2001, Shanley *et al* 2002, van der Kamp *et al* 2003, Fritz 2004, Iwata *et al* 2010b, Komiskey *et al* 2011, Ketcheson *et al* 2012, Fuss *et al* 2016)	(Emerson 1994, Stadler *et al* 1997)
Absent		(Juusela 1941, Zavodchikov 1962, Karvonen *et al* 1986, Munter 1986, Vehvilainen and Motovilov 1989, Nyberg *et al* 2001, Leenders and Woo 2002, Mellander *et al* 2004, Laudon *et al* 2007, Sutinen *et al* 2008, Stähli 2017)	(Lindström *et al* 2002, Luo *et al* 2003)

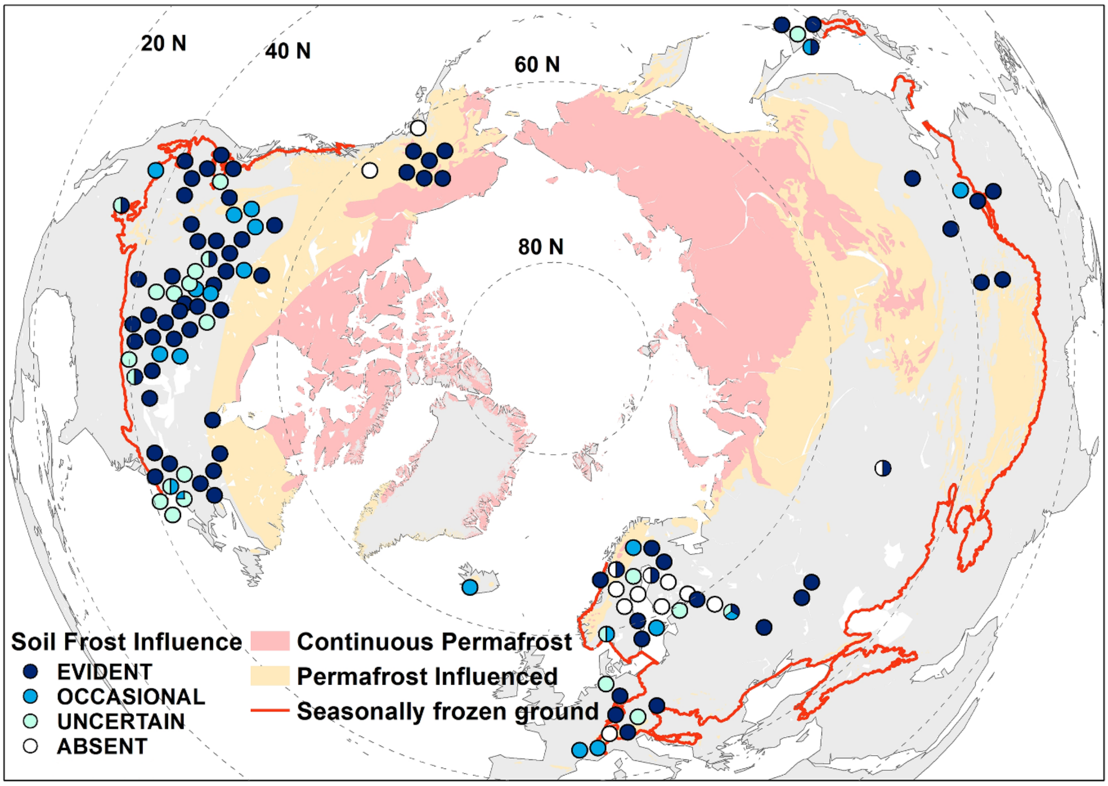

Figure 2. The geographical location of field studies on the hydrological relevance of SFG included in this review. Colors indicate the nature of the conclusion on SFG influence (EVIDENT/OCCASIONAL/UNCERTAIN/ABSENT), with sites with multiple conclusions show by split colors. For overlapping study site locations, points are displaced horizontally for clarity. Region of SFG was estimated as the 0 °C contour of mean air temperature of the three coldest months (Fick and Hijmans 2017), as in Zhang *et al* (2003), with permafrost regions as in Brown *et al* (2002).

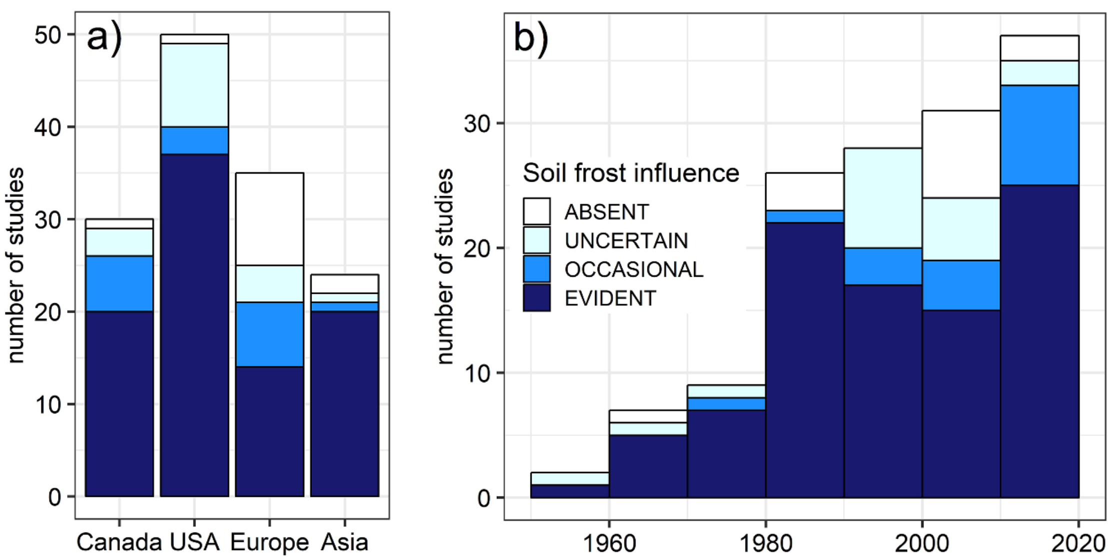

Figure 3. (a) The major geographical regions of published field studies and the nature of the responses reported in each and (b) change in the number of publications reporting a hydrological influence of SFG over time.

4. Key findings of ground freezing regime influence on hydrological fluxes

4.1. Climate conditions associated with hydrological relevance of SFG

Air temperature and precipitation (both rain and snowfall) affect the formation of ground frost. In general, formation of ground frost starts when the ground temperature is below 0 °C and frost melting commences when the air temperature above the ground rises above 0 °C. In the context of SFG, frost penetration can be assumed to be deeper in a colder climate and, with deeper frost penetration, one might expect a more intensive hydrological response. Our

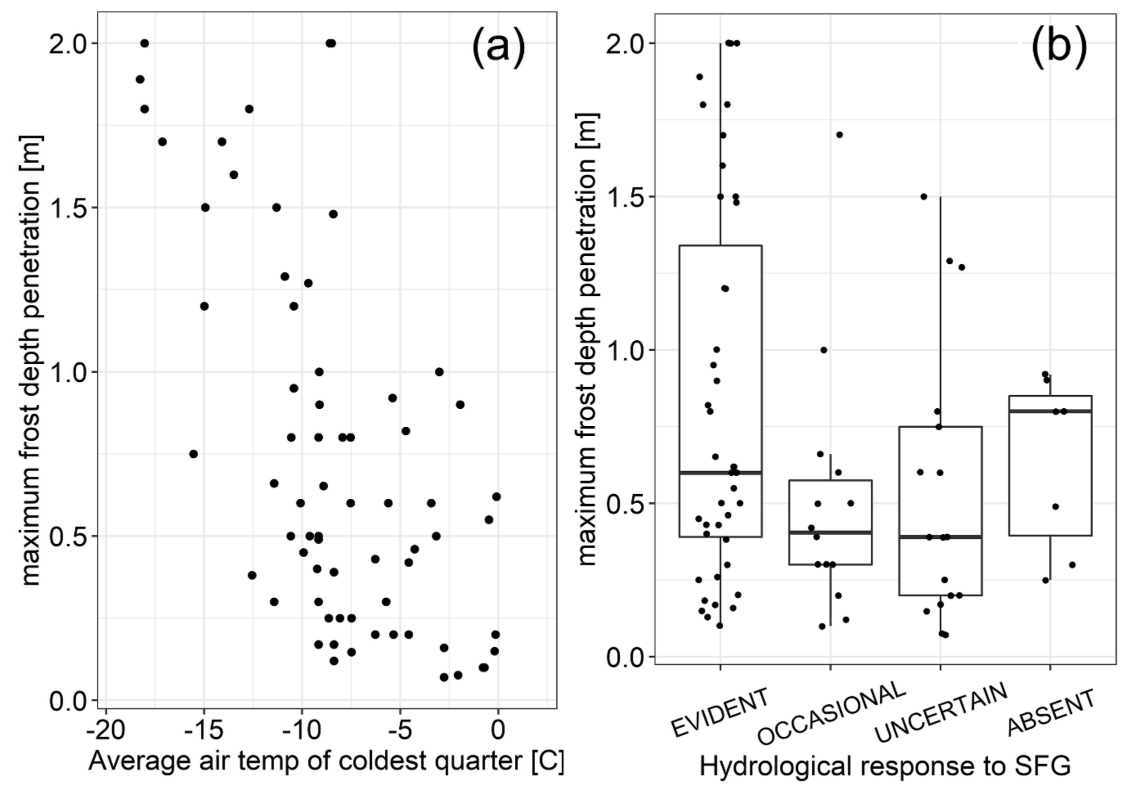

Figure 4. (a) Maximum frost depth penetration reported in each study reviewed, as a function of average air temperature of the coldest quarter of the year, and (b) maximum frost depth penetration, grouped to reported hydrological response to SFG.

review data confirmed the first assumption, and showed a negative association between average air temperature in the coldest quarter of a year and maximum observed frost depth (figure 4(a)). EVIDENT hydrological responses were reported across the range of frost depths from few centimeters to two meters (figure 4(b)). Studies with frost depths more than 1 m predominantly reported EVIDENT responses. While there was a slight decrease towards lower frost depths (median value) on going from the EVIDENT → OCCASIONAL → UNCERTAIN category, the differences were minor and the trend was reversed for the ABSENT category.

The onset and total depth of ground frost penetration are highly dependent on snow conditions. Snow has low thermal conductivity and acts as thermal insulation, and was thus found to have a major influence on ground energy balance (Zhang 2005). At the plot scale, snowpack height was often found to be negatively correlated with ground frost penetration depth (Stähli *et al* 2004, Iwata *et al* 2011). As a result, a thick snowpack in early winter may greatly reduce or even fully prevent the formation of ground frost, even though air temperatures would be below freezing (Hardy *et al* 2001, Iwata *et al* 2018). The data in the studies reviewed did not support the assumption of shallower frost penetration with more snow (figure S2). The snow data were long-term average maximum values from a remote sensing product (Takala *et al* 2011). Therefore snow conditions specific to the study year s^{-1} were not accounted for, even though year-to-year variability in snow depth can be significant. In addition to snow depth, other factors such as snow stratigraphy, snow density, and interaction with micrometeorological conditions can greatly influence the ground thermal regime and frost penetration (Zhang 2005, Lundberg *et al* 2016a). In agreement with our results, a similar weak relationship between ground temperature (not frost penetration explicitly) and snow depth has been reported in other large-scale studies (Karjalainen *et al* 2019).

In addition to the relationship between snow and frost penetration, we were able to explore how snow and climate are reflected in the hydrological response in SFG regions. In our review, studies reporting ABSENT hydrological influence of SFG were associated with higher snow cover, measured as SWE (figures 5(a) and (b)). Similar relationship was not found in other key climate variables of mean annual precipitation (figure S4) or average air temperature of coldest quarter (figure S6). However, the SWE was positively correlated with mean annual precipitation and negatively with cold season air temperature and elevation (figure S8). This highlights that disentangling the influence of one individual climate parameter is difficult, and integrative measures of climate conditions such as climate zones may be more appropriate.

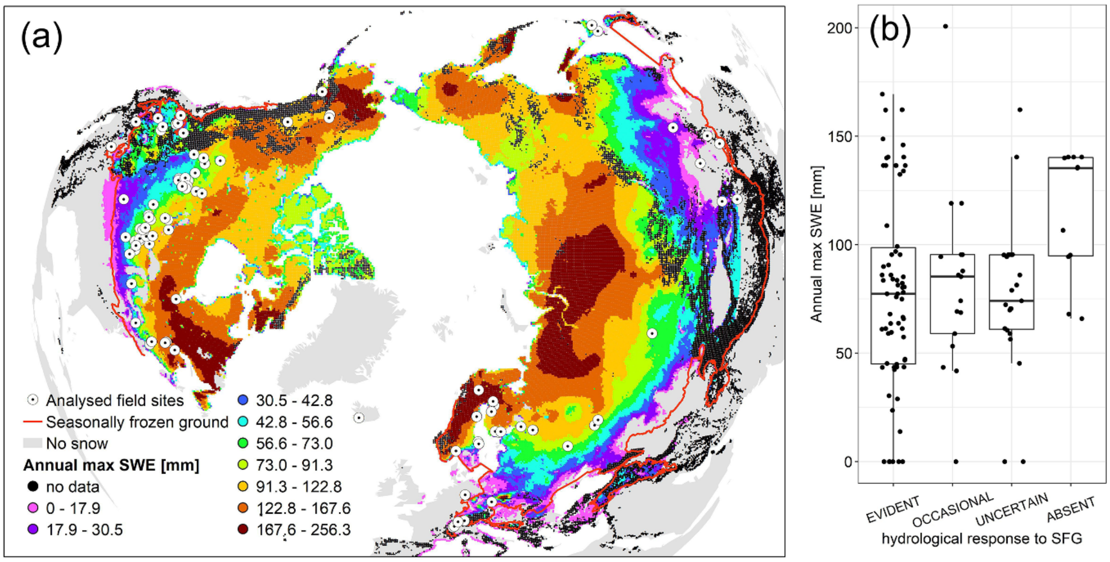

Figure 5. (a) Average annual maximum SWE calculated from Luojus *et al* (2013) with the study site locations in the papers reviewed here, and (b) SWE grouped to reported hydrological response of SFG.

Studies at sites located in the Köppen–Geiger climate zone *snow—fully humid—cool summer (Dfc)* (figure 6) had the greatest annual snowpack (median SWE of sites 140.4 mm) and the highest percentage of ABSENT response (31.8%) (figure 6(b)). In contrast, in studies at sites located in the arid and temperate warm Köppen–Geiger climate zone (the group 'Arid and temperate' in figure 6), the median SWE was lowest (6.9 mm) and the majority (77.3%) of studies reported an EVIDENT snow frost influence on hydrology (figure 6(b)). Most of the studies analyzed (46.6%, $n = 61$) were located in the Köppen–Geiger climate zone *snow—fully humid—warm summer (Dfb)*, with intermediate SWE values (median of sites 76.7 mm).

A plausible explanation for more frequent ABSENT hydrological responses in regions with deeper snow, in our dataset namely northern Europe, is that these regions are more likely to have persistent snow cover throughout winter, with fewer midwinter snowmelt events or rain-on-snow events. In contrast, regions with less snow are more likely to have water entering the ground and refreezing over the snow cover season, which would lead to more ice in the topsoil matrix and less permeable ground. Ice blocks and lenses have been found to form in soils with high water content, thus preventing infiltration (He *et al* 2015, Pan *et al* 2017, Mohammed *et al* 2019). The complex interplay between snow and ground energy balance, due to temporally evolving snow thermal properties, and latent heat sources and sinks due to water phase (in snow and ground) leaves this discussion speculative and in need for more research.

In any case, mid-winter snowmelt events alone do not determine the water and ice content in the SFG, since autumn rainfall largely dictates the ground water content before freezing. Soil moisture conditions in autumn, at the onset of freezing, have been suggested to greatly influence the hydrological response of SFG (Willis *et al* 1961, Bayard *et al* 2005, Mahmood *et al* 2017, Appels *et al* 2018). The studies reviewed here rarely reported any explicit measure of soil ice content, making our dataset insufficient for detailed analysis of this relationship. However, as a proxy we noted studies that flagged soil water content at the onset of freezing, or soil ice saturation, as an important factor influencing the hydrological partitioning in SFG. Soil water or ice content was shown or speculated to be important in 53% of all entries analyzed. This reinforces the intuitive idea that high ice saturation, either from soil moisture conditions prior to freezing or from midwinter snowmelt events, is a key factor in the hydrological response of SFG.

4.2. Soil type characteristics not clearly linked with the hydrological response of SFG

Hydrological and thermal regimes in SFG are closely coupled through intertwined interactions. Ground thermal properties and the associated likelihood of ground frost formation are affected by many factors, including soil water content and soil composition. Soil thermal conductivity is typically lower in organic soils (such as peat) than in mineral soils (Brovka and Rovdan 1999). In general, thermal conductivity increases with increasing water and ice content. On one hand this enhances heat conduction and speeds up ground frost penetration. On the other hand increasing water content increases the heat capacity of the soil, and phase change associated with freezing soil in high water content releases more energy due to high latent heat of freezing, which slows down ground frost penetration. Soil with a low water content has high air-filled porosity and low heat capacity (Stähli

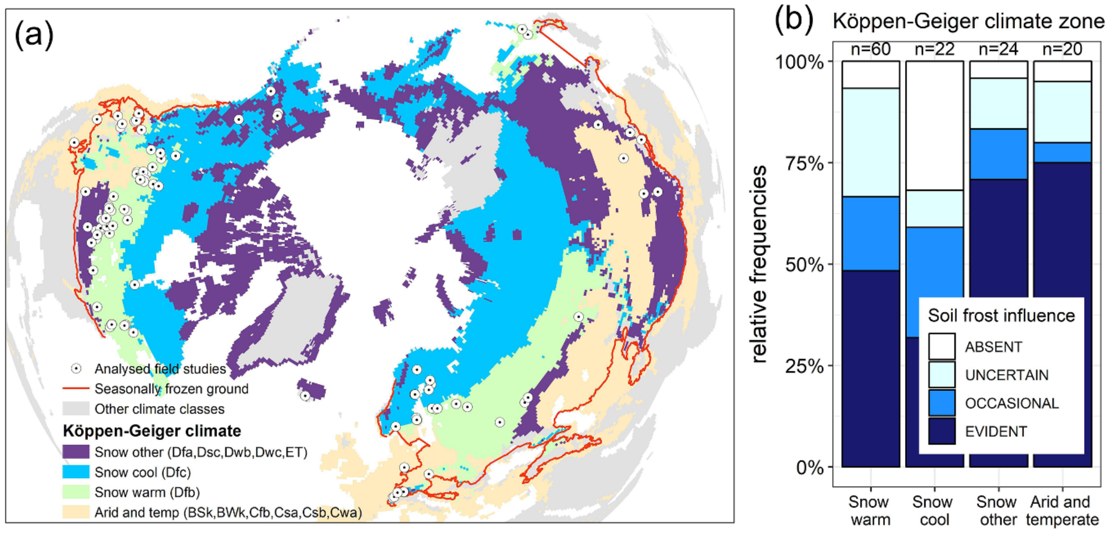

Figure 6. (a) Re-grouped Köppen–Geiger climate regions (Kottek *et al* 2006) indicating the study site locations in the papers reviewed here, and (b) relative frequency of reported hydrological responses in the regrouped Köppen–Geiger climate zones.

et al 2004, He *et al* 2015), which might also contribute to ground frost penetration, but leaves open pore space for initial (first meltwater/rain pulse) infiltration.

Soil type and structure are known to influence water flow in unfrozen soil, with theory and observations in soil physics and groundwater flow showing that fine-grained soil types in general have lower hydraulic conductivity than coarse-grained soils. Soils are only partially frozen even at sub-zero temperatures and fine-grained soils have been found to retain more residual unfrozen liquid water (Kurylyk and Watanabe 2013) than coarse-grained soils, especially when the organic matter content of the soil was high (Mustamo *et al* 2019). For example, some studies reviewed here found that organic peat soils only started to freeze at temperatures lower than −2 °C and were not fully frozen even at −5 °C (Konovalov and Roman 1973, Smerdon and Mendoza 2010). Unfrozen water could provide a domain for water flow in frozen fine-grained soils that is not available in coarse-grained soils, but due to the overall low hydraulic conductivity the amount and rate of water flow are minimal. Preferential flow in soil macropores is an important, but poorly understood, route of water flow in the soil (Beven and Germann 1982). A recent review by Mohammed *et al* (2018) highlighted the importance and poor understanding of macropore flow, particularly in SFG.

Less is known about whether the hydrological influence of SFG differs for different soil types. Comparative laboratory measurements have revealed lower hydraulic conductivity of frozen than unfrozen soil, but comparisons of relative change between different soil substrates have been infrequent (McCauley *et al* 2002, Watanabe and Osada 2016). Because only around 30% of the studies reviewed reported soil hydraulic conductivity, the dataset did not allow for rigorous analysis of differences between SFG response groups (ABSENT, UNCERTAIN, OCCASIONAL, EVIDENT). However, it was possible to identify the USDA soil type in 88% of the studies and it was used to classify soils into clayey, loamy, and sandy types, according to Jarvis *et al* (2009). The classification reflected soil susceptibility to macropore flow, which typically governs total water permeability in SFG (Mohammed *et al* 2018).

Comparing all hydraulic conductivity values reported in the studies reviewed, they were lower for frozen soil (median $= 2.0 \times 10^{-6}$ m s^{-1}, $n = 20$) than for unfrozen soil (median $= 1.35 \times 10^{-5}$ m s^{-1}, $n = 42$) (figure S3). However, the data were not strictly comparable, because most studies did not report both frozen and unfrozen hydraulic conductivity. Our reclassified soil types did not explain the variation in hydrological response in frozen soils (figure 7(a)), with all clayey, silty and sandy soil types having approximately similar frequencies of different SFG responses. While the soil type grouping used in the analysis was somewhat approximate, it indicated that soil type is not likely to be a decisive factor influencing the hydrological response of SFG, although soil type is important for the overall hydrological response.

4.3. Hydrological influence of SFG seems less clear in forested landscape

Vegetation and land use have been shown to influence ground energy balance, and thereby ground freezing regime. Conceptually, forest canopy can have both increasing or decreasing influences on the hydrological response of SFG. As pointed out earlier, trees influence snow accumulation and snowmelt because of snow interception on the canopy (Varhola *et al* 2010). This provides less insulation from cold air temperatures and can lead to more ground freezing than

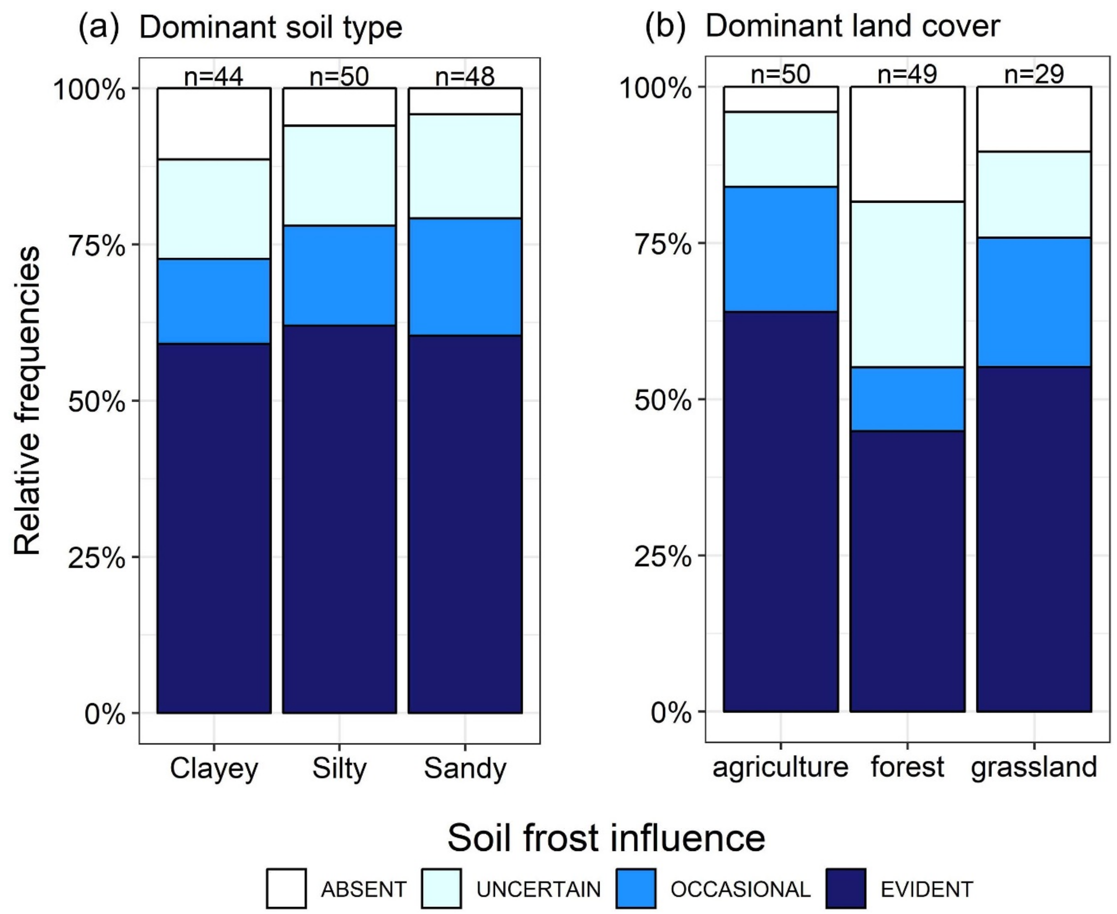

Figure 7. Nature of reported hydrological response (EVIDENT/OCCASIONAL/ UNCERTAIN/ABSENT) to SFG as a function of (a) soil type, with little difference in the distribution of reported hydrological responses between soil types, and (b) dominant land cover, with more ABSENT and UNCERTAIN responses at forest sites relative to forest and grassland.

in areas with deeper snow (Hardy and Albert 1995). A study by Harris (1972) found that infiltration rate was not substantially affected by ground freezing in deciduous forest and abandoned field plots, but that freezing of late winter snowmelt and rainfall closed soil pores. In conifer plantations, on the other hand, a hard snow-ice layer on the ground, caused by snowmelt water from the conifer canopy, can almost completely block infiltration (Harris 1972).

Tree canopies can also create spatial variability in the ground surface energy balance, and thereby make frozen ground 'patchier' (Stähli 2017). Trees have been found to provide shade from direct shortwave solar radiation, emit longwave radiation (best seen in earlier snowmelt near tree trunks), affect snow wind redistribution, and influence soil moisture variability through evapotranspiration (Marks *et al* 2002, Pomeroy *et al* 2009). Permeability in the topsoil, where ground frost is active, is impacted by macroporosity and preferential flow in all land covers and soils, but forest soils host extensive root networks, creating more hotspots for infiltration compared with cultivated land or grassland (Koestel *et al* 2012). Because of large macropores, abandoned field plots and deciduous forest have been found to have high infiltration rates even when the volumetric water content of the frozen ground is nearly 50% (Harris 1972). Both the spatial variability in energy balance and more mature macropore networks can potentially create avenues for focused infiltration, as further discussed in section 4.4 of this paper.

Anthropogenic land use is a major factor determining land cover globally, through urbanization, agriculture, and forestry. For example, studies in the Canadian Prairies found that infiltration rates in perennial grasslands, with a well-developed macropore network, were substantially higher than in cropland, where annual tillage breaks the macropores (van der Kamp *et al* 2003, Bodhinayake and Cheng Si 2004). In unfrozen state, we suggest that major land cover types can roughly be ranked from more to less permeable as: forested, grasslands, agricultural, and urban, but it is not known how ground freezing influences the hydrology of different land-use types.

Studies in our systematic review found that the influence of SFG appeared to have less hydrological relevance in areas where the primary land cover was forest (figure 7(b)). About 44% of the studies at forest sites reported ABSENT or UNCERTAIN influence of SFG on hydrological partitioning, whereas

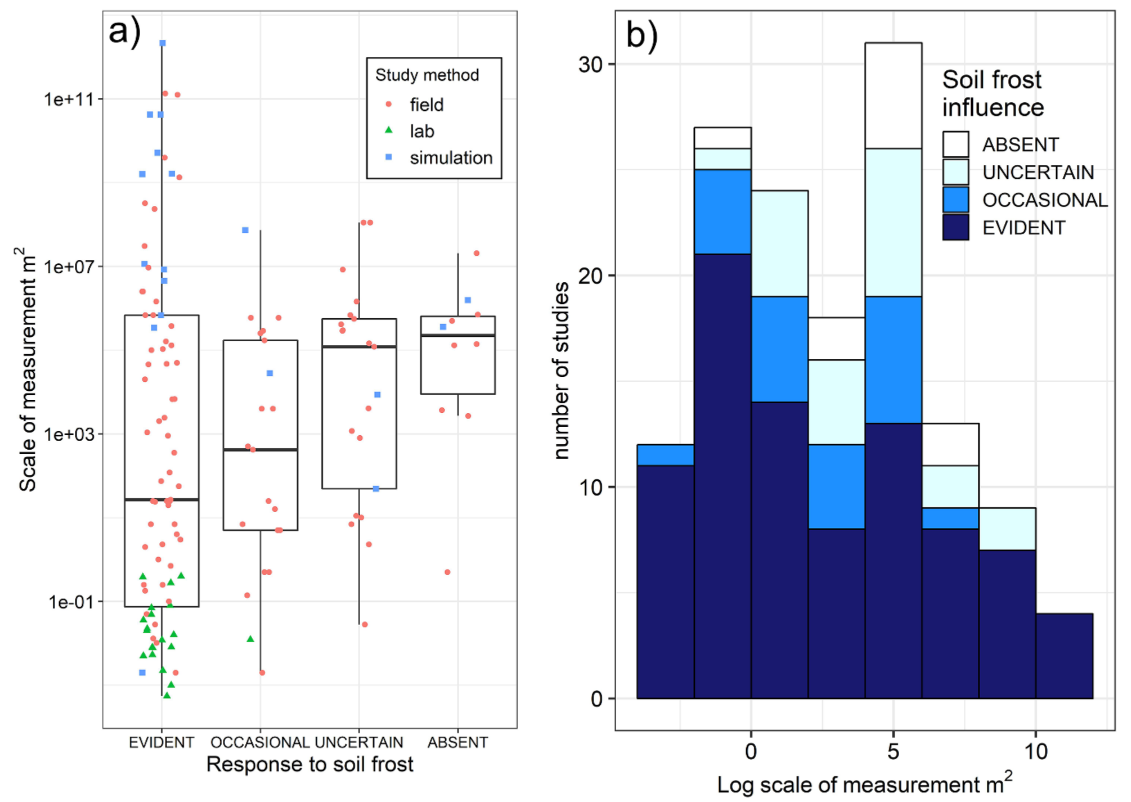

Figure 8. Nature of reported hydrological response (EVIDENT/OCCASIONAL/ UNCERTAIN/ABSENT) to SFG (a) as a function of spatial scale of measurement, showing a difference in median values between the different groups of hydrological response (Kruskal–Wallis test, $p = 0.073$) and (b) as stacked histogram plot with logarithmic scale of measurement on x-axis and number studies grouped to hydrological response of SFG on y-axis.

for agriculture and grassland sites the percentage was 16% and 23%, respectively. Although the differences were not great, the results reinforced the conceptual process understanding of more permeable forest soils when influenced by SFG. That said, accurate classification of the 'dominant' land use in individual studies was not straightforward. For example, Sterte *et al* (2018) reported an EVIDENT influence of SFG in a peatland-dominated sub-catchment, but with the SFG influence masked by a higher proportion of forested areas in the larger catchment. Similar masking results were reported by Shanley *et al* (2002), but for an agricultural area in a forest-dominated catchment.

4.4. Spatial variability in SFG can allow infiltration at landscape scale

The physical traits of the landscape result in large-scale and small-scale variations in frost depth and SFG permeability. This means that even in regions susceptible to ground freezing, there is still marked spatial variability in ground frost depth and ice content due to small-scale processes. Studies investigating a larger part of the landscape for frost penetration and infiltration capacity were more likely to detect more permeable regions, acting as local hotspots for infiltration. Even when infiltration was restricted at a location and preferential water flows occurred horizontally between the snow and ground interface, there were still pathways for infiltration, typically in landscape depressions (Hayashi *et al* 2003). For this reason, one can hypothesize that even when ground frost is relevant at the soil core scale, the relevance diminishes as the scale of the experiment increases and more of the spatial variability in the landscape is sampled (Seyfried and Wilcox 1995, Shanley and Chalmers 1999). The need to account for more infiltration on large spatial scales has also been pointed out by the modeling community (Cherkauer and Lettenmaier 2003, Gouttevin *et al* 2012). Pitman *et al* (1999) suggested that hydrological influence of soil frost may be based on observations at a too small scale to be relevant for large-scale model parameterization.

The studies reviewed covered a spatial scale from soil core (~10 cm^2) to major river basins (~2000 000 km^2) (figure 8). We saw studies falling to EVIDENT category throughout the spatial scale, confirming that the hydrological influence of SFG cannot be disregarded at any scale. Even so, our analysis provided three interesting insights on the scale dependence of the hydrological response. Firstly, the studies included in our review that reported ABSENT or UNCERTAIN influence of SFG on hydrological partitioning were typically conducted on hillslope/small catchment scale (median ~10^5 m^2) (figure 8(a)). This was the scale where the number of studies was the highest (figure 8(b)). All except one of the studies reviewed that reported ABSENT SFG influence were conducted at a scale range of 10^3–10^7 m^2. Secondly, the hydrological effect of ground frost at the scale of soil pore space and soil cores was manifested as uniformly EVIDENT responses in laboratory studies (figure 8(a)). Thirdly, the studies at scales 10^8 m^2 or greater predominantly reported an EVIDENT hydrological response to SFG. The spatial scale did not correlate any climate variables or physiographical or climate variables (figure S8). Of other key physiographical parameters slope did not explain the grouping of SFG response (figure S5), but field studies reported EVIDENT response tended to take place at low elevations (figure S7).

Our conclusion on the scale dependence may be influenced by publication bias, i.e. the tendency and preference to publish only positive results. Laboratory studies are likely to be designed in a way that yields compelling positive results, with any negative results potentially remaining unpublished. The almost uniformly reported EVIDENT small-scale influence may in part result from such selective publishing. Similar problems may be associated with modeling studies, which tend to be biased towards publishing positive results (Beven 2018). In the context of SFG hydrology, if introducing SFG processes to a hydrological model does not significantly improve the simulation, the results may remain unpublished. Even though the majority of our analyzed simulation studies do report EVIDENT hydrological response and show improved model simulations with added SFG routines (Anderson and Neuman 1984, Gray *et al* 1985, Prévost *et al* 1990, Niu and Yang 2006), there are simulation studies in each response category. For example, Stähli *et al* (2001) and Lindström *et al* (2002) and Pitman *et al* (1999) showed and concluded that including ground frost processes did not clearly improve model predictions. Sterte *et al* (2018) obtained mixed results on the simulated influence of ground frost in peatland and forest environments, and concluded that it was landscape heterogeneity and sub-catchment characteristics that played a critical role in regulating surface water and groundwater partitioning in the SFG regions studied.

5. Outlook for changes in hydrology of SFG

The major agent of change in the hydrology of seasonally frozen regions is persistently progressing climate change. As the water formerly stored in ice (sea ice, glaciers, ground ice) thaws (Lemke *et al* 2007, Gerland *et al* 2019) and the warmer atmosphere can transport more water, this will result in more water in the Northern Hemisphere's hydrological cycle (Bring *et al* 2016, Box *et al* 2019). Although these predicted changes will not occur only in SFG regions, this 'intensification of the Arctic freshwater cycle' (Rawlins *et al* 2010) will profoundly affect the hydrological and thermal regime of SFG regions.

Intuitively warmer climate leads to less ground ice in SFG, and therefore a smaller region where SFG is important. Ongoing permafrost thaw and degradation are well documented and predicted to continue (Slater and Lawrence 2013, Hjort *et al* 2018), which will lead to a gradual transition to less permafrost presence globally. Even though predictions from LSM simulations address near-surface permafrost typically to a depth of 3–5 m, such thaw depth is enough to create suprapermafrost aquifers, i.e. perennially unfrozen regions allowing flow between the seasonally frozen topsoil and the permafrost table below (Walvoord *et al* 2012). In regions with less extensive permafrost vertical talik expansion can increase groundwater circulation and reduce hydrological importance of permafrost (Evans *et al* 2020). However in most of the thawed permafrost regions minimum annual ground surface temperature will continue to fall below 0 °C during the 21st century leading to geographical expansion of the SFG region towards the north and higher altitudes in the future (Nan *et al* 2005). The fundamental change in the hydrological regime of these regions will be a transition from permafrost to SFG.

Furthermore, the southern border of SFG (see figure 2) is not necessarily migrating northwards as consistently as the continuous permafrost boundary. For example, in their simulations of future ground ice conditions Lawrence *et al* (2012) found that both permafrost and SFG extent are projected to decline globally, but the areal reduction in SFG area was approximately 2 × 10^6 km^2 smaller (size of Greenland) than that of permafrost in both low and high emission climate scenarios. Observational records of SFG reduction are founded on changes in maximum freeze depth, ground surface or air temperature and frozen period duration (Frauenfeld *et al* 2004, Zhao *et al* 2004, Frauenfeld and Zhang 2011). Even though long-term observations of SFG areal distribution globally are currently missing due to technical challenges, remote sensing techniques offer a lot of promise in this regard (see next section for more discussion).

We speculate that the key factor determining the fate of SFG presence at its southerly fringes is the interplay between snowpack development and ground freezing. The SFG regions typically have at least an intermittent snowpack (see figure 5(a)), and snow processes have profound impacts on ground thermal regime. Some have suggested that we might even see 'colder soils in a warmer climate' (Groffman *et al* 2001, Halim and Thomas 2018). Higher winter average air temperature and predicted increases in precipitation in some regions, reductions in others, will affect the snowpack composition and snow cover duration (Flanner *et al* 2011, IPCC 2014). Snow depth is predicted to decrease in the future due to warmer climate and the number of midwinter freezing–thawing events has already been shown to increase slightly with the current warming climate (Campbell *et al* 2010, Kivinen *et al* 2017). Mid-winter snowmelt water has been found to typically saturate the uppermost soil layer and, when refrozen, can form a nearly impermeable 'concrete frost' layer between ground and snow interface (Haupt 1967, Dunne and Black 1971). Decreased snow cover may amplify the hydrological relevance of SFG (figure 5(b)). Increasing precipitation and the shift in the precipitation phase from snow to rain will reduce snow depth, while rain-on-snow events on existing snowpack will increase the bulk density of the snow. Both processes will reduce the thermal insulation of snowpack, which can promote ground frost development at subzero air temperatures. More intensive ice content in SFG because of warmer winters may change the hydrological response in SFG during the main spring snowmelt (Hardy *et al* 2001). Our analysis also indicated that snow conditions, not air temperature, are linked to the hydrological relevance of SFG, but this needs to be investigated further.

We further hypothesize that the hydrological influence of SFG may also be amplified in more indirect ways. The predicted warmer climate will accelerate land cover change and extend the growing season (Starfield and Chapin 1996, Kim *et al* 2012, Wang *et al* 2020) creating more favorable conditions for agriculture and forestry in regions that are currently experiencing cold winters. At the same time, high-latitude areas are under increasing pressure for natural resource exploitation activities, such as mining (Haley *et al* 2011). These scenarios paint a picture of accelerated land-use change in seasonally frozen regions. In the studies reviewed here, the hydrological relevance of SFG was more obvious in grasslands and agricultural areas than in forested areas (figure 7). Thus, if more of the forested landscape is converted to agriculture or other managed land use, SFG may further intensify the hydrological changes that such conversion would bring about. However, the sole role of SFG in the hydrological change will be difficult to detect because of complex relationship between hydrological processes, landuse change, and water management.

SFG has several non-hydrological environmental repercussions, which are to some degree mediated by hydrology. Increased hydrological connectivity and warmer, more active soils have been directly linked with greenhouse gas emissions, instream and lake processing of organic carbon, and solute transport through runoff into watercourses (Groffman *et al* 2006, Kurganova *et al* 2007, Brooks *et al* 2011, Wagner-Riddle *et al* 2017, Serikova *et al* 2018). The absence of ground frost can also cause problems for agricultural activities, as seasonal frost has been shown to prevent the growth of volunteer tubers and seeds (Hirota *et al* 2011), reduce soil erosion and nutrient leaching during snowmelt (Blackburn *et al* 1990, Wu *et al* 2018), and reduce soil moisture and plant-available water after snowmelt (Yanai *et al* 2017). Simulations by Hagemann *et al* (2016) showed that reduction in soil moisture due to increased SFG runoff created a feedback to precipitation, and reduced model bias in precipitation and evapotranspiration, suggesting that it is crucial to represent SFG to capture the close coupling between land and atmosphere systems. However, our systematic review focused specifically on hydrological fluxes, while the direction of change in other hydrologically mediated environmental changes, however important, was beyond the scope of the study.

To summarize, determining the future occurrence and hydrological importance of SFG is challenging, due to the complexity of interactions between climate, land, water, ecosystems, and anthropogenic activities. There are no simple answers regarding the influences exerted by SFG on hydrology. However, multiple factors indicate increased hydrological relevance of SFG in the future, as suggested by our systematic review. Because of thawing permafrost, changes in snowpack insulation capacities, more frequent mid-winter melt and rain-on-snow events, and land cover change, the hydrological relevance of SFG might actually increase at the current SFG region, and the northern fringes of the SFG-influenced region with widespread permafrost thaw. This, together with an expected reduction in water stored as snow, can change the spatial and temporal water resource availability and hazard susceptibility in SFG regions. Changes in the SFG regime have potential to influence water, sediment, and solute delivery in major northern rivers, which is important for Northern coastal biogeochemistry (Bring *et al* 2016).

6. Key areas for future research

Systematic analysis of the 163 entries in our dataset revealed a biased spatial distribution of studies on the effects of SFG on hydrology (figure 2). The available studies were clustered to North America, while a considerable land area of SFG lies in northern Eurasia. This bias was exaggerated by the fact that we were unable to access all pioneering Soviet literature in the field of SFG research, due to the language barrier and unavailability of published literature in digital format. More important than the unequal number of studies between countries was a disparity in the number of studies in different climate regions and snow regimes. Almost half of the studies reviewed were in regions with snow and a warm summer (*Dfb* in the Köppen–Geiger climate classification, see figure 6), leaving other climate and snow conditions underrepresented. More studies are needed in snowier environments to verify the less evident hydrological influence of SFG. Studies in boundary regions for SFG and permafrost are also needed, in order to better understand shifts from thawing permafrost to SFG and its influences on hydrological processes.

In terms of land cover, forested, agricultural, and grassland areas were fairly equally represented in the hydrological SFG studies reviewed here. However, peatlands were poorly represented, despite comprising a large percentage of land surface area in the Northern Hemisphere. Alarmingly, we found no analysis of SFG influence on urban hydrology, with urban ground frost mentioned in only a few studies (Valeo and Ho 2004, Shahab *et al* 2018). In an era of rapid global urbanization, the effect of SFG on urban hydrology should be studied as a matter of urgency.

Most of the reviewed studies explored SFG influence on infiltration ($n = 81$) runoff ($n = 65$), stream hydrograph ($n = 23$) or percolation ($n = 19$) (see figure 2 for considered fluxes and section 2.1 and table S1 for description). We identified fewerstudies exploring fluxes of groundwater recharge ($n = 9$), water chemistry ($n = 9$), or evapotranspiration ($n = 5$). Tracer techniques based on water and catchment geochemistry are becoming increasingly popular in hydrological partitioning analysis (Penna *et al* 2018, Bowen *et al* 2019). Stable water isotopes in particular are widely used in differentiating snowmelt signal from streamflow, and have potential to estimate the role of SFG in snowmelt runoff generation (Shanley *et al* 2002, Laudon *et al* 2004, Fuss *et al* 2016). We found mixed results about the influence of SFG on evapotranspiration in the nine studies analyzed. The role of SFG on evapotranspiration should receive more attention in ecohydrological studies (Smith *et al* 2019).

The flow of water through the environment is a highly complex process where measurement of any hydrological flux is a challenge. Determining how ground frost influences different hydrological fluxes adds to that challenge. In this review, we devised a system whereby the hydrological influence of SFG was classified into four categories: EVIDENT, OCCASIONAL, UNCERTAIN, and ABSENT. We found that this categorization was useful in summarizing the findings of individual field studies. However, more universal and comparable metrics are needed to understand how SFG modulates the hydrological response. We suggest two key variables to measure in this regard: (a) volumetric ice content in the soil matrix; and (b) hydrological flux decrease between unfrozen and frozen state. More focus on these two variables would also enable advances in numerical modeling of the hydrological response in SFG regions.

Soil volumetric ice content is the key variable influencing the hydraulic properties in frozen ground and the most relevant hydrological parameter, even though measurements of frost penetration depth are more readily available and technically straightforward. Measured changes in soil hydraulic conductivity caused by increasing ice content typically differ by multiple orders of magnitude. Many studies highlight the importance of 'concrete frost', a layer with a high ice content at, or near, the ground surface, which considerably reduces the ground permeability but is not well captured by frost depth measurements. We suggest that soil ice content can serve as a useful proxy for reduced soil hydraulic conductivity, due to the commonly observed log-linear relationship between the two (McCauley *et al* 2002, Watanabe and Osada 2016).

Soil ice content can be determined not only as point measurements using soil coring or various soil moisture sensors, but also by techniques resolving spatial variability, such as geophysical techniques (Lundberg *et al* 2016b). Spatially distributed estimates of soil ice content may prove crucial for a better understanding of SFG hydrological influence across scales (figure 8). Even so, measurements of soil ice saturation made with field-based methods have uncertainties because of complexities in soil structure and lithology, and will inevitably be too small in scale to explore the large-scale (river basin, continental) influence of SFG. Remote sensing techniques provide the greatest potential in characterizing and harmonizing large-scale estimates of seasonal ground freeze/thaw status. Satellite remote sensing has been utilized for several decades to retrieve ground freeze/thaw status with both passive (Zuerndorfer *et al* 1990) and active microwave observations (Rignot and Way 1994). Ground freezing results in decrease of the dielectric constant of ground at microwave frequencies, altering its radar scattering properties. Such observations can produce consistent datasets showing the long-term extent of SFG and can provide freeze/thaw status estimates for the entire Northern Hemisphere (Rautiainen *et al* 2016, Derksen *et al* 2017, Rowlandson *et al* 2018) or globe (Kim *et al* 2012, 2019). Such data have the capability and spatial coverage to examine influence of land use and anthropogenic activities on SFG extent.

A current challenge with utilizing microwave remote sensing data in this context is that the currently available products have either the required high temporal resolution (daily) but low spatial resolution (>25 km), or have high spatial resolution (<100 m) but low temporal resolution (weekly) (Chew *et al* 2017, Derksen *et al* 2017). Another challenge is the validation of remote sensing freeze/thaw status measurements over horizontally and vertically heterogeneous landscapes (Derksen *et al* 2017). Other remote sensing techniques, such as radar interferometry, have been utilized in estimation of active layer thickness and ground freeze/thaw status in deformation studies (Schaefer *et al* 2015, Daout *et al* 2017). When coupled with hydrological analysis (hydrometric measurements or numerical modeling), future satellite missions and improved freeze/thaw status retrieval algorithms could make data from spaceborne devices more readily usable in analyzing the large-scale influence of SFG on hydrological fluxes.

Even though soil ice content is important, a well-developed soil macropore network can govern the hydrological response if large pores remain air-filled (Mohammed *et al* 2018). Failing to account for preferential flow through macropores can lead to gross underestimation of the amount and speed of infiltration through SFG. Our analysis provided an indication of less evident SFG influence on forested areas (figure 7(b)), which may partly have resulted from macropore flow (Espeby 1990, Stähli *et al* 2004). Even so, preferential flow can also play a major role in SFG hydrology of grassland and agricultural areas (van der Kamp *et al* 2003). The role of macroporosity in water flow remains problematic to conceptualize mathematically and measure reliably, not only in frozen, but also in unfrozen conditions, and needs further research (Beven and Germann 2013, Mohammed *et al* 2018). Measuring soil ice content, as we recommend, can account to some degree for the influence of ice build-up in the macropore network (Watanabe and Kugisaki 2017).

Developing a numerical metric to measure the change in hydrological response instigated by SFG would be a major advance in analyzing the hydrological influence of SFG. Future studies attempting to characterize the influence of SFG should perform a comparative measurement of the hydrological flux of interest, with and without frost influence. For some measurements, such as soil hydraulic conductivity and infiltration capacity, reporting the difference between frozen and thawed states should be straightforward. For other fluxes, such as streamflow and groundwater recharge or surface runoff, reporting a runoff (or recharge) coefficient for unfrozen and frozen conditions would be a relatively well-defined metric. Runoff coefficient characterizes the fraction of a given water input (typically precipitation, snowmelt, or irrigation) that ends up in streamflow/groundwater recharge. Analyzing information on thawed/frozen flux change (preferably with measurement of soil ice saturation) could yield more quantitative results and reveal nonlinearities in the hydrological response to SFG, with implications for management and hydrological modeling.

There are plenty of numerical modeling approaches, developed somewhat in parallel within the fields of hydrological, hydrogeological, and earth system sciences, for simulating water flow in SFG. However, a spatially distributed numerical hydrological simulator with a physically-based representation of all key SFG processes below and above ground is still warranted. The ideal model should encompass: (a) the surface water and snow routines and of hydrological and 1D thermo-hydrogeological models; (b) the agility to incorporate spatial data (remote sensing and soil-vegetation interactions) of LSMs; and (c) the physically-based process representation of coupled underground heat and water flow and groundwater dynamics of 3D thermo-hydrogeological models. In addition, the influence of soil macropore water flow in frozen ground is not well represented in any of the existing model families, and should be accounted for. With or without such model fusion and development, utilization of new remote sensing data could result in rapid advances in spatial mapping and hydrological modeling of SFG. As described above for field measurements, comparative modeling studies of frozen and unfrozen systems at different spatial scales (from soil profile to continental scale) would be beneficial.

7. Conclusions

Most studies (∼75%) included in our systematic review confirmed that seasonal freezing of ground has hydrological importance. The SFG influence on hydrology was seen in different climate and physiographical conditions, and across spatial scales (from soil core to large watersheds). The finding stresses that accounting for SFG processes should be an integral component in any hydrological studies in seasonally frozen environments. This is particularly important in regions where the ground frost regime is changing because hydrological changes in SFG can have cascading effects on biogeochemistry, ecosystem functionality, and anthropogenic activities. Even though the majority of studies confirmed the hydrological role of SFG, a significant proportion of reviewed literature (∼25%) reported a minor or negligible influence of SFG on their analyzed hydrological variable. Our analysis of these studies suggested that the hydrological role of SFG may be reduced in climates with deep snow cover and regions forested landscape, which is important for water resource management in a changing climate. Our systematic review identified several knowledge gaps in the existing SFG hydrology literature, and we stress that more studies are needed (a) to explicitly link ground ice content and hydrological fluxes, (b) in urban areas and climates with deep snow (c) at large scale (watershed and beyond), where SFG studies should better utilize and further develop remote sensing products and hydrological modeling.

Data availability statement

The data that support the findings of this study are openly available from IDA research data storage at the following URL/DOI: http://urn.fi/urn:nbn:fi:att:dd319fe3-481c-497c-bc0f-70c1c27e2099.

Acknowledgments

This research was supported by the Academy of Finland, Grant No. 316349 and University of Oulu KVANTUM institute. We thank all the authors cited in Table 2 who have conducted hydrological studies in regions with seasonally frozen ground. Your work made the analysis presented here possible.

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