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Radionuclide transport during glacial cycles: Comparison of two approaches for representing flow transients

Jan-Olof Selroos [a,b,*], Hua Cheng [c], Scott Painter [d], Patrik Vidstrand [e]

[a] Swedish Nuclear Fuel and Waste Management Company, Box 250, SE-101 24 Stockholm, Sweden
[b] Department of Physical Geography and Quaternary Geology/Bert Bolin Centre for Climate Research, Stockholm University, Sweden
[c] Flodea Consult, Stockholm, Sweden
[d] Earth and Environmental Sciences Division, Los Alamos National Laboratory, NM, USA
[e] TerraSolve, Floda, Sweden

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ABSTRACT

The effect of future, transient ice sheet movement and permafrost development on transport of radionuclides from a proposed repository site is investigated using numerical groundwater flow and radionuclide transport modelling. Two different transport approaches are compared, both utilizing groundwater flow simulations of future climate conditions. The first transport approach uses steady-state particle trajectories representing temperate climate conditions, but modifies the transport velocity along the trajectories according to the changing climate. The second approach is pseudo-transient by performing particle tracking in each individual flow field representing a given time epoch.

Two different climate sequences are analyzed. First, a simplified sequence is assessed in order to understand if the two different transport approaches yield significantly different breakthrough characteristics. Second, a sequence representing conditions relevant for real safety assessment applications is considered.

Results indicate that the transport approach using fixed trajectories tends to significantly over predict breakthrough during permafrost conditions relative to the pseudo-transient approach. The major difference between the two approaches is related to discharge locations. The fixed trajectory approach yields discharge locations constant in time whereas the pseudo-transient approach is characterized by discharge centres moving in time according to the different climate conditions.

1. Introduction

Although it has long been recognized that groundwater flow is a key process for subsurface transport of solutes, the transport effects of temporal variability in flow, on several different time scales, were not fully appreciated until relatively recently (Destouni, 1991; Foussereau et al., 2001; Cvetkovic et al., 2012). It is generally found that temporal variation in flow can have quite dramatic effects on mass transport and discharge patterns. The studies performed typically deal with current or near-future climate conditions.

On time scales of glacial cycles, much larger variability in flow conditions is expected (Lemieux et al., 2008; SKB, 2010a; Person et al., 2012). Specifically, a future ice sheet is expected to change flow conditions in a most profound manner. As a pre-cursor to the build-up of an ice sheet, a cold climate yielding permafrost conditions may prevail. Groundwater recharge (and hence flow) is expected to be reduced during such conditions. An ice sheet will create increased gradients for flow at the ice sheet margin where the ice sheet slope is steep, while flow may be reduced further in under the ice sheet (Lemieux et al., 2008). A retreating and melting ice sheet with permafrost removed (melted) is likely to create the greatest flow in the sub-surface due to the large amount of available recharge.

Transport of solutes during time periods as long as those of glacial cycles is of prime interest when the safety of geological repositories for nuclear waste is considered. Potential release of radionuclides typically needs to be considered on time scales of 100,000–1 million years (SKB, 2011), while glacial cycles are on the order of 100,000 years (Lisiecki and Raymo, 2005). A license application for the construction of a final repository for spent nuclear fuel was recently submitted by the Swedish Nuclear Fuel and Waste Management Company (SKB) in Sweden. SKB is responsible for the handling of all spent nuclear fuel within the Swedish nuclear power programme. The repository is to be constructed according to the so-called KBS-3 principle (SKB, 2011), which implies a system of independently functioning barriers. The

* Corresponding author at: Swedish Nuclear Fuel and Waste Management Company, Box 250, SE-101 24 Stockholm, Sweden. Tel.: +46 8 4598400; fax: +46 8 57938611.
E-mail address: jan-olof.selroos@skb.se (J.-O. Selroos).

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repository is to be constructed at approximately 500 m depth in crystalline bedrock. At this depth, tunnels are constructed containing deposition holes; a single waste canister made of copper with a steel insert is placed in each deposition hole. The canisters are surrounded by bentonite clay in the deposition holes. After deposition, the tunnels are backfilled and the repository slowly becomes water saturated once pumping has stopped. Thus, there are three independent barriers, namely the canister, the buffer, and the host rock itself.

A key part of the license application was a safety assessment evaluating the long-term radiological safety. The safety assessment, called SR-Site (SKB, 2011), shows that a repository according to the KBS-3 system can be constructed at the chosen site such that regulatory requirements are fulfilled. The main regulatory criterion is associated with the risk imposed to human beings by potential leakage from the waste canisters. In order to assess the risk, an integral part of the analysis is to model radionuclide leakage from canisters and subsequent transport through the geosphere and in the biosphere.

In SR-Site, the compliance calculations of risk did not include transport simulations based on transient flow conditions. However, a variant case was produced where flow transients were handled in a simplified manner (SKB, 2010b). In the simplified approach (described in more detail below), only the velocity along transport trajectories was changed in a global sense to represent the changing climatic conditions. Clearly this is a very simplistic representation of the changing conditions since both direction of flow paths and flow magnitude will change in a complex manner during a glacial cycle. In SR-Site it is argued that this approach likely is conservative since discharge locations are steady in time; however, it remains to be shown quantitatively that this indeed is the case. Furthermore, it is unclear exactly how well the simplified flow factor approach is able to represent dynamic behaviour in the breakthrough curve implied by changes in both groundwater flow direction and magnitude.

In the present paper, the consequences of the simplification are examined by adopting a stepwise steady-state, i.e. pseudo-transient, approach where transport is simulated sequentially in a series of steady-state flow fields with different boundary conditions and properties reflecting the climatic evolution. The approach thus converges towards a real transient description of the problem. With as many flow fields as time steps in the simulation, the approach coincides with a full transient handling of the problem. Here, the situation is simplified by choosing a representative number of flow epochs with distinctively different flow conditions. The objective is to examine if and how such a move towards a more realistic description of the system provides different answers than the simplified approach adopted in SR-Site.

Typically, present day flow conditions are assumed in safety assessment studies of nuclear waste repositories even though the time scale studied is hundreds of thousands up to millions of years (e.g., Nagra, 1994; Vieno and Nordman, 1999; SKB, 1999, 2006; Arnold et al., 2003; ANDRA, 2005; Cornaton et al., 2008; Park et al., 2008). In a recent study in support of a safety assessment within the Canadian nuclear waste programme (Garisto et al., 2010), transient simulations of groundwater flow and transport of a single radionuclide species have been performed (Walsh and Avis, 2010). The transported species in their study was non-sorbing and not subject to matrix diffusion. They found that glacial cycles do not have significant cumulative impact on the general plume structure. This behaviour is likely site-specific; the very tight Canadian shield rock retains most of the transported mass for long time periods and hence a change of flow direction is expected to simply move the plume back and forth. In addition, transverse dispersion and molecular diffusion are significant contributors to transport in their simulations, which would tend to mask the effects of flow transients. The present study addresses transport in the fractured crystalline rock of the Swedish potential repository site where much faster transport and much higher degree of spatial channeling are envisaged and represented in the flow models. Thus, the cancelling out phenomenon seen by Walsh and Avis (2010) is not expected. In addition, we address the more complex and more realistic transport scenario involving radionuclides that sorb and diffuse into the rock matrix. To accommodate the increased complexity caused by high spatial channeling, transport times on the order of glacial periods, and more realistic radionuclide retention processes, an efficient particle tracking approach is used. Due to its computational efficiency, the approach can handle large model domains on regional scale while still maintaining a high resolution around the repository, thus enabling efficient simulation of radionuclide transport processes on coupled local and regional scales.

2. Groundwater flow simulations

2.1. Climate conditions during a reference glacial cycle

Based on knowledge of climate variations in the past and on inferred future climate change, the extremes within which the climate of Sweden may vary can be estimated with reasonable confidence (SKB, 2010a). Within these limits, characteristic climate-related conditions of importance for repository safety can be identified. The conceivable climate-related conditions can be represented as climate-driven process domains (Boulton et al., 2001) where such a domain is defined as “a climatically determined environment in which a set of characteristic processes of importance for repository safety appear”. The climate domains are used to describe a reference glacial cycle of the coming 120 kyears, comprising a repetition of conditions reconstructed for the last glacial cycle. The reference glacial cycle is not to be seen as a prediction of a future climate development, but as one example of a conceivable future evolution that covers climate-related conditions and sequences that could be expected in a 100 kyears time perspective (SKB, 2010a).

The relevant climate conditions within a reference glacial cycle are presented conceptually in Fig. 1. The reference glacial cycle is made up of a sequence of climate conditions where one climate condition is followed by another; within the cycle, different combinations of climate sequences do occur. For example, permafrost conditions may sometimes be followed by temperate conditions, sometimes by glacial conditions. However, the figure clearly indicates that groundwater flow simulations need to be able to handle multiple climate conditions if a realistic description of the flow system is to be obtained.

Focus in the present paper is on the last and largest ice sheet advance during the reference glacial cycle corresponding to the last stadial of the Weichselian glaciation over Fennoscandia, including the last glacial maximum (LGM) occurring around 18,500 years before present (BP). In Fig. 2 (left plot), the last glaciation of Northern Europe is shown. The onset of glacial conditions is shown through the dotted line representing a mountain-centred ice sheet (see figure caption for details); the maximum glacial extent, i.e., the LGM, is shown by the solid line. The location of the Forsmark site together with an approximate outline of the model domain discussed in more detail in the section below is also indicated in the left plot of Fig. 2.

2.2. Flow model

The groundwater flow modelling of the present study uses a coupled thermal-hydraulic-chemical analysis of the different periods of a glacial cycle. The simulations are performed using the DarcyTools code version 3.2 (Svensson, 2010; Svensson and Ferry,