A confined-unconfined aquifer model for subglacial hydrology

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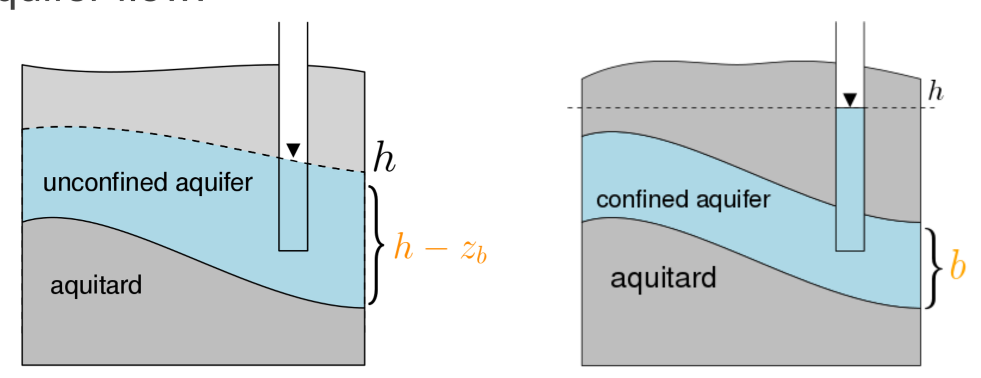
Introduction

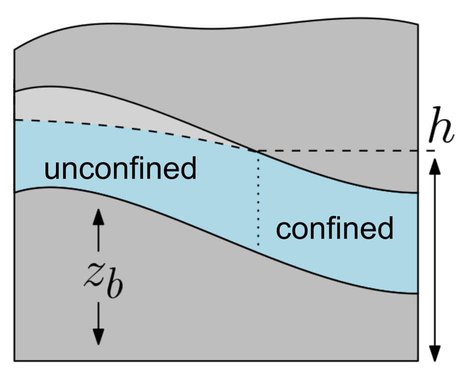
Modeling the evolution of subglacial channels underneath ice sheets is an urgent need for ice sheet modellers, as channels affect sliding velocities and hence ice discharge. Owing to very limited observations of the subglacial hydraulic system, the development of physical models is quite restricted. Subglacial hydrology models are currently taking two different approaches: either modeling the development of a network of individual channels or modeling an equivalent porous layer (De Fleurian et al. 2014) where the channels are not resolved individually but modeled as a diffusive process, adjusted to reproduce the characteristic of an efficient system.

Confined-unconfined aquifer scheme

Subglacial water transport has been described as a diffusive process similar to groundwater flow. There is a distinction between confined and unconfined aquifer flow:



$$S\frac{\partial h}{\partial t} = \nabla\cdot(K(h-z_b)\nabla h) + Q \qquad S\frac{\partial h}{\partial t} = \nabla\cdot(Kb\nabla h) + Q$$



The former has already been used to describe subglacial hydrology, but has some problems that we solve by introducing a new mixed scheme.
We compute the water pressure in terms of hydraulic head h: S is the storage, t time, K permeability, z_b aquifer base, b aquifer thickness and Q water input. Water pressure p_w and hydraulic head h are related through:

$$p_w = (h - z_b)g\rho_w$$

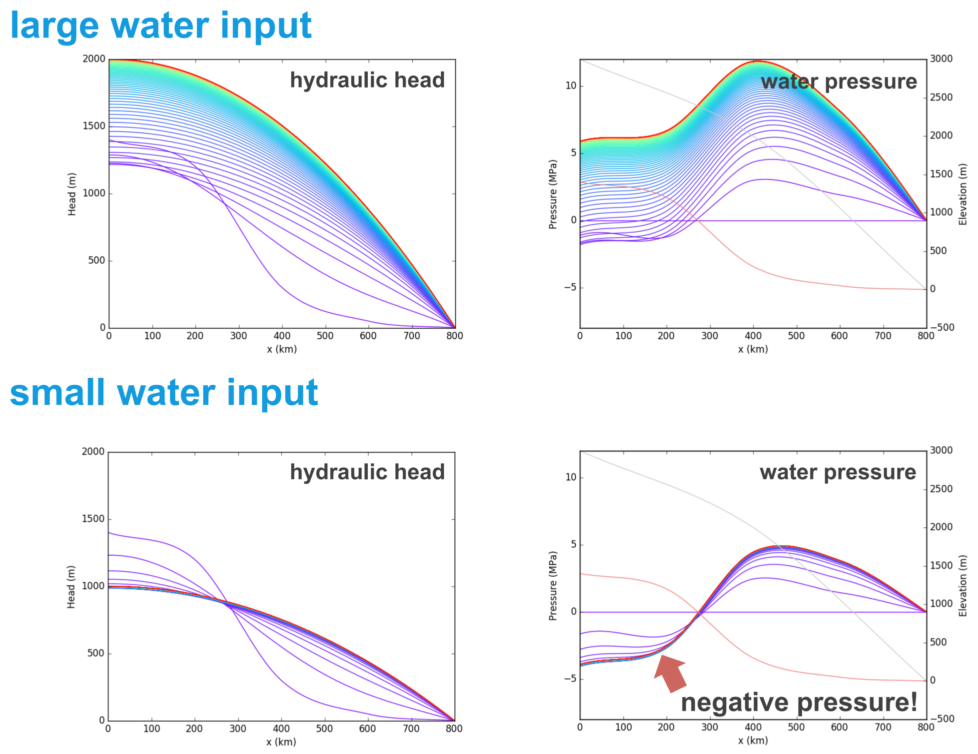


Fig. 1
Using the regular confined aquifer scheme, the absence of sufficient water leads to the hydraulic head dropping below the aquifer base leading to negative water pressure. (Colors denote time steps, red is latest)

The usual confined aquifer approach is inappropriate in small water input situations: The water pressure may drop so low, that the assumption of saturated aquifer flow (confined flow) is violated. This is visible in Fig. 1: in the low water input case (bottom row), the hydraulic head falls below the base which results in negative water pressure. A common fix for this is to limit the water pressure to zero, but this is equivalent with introducing an artificial source.
We solve this by introducing a combined confined-unconfined aquifer scheme, as described in Ehlig and Halepaska (1976):

$$S_e(h)\frac{\partial h}{\partial t} = \nabla\cdot(T(h)\nabla h) + Q. \qquad (1)$$

$$T(h) = \begin{cases} Kb, & h \geq b \quad \text{confined} \\ Kh, & 0 \leq h < b \quad \text{unconfined} \end{cases}$$

$$S_e(h) = S_s b + S'(h)$$

$$S'(h) = \begin{cases} 0, & h \geq b \quad \text{confined} \\ (S_y/d)(b-h), & b-d \leq h < b \quad \text{transition} \\ S_y, & 0 \leq h < b \quad \text{unconfined} \end{cases}$$

With S_e effective storage, T transmissivity, S_y specific yield and d a parameter that enables a gradual transition between the two states.

This means that the transmissivity decreases as soon as the water level falls below the top of the aquifer. As it approaches the base, the transmissivity becomes zero, therefore, limiting the water pressure to not turn negative physically.

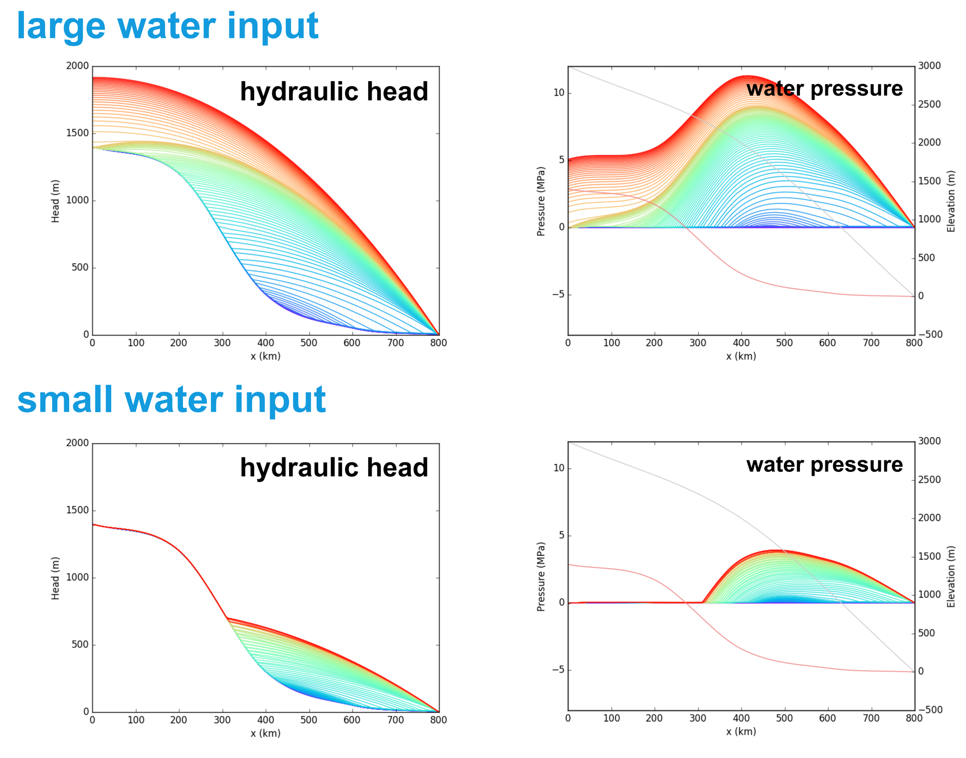
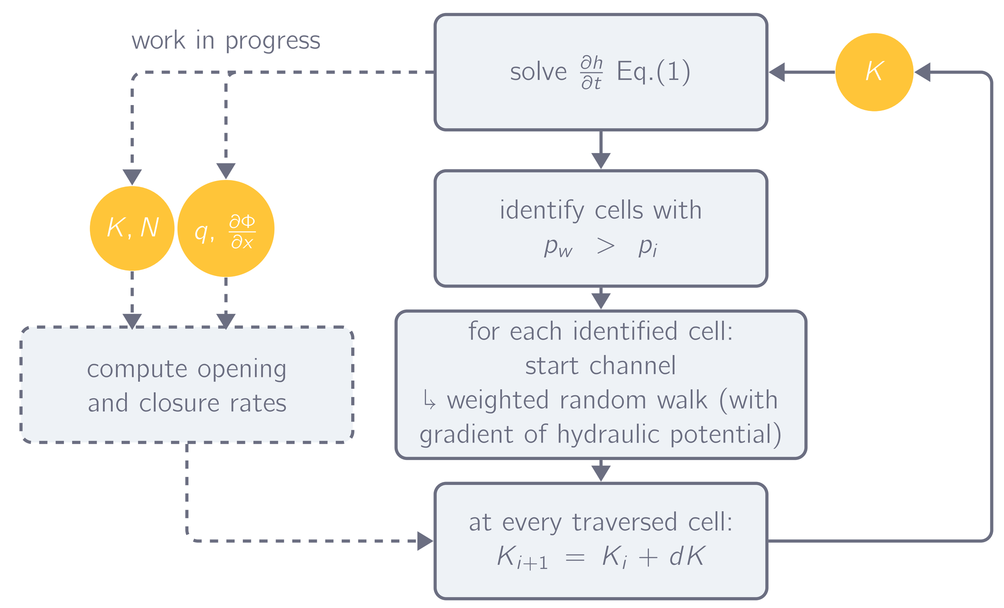


Fig. 2
The new confined-unconfined aquifer scheme overcomes the issue and ensures positive water pressure in all scenarios.

Modelling scheme

The evolution of channel positions is governed by a reduced complexity model that computes channel growths according to simple rules (weighted random walks descending the hydraulic potential).

Channels are represented by adjusting the permeability K and storage of the system according to projected locations of channels.



The adjustment of K at every identified channel cell is currently controlled by the initial overpressure of the channel $dK = |N|c$ where c is a tuning parameter (c=8e-7).

Artificial geometry results

In order to verify and test our model, we use the proposed experiments of the Subglacial Hydrology Inter-comparison Project (SHMIP).

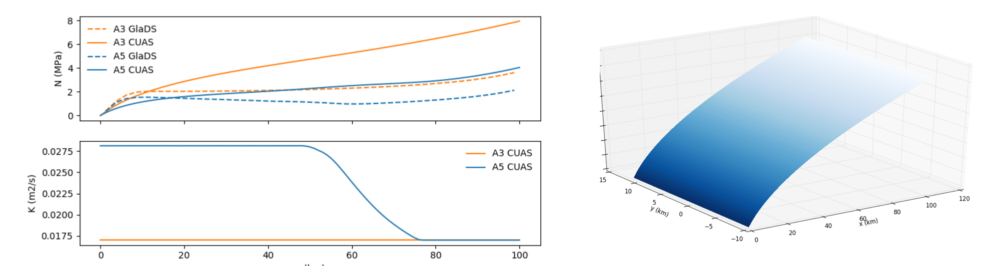


Fig. 3
Left: SHMIP tuning experiments A3 and A5.
Right: Experiment geometry.

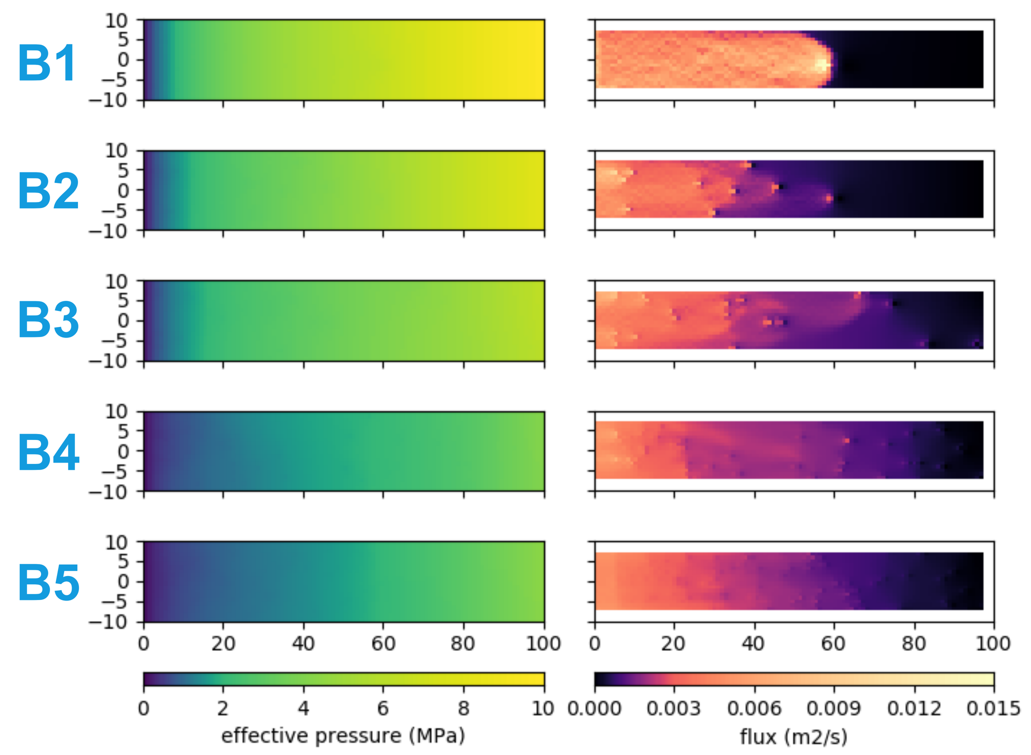


Fig. 4
SHMIP experiment B: influence of distributing a constant global supply through different number of moulins (1, 10, 20, 50, 100).

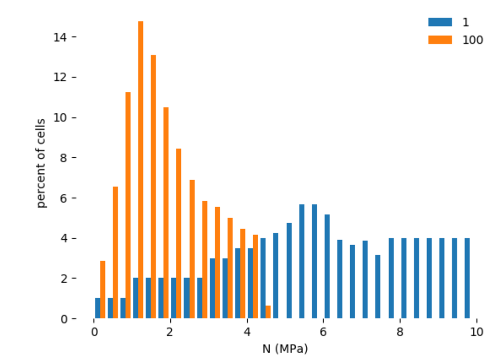


Fig. 5
Histogram of effective pressure for 1 and 100 moulins.

Conclusions

CUAS model:
+ computes effective pressure
+ no more negative pressure
+ one single equation/domain for sheet flow and channels
− more unknown parameters and rules needed
− still dependent on grid size and time step

Channel dynamics / system:
Distributing the same total water input over a larger amount of moulins leads to a more efficient drainage, hence reduced effective pressure potentially reduced effect on sliding.

References
De Fleurian, B., Gagliardini, O., Zwinger, T., Durand, G., Le Meur, E., Mair, D., and Raback, P.: A double continuum hydrological model for glacier applications, Cryosphere, 8, 137–153, doi:10.5194/tc-8-137-2014, 2014
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SHMIP – Subglacial Hydrology Inter-comparison Project, shmip.bitbucket.io, Basile de Fleurian, Mauro Werder

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