FLOW AND TRANSPORT MODELLING IN THE PARIS BASIN OVER GEOLOGIC TIME

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ABSTRACT

We question here the validity of the classical assumption, in hydrogeological studies of flow and transport in large sedimentary basins, that prior to the start of artificial withdrawal by man, these systems were in steady-state. This assumption is generally used both for the initial head distribution in the aquifers and aquitards, and to calculate the age of groundwater, assuming that the present-day velocities can also be used for the past along the flow path, assumed constant. We show, on the example of the Paris basin, that in the past many changes occurred in the recharge of the aquifers because of climate changes, permafrost, and that the boundary conditions changed because of sea-level variations, river incision, general uplift, etc. By trying to quantify these effects by numerical modelling over a period of 5 My at the basin scale, we show that, for the deeper layers, the present situation is far from a steady-state. Sensitivity analysis shows the important causes of the persistence of transient effects, and consequences are drawn for long-term transport studies, e.g. interpretation of groundwater ages and nuclear waste disposal.

Keywords: *Flow and transport modelling; Paris basin; Palaeo-hydrogeology; Paleo-climate; transient effects.*

INTRODUCTION

The Paris basin is a rather large sedimentary basin, on the order of half a million km², containing a series of aquifers and aquitards, ranging from the Triassic to the Tertiary, which are exploited for water supply, geothermal energy, gas storage in aquifers, as well as for petroleum production. Recently, a deep clay layer in the East of the basin at Bure has been selected as a potential nuclear waste disposal site, for a preliminary study. A large amount of data (e.g. several thousands borehole logs) is available, as well as many detailed studies. Many attempts have been made to model flow, heat and salt transport in the basin, as well as groundwater ages, either for a particular aquifer or for the whole basin.

Most of these studies assume that prior to the exploitation of the deep aquifers, which started in the mid 19th century, the basin was in steady-state. But is this assumption realistic ? When flow models are built to predict radionuclide transport in the basin, if nuclear waste is stored there, and the time horizon is the next million years, is it worth considering what happened in the past, and may still be detectable today ? It is clear, for instance, that environmental tracer concentrations are still reflecting the past, and that with these tracers, groundwater ages have been estimated to be from tens of thousands of years (e.g. with ^{14}C) to millions of years (e.g. with He). When comparing the estimated ages using these tracers with calculated ages obtained by models, one usually makes the assumption that the system is in steady state, and that the tracer migration can be calculated with constant velocities and flow paths. Is this correct ?

If we look at the recent past, we know that the Paris basin was subjected to a peri-glacial climate from roughly 110 ky ago to the last glacial maximum, 21 ky ago, and that the present climate was not established before 6 ky ago. The coastline position also changed with the rising of sea-level by about 120 m during deglaciation. Dieng et al. (1990) showed that the changes in sea-level that occurred 21 ky ago on the coast of Senegal could explain the presence, in the large phreatic coastal aquifer, several hundred km away from the coast, of the “Ferlo” piezometric depression, that otherwise was difficult to explain. If we go further back in time, nine major glaciations occurred, from 0.9 My on, major erosion phases also started in the basin, and the morphology of the river system has evolved continuously since then, changing the elevation of the outlets of the aquifers. Going back 2.6 My, another forty glaciation cycles have occurred; 5 My ago, in the early Pliocene, the climate was warm and humid and the hydrologic regime different. Given that the Paris basin is rather large, it is worth exploring the possibility that very significant changes in the flow pattern of the past, due to climatic, eustatic, geomorphologic or tectonic changes, may still have an impact on the present status of the system, which would thus not be in steady-state.

A theoretical analysis of the hydrodynamic requirements necessary for the persistence of anomalous fluid pressures over geologic timescales (Neuzil, 1995) shows that it depends on the diffusivity $D=K/S_s$ of low-permeability layers of the system (permeability K and storativity S_s). If $\tau=Dt/l^2$ is on the order of 0.1, then the transient response can still persist in the system (t is time, l is the representative length, from the centre to the closest boundaries). Taking l=300 km, t=1My, $Ss=10^{-6}$/m, $K=3.x10^{-10}$ m/s, which are reasonable values for such a system, one finds that $\tau = 0.1$: it is thus reasonable to expect transient effects to still be present in the system. In this paper, we will explore what dominant changes can still be perceived in the present state of the system.

DEVELOPMENT OF THE MODEL

The starting point of this work was a 3-D model of the Paris basin developed by Gonçalvès, 2002, Gonçalvès et al., 2004a,b, for a large “Paris basin” extending to Denmark and London, to include the real dimension of the different layers deposited since the Triassic. This model is a basin model evolution, which represents the deposition (and possibly erosion), compaction, deformation, fluid, heat flow and salt transport during the formation of the basin, from the Triassic to the present. The stratigraphy of the basin was extracted from a database of 1100 wells, and divided into 19 units. The lithologic composition of the units was defined as a mixing of several end-member facies (sand, shale, limestone or chalk), and the hydrologic properties (porosity, permeability) were derived from the proportion of each facies, selected compaction laws, and the classical Kozeny-Carman Φ-K relationships, or the Lucia, 1995, Φ-K relationship for carbonates. The outcome of the model was the distribution of the geometry, of the parameters and of the pressure, salinity and temperature in the 3-D system during geologic time and, in particular, at present. With the present boundary conditions, assuming steady-state, the model gave a reasonable fit with the observed heads in the different aquifers.

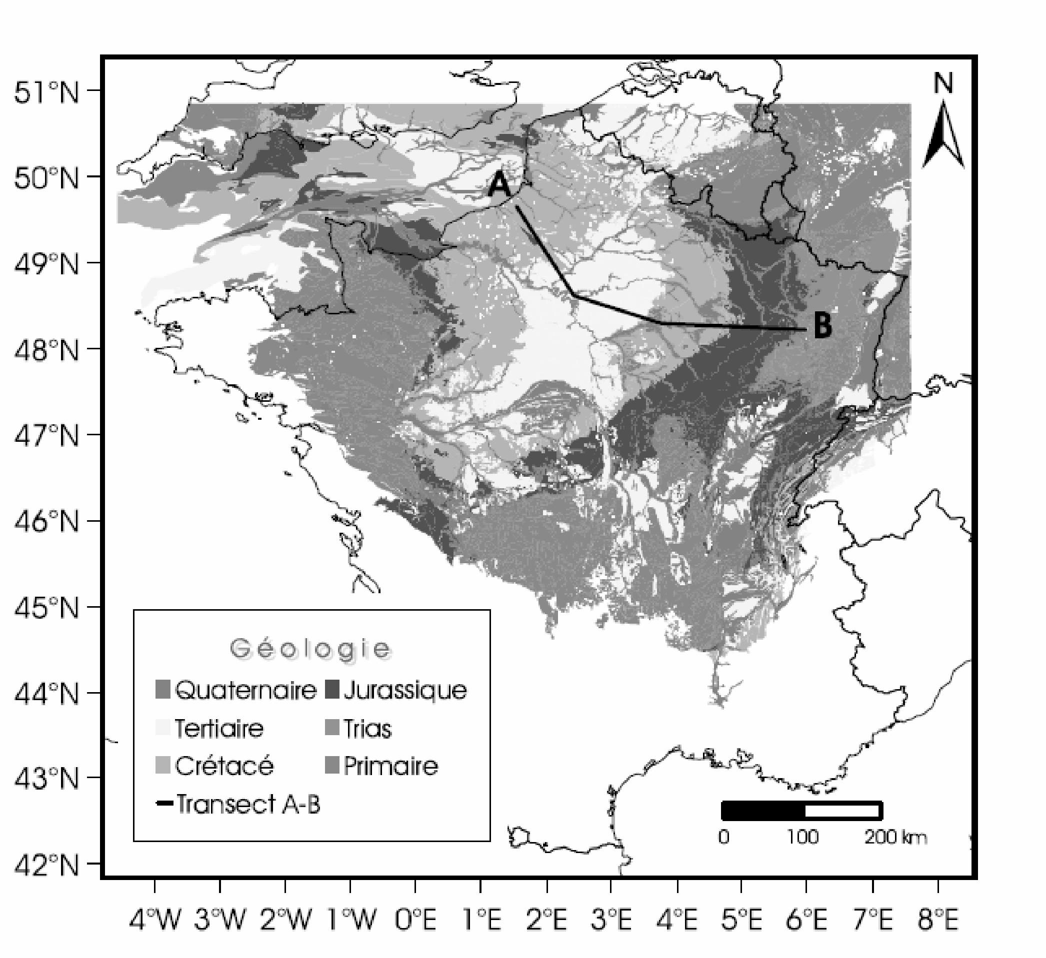


Figure 1 : Geology of the Paris basin

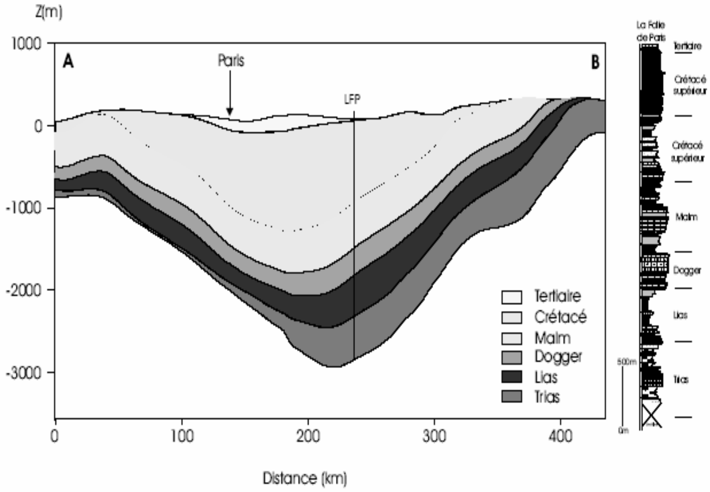


Figure 2 : Cross-section AB (see Figure 1) through the basin

Figure 1 gives the extension of the basin and Figure 2 a cross-section. From this large model, a smaller portion was extracted, over 0.25 Mkm², including geometry and simulated material properties. The model has 20 layers of nested square meshes of 10 km to 2.5 km. The total number of meshes is 58,908. This model will be used to simulate the transient hydrologic response of the basin to the various forcings that have acted on it since 5 My ago The forcings considered are climate, presence of a permafrost, sea-level variations, tectonic uplift, geomorphologic variations due to river incisions. They are translated into net recharge and boundary conditions of the aquifers.

Changes in the forcings of the model with time

(i) To reconstruct the climate of the Paris basin over the last 5 My, the approach was to first adapt a General Circulation Model of the atmosphere, for the entire earth, with a zoomed resolution on the Paris basin, to simulate climate. The selected model was LMDz, from the Institut Pierre Simon Laplace (Sadourny and Laval, 1984; see also Jost, 2005; Jost et al., 2005). On the Paris basin, its mesh-size is 50x50 km². The model can only be run for periods of 10 years, due to very demanding computer resource requirements, and never for a continuous period of 5 My. Three periods were selected : the present, the extreme cold of the Last Glacial Maximum (LGM), 21 ky ago and the warm and humid mid-Pliocene, 3 My ago. Solar orbital forcings, CO_2 concentrations in the atmosphere, sea-surface temperatures, extension of ice sheets and vegetation distribution were available for these three periods. The outcome of the model of interest here is the daily rainfall over the year, averaged from the 10 year calculations and the daily temperatures, distributed over the basin. These data were corrected taking into account the differences between present-day observations and simulations, as the GCMs are not yet truly representative of reality, especially for rainfall. From these corrected data, one can determine the potential evapotranspiration and, with a distributed soil balance reservoir model, the net recharge.

(ii) To extrapolate these three simulated periods to the 5 My of the study, we used a precise palaeo-temperature reconstruction of the past 6 My from ODP core 659 isotopic oxygen composition (Figure 3) from Tiedemann et al., 1994. It shows that the climate can be roughly decomposed into three periods : (a) a global cooling trend in the Pliocene, from 5 to 2.6 My, leading to the Quaternary ice ages ; this first period was decomposed into 5 phases with constant climates ; (b) a 41 ky glacial cycle, from 2.6 to 0.9 My ; (c) a major climate shift at 0.9 My, leading to a 100 ky glacial cycle, with relatively stable warm interglacials, followed by much longer and more variable glacial periods. Each climate variation was accompanied by sea-level fluctuations.

The extrapolation for each of these phases (Figure 3) of the climate scenario is based on a simple correlation between temperature (as given by the continuous oceanic core) and rainfall and potential evapotranspiration. This correlation is calibrated with the three calculated climates at 3 My, 21 ky and present. This approach is crude but consistent with the available data. Attempts at validating the resulting climates with pollen-based data over Europe, where available, showed some discrepancies, but still over-all agreement, see Jost, (2005).

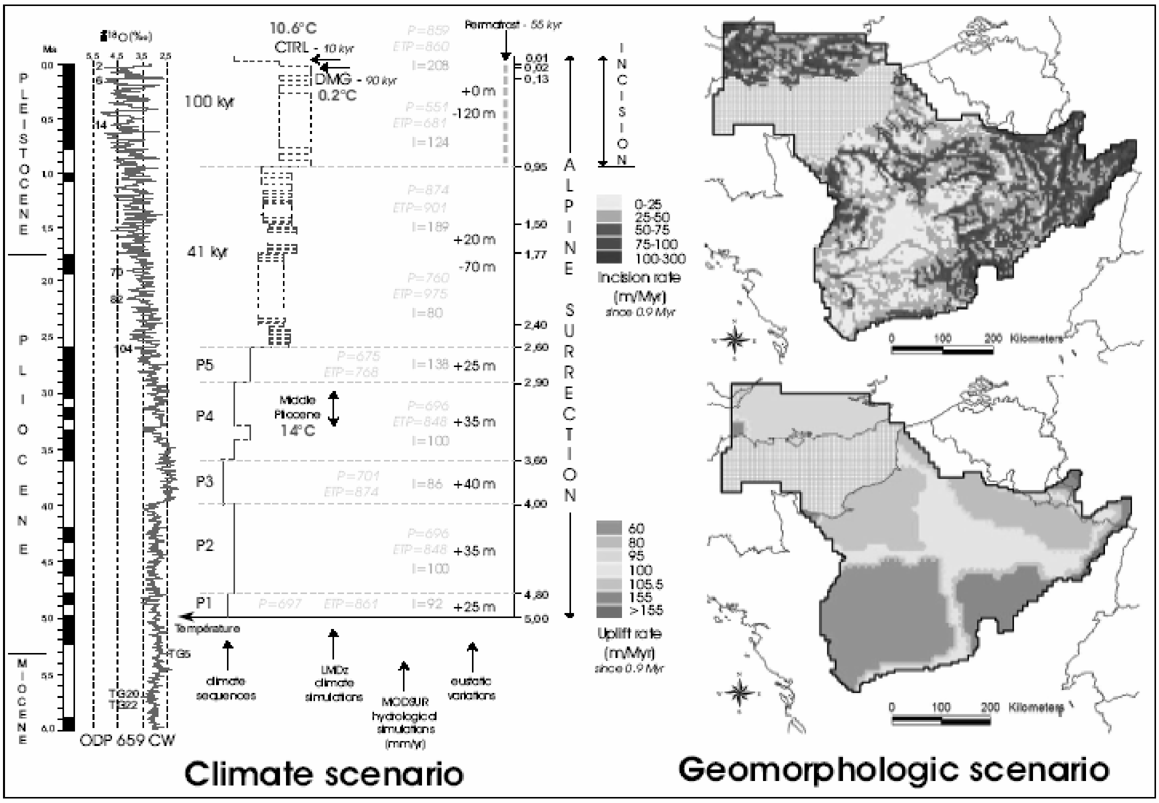


Figure 3 : Climate and geomorphologic scenario

(iii) The presence of permafrost during glaciations in the Paris basin has been demonstrated by Van Vliet-Lanoe (2000). The hydrologic functioning of permafrost has been studied e.g. by Woo and Winter (1993). Furthermore, the temperatures calculated by the GCM at the LGM and corrected for bias also show that the Paris basin had an average annual temperature below 0°C, and that a discontinuous permafrost was present. Very little is known, however, of the permeability of permafrost and of the amount of recharge that can occur through a frozen ground. It is well known that discharge zones can continue to exist in permafrost, the warm groundwater flux being able to maintain an unfrozen ground, where water can seep. In artic zones, one can sometimes observe today such groundwater outlets, as they form ice “cones” above the ground, known as “pingos”, where the seeping water freezes as it reaches the atmosphere, and melts in summer. Lakes and river beds can also continue to serve as outlets.

In a drastic simplification of these phenomena, the permafrost is represented in the model only for the last 0.9 My, assuming its existence 35 ky after the start of each glaciation, and for a duration of 55 ky. The remaining 10 ky in the 100 ky cycle are interglacial. When the permafrost exists, it is assumed to be impermeable to recharge (zero recharge), but permeable to discharge at the outlets without any change compared to unfrozen conditions.

(iv) Sea-level variations are prescribed as changes in the position of the shore line in the model, which is a prescribed head boundary, and value of the prescribed boundary conditions at the marine outlet of the aquifers. We used the eustatic curves published by Greenlee and Moore (1988) and Lambeck (1997) for the recent glaciation.

(v) Geomorphologic changes are based on a detailed study of both the average uplift rate in the basin, due to the tectonic Alpine orogeny, and the incision rate of rivers, which started essentially 1 My ago. The method was developed by Bonnet et al (1998, 2000), based on the analysis of a Digital Elevation Map, and was extended to the whole Paris basin by Guyomard et al. (2005), see also Jost (2005). The model outcome was also compared with data on the age of terraces. The outcome is presented in Figure 3 for both the incision and the uplift rates, which are assumed constant over the whole period.

With these conditions and inputs, the 3-D groundwater model can be run for 5 My. The initial conditions are obtained by a steady-state calculation with the conditions prevailing 5 My ago; any error on this initial condition is likely to have a very small influence at present. The transient calculations are made with constant conditions for a time increment of 1,000 years, after which the conditions are changed, as given by the various changes of the forcings; within each time increment, the time-step is variable, starting from 0.27 y, geometrically increasing by a factor of $\sqrt{2}$ until it reaches 900 years. The CPU time for a 5 My calculation is on the order of 4.5 h with a PC-Linux system.

Results and sensitivity study

The results of the transient calculation are summarized in Figure 4, for the head in the Callovo-Oxfordian clay layer in the Bure site, East of Paris, and in the overlying Lusitanian and underlying Dogger aquifers.

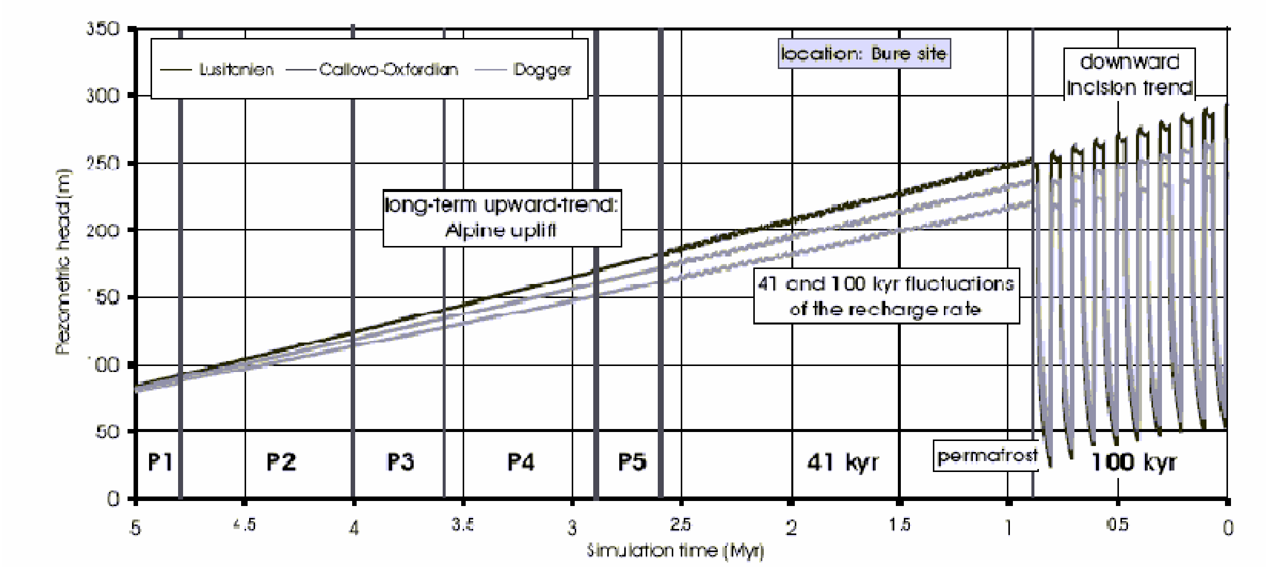
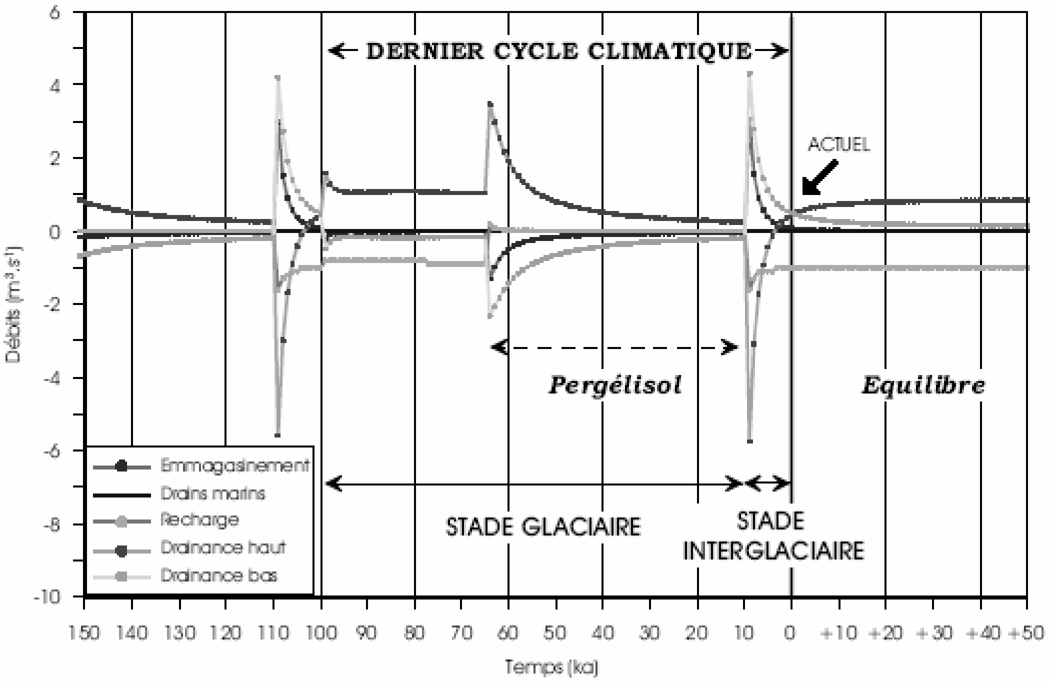


Figure 4 : Transient head in the clay and adjacent aquifers near Bure

One can clearly see a general trend in head increase, due to tectonic uplift, oscillations due to changes in recharge from 2.6 to 0.9 My, and, for the last 0.9 My, the very large effect of the permafrost, which brings recharge to zero for 55 ky. Sea-level change effects are only seen for meshes close to the coastline (not shown). Figure 5 shows the leakage flux exchanged between the Callovo-Oxfordian clay and the two surrounding aquifers, over the last glaciation cycle. It clearly shows that the system is not at equilibrium at present, and that it would require another 20 ky to reach steady state, if the present conditions did not change. This is true for aquitards and deep aquifers, superficial aquifers have reached steady state. Sensitivity studies (Jost, 2005) have shown that permafrost has the largest influence on the behaviour of the system. Since our representation of permafrost is rudimentary, this shows that the topic needs additional research. Sensitivity to the model parameters was also tested, and showed that the vertical diffusivity K/S_s of the aquitards on the order of 10^{-7} m²/s was consistent with the persistence of transient effects for a few tens of thousands of years, and that with a diffusivity of 10^{-6} m²/s, this persistence disappeared in a few thousand years, and with 10^{-8} m²/s, it would persist for hundreds of thousands of years.



(b) Callovo-Oxfordien

Figure 5 : Transient leakage flux through the Callovo-Oxfordian clay

CONCLUSION

This study shows that, in large aquifer systems, the “memory” of past climates or sea-level variations can persist for tens of thousands of years. Although not shown here, it is clear that the large changes with time of the hydraulic head in the aquifers has a great effect on the geometry of the flow path and the velocity : estimating groundwater ages from environmental tracers and comparing them with calculated ages based on a constant flow field is likely to be significantly wrong. This study also shows that the behaviour of permafrost with regard to aquifer recharge needs to be better evaluated. What happens at the early phase of a deglaciation with the melting of the permafrost also needs to be better understood.

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