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Global-scale modelling of glaciers, ice sheets and permafrost: recommendations for Hydro-JULES

Environmental Change, Adaptation and Resilience Programme

Open Report OR/20/020

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Contents

FIGURES

TABLES

Summary

This report is part of the Hydro-JULES research programme supported by NERC National Capability funding (grant number: NE/S017380/1) to the UK Centre for Ecology & Hydrology (UKCEH), British Geological Survey (BGS) and National Centre for Atmospheric Science (NCAS). Hydro-JULES will deliver an open-source, three-dimensional community model of the terrestrial water cycle. As part of work package 4, the BGS will develop an enhanced representation of groundwater in Hydro-JULES and link it to land-surface processes, with the aim of implementing the model on a global scale.

In cold regions, glaciers, ice sheets and permafrost influence regional groundwater flow and recharge processes. This report aims to facilitate the inclusion of cryosphere–groundwater systems in the Hydro-JULES modelling framework by reviewing potential modelling approaches and then prioritising a set of model developments that should be undertaken as part of the ongoing development of the Hydro-JULES modelling framework. All outputs from the Hydro-JULES programme (including this report) are open and freely available to ensure transparency and auditability in the development of the scientific approach.

1 Introduction

The Joint UK Land Environment Simulator (JULES) (Best et al., 2011) is a community land-surface model (LSM) that simulates energy, water and carbon fluxes between the land surface and the atmosphere. It has been developed by a wide community of researchers, coordinated by the UK Met Office (UKMO) and the UK Centre for Ecology & Hydrology (UKCEH). It forms an integral component of the UKMO's operational weather forecasting capability and their contributions to global climate change projections by providing lower boundary conditions for their unified model. JULES has also opened up new opportunities to investigate land-surface feedbacks (e.g. hydrological and biophysical) to climate variability and has been adopted by researchers from a variety of scientific disciplines in the natural and earth sciences.

The need for increasingly sophisticated LSMs prompted the UKMO and UKCEH to release JULES (then known as MOSES) in 2006 as an open-source, community-led LSM (Blyth et al., 2006). Since then, researchers with expertise in physical and biological land-surface processes have continuously improved the JULES source code. It now includes a sophisticated array of land-surface processes, including multilayer snow modelling, dual-layer canopy modelling, dynamic vegetation, soil hydrology and carbon cycling.

In October 2016, the Natural Environment Research Council (NERC) commissioned a new programme of work, Hydro-JULES, to accelerate the development of JULES and help tackle the most pressing and internationally important questions around climate change impacts on the global terrestrial hydrological system. The five-year research programme (April 2019 – March 2024) brings together UKCEH, the BGS and the National Centre for Atmospheric Science (NCAS) to develop a world leading, open source, large scale (national to global) and integrated terrestrial hydrological model that goes from global weather, through the terrestrial hydrological system, to consequent impacts.

The new Hydro-JULES modelling framework will include developments to the JULES source code and computational interfaces between JULES and other process models. As part of this, the BGS team are developing a more sophisticated representation of groundwater flow and recharge processes that can be applied at global scales. A key consideration for this is how groundwater systems in cold regions, where glaciers, ice sheets and permafrost can influence groundwater flow and recharge processes significantly, can be simulated.

Approximately 10 per cent of the land-surface area on Earth is covered by ice while 24 per cent of land in the northern hemisphere includes permafrost (NSIDC, 2019). This report aims to facilitate the inclusion of interactions between the cryosphere and groundwater systems in the Hydro-JULES modelling framework by reviewing current modelling techniques and making recommendations for including them in the Hydro-JULES modelling framework. Note that this report focuses on glaciers, ice sheets and permafrost but does not consider snow, as this is already included in the JULES code and has been widely documented (Best et al., 2011).

Section 2 begins by providing an overview of key concepts in glacier, ice sheet and permafrost hydrology and how these systems interact with groundwater systems. It also discusses the transient nature of the cryosphere and sensitivity to climate variability, which is an important consideration in the development of the Hydro-JULES modelling framework. Based on this overview, Section 3 reviews approaches for modelling the principal processes that govern water flow through cryosphere–groundwater systems. Finally, Section 4 provides a set of recommendations for including and/or improving the representation of cryosphere–groundwater systems in the Hydro-JULES modelling framework.

2 Water flow from glaciers and ice sheets to groundwater

2.1 GLACIER HYDROLOGY

The study of water storage and transport in glaciers and ice sheets forms a significant research topic in glaciology and hydrology as it has important practical implications for social, economic and environmental wellbeing (Milner et al., 2017). Meltwater run-off from glaciers provides water, energy and food security for millions of people around the world (Immerzeel et al., 2020) and sustains highly vulnerable alpine river and wetland environments that provide important ecosystem services (Polk et al., 2017).

Meltwater may derive from a number of sources including supraglacial (ice surface) melt, englacial (internal) strain heating due to ice deformation and basal (at the ice bed) melt due to geothermal and frictional heating. Meltwater is stored in:

- snow and firn (partially compacted snow on the way to forming ice) on the ice surface
- supraglacial lakes and streams
- englacial fractures and crevasses
- subglacial tunnels and cavities

(Figure 1)

Surface stores can drain to the glacier bed via moulins (deep vertical shafts into which water can enter from the surface). Where ice is overriding permeable geological formations, basal water can infiltrate the subsurface.

Subglacial recharge can modify regional groundwater flow fields significantly, particularly in low-storage bedrock where infiltration can lead to large increases in pore pressure (Lemieux et al., 2008b). The significance of subglacial recharge fluxes from past glaciations has been demonstrated by the presence of glacial meltwater at great depth in present-day aquifers in glaciated basins (e.g. Grasby and Chen, 2005).

An important consideration in estimating subglacial recharge is the thermal regime of the ice. In very cold environments where all of the ice is below melting point, subglacial recharge is negligible. These are known as cold-based glaciers. Conversely, glaciers where all of the ice is at melting point are known as temperate or wet-based (Cuffey and Paterson, 2010). These are found in warmer environments and have the potential to sustain large subglacial recharge fluxes from surface melting.

Polythermal glaciers represent those with beds that are both cold- and wet-based. These are typically found in colder environments with regions of wet-based ice where the ice overburden and subsequent basal pressure are large enough to attain pressure melting point. These glaciers are typically frozen around the glacier margins where the ice is thin, but wet-based away from the margins where ice overburden pressures are high (Glasser and Hambrey, 2003). These glaciers are therefore likely to show distinct zones of subglacial recharge.

The thermal regime of rapidly melting polythermal glaciers can be further complicated by an apparent delayed response to the prevailing climate (Rippin et al., 2011). Here, temperate ice may be present, not because the ice is thick, but as a remnant of a previous polythermal state when the ice was thicker.

Quantitative assessments and modelling studies of subglacial recharge have been driven, to some extent, by the nuclear industry, as large-scale groundwater flow patterns due to past glaciations can dictate the development of safe, deep, geological repositories for radioactive waste (Heathcote and Michie, 2004).

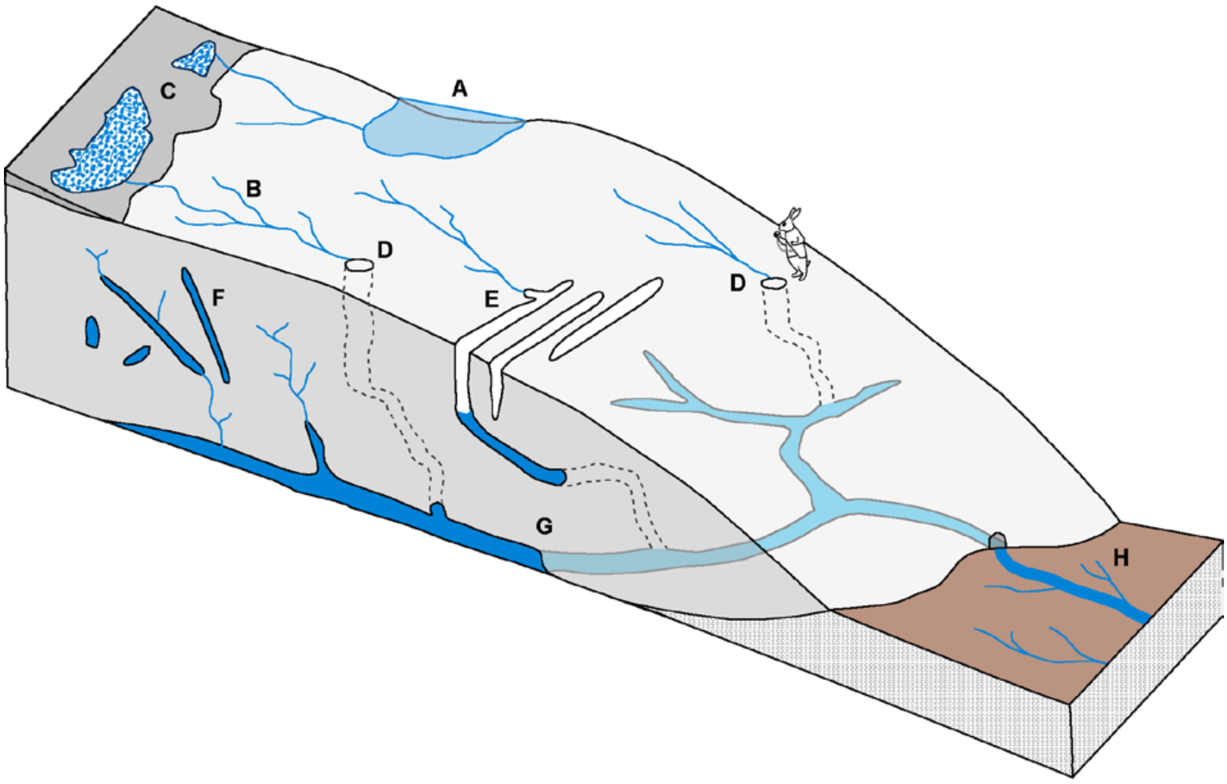

Figure 1 Elements of the glacier water system including: (A) supraglacial lake; (B) surface streams; (C) swamp zones in firn; (D) moulins; (E) crevasses; (F) water-filled fractures; (G) subglacial tunnels; (H) run-off to glacier foreland. Re-used from Cuffey and Paterson (2010) with permission of Elsevier.

2.2 PROGLACIAL AND PERMAFROST HYDROLOGY

Meltwater that does not reach the glacier bed or infiltrate the subsurface inevitably flows into the proglacial regions, where it can interact with groundwater systems through meltwater river channels (Figure 2). Meltwater-fed river channels emanating from glacier-covered regions can perturb proglacial groundwater-level dynamics through the bidirectional exchange of water between river and aquifer (Baraer et al., 2015, Ó Dochartaigh et al., 2019). In some cases, particularly in arid regions where diffuse recharge fluxes are small, meltwater river channels are the primary source of groundwater recharge (Liljedahl et al., 2017). A number of studies have highlighted the sensitivity of proglacial groundwater-level dynamics to changes in meltwater run-off (Levy et al., 2015, Robinson et al., 2009). In these systems, groundwater-level dynamics are closely coupled to river-stage variability and may exhibit behaviour that is more strongly tied to climatic conditions and run-off generating processes (e.g. melt) away from the aquifer in the run-off bearing, glacierised regions.

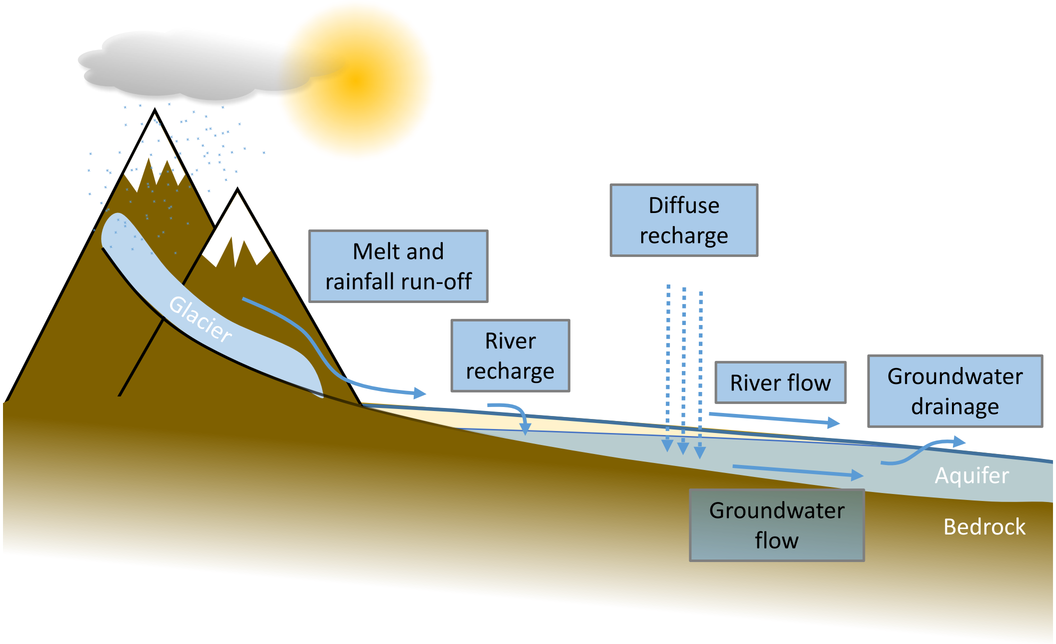

Figure 2 Conceptual model of proglacial water cycling in a typical unconfined aquifer in the foreland region of glacierised mountains.

The presence of permafrost in the foreland regions of glacierised basins greatly reduces soil permeability, which can inhibit groundwater recharge and groundwater discharge to the surface (Woo, 2012). Permafrost may be:

- continuous: all water within the soil is frozen
- discontinuous: a large body of permafrost that contains unfrozen sections
- sporadic: small isolated patches of permanently frozen ground

(Lemieux et al., 2008b).

Discontinuous and sporadic permafrost allow groundwater and surface water to interact. For example, taliks (permanently unfrozen sections within continuous permafrost) provide a pathway for recharge and discharge of deep groundwater.

2.3 CRYSOPHERE-CLIMATE COUPLING

Glaciers and ice sheets are in a continuous state of mass flux due to mass and energy exchanges at the ice surface. They gain mass through the accumulation of snow on the ice surface, which then forms ice by compaction and melt and refreezing processes. They lose mass by ablation processes, including melt and sublimation. Accumulation is strongly dependent on local precipitation patterns, while melt and sublimation are driven by energy transfer to the ice surface from the Sun and the atmosphere. Changes in the total mass of glaciers and ice sheets are therefore largely determined by the climate.

For most glaciers, surface mass balance correlates strongly with elevation (Figure 3). Over the higher region of a glacier, precipitation inputs are typically greater and surface air temperature is lower, which reduces heat fluxes to the ice surface. The region where net surface mass balance is positive is referred to as the accumulation zone. A lower region, where ablation processes dominate and the net surface mass balance is negative, is referred to as the ablation zone.

Glaciers may also lose mass due to the separation of ice blocks from the ice edge. This process is known as calving and is an important component of the mass balance of lake- and marine-terminating ice.

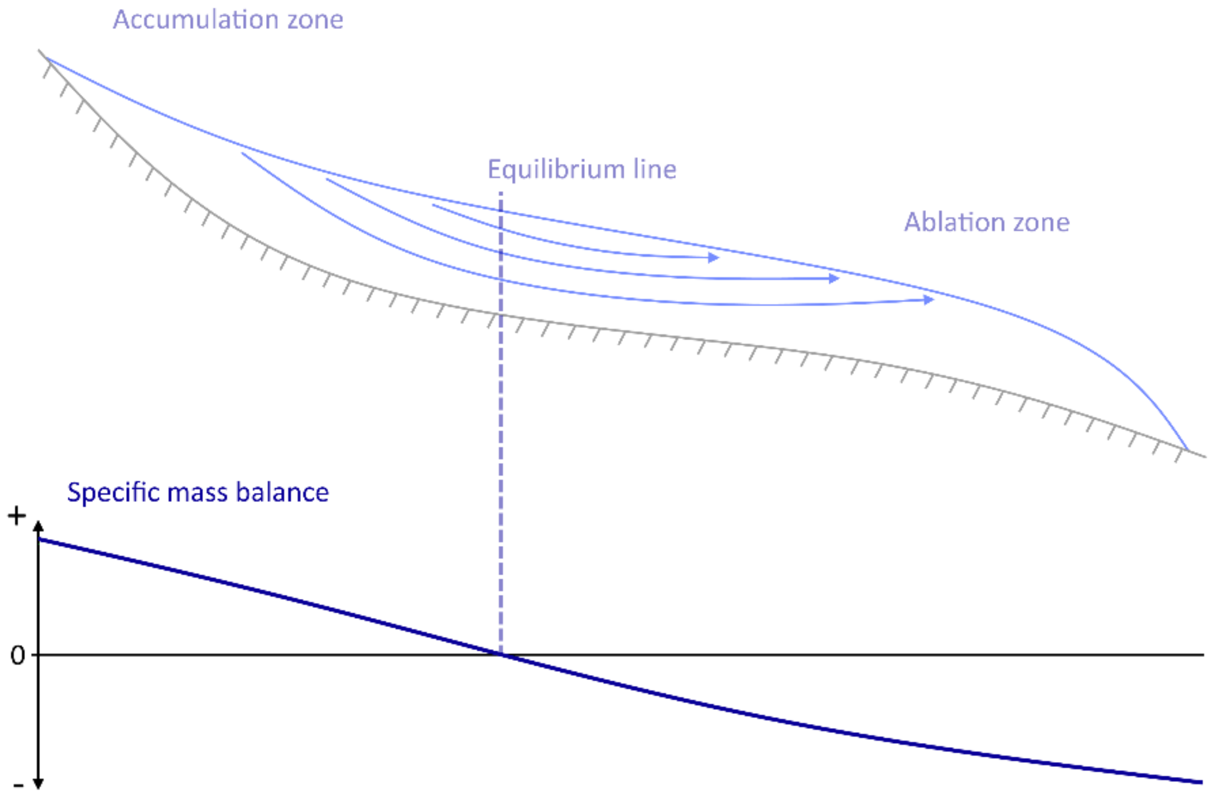

Figure 3 Typical surface mass balance pattern along glacier cross-section.

Accumulation and ablation processes are also controlled by the movement of ice masses. Gravity pulls ice vertically downwards, which causes it slide over bedrock and flow viscously. This serves to transport ice mass from the accumulation zone to the ablation zone and therefore significantly influences net mass balance. Flow near the ice margin also controls the quantity of ice available to lake and marine calving.

Glaciers do not necessarily flow at a constant speed. Many temperate glaciers show seasonal speeding up of ice flow due to the periodic lubrication of the glacier bed from meltwater during the melt season. Other glaciers show more pronounced cyclical flow instabilities, with long periods (typically tens to hundreds of years) of quiescence with little ice movement, rapid downwasting in the ablation zone and thickening of ice in the accumulation zone, and short periods of rapid ice flow velocity (surges). The ice flow regime of surging glaciers is complex and extremely challenging to represent in even the most sophisticated ice flow models.

The distribution of permafrost, which is not overlain by ice, is also strongly controlled by energy exchanges between the land surface and the atmosphere. Typically, permafrost exists below a layer of soil (up to around 4 m thick) that freezes and thaws each year. This is known as the active layer, the base of which forms the top of the permafrost (Figure 4). Only the ground that remains permanently frozen for two or more years is considered permafrost (Osterkamp and Burn, 2015). Similarly, the base of the permafrost occurs where the equilibrium temperature reaches 0°C (e.g. due to geothermal heating or sensible heating from groundwater).

Energy exchanges at the land surface (e.g. solar radiation and atmospheric turbulent heat fluxes) are strongly influenced by the presence of snow and vegetation. Snow and vegetation insulate the subsurface from energy exchanges with the atmosphere. Vegetation also affects soil water content and evaporation fluxes that serve to reduce the ground surface temperature.

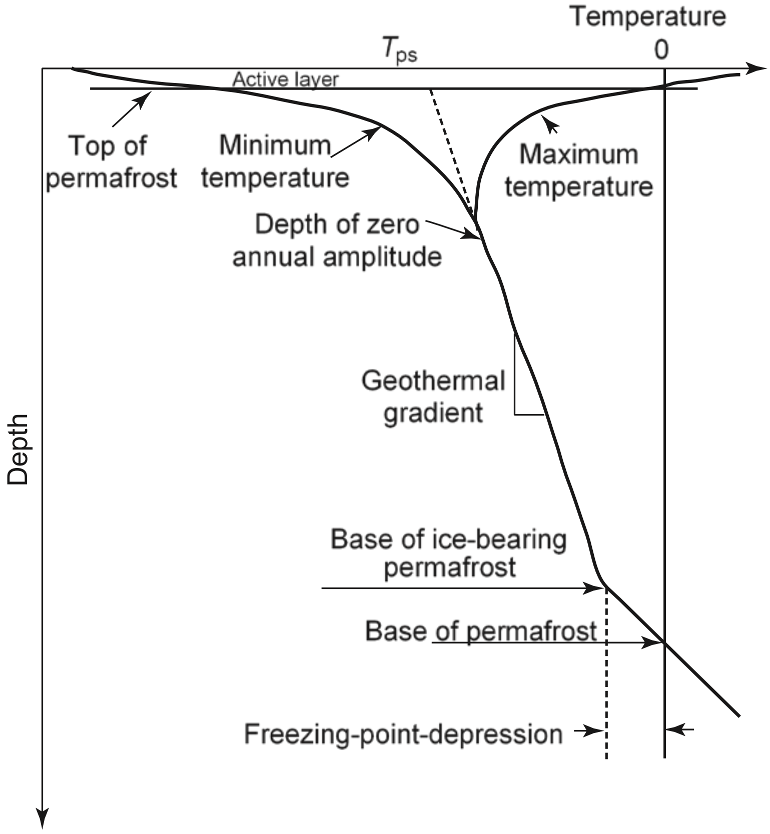

Figure 4 Idealised permafrost and seasonal temperature distribution. Re-used from Osterkamp and Burn (2015) with permission of Elsevier.

2.4 SUMMARY

Meltwater from glaciers and ice sheets may emanate from, and travel through, a cascade of supra-, en-, sub- and proglacial hydrological stores. Where ice overrides permeable geological formations, basal meltwater can infiltrate the subsurface. Meltwater may also run off to the foreland region of glaciers where it can subsequently interact with aquifers via surface–groundwater exchange mechanisms. Where permafrost is present, the efficiency of these exchanges and regional groundwater flow fields will be affected.

Glaciers, ice sheets and permafrost are highly dynamic systems that are strongly coupled to local climate dynamics. Consequently, hydrological coupling between the cryosphere and groundwater is also transient. With this in mind, Section 3 will review current approaches to modelling water flow through cryosphere–groundwater systems, with a focus on the following processes:

- subglacial water exchanges across the ice–aquifer interface
- proglacial meltwater cycling
- permafrost dynamics and hydrology
- ice and snow surface energy balance
- ice frontal ablation (calving)
- ice dynamics

3 Modelling water flow through cryosphere–groundwater systems

This section will review established approaches to modelling the key cryosphere–groundwater hydrological processes identified in Section 2 and, for comparison, detail the current capability of the JULES model.

3.1 SUBGLACIAL WATER EXCHANGES ACROSS THE ICE–AQUIFER INTERFACE

3.1.1 Established modelling approaches

Much of the text in this section draws on the comprehensive review of modelling water flow under glaciers and ice sheets undertaken by Flowers (2015).

Many of the modelling studies of subglacial drainage examine the interplay between ice sheets and groundwater, typically over glacial timescales (Lemieux et al., 2008a). For these studies, the ice–groundwater system is typically modelled using established groundwater model software (e.g. MODFLOW) with prescribed upper-boundary conditions to mimic the presence of the overlying ice mass. Here, the ice sheet is usually treated as an inert source of overburden pressure and recharge.

In the past, Dirichlet boundary conditions (specified hydraulic head) have been used by assuming subglacial water pressure to be in equilibrium with ice overburden pressure (Forsberg, 1996), although verifying this assumption from field observations is practically impossible. Other studies have derived subglacial water pressure from past glaciations using proxies in the field such as stress characteristics of superficial sediments that were overridden by ice (Piotrowski, 1997). These proxy estimates indicate the potentiometric surface at the ice-bed interface is approximately 72 per cent of the ice thickness.

Alternatively, a specified flux boundary condition can be used based on estimated subglacial recharge rates. The dominant source of water under ice sheets is often assumed to be geothermal melting, for which a fixed rate of 6 mm yr^{-1} has been used in the past (Breemer et al., 2002, Carlson et al., 2007). This assumption, however, neglects other sources of basal water (e.g. surface melt conveyed to the bed via the englacial drainage network). Furthermore, it has been shown that subglacial aquifers don't have the capacity to evacuate all of the meltwater at the base of most ice sheets and, as such, specified flux boundary conditions can cause unrealistically high aquifer hydraulic heads (Breemer et al., 2002). Breemer et al. (2002) overcame this by introducing a high-permeability interfacial drainage layer between the bedrock and ice sheet. It should be noted, however, that this layer remains largely conceptual in nature, given that subglacial drainage pathways under a given ice mass may consist of a complex network of discrete channelised and distributed flow systems (Flowers, 2015). Lemieux et al. (2008a) and Boulton et al. (1995) used dynamic boundary conditions that implemented a specified recharge flux equal to the basal melt rate — unless the simulated hydraulic head at the glacier base exceeded the ice overburden pressure, in which case a fixed hydraulic head was used to recalculate infiltration rates and excess was assumed to be drained away by surficial drainage pathways.

Sterckx et al. (2017) experimented with applying fixed hydraulic heads and specified flux boundary conditions at the base of a theoretical ice sheet. They concluded that, where the fluxes exceed 10 mm y^{-1}, as might be expected at the base of wet-based ice, a fixed head boundary gives the same solution as a specified flux boundary. Where fluxes are known to be no larger than a few millimetres per year, e.g. at the base of colder ice sheets and/or over impermeable geology, a fixed head boundary diverges from the fixed flux boundary solution.

For modelling water exchanges between glaciers and groundwater, the availability of additional observation data has led to the development of more sophisticated glacier hydrology models that include the influence of surface meltwater inputs to subglacial water stores. For example, Flowers and Clarke (2002) developed a multilayer finite difference model to represent surface, englacial, subglacial and groundwater drainage systems for the polythermal Trapridge Glacier.

Each layer in the model is two dimensional and vertically integrated, but allows vertical exchanges between adjacent layers, which are solved based on fluid potential gradients:

$$\frac{\partial h_r}{\partial t} + \nabla \cdot q_r = M - \psi_{r:e} + \psi_{r:s} - \psi_{r:a} \qquad surface \tag{1}$$

$$\frac{\partial h_e}{\partial t} + \nabla \cdot q_e = \psi_{r:e} - \psi_{e:s} \qquad englacial \tag{2}$$

$$\frac{\partial h_s}{\partial t} + \nabla \cdot q_s = b_s - \psi_{r:s} + \psi_{e:s} - \psi_{s:a} \qquad subglacial \tag{3}$$

$$\left(\frac{h_a}{\rho_a}\right)\frac{\partial \rho_a}{\partial t} + \frac{\partial h_a}{\partial t} + \nabla \cdot q_a = \psi_{s:a} + \psi_{r:a} \qquad aquifer \tag{4}$$

where h and q are the water volumes [L^3] and horizontal fluxes [L^2 T^{-1}] for the surface, englacial subglacial and aquifer layers (subscript r, e, s and a respectively). ψ represents the exchange terms between adjacent layers. M and b_s are the surface and basal source terms. Horizontal fluxes are calculated for each layer using Darcy's law with a hydraulic conductivity that varies between layers and can be set to vary as a function of h to emulate variable flow efficiency of the subglacial drainage system, for example.

3.1.2 Current JULES capability

JULES currently represents glaciers and ice sheets using the ice surface tile type (Best et al., 2011). A recent update to the JULES source code also allows one to specify the presence of ice using glaciated and unglaciated elevated tiles, which allow for more accurate representation of subgrid glacier hypsometry (Shannon et al., 2019). In both cases, the subsurface is assumed to be impervious to water and therefore JULES is currently not able to represent water exchanges across the ice–aquifer interface or the groundwater flow field immediately beneath ice.

3.2 ICE LOADING

The weight of the ice can alter large-scale groundwater flow patterns by changing the hydrogeological properties of the subsurface (Lemieux et al., 2008b). Ice loading leads to compaction of the underlying geological medium, leading in turn to localised regions of reduced porosity and hydraulic conductivity and increased pore pressure (Neuzil, 2012).

3.2.1 Established modelling approaches

In ice-sheet modelling studies that simulate ice evolution over glacial timescales, compaction due to ice loading is typically represented in groundwater models by including an additional term in the continuity equation for transient groundwater flow, which accounts for direct ice loading (compaction) by assuming strain is purely vertical (Lemieux et al., 2008b, Sterckx et al., 2017):

$$-\nabla \cdot (-K\nabla h) + W = S_s \frac{\partial h}{\partial t} - S_s \zeta \frac{1}{\rho g}\frac{\partial \sigma_{zz}}{\partial t} \tag{5}$$

where K is the hydraulic conductivity [L T^{-1}], h is the hydraulic head [L], W represents net flux (per unit volume) from external sources [T^{-1}] and S_s is the specific storage [L^{-1}], σ_{zz} is the vertical stress [M T^{-2} L^{-1}] due to ice loading and ζ is the loading efficiency, which ranges between 0 and 1 and determines how much of the ice loading is transferred directly to the subsurface water (assuming the rock grains are incompressible). It is given by:

$$\zeta = \frac{\beta_{pm}}{\beta_{pm} + \phi\beta_w} \tag{6}$$

where β_{pm} and β_w are the rock and water compressibility [L T^2 M^{-1}] and ϕ is the rock porosity.

3.2.2 Current JULES capability

JULES currently has no representation of changes in hydrogeological properties due to ice loading.

3.3 PROGLACIAL MELTWATER CYCLING

3.3.1 Established modelling approaches

Proglacial meltwater cycling is typically modelled using a distributed surface–groundwater model forced with river stage and diffuse recharge boundary conditions. For these, water exchanges between meltwater channels and proglacial aquifers are simulated according to standard, Darcy-type flux equations. Allen et al. (2004) implemented a steady-state distributed MODFLOW groundwater model of the alluvial Grand Forks Aquifer in southern British Columbia and forced the model with hypothetical steady-state river stage and diffuse recharge inputs to determine groundwater level sensitivity to changes in these boundary conditions. Scibek et al. (2007) used a transient version of the Grand Forks groundwater model, forced with future climate change scenarios and river-stage simulations from a statistical mountain hydrology model. Okkonen and Kløve (2011) implemented a numerical model chain consisting of a land-surface model to simulate frozen soil hydrology, a hydrological model to simulate river stage and a MODFLOW groundwater model to simulate groundwater storage fluctuations for a snow-dominated esker aquifer in Finland. Huntington and Niswonger (2012) and Somers et al. (2019) both used the integrated surface–groundwater model GSFLOW (Markstrom et al., 2008) to simulate meltwater cycling in Californian and Peruvian mountain aquifers, respectively.

3.3.2 Current JULES capability

Currently JULES is not able to simulate proglacial meltwater cycling, given that it does not have a distributed groundwater flow model that can simulate lateral groundwater flow in proglacial regions and water exchanges between proglacial aquifers and meltwater channels. However, a key aim of the BGS's Hydro-JULES development is to include a distributed groundwater flow model into the modelling framework.

3.4 PERMAFROST DYNAMICS AND HYDROLOGY

3.4.1 Established modelling approaches

Process-based permafrost models resolve the thermal state of the ground based on the principles of heat transfer, defined by the transient heat flow equation:

$$C\frac{\partial T}{\partial t} = \lambda \nabla^2 T \qquad 7$$

where C is the volumetric heat capacity of the ground (J m^{-3}), T is the temperature and λ is the thermal conductivity (W m^{-1} K^{-1}).

A number of analytical, steady-state solutions to equation 7 have been proposed, which can be used to map permafrost distribution with limited input data. For example, Lunardini (1981) proposed a solution for estimating the permafrost active layer depth for any location with known soil texture and mean summer air temperature. Others have derived solutions to map the presence of permafrost and the mean annual temperature at the base and top of the active layer (Riseborough et al., 2008). Powerful statistical models have also been used to map permafrost attributes at the global scale based on topographic, geomorphological and climate data (Boeckli et al., 2012).

Analytical and statistical approaches provide a useful first-order estimate of permafrost distribution. However, they neglect heterogeneous properties of the subsurface and transient boundary conditions which bring about highly dynamic and complex permafrost distributions. For this, numerical finite-element and finite-difference models, driven by transient climate data, can be used to solve the heat-flow problem in space and time.

Finding a robust solution to the transient permafrost problem requires one to account for a multitude of controls on ground heat flow. For example, one must first resolve the ground-surface energy balance, which, as well as being controlled by prevailing climate variability, is also perturbed by snow and vegetation dynamics that can serve to insulate the ground surface. Spatially, one must also account for heterogeneous thermodynamic properties of the subsurface brought about by regional geological controls and the presence (or lack of) water and ice. Water content is especially important given that freeze–thaw processes and the release and absorption of the latent heat of fusion of the soil water are central to heat flow dynamics in permafrost soils. These are usually accounted for by subsuming their effect into the volumetric heat capacity parameter in equation 7 (Riseborough et al., 2008). In solving the heat-flow equation for permafrost soils, one must therefore also account for water content and transport through the subsurface.

Numerical permafrost models that have been developed specifically for large-scale applications such as GIPL2 (Jafarov et al., 2012) and CryoGrid2 (Czekirda et al., 2019, Westermann et al., 2013) typically only solve heat flow in the vertical dimension with no account of lateral heat flow due to computational requirements. For similar reasons, simple routines to take the principal drivers of permafrost dynamics into account are employed. For example, near-surface atmospheric air temperature may be used as the upper (ground surface) model boundary condition, although it should be noted that the updated CryoGrid3 model code resolves the full energy balance at the surface (Westermann et al., 2016). Similarly, snow dynamics are typically solved using simplified empirical snow-depth models. GIPL2, CryoGrid2 and CryoGrid3 all assume that the total of the water and ice content in the soil is static.

State-of-the-art, fully coupled, multidimensional, thermo-hydraulics numerical-modelling approaches are being developed to model the evolution of permafrost-impacted landscapes and groundwater systems simultaneously (Coon et al., 2016, Nagare et al., 2015). These models couple the groundwater flow equation and heat transfer equation with dynamic freeze–thaw processes, allowing one to simulate the interdependence between permafrost formation and groundwater flow pathways. These approaches can, in theory, be used to simulate the dynamic behaviour of hydrologically important permafrost features, such as the opening and closure of taliks. In practice, however, these approaches are currently impractical at the global scale. In a recent thermo-hydraulics model inter-comparison study, test cases were only computationally feasible using 2D domains on the scale of individual taliks (Grenier et al., 2018).

3.4.2 Current JULES capability

Earlier versions of JULES included a number of processes that are important for simulating near-surface (less than 3 m deep) permafrost, including a multilayer snow scheme and the effect of soil freezing and thawing on the energy budget. The model also includes a physics-based representation of vertical water percolation through the soil column by solving Richard's equation. In this respect, it is arguably superior to other large-scale permafrost models. Analysis of pan-Arctic permafrost simulations when these processes are included show them to be comparable to observations (Burke et al., 2013).

For simulating deeper permafrost dynamics (which may extend to more than 100 m deep), the number and cumulative depth of soil layers in the JULES model can be increased. Some representation of deeper permafrost and soil layers is important as these deeper layers can act as a heat sink, which influences thermodynamics closer to the surface.

JULES simulations of the active layer are consistently too deep when compared to observations, which Chadburn et al. (2015) partly attributed to the lack of the natural heat-sink effect of the deeper soil zone. They detailed a set of updates to the JULES code (version 4.2), which included added permafrost-relevant processes to overcome the active-layer bias problem.

Firstly, they include a bedrock column that can be added to the base of the main soil column. The bedrock column is structurally almost identical to the soil column and can be specified as a stack of layers with variable thickness. In this respect, it can be thought of as a continuation of the soil column deeper into the subsurface. By including the bedrock column, the heat-sink effect of deeper subsurface layers can be better represented. Unlike the soil column, however, the bedrock column is assumed to be hydrologically inactive and therefore cannot simulate dynamic soil water and ice content. The computational gains of removing this process allow users to specify a much deeper, highly discretised subsurface without significantly increasing computation burden.

In their study, Chadburn et al. (2015) conducted experiments using a 28-layer, 10 m-thick, hydrologically active soil column underlain by a 100-layer, 50 m-thick, hydrologically inactive bedrock column. Additionally, they modified the thermal and hydraulic properties of soil to account for the presence of organic matter and moss, which can serve to insulate the soil and store more water than mineral soils. Finally, they noted that, when snow cover is more than 10 cm thick, JULES effectively switches off the multilayer snow model and modifies the surface soil layer properties to mimic the effect on the hydrological and energy balances. They noted that this doesn't properly represent the insulating effect of very thin snow coverage and so include an explicit snow layer for very thin snow cover.

They also showed that the model was able to capture soil temperature observations at 32 cm depth and the active layer depth (approximately 0.5 m) at the Samoylov Island field site in the Lena River delta, Siberia. However, they also noted a number of improvements that could be made to JULES source code, including subgrid heterogeneity and lateral hydrological and heat exchanges.

3.5 ICE AND SNOW SURFACE ENERGY BALANCE

3.5.1 Established modelling approaches

The energy available for melt and sublimation of ice and snow, Q_M (W m^{-2}), can be determined by solving the surface energy balance equation:

$$Q_M = SW_{\downarrow}(1-\alpha) + LW_{\downarrow} - LW_{\uparrow} + Q_H + Q_E + Q_R + Q_G \tag{8}$$

where α is the surface albedo, $SW_{\downarrow}$ is the incident solar radiation, $LW_{\downarrow}$ and $LW_{\uparrow}$ are the incoming and outgoing longwave radiation terms, Q_H and Q_E are the turbulent and sensible latent heat fluxes, Q_R is the sensible heat flux from rainfall and Q_G is conduction of heat from the ground. In reality, the majority of large-scale modelling studies have avoided using the full energy balance equation due to computational constraints and data limitations. Instead, they use simpler equations that lump a number of terms in equation 8 into a smaller number of parameters (or miss them out entirely).

Simplified 'index' models of the surface energy balance have been widely applied in the past. The classical temperature-index model (TIM) simulates melt as a linear, piecewise function of temperature only (Braithwaite, 1995). This can be justified because of the influence temperature has on the total energy balance of ice and snow (e.g. long-wave radiation balance and turbulent sensible heat flux). A review of past global-scale glacier mass balance models (Table 1) reveals that almost all of them have implemented variations of the classic TIM method. Some also include a semi-physical representation of refreezing processes (Bliss et al., 2014, Huss and Hock, 2015).

A key drawback of the classic TIM method is that it doesn't account for the influence of other climate variables, such as wind speed and humidity, that may also have significant control over the surface energy balance, particularly in areas where sublimation is the dominant ablation process.

3.5.2 Current JULES capability

JULES implements the full energy balance approach, including radiative, turbulent and ground heat fluxes. It simulates melt, sublimation and refreezing processes and has the option to simulate snow compaction and albedo evolution due to ageing. The method has been applied at the global scale already (Shannon et al., 2019).

3.6 ICE DYNAMICS

3.6.1 Established modelling approaches

Ice moves across the bedrock topography by sliding and flowing viscously under the force of gravity. A proper physical representation of these processes is computationally intensive and requires observation data that are only available for a handful of glaciers around the world. For global-scale glacier models, a range of simplified treatments of ice dynamics have been implemented (Table 1).

3.6.1.1 Volume, area and length scaling

Several studies have implemented the volume, area and length scaling methods (Radić et al., 2008) to simulate glacier geometry evolution. These methods are based on empirical relationships between glacier volume (V), area (A) and length (L), which have been derived from analyses of global glacier geometric data:

$$V = c_a A^{\gamma} = c_I L^{q} \qquad 9$$

The parameters c_a, γ, c_I and q are unknown and glacier specific. As such, they must be specified through available observations of glacier geometries. These studies have shown that such empirical relationships have some physical basis (Bahr, 1997, Bahr et al., 1997). Some studies have implemented volume–length (V–L) relationships only, while others have implemented methods that preserve the relationships between volume, length and area (V–A–L). Given simulations of glacier mass balance, the model is used to determine changes in length and area that can then be converted to changes in the 3D glacier geometry, given information on the bedrock elevation and by making some assumptions about ice-mass redistribution (e.g. area and length variations are typically assumed to occur at the ice margin only).

3.6.1.2 Δh parameterisation

The Global Glacier Evolution Model (GloGEM) (Huss and Hock, 2015) and PyGEM (Rounce, 2019) both use the Δh parameterisation to simulate the evolution of glacier geometry in response to changes in mass balance. The Δh model is an empirical function that relates ice thickness change across a glacier to the glacier's elevation distribution (Huss et al., 2010). Typically, elevation changes are largest at low elevations in the ablation zone and smallest at high elevations in the accumulation zone. The model defines the spatial distribution of glacier surface elevation change in response to a disequilibrium in mass balance. It is parameterised using the following polynomial:

$$\Delta h = (h_r + a)^{\gamma} + b \cdot (h_r + a) + c \qquad 10$$

where Δh is the normalised surface elevation change, h_r is the normalised elevation range and a, b, γ and c are fitted parameters. These can be determined by comparing the elevation change between two or more digital elevation models (DEMs) that cover a sufficiently long time period to show elevation changes. By distributing simulated glacier mass balance changes over the entire glacier using the fitted model (typically on an annual time scale), the approach has been shown to replicate glacier retreat dynamics in a comparable fashion to more complex 3D, finite-element ice-flow models.

This approach offers an advantage over the V–A–L method in that information on mass redistribution is implicitly included in the model and therefore there is no need to make assumptions about where lost or gained mass is distributed. The original Δh model can only be used to simulate glacier retreat, but this has been modified recently to simulate glacier advance as well (Mackay et al., 2019)

3.6.1.3 1D FLOW LINE MODEL

Both of the empirical methods detailed assume an instantaneous mass redistribution, which is not physically justifiable. The Open Global Glacier Model (OGGM) implements a more physically based ice-flow model to simulate the redistribution of ice mass over time (Maussion et al., 2019). In this model, ice flow is simulated using a depth-integrated flow line model. The following continuity equation is solved along the main glacier flow lines:

$$\frac{\partial S}{\partial t} = w\dot{m} - \nabla \cdot uS \qquad 11$$

where S is the area of the cross-section perpendicular to the flow line, w is the width of the cross-section, $\dot{m}$ is the mass balance [M L^{-2} T^{-1}] and u is the average ice flow velocity, which includes ice deformation (u_d) and basal sliding (u_s). The ice deformation component is calculated using the shallow-ice approximation (SIA):

$$u_d = \frac{2A}{n+2} h\tau^n \qquad 12$$

where A is the ice creep parameter, h is the local ice thickness, τ is the basal shear stress and n is the exponent in Glen's flow law. The sliding component is calculated following:

$$u_s = f_s \frac{\tau^n}{h} \qquad 13$$

where f_s is a sliding parameter that, along with A, is typically reserved as a calibration parameter.

3.6.2 Current JULES capability

In JULES, ice geometry evolves through downwasting only (that is, the thinning of glaciers by the melting of ice). This approach neglects the strong feedbacks between ice dynamics and mass balance.

3.7 FRONTAL ABLATION

3.7.1 Established modelling approaches

The majority of global-scale glacier models have no representation of frontal ablation processes. The exceptions to this are the OGGM and GloGEM. The OGGM code has a simple model for representing calving at the margins of marine-terminating glaciers. Here, the glacier margin is not allowed to extend into the sea, so all ice flow beyond the coastline is assumed to be lost to calving processes. GloGEM uses a slightly more sophisticated approach, which assumes a linear relation between calving rate and water depth for marine-terminating glaciers.

3.7.2 Current JULES capability

JULES currently has no representation of frontal ablation processes.

3.8 SUMMARY

This section has reviewed the current modelling of principal processes in cryosphere–groundwater systems. The key findings from this section are:

- JULES currently lacks any representation of water flow across the ice–aquifer interface and therefore cannot simulate subglacial recharge processes. Past approaches to modelling these processes indicate that they could be incorporated into the Hydro-JULES modelling framework as static or transient boundary conditions. For glaciers where surface meltwater exchanges to the ice bed are more important, a more sophisticated glacier hydrology model could be implemented, although these can only be reasonably validated with good subglacial observation data that are only available for a handful of glaciers.
- JULES does not have any representation of how changes in ice loading can lead to changes in subsurface hydrogeological properties. Even so, these processes are only

likely to be important if the Hydro-JULES modelling framework were to be applied on glacial time scales, which is currently outside of the remit of the project.

- JULES cannot represent proglacial meltwater cycling due to it lacking a distributed groundwater flow model that can simulate lateral groundwater flow in proglacial regions and water exchanges between proglacial aquifers and meltwater channels. However, the inclusion of these processes is already underway as part of the Hydro-JULES project.
- JULES already has the ability to simulate permafrost dynamics and hydrology. Analysis against shallow soil temperature data and active layer depths indicates it can capture shallow permafrost dynamics adequately.
- JULES already has a very sophisticated, albeit computationally intensive, snow and ice surface energy balance routine that is far superior to routines employed in currently available global glacier-mass balance models.
- JULES has no representation of frontal ablation processes or ice dynamics.

Table 1 Overview of global glacier models. L = lumped; D = distributed; E = elevation bands; d= daily; m = monthly; y = yearly; a = adaptive.

Reference	Model name	Surface energy balance			Glacier evolution			Frontal ablation			Coverage	Data requirements	Open source?
		Spatial dis.	Time step	Form	Spatial dis.	Time step	Form	Spatial dis.	Time step	Form			
Bliss et al. (2014)	-	E	m	Classic TIM + refreezing	L	y	Empirical V–L scaling	-	-	-	All glaciers globally, excluding peripheral glaciers in Antarctica and ice sheets.	Climate (T and P only); ice coverage map; DEM.	No
Huss and Hock (2015)	GloGEM	E	m	Classic TIM + refreezing	E	y	Empirical Δh model	E	y	Oerlemans and Nick (2005).	All glaciers globally, including peripheral glaciers in Greenland and Antarctica, but excluding ice sheets.	Climate (T and P only); ice coverage map; ice thickness map.	No
Kaser et al. (2010)	-	L	m	Classic TIM	L	y	Downwasting model	-	-	-	17 large, glacierised river basins.	Climate (T and P only); ice coverage map; DEM.	No
Marzeion et al. (2018)	-	L	m	Classic TIM	L	?	Empirical V–A–L scaling	-			All glaciers globally, including peripheral glaciers in Greenland and Antarctica but excluding ice sheets.	Climate (T and P only); glacier area and elevation distributions.	No
Maussion et al. (2019)	OGGM	L	m	Classic TIM	D	a	1D flow line (SIA equation)	D	a	No ice beyond marine termination.	All glaciers globally, including peripheral glaciers in Greenland and Antarctica but excluding ice sheets.	Climate (T and P only); DEM; ice coverage map.	Yes
Radić et al. (2014)	-	E	m	Classic TIM + refreezing	L	y	Empirical V–L scaling	-	-	-	All glaciers globally, including peripheral glaciers in Greenland and Antarctica but excluding ice sheets.	Climate (T and P only); ice coverage map; DEM.	-
(Rounce, 2019)	PyGEM	E	m	Classic TIM + refreezing	E	y	Empirical Δh model	-	-	-	All glaciers in high-mountain Asia.	Climate (T and P only); ice coverage map; ice thickness map.	Yes
Shannon et al. (2019)	JULES	D	d	Full energy balance + refreezing	D	d	Downwasting model	-	-	-	All glaciers globally, excluding peripheral glaciers in Antarctica and ice sheets.	Climate (all major met. variables); ice coverage map; ice thickness map.	Yes

4 Recommendations

Based on the findings in this report, this final section details recommendations for improving the representation of the key processes reviewed in Section 3 for the Hydro-JULES modelling framework. They have been prioritised based on their importance in better representing cold-region groundwater systems as well as their likelihood of completion within the Hydro-JULES project timeline and potential research impact.

4.1 ICE DYNAMICS

Priority: Highest

Currently, the most sophisticated ice dynamics approach that has shown to be feasible on a global scale is the 1D flow-line model based on the SIA implemented in OGGM. It is recommended that this approach is adopted in the Hydro-JULES modelling framework. To do so, one could modify the JULES source code directly. However, it is recognised that the implementation of this method in the OGGM model was not trivial and so this approach could take considerable time and effort with a risk of failure. Instead, it is recommended that the OGGM software is implemented directly within the Hydro-JULES modelling framework through developing appropriate ‘code wrappers’ to exchange information between JULES and OGGM during runtime. Here, OGGM would be used to define the extent and hypsometry of ice/glaciated tiles in JULES and JULES would provide the surface mass balance calculations to drive OGGM. Given that OGGM is open source, free to use and written in Python, it is anticipated that this approach can implemented within the project timeline with high probability of success.

It should be noted that OGGM (and all other global glacier models) does not currently simulate the dynamics of ice sheets. It is therefore suggested that, unless time permits, the focus on implementing ice dynamics should focus on all glaciers globally, including peripheral glaciers in Greenland and Antarctica but excluding the ice sheets.

4.2 PROGLACIAL MELTWATER CYCLING

Priority: High

The inclusion of proglacial meltwater cycling in the Hydro-JULES modelling framework will require the implementation of a distributed groundwater model that can simulate lateral groundwater flow and water exchanges with meltwater river channels. Both of these processes are already being included as part of the wider model development within Hydro-JULES and therefore this capability has a high chance of success and should be prioritised.

4.3 WATER EXCHANGE ACROSS THE ICE–AQUIFER INTERFACE

Priority: High

It is recommended that a boundary condition-type approach is adopted in order to represent water exchanges across the ice–aquifer interface, whereby the boundary condition is specified at the ice–aquifer interface i.e. at the upper bound of the groundwater model that is currently being developed for Hydro-JULES. To start with, the simplest fixed head and fixed flux boundary conditions should be implemented and tested, but the goal should be to implement a more sophisticated dynamic boundary condition like those adopted by Lemieux et al. (2008a) and Boulton et al. (1995), which should help to mitigate issues of unrealistically high groundwater heads underneath the ice.

4.4 PERMAFROST HYDROLOGY AND DYNAMICS

Priority: Moderate

JULES already has a significant permafrost-simulating capability and therefore the priority in developing this further is lower than other processes. Even so, the potential impact of such developments is perceived to be high so if time is available, additional developments of the permafrost components on JULES should be made. In particular, previous work has highlighted the need to be able to include subgrid heterogeneity (i.e. thermal and hydrological dynamics) and lateral heat and hydrological exchanges in the subsurface. These aspects should be prioritised if time is available.

4.5 FRONTAL ABLATION

Priority: Low

OGGM already has a very simple frontal ablation model within it, which will be included as part of the proposed integration of OGGM into the Hydro-JULES modelling framework. Developing this method further is deemed low priority, considering that the surface mass balance is the main driver of ice sheet and glacier evolution.

4.6 ICE LOADING

Priority: Low

Ice loading is only deemed important for simulations that span glacial cycles. Such long simulations are currently outside of the remit of the Hydro-JULES project. As such, the inclusion of ice loading is of low priority.

4.7 ICE AND SNOW SURFACE ENERGY BALANCE

Priority: Lowest

JULES has a very sophisticated surface energy balance routine that is far superior to other global-scale glacier models. Further improvement of this is deemed unnecessary and of lowest priority.

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British Geological Survey holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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