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Numerical modelling of coupled groundwater flow and permafrost thaw under climate change: Applications to monitored field sites at Umiujaq (Nunavik, Quebec) and Iqaluit (Nunavut), Canada

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Numerical simulations have been completed at two monitored field sites in northern Canada to investigate the behavior of coupled groundwater flow and permafrost thaw in the context of climate change. The numerical model, HEATFLOW/3D, includes groundwater flow and heat transport with latent heat, and temperature-dependent water density and viscosity, relative permeability, thermal conductivity and unfrozen water content. Analytical solutions and numerical benchmarks from the Interfrost consortium (wiki.lsce.ipsl.fr/interfrost) were used for model validation.

The first site, near the village of Umiujaq in Nunavik, northern Quebec, Canada, is located in a small two square kilometre catchment containing degrading permafrost. A two-dimensional vertical-plane cryo-hydrogeological numerical model was developed for the site based on a 3D geological model which included up to 30 m of Quaternary sediments composed of sands, gravels and marine silts, as well as fractured bedrock. Field-based groundwater recharge and observed air temperatures were applied as components of the surface boundary conditions, while model calibration was based on detailed observed temperature profiles and ground heat fluxes. The simulations suggest that both supra- and sub-permafrost groundwater flow is contributing to permafrost thaw, driven by increasing air temperatures. The relatively short and rapid flow paths were consistent with the observed hydro-geochemical signatures dominated by Ca-HCO_3 water types. Cooled sub-permafrost groundwater flow maintains cold temperatures in the downgradient discharge zone. Model calibration and predictive simulations based on IPCC climate warming projections suggest the active zone thickness is increasing by 12 cm/yr while the base of the permafrost is thawing at a rate of about 80 cm/year, with complete permafrost thaw by around the year 2040.

The second site is located at the Iqaluit airport, in Nunavut, northern Canada, where permafrost degradation is contributing to deformation of the airport taxiway. In comparison to the Umiujaq site, Iqaluit lies in the continuous permafrost zone where thermal conduction and supra-permafrost groundwater flow play active roles in permafrost dynamics. The same HEATFLOW/3D code was applied to the Iqaluit site, in a 2D vertical plane across the taxiway. At this site, the insulating effect of snow cover on the taxiway shoulders is shown to significantly affect permafrost thaw dynamics. Despite increasing mean air and ground surface temperatures over time, groundwater cooling along the permafrost table is paradoxically shown to temporarily increase the height of the permafrost table in downgradient areas. The simulations suggest that the maximum depth of the active layer will increase from 2 m in 2012 to 8.8 m in 2100 and, over the same time period, thaw settlement along the airport taxiway will increase from 0.11 m to at least 0.17 m.

In both the Umiujaq and Iqaluit models, a quantitative parameter sensitivity analysis showed that variations in the hydraulic and thermal conductivity of the uppermost soil layers and the shape of the unfrozen water saturation function had the most significant effects on permafrost degradation.