

THE EFFECT OF GLACIATION ON RADIONUCLIDE TRANSPORT FOR A DEEP GEOLOGICAL REPOSITORY IN A SEDIMENTARY ROCK SETTING

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Abstract

This modelling study investigates potential effects of repeated loading and unloading of kilometres-thick ice-sheets on groundwater flow and radionuclide transport for a conceptual repository constructed 500 m below ground surface in a hypothetical sedimentary rock setting in Southern Ontario, Canada. Multiple modelling scenarios have been simulated to examine the sensitivity of model conceptualizations and key parameters. Results indicate that while repeated glacial cycles can boost radionuclide transport, the amount reaching the surface remains minimal owing to the extremely low permeability offered by the surrounding sedimentary rocks. No significant incremental adverse effects to humans and the environment are therefore anticipated as a result of these glacial cycles.

1. Introduction

Over the past one million years, North America has experienced multiple glacial cycles, and almost the entire Canadian land mass has been covered by kilometres-thick ice-sheets [1]. While elevated levels of greenhouse gases may delay the onset of the next glacial cycle [2], the dominant factors controlling these cycles (e.g. plate tectonics and solar insolation variation due to Earth orbital dynamics) are still present and thus glaciation is anticipated to eventually reoccur. Glaciation is the most significant external environmental perturbation that a Canadian deep geological repository (DGR) for used nuclear fuel will experience over the next one million years.

Over the last couple of decades, a significant amount of research effort has been devoted to explore the potential hydro-mechanical effects of glaciation on groundwater flow and contaminant transport [e.g. 3-6]. In 2013, the Nuclear Waste Management Organization (NWMO) [7] performed a regional-scale glaciation scenario modelling study as part of its comprehensive long-term postclosure safety assessment for a hypothetical DGR in sedimentary rock formations. Due to the vast domain covered by the regional-scale paleo-hydrogeological model (~18,000 km²), the grid resolution is low and thus repository features are not represented. Results of the NWMO [7] paleo-hydrogeological simulations show that glaciation tends to increase the penetration of recharge water from the ground surface. Nevertheless, sensitivity analyses also demonstrate that fresh recharge water will not reach the repository horizon and solute transport within the repository vicinity remains diffusion-controlled throughout the glacial cycle.

The present study is focussed on glaciation effects on groundwater flow and radionuclide transport for a hypothetical DGR hosted in a sedimentary rock formation. Unlike the NWMO [7] regional-scale paleo-hydrogeological simulations, detailed repository features are explicitly accounted for in this study. Other main differences between the two are: (1) eight repeated cycles of glaciation are simulated whereas only one glacial cycle was considered previously; and (2) a radionuclide source term (I-129) is released from three assumed defective containers whereas previously a tracer was applied. Because an assumed source term is used, the potential dose rate can be inferred from the transport results of this study. This present study is a continuation of the previous work [7].

2. Computer code and hydro-mechanical coupling

In this study, FRAC3DVS-OPG (FRAC) Version 1.3 is used to perform hydrogeological simulations. FRAC is a 3-dimensional (3D) physically-based numerical model that describes groundwater flow and solute transport using a control-volume finite element approach [8]. FRAC solves Richards' equation for variably-saturated groundwater flow and the classical advection-dispersion equation for contaminant transport. It includes a 1D hydro-mechanical coupling module that solves the following equation to account for surface loading conditions, e.g. the loading and unloading of glacial ice-sheets:

$$\frac{\partial}{\partial x_i} \left(K_{ij} \frac{\partial h}{\partial x_j} \right) + \frac{S_s \zeta}{\rho g} \frac{\partial \sigma_{zz}}{\partial t} \pm Q = S_s \frac{\partial h}{\partial t} \quad (1)$$

where K is the hydraulic conductivity tensor [LT^{-1}]; h is the hydraulic head [L]; ρ is the fluid density [ML^{-3}]; g is the gravitational constant [LT^{-2}]; S_s is the 1D specific storage coefficient [L^{-1}]; ζ is the 1D loading efficiency [-]; σ_{zz} is the total vertical stress [$ML^{-1}T^{-2}$]; t is the time [T]; and Q is the sink or source term [$L^3L^{-3}T^{-1}$].

In the 1D hydro-mechanical coupling module, only vertical strain is considered and lateral strains are neglected. FRAC also has a feature to simulate permafrost and this is achieved by alternating the permeability of permafrost affected elements between their original permeability and the specified permafrost permeability which is 5.0×10^{-11} m/s in this study. Note that no other parameters such as effective diffusion coefficient and porosity can be modified for permafrost affected elements in FRAC. More details about FRAC and its 1D hydro-mechanical coupling are available from its user manual [8].

3. Site description and model data

The hypothetical DGR is assumed located within the Michigan Basin in Southern Ontario, Canada (see Figure 1). Topography of this region is relatively flat, with elevation generally ranging from 200 to 400 m above sea level. At the hypothetical repository site, a 30 m thick layer of Quaternary-aged glacial drifts overlays an approximately 650 m thick sequence of Silurian and Ordovician-aged sedimentary rocks underlain by the Precambrian-aged metamorphic basement rocks. The repository is assumed constructed 500 m below ground surface (mBGS) in the Ordovician-aged Cobourg formation. The Cobourg formation is comprised of fine-grained to argillaceous limestone, offering both mechanical strength and low permeability. Field studies suggest that fractures in this region are generally sparse and they are not expected to reach Ordovician-aged rocks [9].

Groundwater in the study area can be classified into three systems based on its characteristics, shallow (< 215 mBGS), intermediate (215~250 mBGS) and deep (> 250 mBGS) groundwater systems. Previous field studies show that shallow groundwater is generally fresh and oxygenated with low total dissolved solid (TDS). On the other hand, deep groundwater in the study region has high TDS, between 200 and 300 g/L, with a geochemically reducing condition. The intermediate groundwater system is a transitional zone between the shallow and deep groundwater systems. For more detailed descriptions of the geosphere and repository features, please refer to NWMO [7].

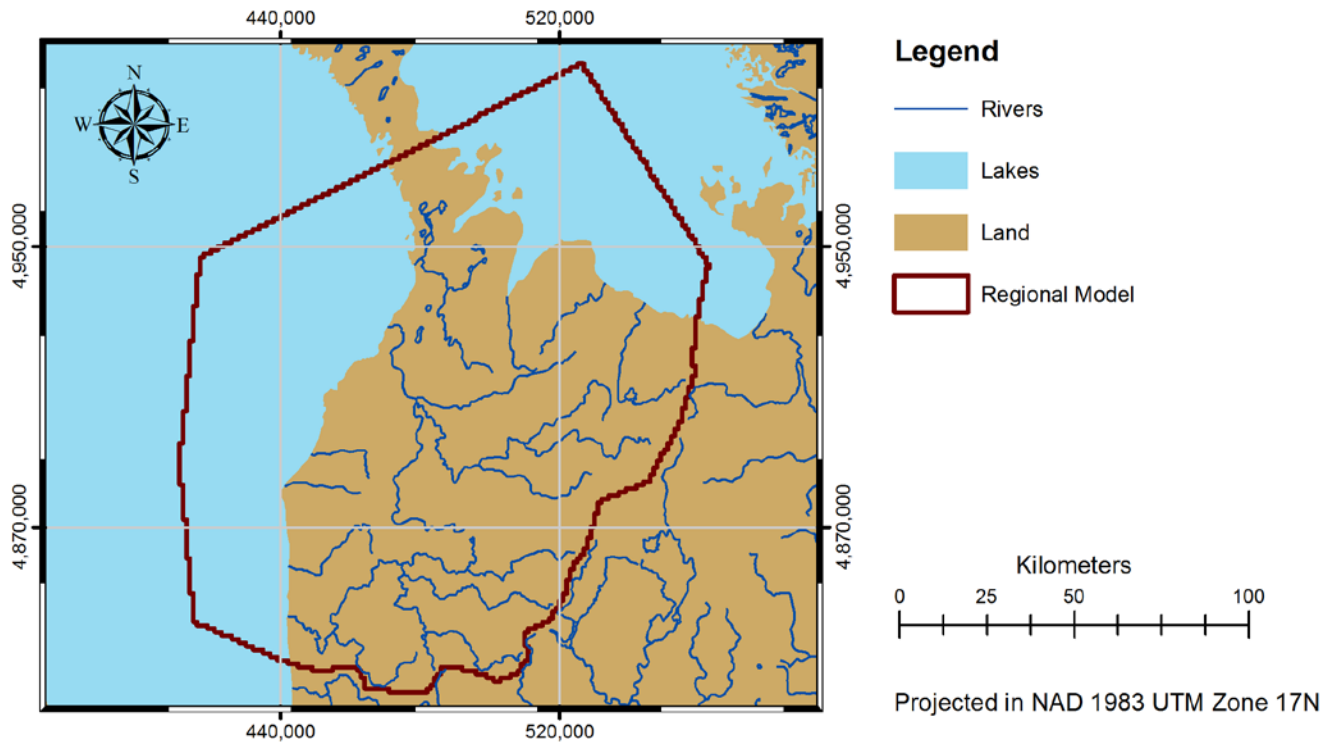


Figure 1 Map of the study area and the Regional Model outline

Paleo glacial data obtained with the University of Toronto (UofT) Glacial System Model (GSM) are used in this study. The glacial data are based on the nn9930 (warm-based) scenario [1]. The GSM produces several outputs with a spatial resolution of 1.0° (longitude) by 0.5° (latitude) and a temporal resolution of 500 a, but only the ice thickness and permafrost depth outputs are applied to the paleo hydrogeological simulations. Ice thickness is applied as both hydraulic and mechanical boundary conditions along the ground surface, and permafrost is applied as permeability reduction to the elements whose centroid is within the permafrost range. To avoid abrupt changes which may introduce numerical instabilities, both outputs are spatially and temporally interpolated. The dataset contains one full glacial cycle of glacial climate outputs, from 120 ka ago to present day. GSM simulated ice-sheet thickness and permafrost depth at the hypothetical repository site are plotted in Figure 3.

If a container fails, then upon contact with water, the used fuel may release radionuclides. Of these, I-129 is the most radiologically significant radionuclide in terms of human dose [7] due to the fact that I-129 has a very long half-life (15.7 Ma) with little adsorption in the subsurface. Thus, I-129 is selected for study as a key radionuclide. Note that the I-129 source term and its release location in this study are

identical to those of the Normal Evolution Reference Case in NWMO [7], assuming a pinhole release from three defective containers located in the most vulnerable location starting at 10 ka postclosure.

4. Modelling approach

One of the daunting challenges associated with paleo-hydrogeological simulations is the enormous computational load. The computational load is due to a combination of the following factors: (1) boundary conditions along ground surface owing to the advent and retreat of ice-sheets are highly dynamic; (2) the required simulation time is exceptionally long compared to typical hydrogeological simulations, ranging from one glacial cycle (120 ka) to eight cycles (960 ka); (3) a large number of total nodes, e.g. a few million, is a must in order to explicitly represent the repository features; and (4) in some special cases density effects are simulated and this further increases the computational load. To overcome this, a two-model approach is adopted in this study, one large-scale model with a coarse grid resolution and one small-scale model with a fine grid resolution and explicit representation of the repository features. In total, three models of various scales (Regional Model, Sub-Regional Model and Site Model) are developed to investigate two different scenarios (With-Well scenario and No-Well scenario). Two of the three models are used in each scenario. Specifically, the With-Well scenario is simulated with the Sub-Regional Model and the Site Model, and the No-Well scenario is simulated with the Regional Model and the Site Model.

4.1 With-Well scenario

The With-Well scenario has one water supply well pumping groundwater from the bottom of the Guelph rock formation for the use of a self-sufficient farming family living on the ground surface above the hypothetical repository. The Guelph formation has an assumed thickness of 71 m at the repository site and is the first permeable formation that radionuclides released from the repository will encounter towards the release points. The bottom of the Guelph formation is at a depth of about 210 mBGS in this hypothetical site, so assuming the well reaches this depth is conservative. The Sub-Regional Model only simulates groundwater flow and it provides transient boundary conditions to the Site Model. I-129 transport simulation is conducted using the Site Model.

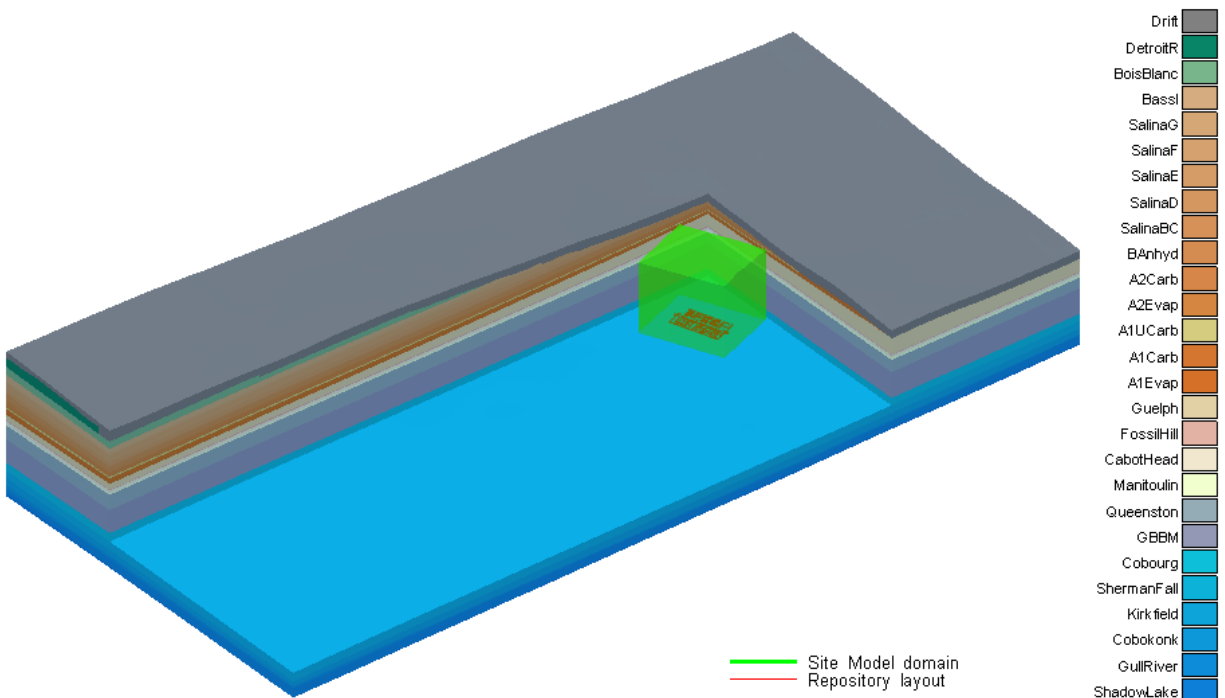
4.2 No-Well scenario

On the other hand, the No-Well scenario does not have a water supply well and all the flow boundary conditions are therefore unperturbed by the well abstraction. This scenario is ideal to capture and illustrate the evolution of the assumed radionuclide plume over the next one million years. Unlike the With-Well scenario, both models in the No-Well scenario conduct transport simulations. The Site Model computes the upward I-129 transport rate entering the Guelph formation. The Regional Model then simulates the 3D evolution of the I-129 plume with glacial climate using the Site Model computed I-129 transport rate as the contaminant source term released at the bottom of the Guelph formation.

5. With-Well scenario

5.1 Sub-Regional Model

5.1.1 Model description



Note: vertical exaggeration = 10

Figure 2 With-Well Sub-Regional Model property assignment

The Sub-Regional Model has a rectangular domain of 25 km (west-east) by 50 km (north-south) within the central area of the Regional Model domain. Its orientation is chosen based on the assumption that glaciers advance and retreat along the north-south direction. For convenience, the origin of this model is set at the south-west corner of the model domain with its x- and y- axes in the east and north directions respectively. Horizontally the domain is discretized into a 500 m square mesh, and vertically the model is discretised into 58 layers, resulting in 303,909 nodes and 290,000 elements in total.

The model comprises 27 geological units, with drift at the top and the Shadow Lake formation at the bottom (see Figure 2). Geology data of the Sub-Regional Model are the same as those of NWMO [7] Regional Model and thus the parameter values are not listed here. A no-flow boundary condition is given to the four lateral and bottom sides of the model and transient hydraulic head and stress-loading boundary conditions calculated from ice thickness data are applied along the model top surface. Elements whose centroids are within the permafrost depth are defined and simulated as the permafrost formation. The water supply well location in the Sub-Regional Model is slightly off (by ~250 m) from the specified location in NWMO [7] Site Model due to the coarser grid resolution of the Sub-Regional

Model. Unlike the NWMO [7] Reference Case, the water supply well in this present study does not exist and operate constantly. The well is only assumed present and pumps water (at a rate of 1307 m³/a, the same as NWMO [7] Reference Case) when there is no glacier or permafrost and a self-sufficient farming family is assumed living at the repository site (see Figure 3).

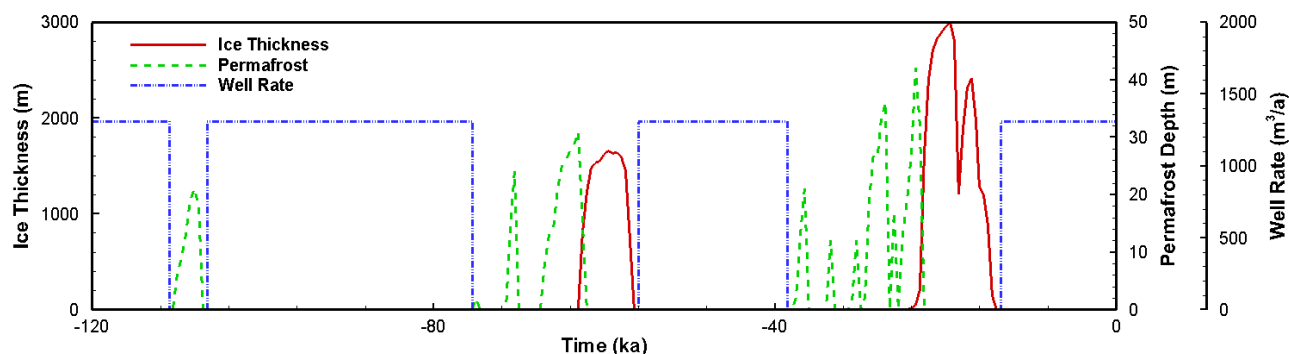


Figure 3 UofT GSM (nn9930) simulated ice thickness and permafrost depth at the repository site and water supply well operation for the With-Well scenario during one full glacial cycle

5.1.2 Effect of density

In a sensitivity analysis, the density effect of high salinity in median to deep groundwater on radionuclide transport is investigated. Two sub-cases are conducted with constant climate, one with constant density of fresh water and another with variable density. The constant density model is run to steady state and the variable density model runs for one million years and reaches a ‘pseudo-steady’ state where head and concentration profiles do not evolve much with time. Velocity and MLE results are compared and comparisons show good similarities for most part of the domain between these two models. Results suggest that radionuclide transport is unlikely to be markedly affected by the assumption of fresh water instead of brine. Meanwhile, computational load of the variable density model is far more than that of the constant density model due to the high non-linearity in the density-dependent flow governing equation. Therefore, a constant density of fresh water is assumed for all other modelling cases in this present study.

5.1.3 Flow results

After obtaining the present-day climate steady-state solution as the initial condition, the Sub-Regional Model simulates eight glacial cycles over 960 ka, driven by the UofT GSM simulated glacial climate data. Presented in Figure 4 are the velocity magnitude results for the repository vicinity and selected formations. The loading and unloading of ice-sheets substantially increases groundwater velocity by up to two orders of magnitude. Even with this increase, groundwater velocity around the repository vicinity remains low because of the extremely tight sedimentary formations (see the dark blue line in Figure 4). As expected, there is little cumulative effect in the velocity results, with velocities generally repeating themselves after the second glacial cycle. The small differences in the first cycle are due to the initial condition effect. Note that hydraulic head results (not shown) exhibit similar responses to glaciation as velocity results.

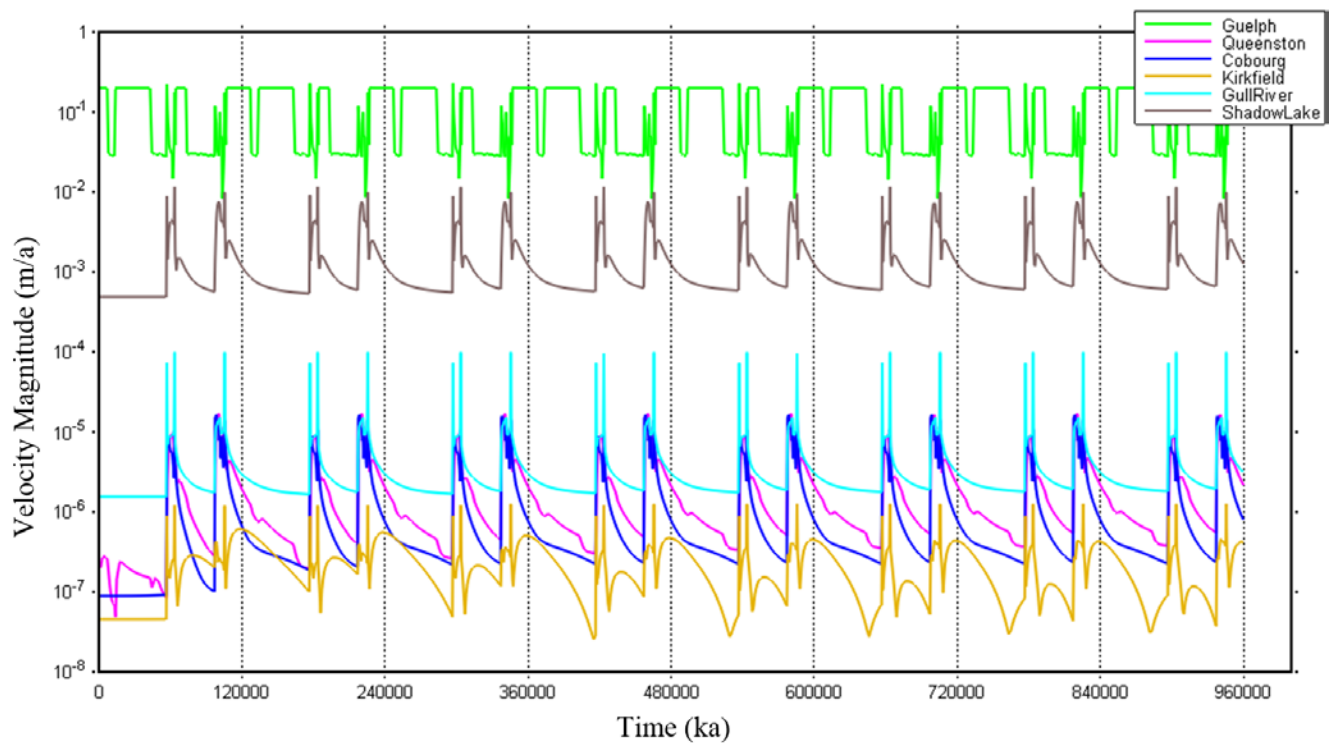


Figure 4 With-Well Sub-Regional Model simulated Velocity magnitude in repository vicinity and selected formations simulated

5.2 Site model

5.2.1 Model description

The Site Model in the present study is very similar to the NWMO [7] Site Model but with some simplification. It covers a rectangular domain of approximately 4.0 by 5.2 km. See Figure 2 for the location of its domain with respect to the Sub-Regional Model. The NWMO [7] Site Model has almost 12 M nodes which are not tractable for glaciation scenario modelling. To reduce the number of nodes, some simplifications were made. In addition, the vertical domain of the With-Well Site Model extends from the bottom of the Shadow Lake formation to the top of the Salina A2 Carbonate formation, instead of ground surface. In total, the With-Well Site Model has 3.89 M nodes and 3.79 M elements. For convenience, a new local coordinate system is used for the Site Model. The Site Model uses the I-129 source term for transport simulation. A no-flow boundary condition is assigned to the bottom of the Site Model and time-varying specified head boundary conditions are extracted from the Sub-Regional Model for the remaining sides.

To assess the accuracy of the Site Model, flow results such as head and velocity are compared against those of the driving Sub-Regional Model and the comparisons generally show good agreements between these two models (not shown). As another measure to verify model fidelity, Site Model transport results for constant climate are compared against those of the NWMO [7] Site Model. Both I-129 transport at well and concentration contour at the repository horizon results match well between these two models (not shown).

5.2.2 Transport results

Once confidence in the Site Model fidelity is established, two sub-cases were simulated, one for glacial climate and one for constant climate. Figure 5 shows the I-129 transport rate at various locations for these two sub-cases, with solid and dash lines representing glacial and constant climate results respectively. The transport rates into the Blue Mountain/Georgian Bay and Queenston formations are very similar between these two sub-cases, indicating that glaciation has little effect on the I-129 transport around the repository vicinity. The insensitivity to glaciation in the repository vicinity is due to the extremely low permeability of the surrounding sedimentary rocks. Results also show that glaciation events boost I-129 transport rates into the Guelph formation and at the pumping well compared to the constant climate result. The glacial well results are intermittent, reflecting the time period that the well is in operation. Each time when the well is not present due to either ice-sheets on top or permafrost underneath there is a sharp decrease in the I-129 transport rate into the Guelph formation, indicating that the water supply well (when in production) boosts the transport rate entering the Guelph formation. The high initial transport rate as the well is turned on is due to the capture of I-129 that entered the Guelph formation over the previous period of no well operation. Except for the initial peak, the well transport rate is virtually identical to the transport rate into the Guelph formation for both the glacial and constant climate. Indeed, essentially all I-129 transport entering the Guelph formation has been captured by the well.

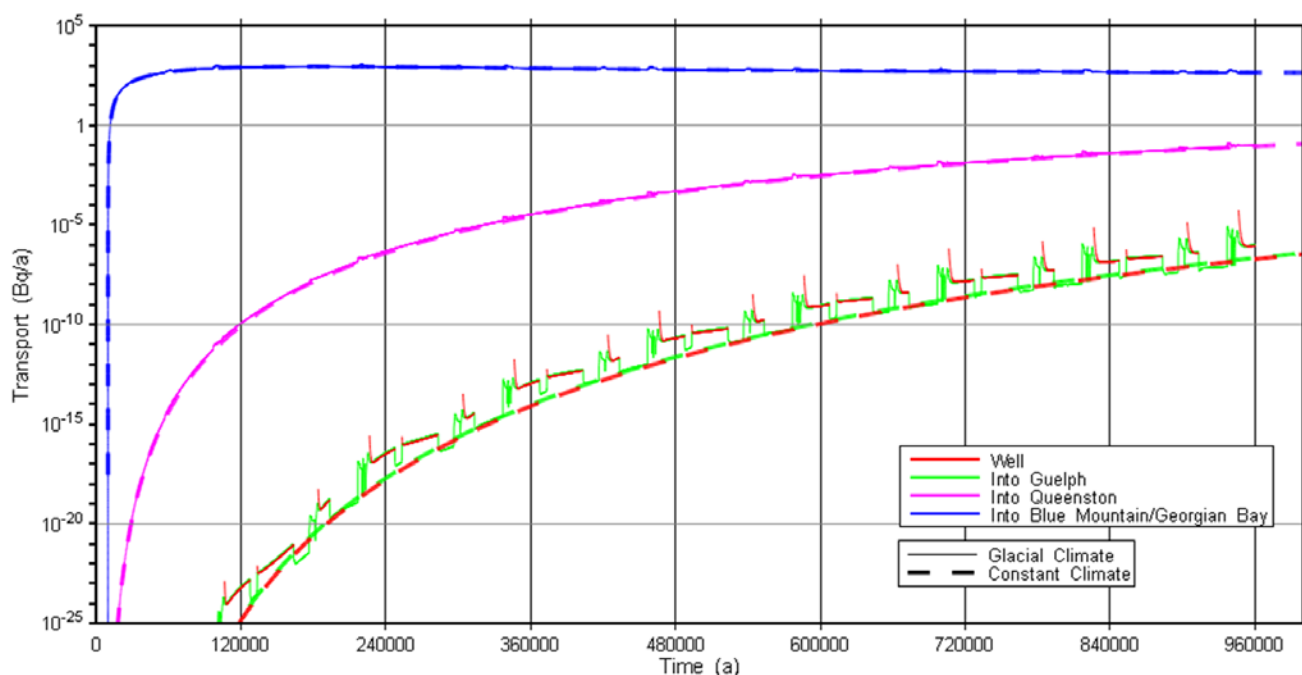


Figure 5 With-Well Site Model transport results for glacial and constant climate

In the NWMO [7] study, dose rates are conservatively estimated for the self-sufficient farming family based on the radionuclide transport results through the water supply well. A peak I-129 transport rate of 7.4 Bq/a at the well corresponds to a maximum dose rate of 2.0×10^{-9} Sv/a at 10 Ma postclosure, which is far below the 3.0×10^{-4} Sv/a interim dose acceptance criterion for the radiological protection of people. Results in Figure 5 show that the well transport rate with glaciation is about one or two orders

of magnitude higher than that of constant climate. Given the large safety margin that exists for the constant climate case, the dose rate under a glacial climate would meet the interim acceptance criterion with wide margins.

6. No-Well scenario

6.1 Site Model

6.1.1 Model description and modelling cases

The Site Model in the No-Well scenario is almost identical to the With-Well Site Model but with a few geological layers at the top removed. The Guelph formation bottom is chosen as the top surface of the No-Well Site Model. There are two reasons that the model top surface is chosen at the bottom of the Guelph formation. First, this is equivalent to a zero concentration boundary condition at the model top which is highly conservative in terms of calculating the diffusive I-129 transport entering the Guelph formation. Second, the removal of the layers above the Fossil Hill formation reduces the already substantial computational load. The new No-Well Site Model has 3.1 M nodes and 3.0 M elements. Since the model top is well below the maximum permafrost depth, the entire model is not affected by permafrost. Time varying specified head and mechanical loading boundary conditions reflecting the ice-sheet thickness on ground are applied to the model top surface, and a no-flow boundary condition is applied to the bottom and four lateral sides. The No-Well Site Model uses the same I-129 source term released at the same location as the With-Well Site Model. To investigate the sensitivity of radionuclide transport to the key parameter – loading efficiency, four modelling cases are designed. The characteristics of each case are briefly summarized below. Note that the parameter values used in the sensitivity cases are not realistic and are instead meant to represent the bounding situations.

- 1) **Control (constant climate):** constant climate is used, otherwise same as Reference case;
- 2) **Reference:** glacial climate is used with normal parameter values;
- 3) **All LE = 1.0:** all loading efficiency sets to 1.0, otherwise same as Reference case;
- 4) **All LE = 0.0:** all loading efficiency sets to 0.0, otherwise same as Reference case.

6.1.2 Transport results

No-Well Site Model results of the I-129 transport into Guelph for the four cases are presented in Figure 6. Note that the repeated spikes of hydraulic head at ground surface in light grey colour represent the evolution of ice thickness on ground at the repository site. It is illustrated that each glacial loading corresponds to a sharp increase in I-129 transport into the Guelph formation for the Reference and All LE = 0.0 cases. Results of the All LE = 1.0 case are virtually identical to the Control case, roughly one order of magnitude lower than the Reference case. This indicates that glaciation has little effect on radionuclide transport if all ice load is borne by the pore water when the vertical hydraulic gradient is at a minimum. On the other hand, when ice load is entirely borne by the rock skeleton in the All LE = 0.0 case, vertical hydraulic gradient is at a maximum and thus the I-129 transport into the Guelph layer increases to approximately 10 times that of the Reference case.

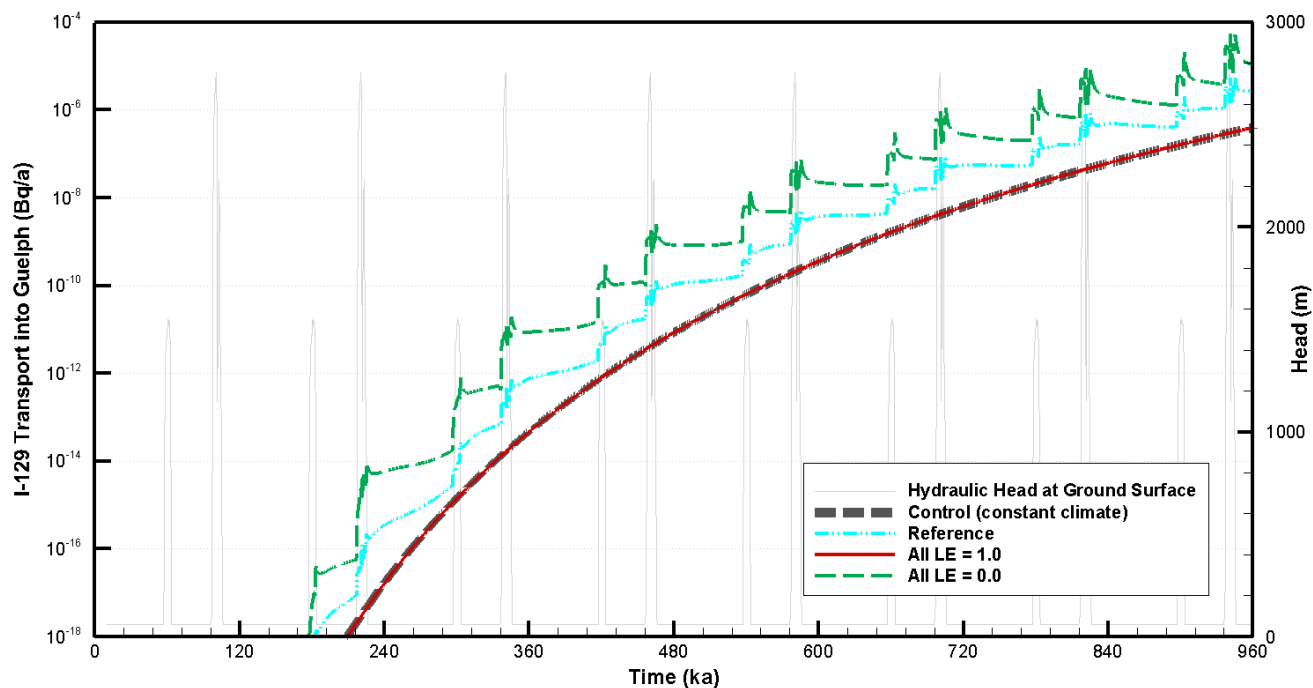
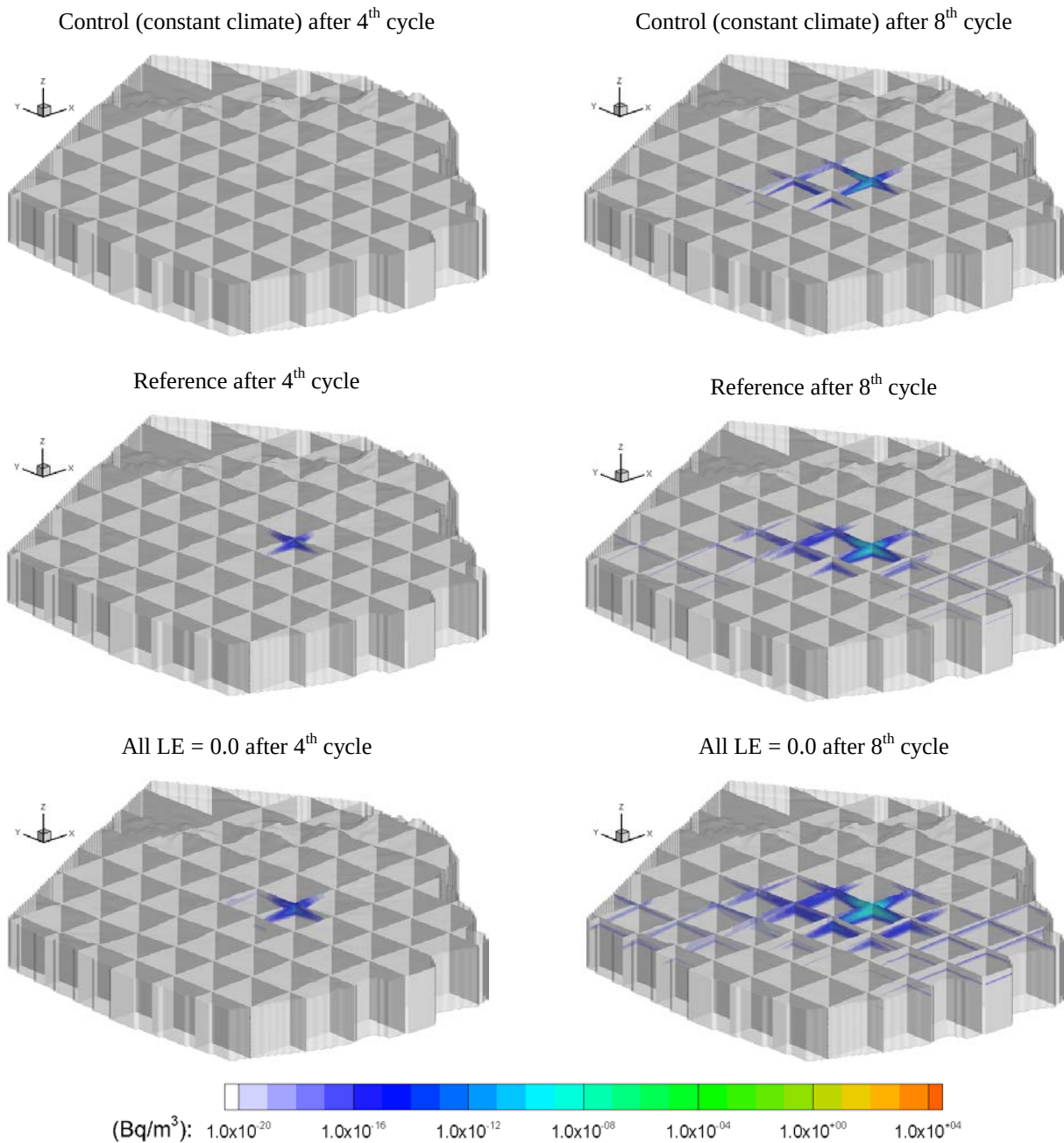


Figure 6 No-Well Site Model I-129 transport into Guelph results for various cases

6.2 Regional Model

As shown in Figure 1 the Regional Model domain covers a vast area ($\sim 18,000 \text{ km}^2$) and it is almost identical to the NWMO [7] Regional Model with some minor modifications. Its domain outline overlaps with surface water and groundwater divides, where no groundwater flow is expected to flow across. Horizontally the domain is discretized into a 1.0 km by 1.0 km square mesh and vertically the Regional Model has 102 layers, resulting in almost 2.0 M nodes and elements in total. A no-flow boundary condition is applied to all external nodes except for the top model surface. For the top surface, time-varying specified hydraulic head and stress-loading boundary conditions calculated from ice thickness data are applied. Similarly, all elements whose centroids are within the permafrost depth are defined and simulated as the permafrost formation. Among the four modelling cases described in previous section, three representative cases (Control, Reference and All LE = 0.0) are selected for further examination using the Regional Model. Parameter values and boundary conditions are adjusted accordingly in the Regional Model. The I-129 transport entering the Guelph formation computed from the No-Well Site Model is used as the source term released at the bottom of the Guelph formation (above the repository) in the Regional Model.

Results of 3D I-129 plume distribution for the three selected sensitivity cases after four and eight glacial cycles are presented in Figure 7. Among the three simulated cases, the Control case I-129 plume has the lowest concentration with limited spreading. The Reference case generally has higher I-129 concentration with more spreading compared to the Control (constant climate) case. When all loading efficiency is set to 0.0, the plume grows larger with higher concentration. Note that 1.0 Bq/m^3 corresponds to an effective I-129 drinking water dose of $1.1 \times 10^{-7} \text{ Sv/a}$ based on a water consumption rate of $0.84 \text{ m}^3/\text{a}$ per person.



Note: vertical exaggeration = 10

Figure 7 No-Well Regional Model simulated 3D I-129 plume distribution

7. Summary and conclusion

In this present study, the effect of repeated loading and unloading of kilometre-thick ice-sheets on radionuclide transport is investigated. Simulation results generally show that glaciation may drastically increase the vertical hydraulic gradient and hence the advective velocity. Results also show that glaciation has little effect on radionuclide transport in the repository vicinity although it substantially

boosts radionuclide transport into the Guelph formation. Numerous results indicate that radionuclide transport before entering Guelph at this study site is largely controlled by diffusion. Even with a very conservative assumption, the estimated human dose rate under a glacial climate is still well below the interim dose acceptance criterion. No significant adverse effects to humans and the environment are therefore anticipated as a result of these glacial cycles.

8. Acknowledgement

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9. References

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