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# Exchange and pathways of deep and shallow groundwater in different climate and permafrost conditions using the Forsmark site, Sweden, as an example catchment

Emma Bosson · Jan-Olof Selroos · Martin Stigsson ·  
Lars-Göran Gustafsson · Georgia Destouni

**Abstract** This study simulates and quantifies the exchange and the pathways of deep and shallow groundwater flow and solute transport under different climate and permafrost conditions, considering the example field case of the coastal Forsmark catchment in Sweden. A number of simulation scenarios for different climate and permafrost condition combinations have been performed with the three-dimensional groundwater flow and transport model MIKE SHE. Results show generally decreasing vertical groundwater flow with depth, and smaller vertical flow under permafrost conditions than under unfrozen conditions. Also the overall pattern of both the vertical and the horizontal groundwater flow, and the water exchange between the deep and shallow groundwater systems, change dramatically in the presence of permafrost relative to unfrozen conditions. However, although the vertical groundwater flow decreases significantly in the presence of permafrost, there is still an exchange of water between the unfrozen groundwater system below the permafrost and the shallow groundwater in the active layer, via taliks. ‘Through taliks’ tend to prevail in areas that constitute groundwater discharge zones under unfrozen conditions, which then mostly shift to net recharge

zones (through taliks with net downward flow) under permafrost conditions.

**Keywords** Groundwater flow · Numerical modelling · Permafrost hydrology · Climate change

## Introduction

The development of permafrost reduces groundwater recharge and flow (Bosson et al. 2012) relative to unfrozen soil conditions. However, even if groundwater flow is impeded by permafrost, it still exists and its contribution to surface water is detectable in stream flow (Bense et al. 2009; Frampton et al. 2011; Ge et al. 2011; Bosson et al. 2012). That is, the change and redistribution of groundwater flow by permafrost change is manifested in associated stream discharge changes. The mechanisms of importance for flow exchange and redistribution between shallow and deep groundwater during permafrost change, however, are still poorly understood and remain to be quantified.

The aim of the present paper is to quantify and illustrate the exchange of water between shallow groundwater in Quaternary deposits (QD) and deeper groundwater in bedrock under different climate and permafrost conditions. Berglund et al. (2009) have presented a conceptual model of how the shallow groundwater in contact with the biosphere and the deeper groundwater in the geosphere are coupled and relate to each other. The present study is based on this conceptual model, which is here implemented in the distributed three-dimensional (3D) numerical tool MIKE SHE (Graham and Butts 2005; Refsgaard et al. 2010).

This study is based on, extends and elaborates further a previous simulation study reported by Bosson et al. (2010), which was a safety assessment part of the formal application to start construction of a repository for spent nuclear fuel in Sweden (SKB 2011). The safety assessment included also hydrogeological modelling of the deep bedrock as summarized by Selroos and Follin (2010), and a special study on hydrogeological effects of a glacial advance and retreat over the site (Vidstrand et al. 2010).

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E. Bosson · J.-O. Selroos · G. Destouni  
Department of Physical Geography and Quaternary Geology,  
Bert Bolin Centre for Climate Research,  
Stockholm University, 106 91 Stockholm, Sweden

E. Bosson (✉) · J.-O. Selroos · M. Stigsson  
Swedish Nuclear Fuel and Waste Management Co, Box 250101 24  
Stockholm, Sweden  
e-mail: emma.bosson@skb.se  
Tel.: +46-8-4598400  
Fax: +46-8-57938611

L.-G. Gustafsson  
DHI Sweden AB,  
Lilla Bommen 1, 411 04 Göteborg, Sweden

However, the most detailed description of the shallow groundwater system and its coupling to the deeper part of the geosphere was presented in Bosson et al. (2008, 2010).

The simulation work reported by Bosson et al. (2010) focused on the identification of groundwater flow paths in the bedrock and the overlying Quaternary deposits of the proposed repository site at Forsmark, in the municipality of Östhammar, Sweden, as a function of prevailing and possible future climate and landscape conditions (i.e., position of shoreline, land use, Quaternary deposits). Over the time period considered in the safety assessment (100,000–1,000,000 years), both the landscape and the climate in Forsmark will change. A recent study by Bosson et al. (2012) has shown that this will influence both the location and the distribution of recharge and discharge areas in, and flow paths through the landscape. Such changes are then also expected to influence the exchange and flow paths between deep and shallow groundwater, which was not investigated by Bosson et al. (2012). In the present study, new particle-tracking simulations with the aim of studying potential flow paths between the Quaternary deposits and bedrock under different climate conditions have, hence, been performed. The primary objective of the present study is to take advantage of, extend and link the previous hydrological and hydrogeological simulation work and studies reported for the Forsmark site and its possible future climate and permafrost conditions (Bosson et al. 2010, 2012), in order to further analyze and quantify how these conditions influence the exchange and flow paths between deep and shallow groundwater.

## Materials and methods

### **The Forsmark catchment, present and future conditions**

The Forsmark site is located within the Forsmark catchment in the county of Uppland, approximately 120 km north of Stockholm, and borders the Baltic Sea. The catchment has a flat topography, with the present study area being almost entirely less than 20 m above the present sea level (m a.s.l.). Investigations at the site in connection to the possible nuclear waste disposal there have resulted in a wealth of hydrological and hydrogeological data and knowledge (Johansson 2008; Follin 2008). Shallow lakes in the area, with mean depth ranges from 0.1 to 1 m, generally feature low permeability bottom sediments and are connected via small water brooks. Till is the dominating type of the mostly shallow Quaternary deposits; the hydraulic properties of the Quaternary deposits, the lake sediments and the bedrock are described in the Appendix. Measurements indicate a shallow groundwater system in the Quaternary deposits with mean levels within a depth of less than a metre in most of the area. The groundwater levels are strongly correlated to surface topography. The shallow groundwater system overlies a larger-scale regional groundwater flow system in the deeper bedrock (Follin 2008; Johansson 2008).

In the time frame of a safety assessment for nuclear waste disposal (SKB 2011), the climate as well as the landscape will develop and thus result in changed hydrological and hydrogeological conditions (Selroos and Follin 2010; Bosson et al. 2010, 2012). Changes in exposed land will occur as a net result of isostatic and eustatic changes (SKB 2010b; Pässe 2001), and the Quaternary deposits will change due to erosion and depositional processes (Brydsten and Strömngren 2010). New lakes and streams will form preferentially in depressions of the present sea bottom. Many of the future lakes are deeper and larger than present-day lakes in the Forsmark catchment. Also the climate will change; in a basic climate scenario for the site (SKB 2010b), only natural climate variability and change is considered, with a first period of periglacial site conditions including permafrost occurring around year 10,000 (10,000 AD). More detailed descriptions of the landscape and climate development simulations for Forsmark are given in SKB (2010a, b).

At present, the locations of recharge and discharge areas in the Quaternary deposits of the Forsmark site are governed by the local topography. Scenario simulations of the possible future hydrology in Forsmark indicate that the pattern of recharge and discharge areas is independent of the landscape conditions (shoreline, stratigraphy, spatial distribution of Quaternary deposits, vegetation) as long as a temperate climate prevails at the site (Bosson et al. 2010). For simplicity and clarity, only one scenario is therefore considered in the present investigations for the landscape configuration (relevant for the possible first period of periglacial site conditions with permafrost occurring around year 10,000 AD), in combination with different climate and permafrost conditions.

### **Permafrost implementation in MIKE SHE**

Since functionality for thermal modelling is not included in MIKE SHE, permafrost is implemented in the current study as in previous studies (Bosson et al. 2010, 2012) by simply modifying the hydraulic properties (i.e., reducing the hydraulic conductivity) in order to mimic a low permeability permafrost layer impeding groundwater flow. On top of the permafrost layer, an active layer of 1 m thickness is introduced where the properties are changed in a stepwise manner during the year to describe freezing and thawing processes; this is described in more detail in the Appendix and by Bosson et al. (2010, 2012). A number of through taliks, unfrozen areas in the permafrost (French 2007), are further simulated under permafrost conditions as objects (model volumes) with the same hydraulic properties as under temperate climate conditions. The process of identifying through taliks is summarized in the following, and the reader is referred to Bosson et al. (2010) for more detailed description.

The potential for a talik to prevail is, among other factors, dependent on the depth of the permafrost. The thinner the permafrost, the more taliks can prevail. The present study uses site-specific model results for Forsmark (Hartikainen et al. 2010; SKB 2006) to locate taliks. In the work of SKB (2006), two types of circular lakes with flat

bathymetry were considered: (1) shallow lakes with bottom temperature above 0 °C, and (2) deep lakes with bottom temperature above 4 °C. The depth of the shallow lake type was set to 2 m and the depth of the deep lake type was set to 8 m. The SKB (2006) results showed then that a through talik can develop beneath a lake if:

1. The radius of a shallow lake (with its surface area interpreted as a circle) exceeds the thickness of the surrounding permafrost
2. The radius of a deep lake (interpreted as for a shallow lake) is greater than or equal to 0.6 times the thickness of the surrounding permafrost

In the present study, all lakes with a mean depth between 0.5 and 4 m are considered as shallow (bottom temperature above 0 °C) and all lakes with a mean depth >4 m are considered as deep lakes (bottom temperature above 4 °C). If a lake fulfills the conditions 1 or 2 relative to the prevailing permafrost thickness, an unfrozen column is simulated in the QD and bedrock under the lake to represent a through talik. The modeled future streams in Forsmark are all too small for through taliks to prevail beneath them. Under modeled permafrost conditions, through taliks are therefore only present under lakes, while the too small streams and lakes are still surface-water bodies under such conditions. However, surface water is then only flowing during the relatively short period with positive temperatures in each year (Bosson et al. 2012).

### Flow and particle-tracking simulations

Table 1 outlines the four main scenarios of different climate and permafrost condition combinations, referred to as cases A, B, C and D, which are simulated in this study. These include a temperate climate case (A) and three periglacial climate cases: one without permafrost (B) and two with continuous permafrost (C and D) of different depth and associated number of through taliks. In case C the permafrost reaches a depth of 100 m, resulting in 46 through taliks, while in case D the permafrost reaches a depth of 240 m, resulting in only 5 through taliks; this selection of permafrost depth cases has also been used and is described in more detail in Bosson et al. (2010, 2012). The shore line of the 10,000 AD landscape scenario is applied in all cases and is

situated at -31.42 m a.s.l. relative to the present shoreline. The total model area (Fig. 1) is 180 km<sup>2</sup> and consists of both land and sea. The land area constitutes 178 km<sup>2</sup> and the sea 2 km<sup>2</sup> of the total model area.

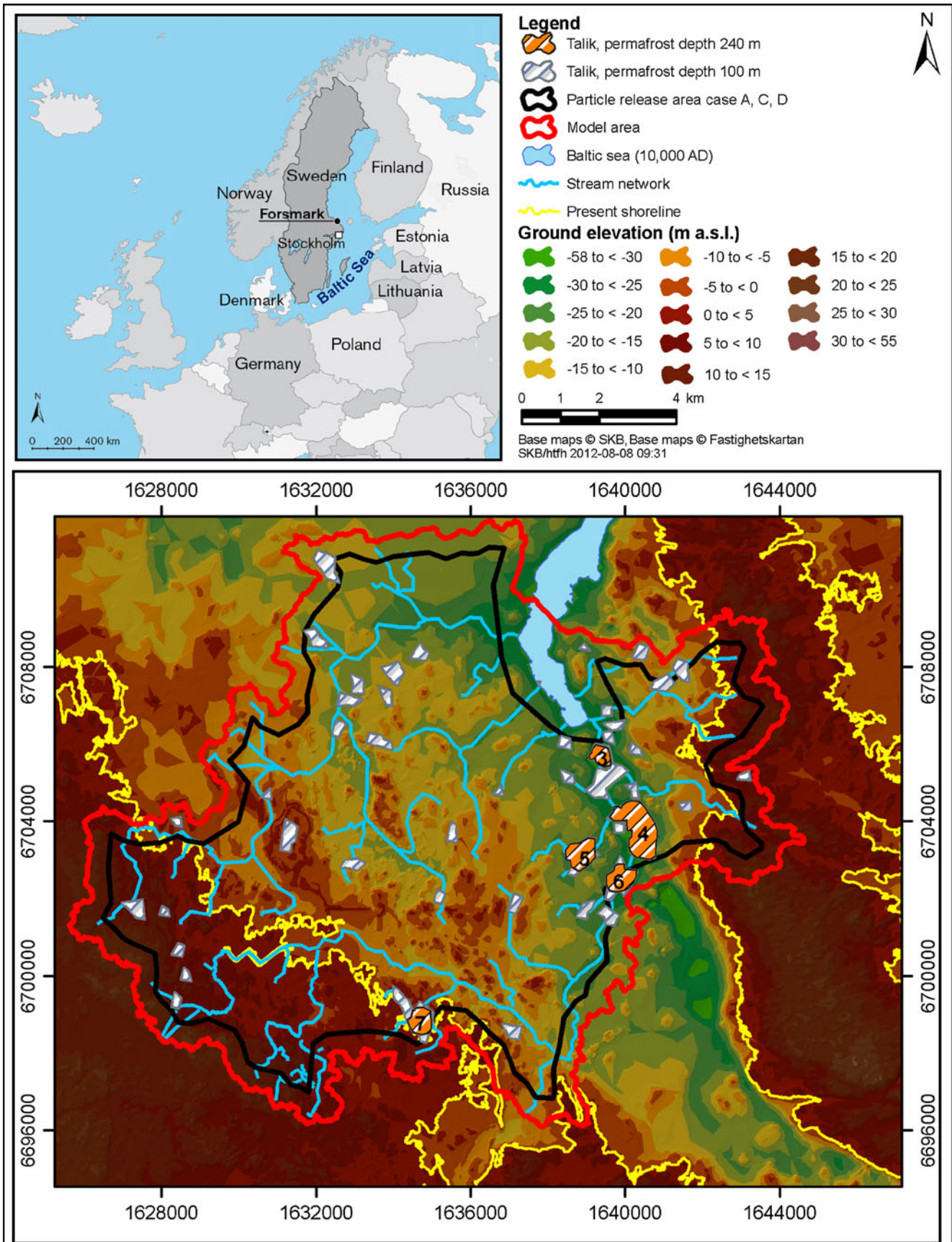
For all cases A–D, flow simulations are performed. In addition, for cases A, C and D, complementary particle-tracking simulations are carried out. All simulations are based on the calibrated MIKE SHE model of Forsmark, which represents well the present hydrological conditions based on all relevant available data from the site, which were used for calibration and validation in the modelling process (Bosson et al. 2008, 2010, 2012). Specifically, the developed and calibrated model was validated against independent data time series of both surface and ground-water levels, as well as against surface-water discharge.

The location of taliks in the permafrost cases C and D, and the area for release of simulated particles at 400 m depth into the bedrock in the particle-tracking calculations are shown in Fig. 1. The model domain extends from ground surface, where the time varying precipitation and potential evapotranspiration forms the top boundary condition, down to 600 m depth where a no-flow boundary condition is assigned. The lateral boundaries are no-flow boundaries except the boundary under the sea where a time varying head boundary condition is assigned. The MIKE SHE model simulates both surface and groundwater flow, as well as water flow in the unsaturated zone; fully transient simulations were performed in all cases. More information on the MIKE SHE modelling tool and the boundary conditions used in this study is found in the Appendix.

Meteorological data in terms of air temperature ( $T$ ), precipitation ( $P$ ) and potential evapotranspiration (PET) for the temperate climate case (A) are available from specific Forsmark site investigations (Johansson 2008). A representative hydrological year with a  $P$  time series that reproduces the long term annual mean  $P$  has been selected and used as input data in the present study, together with the PET and  $T$  time series for the corresponding period. For the periglacial climate cases (B, C, D), site specific, simulated time series of  $T$ ,  $P$  and PET from climate modelling (Kjellström et al. 2009) have been used as driving data for the hydrological MIKE SHE model. In all cases, a hydrological year is repeated in the simulations until an annual periodic steady state is reached. A detailed description of the meteorological

**Table 1** Description of simulation cases A–D. Flow ( $F$ ) simulations are performed for all cases and particle tracking ( $PT$ ) simulations are performed for cases A, C and D

Case	Case description	Change of conditions between cases	Simulations
A	Cool temperate climate with future landscape and shore line		F, PT
B	Arctic periglacial climate with future landscape and shore line and without permafrost	Between A and B: climate	F
C	Arctic periglacial climate with future landscape and shore line and with 100 m permafrost	Between B and C: permafrost, there or not there	F, PT
D	Arctic periglacial climate with future landscape and shore line and with 240 m permafrost	Between C and D: permafrost depth	F, PT



**Fig. 1** Model area for all simulation cases and particle release cases. The location of the inland taliks in cases C and D are also marked in the figure. The areas containing taliks in both case C and D are specifically marked with their numbers (talik numbers 3–7)

data handling and the simulation process is found in the [Appendix](#) and in Bosson et al. (2010).

The particle-tracking simulations are run for 5,000 years, a time considered long enough to capture the travel time of the majority of the released particles, based on flow simulation results with the representative hydrological year repeated 5,000 times. Five particles per cell are introduced at 400 m depth within the area shown in Fig. 1. The particles are released at great depth to be able to trace flow paths of deep groundwater towards the surface system. In addition, particles are released at the surface in identified recharge areas. In case A, particles are released at the bottom of the

Quaternary deposits and in cases C and D, particles are released at the bottom of the active layer. These particles that are released near the surface trace the flow paths all the way from recharge areas to discharge areas clarifying the exchange between shallow and deep groundwater.

**Results**

**Flow modelling results**

Figure 2, illustrating the groundwater flux between the QD and the bedrock shows that, in the non-permafrost,

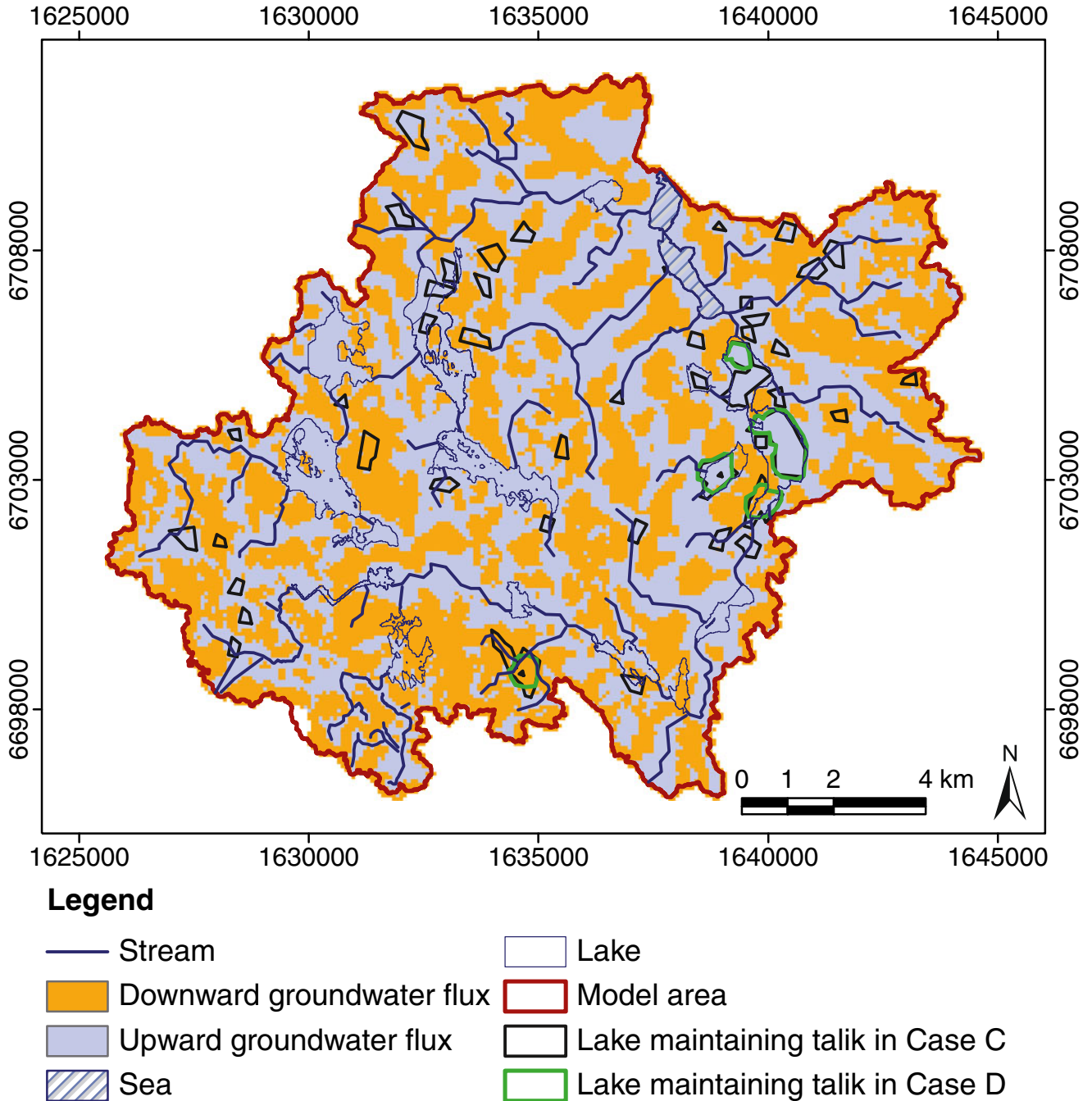


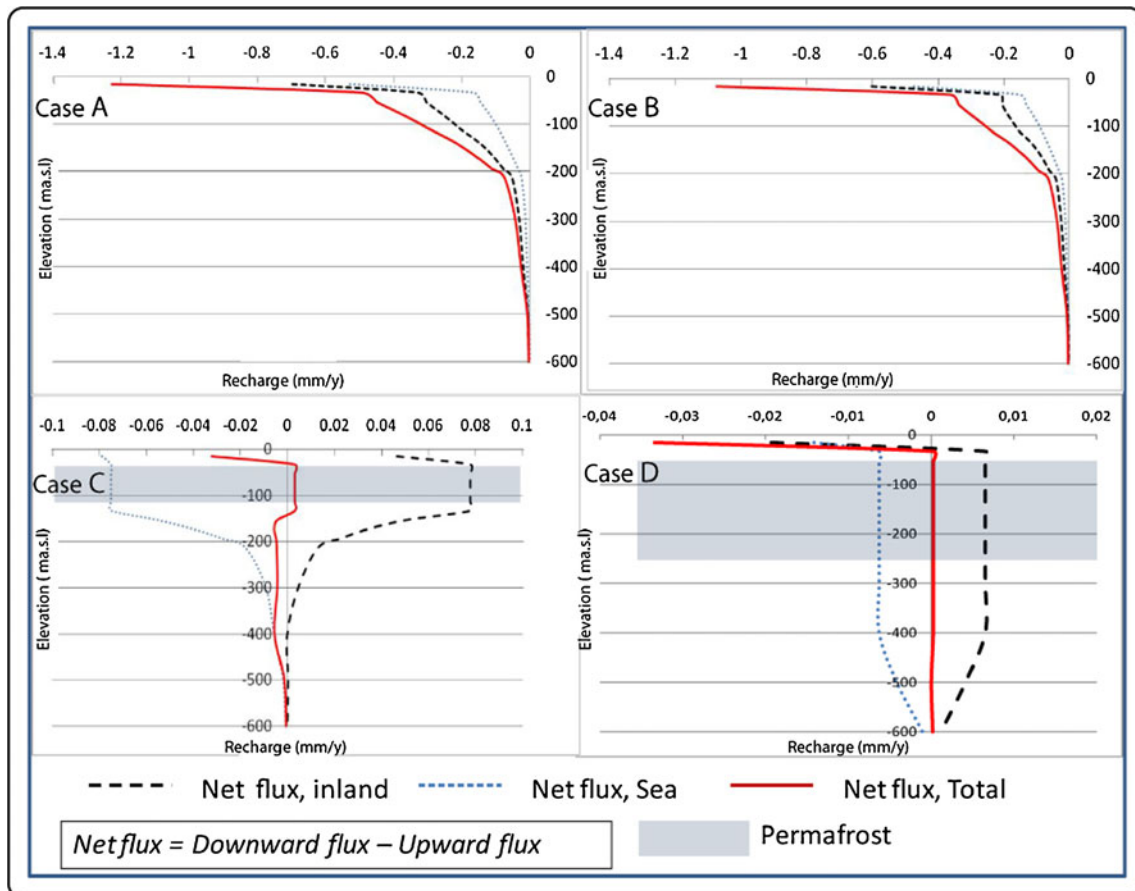
Fig. 2 Mean annual groundwater flux at the interface between the Quaternary deposits and the bedrock in case A

temperate climate case A (and similarly in the non-permafrost, periglacial climate case B, not shown due to similar results as in case A), the exchange of water between the deep groundwater system and the more shallow groundwater system in the Quaternary deposits is concentrated to areas under lakes and stream valleys and to regional topographical lows. For the periglacial climate cases with permafrost (C/D), the recharge and discharge areas of groundwater are concentrated to taliks and the sea bottom only. Figure 3 further shows the variability with elevation of vertical net groundwater flux (downward flux minus upward flux over the considered areas) for all cases A–D. In general, the vertical groundwater flux decreases with increasing depth. The net flux results are shown for: (1) only the areas that correspond to inland through taliks (mapped in Fig. 1) in the permafrost cases C or D (black dashed lines), (2) only the sea (blue dotted lines), and (3) the combined area of the case C/D inland taliks and the sea (red solid lines). For the non-permafrost cases A and B, only the through talik area of case C has been used in the calculation of net flux shown in Fig. 3, in order to obtain a consistent comparison between permafrost and non-permafrost cases.

In case A, the total net recharge over the whole model area and corresponding total net discharge are 30 mm/y

(quantified when the simulation has reached the annual periodic steady-state conditions). These values represent the total water volume, normalized by the total surface area of the model domain, entering and leaving the saturated zone of the model on an annual basis. In this case, and case B, the exchange of groundwater between the Quaternary deposits and the bedrock may take place anywhere in the model domain (with Fig. 2 mapping where for case A). In contrast, in the permafrost cases C and D, the only possible contact between deep and shallow groundwater is through the prescribed inland through taliks and beneath the sea. The bedrock and Quaternary deposits beneath the sea bay are prescribed to be unfrozen in cases C and D; thus, groundwater can flow from the unfrozen groundwater system beneath the permafrost, through the bedrock, and towards the sea bottom. Hence, the bedrock under the sea acts as a through talik (with submarine groundwater discharge) in these cases.

In case A, the total net groundwater flux at the surface (which is here primarily negative, i.e., a total net discharge) is in only the areas that correspond to the locations and extents of the taliks in case C/D is approximately 1.2 mm/y (0.7 mm/y in the inland areas constituting taliks during periglacial conditions, and



**Fig. 3** Vertical groundwater flux (volumetric flow normalized by the whole model area) as function of elevation for all simulation cases (A, B, C and D). Net recharge (in mm/y) is calculated as total recharge minus total discharge flux at different elevations and shown for: the areas that correspond to the locations and extent of inland through taliks in cases C or D (black dashed line), the sea area (blue dotted line), and the total combined sea and inland through talik area (red solid line)

0.5 mm/y constitutes submarine discharge under the sea). This should be compared to the total net recharge (discharge) of 30 mm/y when considering the whole domain in case A. Thus, only 4% of the total recharge (discharge) under the temperate climate conditions occurs in areas that are taliks under the periglacial climate and permafrost conditions (C/D). Also in case A, the major part of the prescribed inland through taliks under permafrost conditions, as well as the sea, constitute net discharge areas and the main recharge occurs in the areas outside these locations, as can also be seen in Fig. 2.

In the periglacial climate without permafrost conditions (B), the net groundwater flux at the surface (which is also in this case mostly negative, i.e., a net discharge) in the areas of case C/D taliks is reduced to 1.1 mm/y (0.6 mm/y in the inland areas and the submarine discharge is 0.5 mm/y) in comparison to case A. The climate shift from the cool temperate climate in case A to the periglacial climate in case B does not influence the flow pattern in the case C/D talik areas and below the sea. The major part of the prescribed talik areas are also in this case net discharge areas, as in case A. This is explained by the fact that the through taliks under permafrost conditions are preferentially located in low-lying areas, which constitute discharge regions in the absence of permafrost.

In the presence of permafrost, the vertical groundwater flux, occurring here only in the prescribed talik areas, both decreases significantly and changes its predominant direction relative to non-permafrost conditions. The total net flux (which is here mostly positive, i.e., indeed a net downward direction) in the inland taliks surrounded by permafrost in case C is about 0.08 mm/y, and in case D only 0.007 mm/y. Thus, the vertical groundwater flux within the part of the taliks surrounded by permafrost decreases as the permafrost depth increases and the number of through taliks is reduced. In the active layer, above the permafrost, lateral inflow and outflow occur during the active period (and to some extent also during the thawing and freezing periods) resulting in an annual mean net discharge in the active layer of approximately 0.03 mm/y in both case C and D (compared to 1.2 mm/y for case A and 1.1 mm/y for case B, Fig. 3). However, regarding the groundwater flux in only the inland through talik areas there is a net recharge in the active layer in case C with a magnitude of 0.05 mm/y, whereas discharge occurs in the active layer in the case D taliks with a magnitude of 0.02 mm/y. This is due to more taliks located in recharge areas in case C than in case D.

Furthermore, in the permafrost cases C and D, the total net groundwater flux in the combined inland talik areas and the sea is almost zero (Fig. 3), since the flow system is under periodic annual steady state and most inland taliks constitute recharge areas. The inland taliks are the only recharge areas that exist across the whole land domain under permafrost conditions, while the sea constitutes the main discharge area. However, some inland taliks can still constitute discharge areas also under permafrost conditions. The explanation for the total net groundwater flux not being identically equal to zero in the permafrost cases

C and D in Fig. 3 is that some exchange of water occurs through the model boundary beneath the sea, as a small seepage of water through this boundary. In all cases A–D, the highest groundwater fluxes are found in the upper part of the profile. This is due to the main water turnover occurring in the Quaternary deposits (cases A and B) and the active layer (cases C and D).

The vertical groundwater flux is constant with depth within the extent of the permafrost layer in cases C and D (Fig. 3) because no lateral exchange of groundwater can occur between the permafrost and the taliks. Outside this zone, the net flux in the talik areas (black lines in Fig. 3) increases with depth above the permafrost layer, due to lateral inflow in the active layer feeding the vertical groundwater flux, and decreases with depth below the permafrost. The lateral exchange of water between the zone of the inland permafrost layer and the sea is zero; hence, the same flow pattern as in the inland taliks, i.e., constant vertical groundwater flux with depth, is seen beneath the sea over this depth zone. In cases A and B, the net flux variability with depth is similar (differences are smaller than 10 %). This is due to the fact that only climate differs between these two cases, which have both no permafrost, and share the same shoreline and landscape characteristics. Furthermore, the difference in total net recharge between the two cases is only 0.1 mm/y. Given these similarities between the cases, results for case B are not further shown and discussed in the following result illustrations and discussions.

Table 2 summarizes the net groundwater recharge and discharge fluxes of each individual through talik (including that beneath the sea), i.e., the net vertical groundwater flow (defined as positive downwards, i.e., for the recharge direction) normalized with the cross-sectional area of each individual talik. For the non-permafrost temperate climate case A, the areas corresponding to each individual talik in case C have been used for the normalization. Taliks 8–45 do not constitute through taliks for the deeper permafrost depth in case D, and hence no groundwater flow can occur in these areas for this case. The flux of the discharging groundwater into the sea (i.e., the submarine groundwater discharge) is highest in case A and decreases both in the presence of permafrost and with increasing permafrost depth. In cases C and D, the submarine discharge is higher

**Table 2** Vertical groundwater flux into the sea and through each inland talik (Fig. 1) in mm/y, i.e., the vertical flow at the ground surface normalized with each respective flow cross-sectional area. Positive values indicate net recharge and negative values indicate net discharge. Taliks 8–45 are not present in case D, i.e., no vertical groundwater flow can occur in these areas in case D

Talik	A	C	D	Area (km <sup>2</sup> )
Sea	-12.91	-9.66	-0.82	1.34
3	-9.86	-3.97	0.83	0.71
4	-12.52	-6.24	-0.08	0.94
5	-11.02	0.5	0.76	0.45
6	-2.06	-2.1	-0.2	0.45
7	19.63	6.69	2.61	0.56
8–45	-9.96	4.43	-	4.32

than the recharge/discharge flux in any other talik, whereas in case A the discharge flux in taliks 3, 4, 5 and 8–45 is of the same magnitude as that into the sea.

Among the inland through taliks, the greatest net flux differences between unfrozen and permafrost conditions occur in taliks number 5 and 8–45. In talik 5, the net flux is downwards (net recharge) during permafrost conditions, and upwards (net discharge) with a much higher magnitude under unfrozen conditions. Also in taliks 8–45, which constitute through taliks only in case C, there is a mean net discharge flux of 9.96 mm/y in the unfrozen case A, and a mean net recharge flux of 4.43 mm/y in the permafrost case C. The taliks 3, 4 and 6 in case C, and 4 and 6 in case D remain net discharge areas, i.e., have a net flux direction upwards, as they are also in the unfrozen case A. In general, the groundwater flux in the areas of case D taliks decreases with deeper permafrost. However, in one talik (talik number 3), both the direction and magnitude of the groundwater are different between the two permafrost cases C and D (3.97 mm/y upwards in case C, and 0.83 mm/y downwards in case D), and in talik 5 there is a slight increase in groundwater flux with deeper permafrost (0.50 mm/y in case C, 0.76 mm/y in case D).

### Particle-tracking results

Figure 4 shows results from the particle-tracking simulations in terms of particle-breakthrough curves and particle-pathway lengths to the Quaternary deposits for particle release at 400 m depth. Under permafrost conditions, between 69% (case D) and 83% (case C) of the particles reach the Quaternary deposits within the 5,000-year simulation period. In the unfrozen case A, 76% of the deeply released particles reach the Quaternary deposits layers, with the discharge being concentrated to depressions close to the streams, lakes and wetlands. The particle-tracking results thus follow the discharge pattern shown in Fig. 2. Only 19% of these particles that reach the Quaternary deposits in the unfrozen case A discharge then in any of the areas that constitute through taliks in cases C and D, while 72% discharge in stream valleys, lakes and wetlands, and only 9% discharge directly in the sea by submarine groundwater

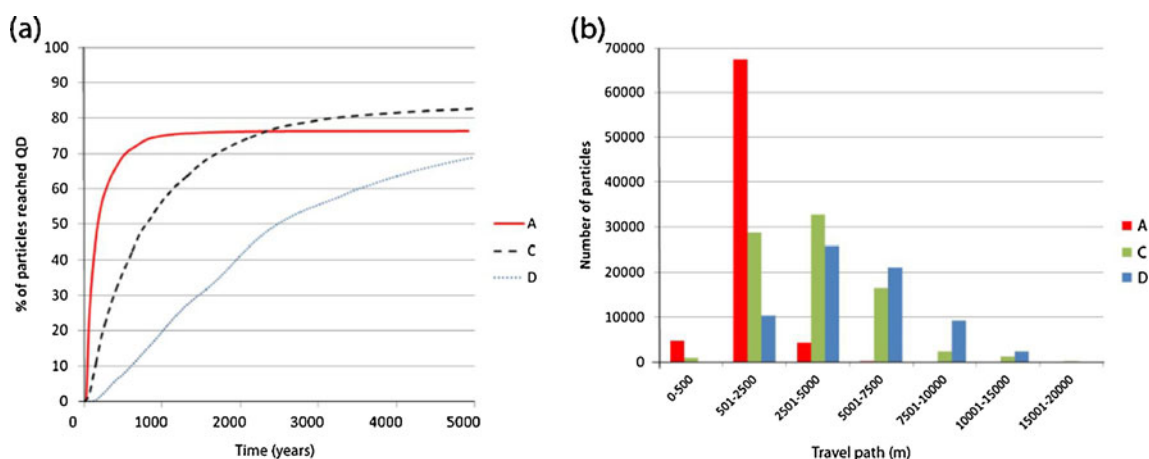
discharge. Thus, the main discharge areas of deep flow paths under unfrozen conditions are not concentrated to the areas that constitute through taliks under permafrost conditions.

In the permafrost cases C and D, the only pathways for the deeply released particles to reach the Quaternary deposits layers are via the inland through taliks and the unfrozen sea bay. The majority of the particles that reach the Quaternary deposits when permafrost is present, that is 89% in case D and 45% in case C, discharge then into the sea by submarine groundwater discharge.

The travel lengths for the deeply released particles that reach the Quaternary deposits are longest in case D (mean travel length of 5,107 m), where only five inland through taliks and the sea bay constitute unfrozen paths to the surface (Fig. 4). The shortest travel lengths (mean travel length of 1,275 m) occur in the unfrozen case A, where no permafrost impedes groundwater flow in the bedrock. The mean travel length in case C is 3,681 m, showing that travel length increases with increasing permafrost depth.

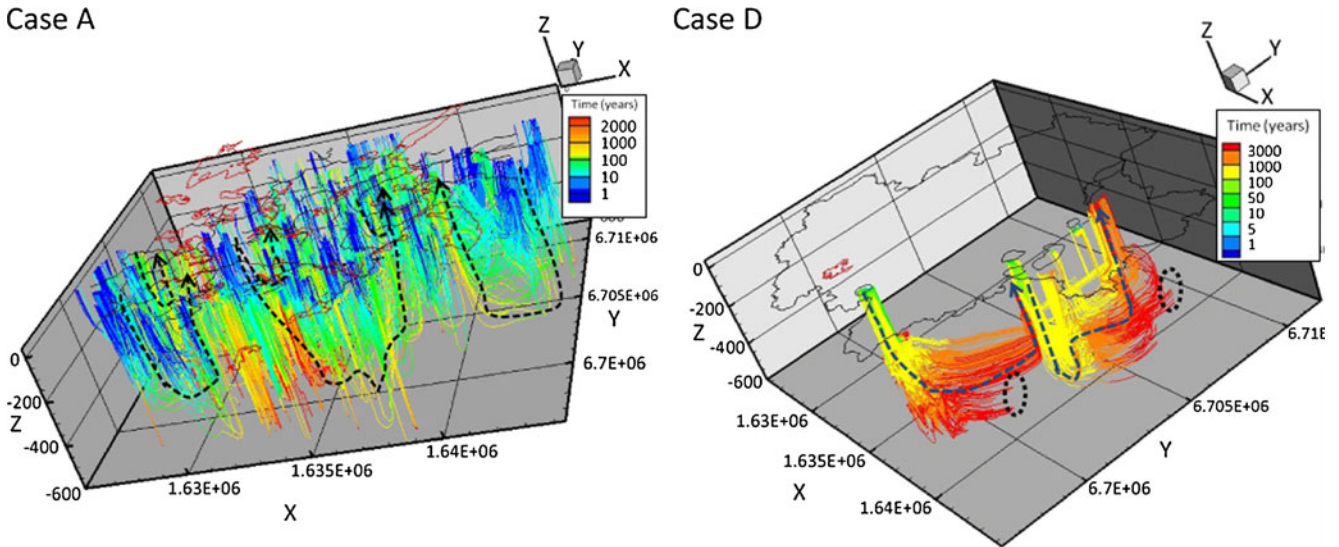
When permafrost is present, the movement of deeply released particles under the permafrost is preferentially horizontal and becomes vertical only once the particles reach a through talik with upward groundwater flow (Fig. 5). The transport pathways in the taliks through the permafrost up to the Quaternary deposits and the ground surface are then relatively short.

Figure 6 shows breakthrough curves at different control planes (CPs) for the particles that are released near the surface (in recharge cells) and reach the bottom of the permafrost (case C and D) or the depth of –50 m into the bedrock (case A); the different control planes for each case are further illustrated in Fig. 7. In the unfrozen case A, the transport and associated breakthrough curves are subdivided into three components (breakthrough components; BCs), where one is for the transport down to –50 m into the bedrock (which is CP 1 for the downward transport from the surface to that bedrock depth, i.e., for BC 1), the second is for the transport through the underlying bedrock and back to the –50 m depth level (which is CP 2 for the essentially horizontal-to-upward transport to that bedrock depth, i.e., for BC 2), and the



**Fig. 4** a Breakthrough curve and b particle pathway lengths to the Quaternary deposits (QD) for particles released at 400 m depth in cases A, C and D

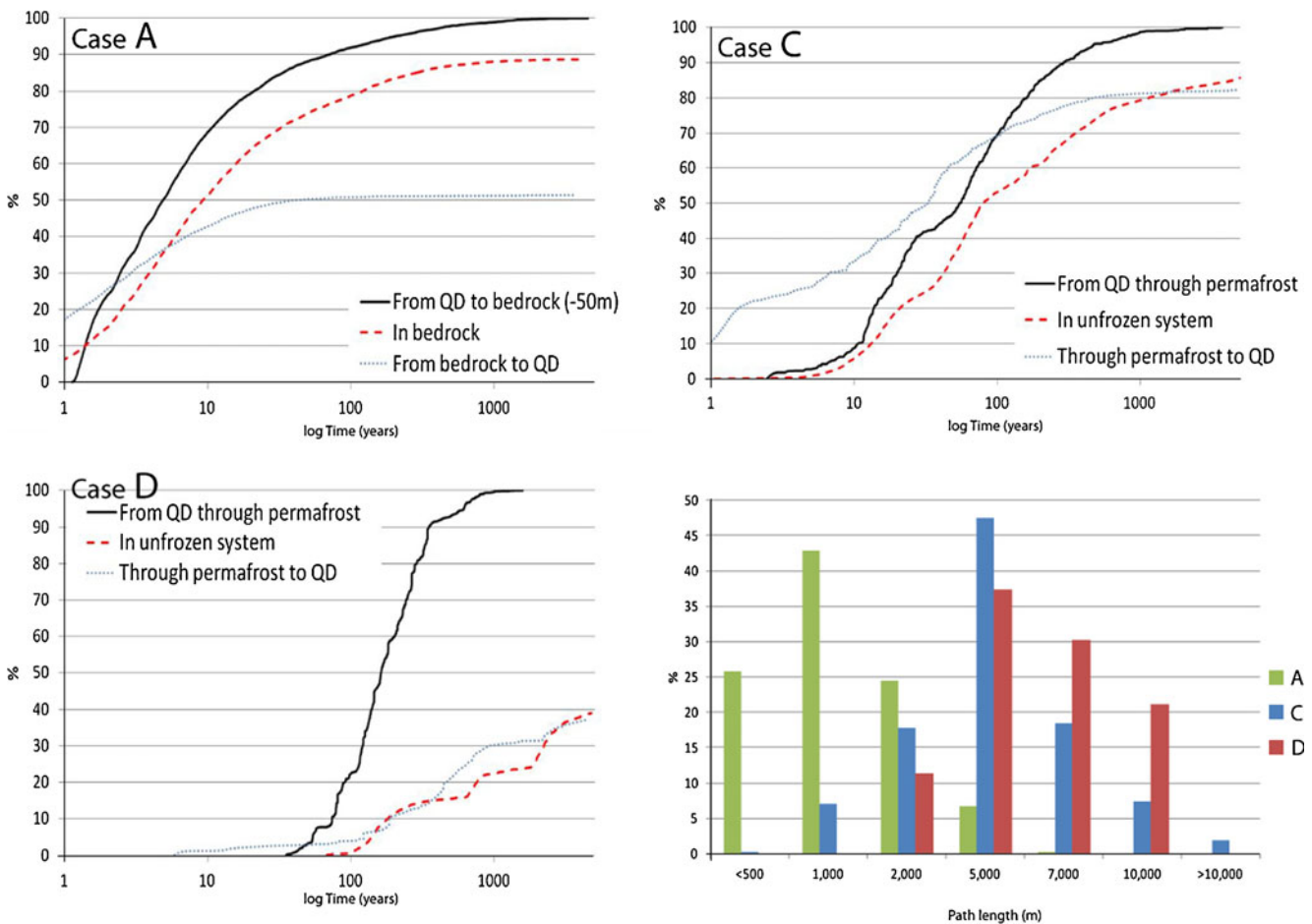




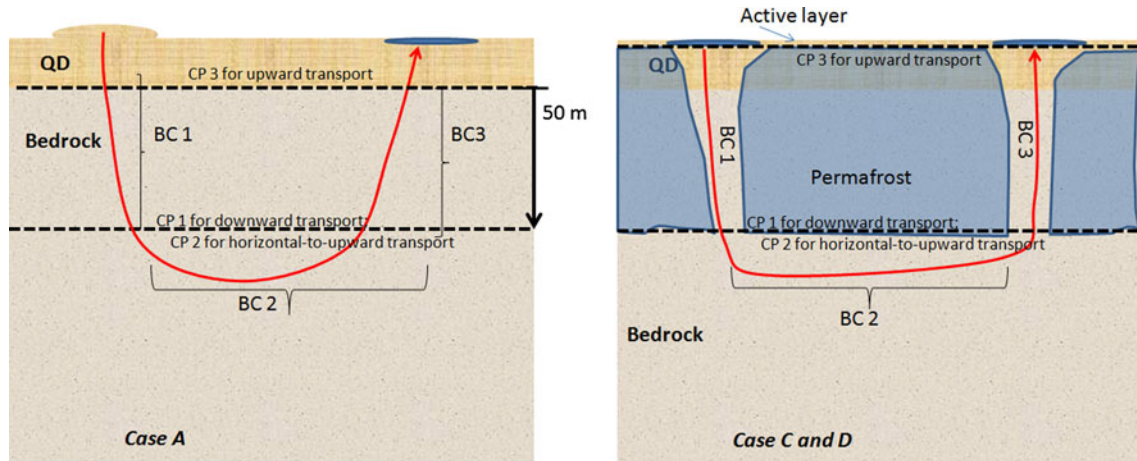
**Fig. 5** Particle pathways from release at the surface down to and through the bedrock towards a net-discharge talik area and back to the Quaternary deposits, for simulation cases *A* and *D*. The colours quantify the travel times along each particle pathway. For case *A*, the stream network and lakes at the surface are marked with *red lines*. For case *D*, the taliks are marked with *red lines*. The main particle pathways are explicitly marked with *arrows*; the positions in the bedrock (*case D*) where the particle flow paths end due to slow transport velocities in the deep bedrock are also marked (*black dashed lines*)

third is for the transport from -50 m up to the Quaternary deposits (the bottom of which is CP 3 for the upward

transport, i.e., for BC 3). For permafrost cases *C* and *D*, the breakthrough curves are also subdivided into three



**Fig. 6** Breakthrough curves at different control planes for different transport components, and total particle pathway lengths back to the Quaternary deposits (*lower right*) for particles released near the surface in simulation cases *A*, *C* and *D*



**Fig. 7** The different breakthrough components (*BC 1–3*) and associated control planes (*CP 1–3*) for particle breakthroughs and pathway lengths illustrated in Fig. 6

components, including the transport: (1) from recharge in the active layer through the frozen bedrock (the bottom of which is CP 1 for the downward transport from the active layer, i.e., for BC 1) (2) through the unfrozen system beneath the permafrost (the bottom of which is CP 2 for the essentially horizontal-to-upward below-permafrost transport, i.e., for BC 2), and (3) from the bottom of the permafrost up to the active layer (the bottom of which is CP 3 for the upward transport, i.e., for BC 3). In case A, some of the particles reach the  $-50$  m depth from above, but do not reach back to this level again in the transport through the bedrock, and even fewer get all the way back up to the Quaternary deposits. This is primarily due to the horizontal flow component in the system moving particles out across the vertical open boundary below the sea; i.e., the applied boundary conditions, in combination with the prevailing topography, results in both a local recharge/discharge flow system and a regional, predominantly horizontal flow component out from the local flow system. The particle pathways in case A are explicitly illustrated in Fig. 5.

In both permafrost cases C and D, the longest travel times (slowest breakthrough component) are in the unfrozen system below the permafrost, while the shortest travel times (fastest breakthrough component) are in the taliks through the permafrost both for the recharging particles (going from the Quaternary deposits to the unfrozen bedrock) and the discharging particles (going from the unfrozen bedrock back to the Quaternary deposits). In case C, with 100-m-deep permafrost, it takes about 290 years for 90 % of the particles to go through the permafrost zone in the taliks, while the corresponding time for case D, with 240 m deep permafrost, is 350 years. Among the particles reaching the deep unfrozen system, 86 % reach a discharge talik within the simulation time in case C and 40 % in case D. Some of the particles entering the taliks, 4 % in case C and 2 % in case D, do not reach the Quaternary deposits again within the simulation time. Figure 5 illustrates the particle pathways in case D and how some are terminated in the bedrock; with a longer simulation time, these pathways and associated particles would eventually terminate in discharge taliks.

The lower right plot in Fig. 6 illustrates the total pathway length distribution for the entire transport of particles that reach the Quaternary deposits again after near-surface release. The longest mean travel length, 4,943 m, is found in case D and the shortest in case A, 918 m. The longest individual pathway length, however, is found in case C, due to longer distances between some of the recharging and discharging taliks in case C compared to case D. The results indicate a fraction of relatively short, shallow and fast transport pathways for groundwater in case A, which are closed when permafrost is present (Fig. 5), resulting in the generally longer and deeper pathways in the permafrost cases C and D.

## Summary and conclusions

The effect of permafrost on groundwater circulation is here studied by prescribing permafrost and through talik properties in a groundwater flow model of the Forsmark catchment. The resulting flow and exchange characteristics between deep and shallow groundwater during such periglacial conditions are compared against corresponding temperate conditions (i.e., conditions without permafrost and taliks).

Inland areas that constitute net discharge zones for groundwater under unfrozen conditions can under permafrost conditions shift to being through taliks that recharge groundwater. This is because the areas where through taliks form tend to be depressions (low points) in the terrain; hence, the topographically driven flow under unfrozen conditions will tend to discharge in these low point locations. Conversely, during permafrost conditions, the inland through taliks preferentially act as groundwater recharge areas because they are the only flow paths open to feed the groundwater that subsequently discharges into the sea. A shift from temperate to periglacial conditions thus changes the pattern and directions of vertical groundwater flow and, hence, also the exchange characteristics between deep and shallow groundwater. In general, both the total groundwater recharge and the corresponding total discharge decrease with increasing permafrost depth. Specifically for permafrost conditions, the

submarine groundwater discharge directly into the sea constitutes the major part of total groundwater discharge into any surface water in the region. However, also under current climate and unfrozen conditions, the simulations indicate some considerable submarine groundwater discharge directly into the sea. Recently performed field investigations of the sea bottom (Nyberg et al. 2011) also indicate such possible submarine groundwater discharge. This quite uncertain groundwater flow component (Prieto and Destouni 2011) needs further investigation by both model and field studies.

Furthermore, in the presence of permafrost, both the distances of flow and transport pathways, and the associated travel times of deep groundwater and solute to reach the surface are longer than under unfrozen conditions. This is because the mainly topographically driven flow of even the deeper groundwater during unfrozen conditions changes dramatically in the presence of permafrost. The through talik locations will then govern the pathways of deep groundwater flow and transport. In general, the pathways of the deep groundwater flow under permafrost will be predominantly horizontal and turn to vertical only when they reach and flow the relatively short distance up through the prevailing taliks.

The particle-tracking results for particle release at the surface (in recharge cells in the Quaternary deposits) show the existence of a fraction of short, shallow and fast flow and transport pathways under unfrozen conditions, which are closed in the presence of permafrost. This pathway closure yields generally longer pathways and travel times through the whole shallow-through deep-back to shallow groundwater system under permafrost than under unfrozen conditions. The travel times through the depth extent of the permafrost layer are then shorter than the travel times through the unfrozen groundwater system below the permafrost. These particle-tracking results also show that, even though most taliks are net-recharge areas, discharge taliks exist too under permafrost conditions, and they show how the different taliks are connected under such conditions.

The main implication of the present simulation results is an increased understanding of climate change effects on the pathway and travel-time characteristics of groundwater flow and solute transport. A change from a cool temperate climate to a periglacial climate without permafrost has only small effect on the groundwater circulation; this is due to the similarity in total net groundwater recharge and recharge-discharge flow pattern between these two non-permafrost cases. With permafrost and through taliks present, larger changes in groundwater circulation occur. Specifically, the deeper the permafrost and the fewer the number of through taliks, the smaller the net vertical groundwater flow will be. However, even with deep permafrost and only a few taliks, exchange flow and solute transport between deep and shallow groundwater exist. In general, the present results shed light on how groundwater flow dynamics and solute transport characteristics may change during climate and associated permafrost transitions.

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## Appendix: The MIKE SHE model—boundary conditions and input data

MIKE SHE is a 3D dynamic, physically based modelling tool that represents the main processes in the terrestrial part of the hydrological cycle. The model consists of four main units; the saturated zone, the unsaturated zone, the overland flow compartment and the evapotranspiration compartment. The water table fluctuates depending on the hydrological conditions, thus the extent of the unsaturated zone is not fixed in time.

The water on the ground surface can infiltrate, evaporate, or form overland flow. Once the water has infiltrated the soil, it enters the unsaturated zone. In the unsaturated zone, it can either be extracted by roots and leave the system as transpiration, or percolate down to the saturated zone. MIKE SHE is fully integrated with a channel-flow code, MIKE 11. The exchange of water between the two modeling tools takes place during the whole simulation, i.e., the two programs run simultaneously. For more detailed descriptions of the processes included in MIKE SHE and MIKE 11, see Bosson et al. (2012) and Graham and Butts (2005).

### Boundary conditions

The top boundary conditions are based on the precipitation ( $P$ ) and the potential evapotranspiration (PET). In the present study the  $P$  and PET are assumed to be uniformly distributed over the area and are given as time series. The bottom boundary condition is a no-flow boundary condition; the model extends down to 600 m below the present sea level. In the Forsmark catchment, the groundwater divides are assumed to coincide with the surface-water divides. Thus, a no-flow boundary condition is applied on the vertical boundaries for the on-shore part of the model. The vertical boundary under the sea has a time varying head boundary condition; the present-time varying sea level is used as input data.

At present, no lateral inflows via the surface stream network occur in the Forsmark catchment. However, new lakes and streams are formed as a result of the landscape development. In the MIKE SHE model describing future conditions in the Forsmark catchment, lateral inflows via streams exist and occur in five discrete points. The future stream network and the handling of the lateral boundary conditions in the surface-water model are further described in Bosson et al. (2010).

### Input data and hydrogeological conditions

#### Driving climate data

Local meteorological data from the site investigations were used to describe the temperate climate in the hydrological simulations. A selected year considered to represent the current long-term average situation at the

**Table 3** Hydraulic parameters assigned to each layer in the Quaternary deposits (QD) model

Layer	$K_h$ (m/s)	$K_v$ (m/s)	$S_y$ (-)	$S_s$ ( $m^{-1}$ )
L1, Gyttja	$3 \cdot 10^{-7}$	$3 \cdot 10^{-7}$	0.03	0.006
L1, Peat	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	0.2	0.006
L2, Sand/gravel	$1.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$	0.2	0.004
L3, Clay	$1.5 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	0.05	0.006
Z1:				
Till	$1.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-5}$	0.15	0.001
Gyttja	$3 \cdot 10^{-7}$	$3 \cdot 10^{-7}$	0.03	0.006
Clay	$5 \cdot 10^{-6}$	$5 \cdot 10^{-7}$	0.05	0.006
Sand	$7.5 \cdot 10^{-4}$	$7.5 \cdot 10^{-5}$	0.2	0.004
Peat	$5 \cdot 10^{-6}$	$5 \cdot 10^{-7}$	0.2	0.02
Bedrock	$1 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	0.15	0.001
Z2, Peat	$3 \cdot 10^{-7}$	$3 \cdot 10^{-7}$	0.05	0.005
Z3, Glaciofluvial deposit	$1.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$	0.2	0.35
Z4, Clay	$1.5 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	0.03	0.006
Z5:				
Fine till	$5 \cdot 10^{-7}$	$5 \cdot 10^{-8}$	0.03	0.001
Coarse till	$7.5 \cdot 10^{-6}$	$7.5 \cdot 10^{-7}$	0.05	0.001
Z6	$1.5 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	0.15	0.001

site (Bosson et al. 2010) with a mean annual air temperature (MAAT) of  $+6.4^\circ\text{C}$  and an annual precipitation ( $P$ ) of 583 mm were used as input data. The annual potential evapotranspiration (PET) was 420 mm. Simulated time series describing possible future periglacial climate conditions at the site (Kjellström et al. 2009) were used as input data to describe the periglacial climate conditions. The MAAT of the periglacial climate time series was  $-7^\circ\text{C}$ , annual  $P$  412 mm and annual PET 216 mm.

#### Hydraulic properties: temperate conditions

The geological description of the Forsmark MIKE SHE model consists of two main parts, the Quaternary deposits (QD) and the bedrock. The QD is described using a geometrical regolith model describing the total regolith depth and the spatial variability of the bedrock topography, but also the horizontal spatial distribution of different QD types are described. The layers are denoted Z1-Z6 and L1-L3, each having different thicknesses and properties. Layer L1-L3 describes the lake sediments in detail. The typical sediment stratigraphy from down and up consists of glacial and/or post-glacial clay, sand and gravel, clay-gyttja, and gyttja. A detailed description of the QD in the Forsmark area is given in Hedenström and Sohlenius (2008). Hydraulic properties were assigned to each layer in the geological model

according to Table 3, the values are based on site data and knowledge from the calibration process of the MIKE SHE model (Bosson et al. 2008, 2010).

At present, the QD are often shallow and the mean depth within the catchment is approximately 5 m and the maximum observed depth on land is 16 m. However, when studying future conditions, the shore line displacement, which is approximately 6 mm/y in Forsmark, has to be taken into consideration. In the present study the shore line of 10,000AD is applied and is situated at  $-31.42$  m relative to the present sea level. The QD covering future land areas have a mean depth of 6 m and a maximum depth of 47 m where the deepest QD-layers are found under future lakes and the sea bay (Brydsten and Strömgen 2010).

The upper ca. 200 m of the bedrock are highly fractured and water conductive. Horizontal sheet joints are present in the upper bedrock and are interconnected hydraulically. According to hydraulic tests performed in percussion-drilled boreholes, the horizontal hydraulic conductivity of the fractures/sheet joints in the upper rock is very high, and the groundwater flow in the area is dominated by the horizontal component. In the MIKE SHE model, the hydraulic conductivity of the background bedrock is in the range  $10^{-10}$  to  $10^{-8}$  m/s, whereas the hydraulic conductivity of the deformation zones varies from  $10^{-6}$  to  $10^{-4}$  m/s. The hydraulic properties of the bedrock are described in detail in Joyce et al. (2010).

#### Hydraulic properties: periglacial conditions

During periglacial conditions, the hydraulic properties are changed in the model in order to mimic a low permeable permafrost layer and an active layer thawing and freezing depending on the annual varying weather conditions. A hydraulic conductivity of  $10^{-20}$  m/s is applied to the layers with permafrost while the hydraulic properties within the taliks are assumed the same as under temperate climate conditions. The year is divided into seven periods; two freezing periods, one frozen period, three thawing periods and an active period during the summer. The properties in the overland flow compartment and the unsaturated zone of the model (Manning number, infiltration capacity and hydraulic conductivity) are also changed during the different periods in order to reduce the infiltration and make the surface water immobile, i.e. frozen, during the frozen period. The step-wise changing of the hydraulic conductivity on an annual basis is presented in Table 4.

**Table 4** Annual variations in horizontal and vertical conductivity (m/s) for the seven periods in the different saturated layers to reflect permafrost conditions; K refers to the K-values used under temperate climate conditions presented in Table 3

	Freeze 1	Freeze 2	Frozen	Thaw 1	Thaw 2	Thaw 3	Active
Horizontal and vertical conductivity ( $K$ ) in active layer	$K/30$	$K/300$	$1 \cdot 10^{-20}$	$K/1000$	$K/100$	$K/10$	$K$
Horizontal and vertical conductivity ( $K$ ) in permafrost layers	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-20}$
Horizontal and vertical conductivity ( $K$ ) in taliks	$K$	$K$	$K$	$K$	$K$	$K$	$K$
Horizontal and vertical conductivity ( $K$ ) in unfrozen layers beneath the permafrost	$K$	$K$	$K$	$K$	$K$	$K$	$K$

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