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The potential for groundwater heat pump systems for mitigating urban heat islands: aquifer suitability evaluation in Canada's major cities

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ABSTRACT

Urban heat islands (UHI) are a growing issue in the context of global warming and pose significant threats to the public's health and well-being. The heat rejected into the city air from conventional air conditioners is a significant contributor to UHI. Geothermal energy is an alternative for mitigating this issue by redirecting this heat into the subsurface. This study assesses the suitability for open-loop geothermal technology of 10 selected Canadian cities that commonly experience UHI effects during summer, focusing on groundwater heat pump (GWHP) systems. Utilizing six key criteria related to hydrogeology and geochemistry, an evaluation tool in the form of an index is developed to perform a preliminary assessment of aquifer suitability. Results indicate that Vancouver, Winnipeg, and Kitchener/Waterloo/Cambridge are cities with highly favorable conditions for implementing GWHP systems. The other evaluated cities (Toronto, Montreal, Calgary, Edmonton, Ottawa/Gatineau, Quebec City, and Saskatoon) show moderate potential. While these results are contingent on the hydrogeological data available for these major cities, which are often limited, this study, nonetheless, yields promising results for several Canadian cities and has allowed to verify the usefulness of the developed index for conducting systematic preliminary assessments of site suitability.

RÉSUMÉ

Les îlots de chaleur urbains (ICU) constituent un problème croissant dans le contexte du réchauffement climatique et représentent une menace importante pour la santé et le bien-être de la population. La chaleur rejetée dans l'air des villes par les climatiseurs conventionnels contribue de manière significative à la formation de ces îlots. L'énergie géothermique représente une alternative intéressante pour atténuer ce problème en redirigeant cette chaleur dans le sol. Cette étude évalue la pertinence d'utiliser les systèmes géothermiques à boucle ouverte dans 10 villes canadiennes sélectionnées qui subissent fréquemment les effets des ICU pendant l'été, en se concentrant sur les systèmes de pompe à chaleur d'aquifère (PACA). À partir de six critères clés liés à l'hydrogéologie et la géochimie, un outil d'évaluation sous forme d'indice a été développé afin de permettre une évaluation préliminaire des aquifères. Les résultats indiquent que Vancouver, Winnipeg et Kitchener/Waterloo/Cambridge sont des villes présentant des conditions très favorables à la mise en œuvre de systèmes de PACA. Les autres villes évaluées (Toronto, Montréal, Calgary, Edmonton, Ottawa/Gatineau, Québec et Saskatoon) présentent un potentiel modéré. Bien que ces résultats dépendent des données hydrogéologiques disponibles pour ces grandes villes, qui sont souvent limitées, cette étude fournit néanmoins des résultats prometteurs pour plusieurs villes canadiennes et a permis de vérifier l'utilité de l'indice développé pour réaliser des évaluations préliminaires systématiques de la viabilité des PACA.

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Introduction

Urban heat islands (UHI) are characterized by elevated temperatures in urban areas compared to their rural surroundings. Detrimental impacts include adverse effects on public health and energy consumption (Uejio et al. 2011; Moonen et al. 2012). As global temperatures continue to rise, UHI become a pressing concern, necessitating innovative mitigation strategies (McGeehin and Mirabelli 2001).

In 2025, 68% of Canadian households reported using air conditioning or other cooling equipment (e.g. heat pumps) to cope with summer heat (Statistics Canada 2025), a figure that has been steadily increasing from 55% in 2013 to 61% in 2019 and 64% in 2021 (Statistics Canada 2023a), reflecting the growing need for space temperature regulation during the warmer months. In 2020, total residential space cooling energy use in Canada was 35.9 petajoules (PJ, Natural Resources Canada 2022). The commercial and institutional sectors also contributed 54.8 PJ in the same year (National Energy Use Database (NEUD) 2021). However, traditional air conditioners themselves are a contributor to UHI due to the heat they reject (Magli et al. 2015; Vujovic et al. 2021).

The escalating demand for cooling solutions, coupled with the associated rise in energy consumption, emphasizes the urgency of finding sustainable alternatives. In this context, it is crucial to explore cooling technologies that use electricity without releasing additional heat into the surrounding air. Geothermal heat pumps emerge as a promising option for a cooling alternative, either on their own or in conjunction with other technologies. Within the realm of geothermal system options, open-loop systems that utilize groundwater, comprising both injection and pumping wells, also known as ground-water heat pump (GWHP) systems, present a promising avenue for both heating and cooling. This method stands out for its low carbon footprint and high energy efficiency, leveraging electricity while minimizing environmental impact (Blum et al. 2010; Possemiers, Huysmans, and Batelaan 2014; Sciacovelli, Guelpa, and Verda 2014; Pellegrini et al. 2019; Stemmler et al. 2021; Menberg et al. 2025). Implementing this technology on a wide scale has particular potential for mitigating UHI because these systems reject heat in the subsurface instead of the ambient city air. A study by Schibuola and Tambani (2022) has found that the average UHI intensity of a modeled urban area in Treviso, Italy, was reduced by 45% when using GWHPs instead of conventional air conditioning systems. An additional benefit is that GWHP systems can be used for both cooling and heating, with good performance in cold climate countries (Minea 2022). Therefore, this can also contribute to decarbonizing the Canadian heating sector, considering that 99% of residential greenhouse gas (GHG) emissions stem from space and water heating (National Energy Use Database (NEUD) 2021).

Although less commonly installed than their closed-loop counterparts (which extract energy from the ground using heat carrier fluids circulating in sealed boreholes or tubing), open-loop systems exhibit better energy efficiency and cost-effectiveness. Under favorable hydrogeological conditions (including a permeable unit and low iron concentrations) and moderate energy requirements (e.g. above a capacity of 528 kW), installation of a GWHP system could cost as little as 20% of the cost of a closed-loop system due to the lower number of wells to be installed (Kavanaugh and Rafferty 2014). Aquifer thermal energy storage (ATES) systems are another open-loop option that use the same equipment as GWHPs, but with a focus on storing energy seasonally to maximize performance. Despite the need for thorough characterization, higher maintenance requirements, and the risks of aquifer warming and well clogging, the higher energy efficiency and smaller number of boreholes of GWHP and ATES systems make them an appealing choice, especially in urban environments where space is limited (Kranz and Frick 2013; Kavanaugh and Rafferty 2014). While surface water offers another viable option, groundwater proves to be more readily available locally in urban settings and its use would normally have less impact on the local environment.

Currently, open-loop geothermal systems are not widely used in Canada and there is a lack of documentation regarding this type of installation. Geothermal heat pumps are concentrated in the major Canadian cities, especially those of southern Ontario and Quebec, but there is generally no distinction available in datasets between open and closed-loop systems (Lund and Toth 2021). At the time of writing, no government data are publicly available on the number of systems installed and in use. Knowledge of geological and hydrogeological conditions beneath highly populated Canadian cities is not sufficient to guarantee the successful implementation of open-loop geothermal systems. The resources in question are aquifers, extensive bodies of permeable rock and/or sediment that hold

groundwater. Ferguson (2012) provided useful insights into characterizing the uncertainty in heating and cooling performance of an aquifer in Manitoba, Canada using geostatistical information. However, there are no comparative investigations of aquifers from multiple Canadian cities with a systematic approach that uses readily available information.

The primary objective of this study is to assess the suitability of some of the important aquifers underlying 10 major Canadian cities impacted by UHI for cooling buildings using GWHP systems. To achieve this, an index integrating six key criteria is first developed, following an approach similar to that of the DRASTIC index (Aller et al. 1987). This index was developed in the 1980s by the U.S. Environmental Protection Agency (EPA) and the American Water Works Association to provide first-order estimates of aquifer vulnerability. It takes into account seven parameters, each of which has been assigned a weighting based on its relevance to potential surface contamination. This index has been widely criticized for its shortcomings, which include: 1) a weighting system that does not adapt to local hydrogeological conditions; 2) the partly subjective parameter ratings that may not reflect actual field conditions, especially in heterogeneous media; 3) a simplified hydrogeological representation; 4) lack of consideration for land use, anthropogenic factors and the specific behavior of contaminants (e.g. sorption, degradation), all of which often lead to a weak correlation between DRASTIC scores and observed contamination levels (Mohanta et al. 2025). Nonetheless, the DRASTIC index remains widely used due to its simplicity and the use of readily available parameters. Although it is not accurate, it rapidly provides useful information on vulnerability, including which areas should be avoided for industrial activities and where further studies are required, for instance to establish a protection zone around a municipal well.

It is in this same spirit that we developed an index for GWHP, making sure that the data used to assess the cooling potential were both relevant and readily available. The information regarding targeted aquifer and groundwater characteristics was thus sought for each city. The overarching purpose is to determine whether GWHP technology constitutes a viable and effective solution for mitigating the impact of UHI in the Canadian context. Focusing on GWHP rather than aquifer thermal energy storage (ATES) is justifiable due to the scalability of GWHP systems, which can be implemented from residential to commercial and industrial scales. While ATES excels in large-scale applications, the flexibility of GWHP systems positions them as a pragmatic choice for a wider array of possibilities. The suitability evaluation tool developed in this study, while initially designed for GWHP, could nonetheless easily be adapted for ATES.

This study is part of a larger research project that aims to provide new knowledge to mitigate UHI using aquifers in Canada. This investigation holds significance for decision-makers and urban planners facing the challenge of UHI. The findings should provide incentives to consider geothermal systems, and in particular open-loop designs, as a viable alternative with the potential to enhance energy efficiency and environmental sustainability in Canada.

Methodology

Criteria selection and potential index development

To assess the potential for cooling spaces using groundwater in major Canadian cities, a literature review determined the most important factors for aquifer suitability for GWHP systems. Bloemendal, Olsthoorn, and van de Ven (2015) and Lu et al. (2019) give the most impactful factors (summarized in Annex A) on the suitability for ATES system implementation. These are virtually the same as those that apply to GWHP systems and have been adapted for our study.

Aquifers that have clean freshwater, lower temperature and from which large quantities of water can be extracted (i.e. permeable with high recharge) are more favorable and will provide more efficient and economical cooling systems with better life expectancy. Saline water and polluted water can still function with these systems, but will require more expensive maintenance to prevent corrosion, clogging or further pollution (Zuurbier et al. 2013; Abesser et al. 2014). In terms of ambient groundwater flow, high groundwater flow velocity can be detrimental to the effectiveness of ATES systems, as it can dissipate the stored energy (Bloemendal and Olsthoorn 2018). On the other hand, a high rather than low groundwater flow is beneficial to GWHP systems because the thermal plume at the injection well will dissipate faster and the aquifer temperature near the pumping well is less likely to be affected. Granular

aquifers generally perform better than bedrock aquifers because their interconnected porosity is often higher and less variable.

Data for this study were found from publicly available databases and groundwater studies, published in the form of reports, theses, or papers, carried out specifically for the targeted cities or aquifer systems to supplement the national database (Groundwater Information Network 2024). Based on this data review and the suitability factors reported in Bloemendal, Olsthoorn, and van de Ven (2015) and Lu et al. (2019), the aquifer's hydraulic conductivity (K), mean aquifer thickness (AT), mean annual aquifer recharge (R), groundwater salinity (S), and ground temperature (T) as a proxy for groundwater temperature are selected as criteria. The empirical equation of Ouzzane et al. (2015) is used to estimate the undisturbed ground temperature (T_g) from the annual ambient air temperature (T_{amb}) to approximate the groundwater temperature beneath Canadian cities, considering that its temperature (in Kelvin for Equation 1) remains relatively constant throughout the year.

$$T_g = 17.989 + 0.951 T_{amb} \quad (1)$$

Average annual outside air temperatures recorded for each city by Environment and Climate Change Canada (2022) are used as input for the formula. Given that shallow underground temperatures are affected by complex processes such as groundwater recharge or discharge and UHI themselves, it is difficult to give an exact depth to which this ground temperature is found. However, it is likely to be characteristic of the first tens of meter below the surface, where the static water table is generally found in Canada.

Iron concentration (F) is added as a final criterion because of the associated clogging issues. High concentrations of ferrous iron (Fe^{2+}) are one of the most common culprits of well clogging due to oxidation reactions triggered by bacteria (Fujita et al. 2022). During well pumping, mixing oxygenated water in upper layers with reduced iron-rich water in bottom layers leads to precipitation (i.e. iron oxide) and hence clogging (van Beek 2010; Burté et al. 2019).

The DRASTIC index and the one developed here thus share similarities, particularly with regard to two of their parameters (criteria): aquifer hydraulic conductivity and recharge. Another parameter in each index also shares similarities: aquifer media for DRASTIC, representing the geological and lithological characteristics of the aquifer and aquifer thickness for our index, as they are both related to the 'potential' of the aquifer. The other DRASTIC parameters include, unsurprisingly, parameters related to possible contamination from the surface, such as the water table depth, ground topography (or slope) and the composition of the soil/zone overlying the aquifer (i.e. soil media and impact of the vadose zone), while our index include parameters more relevant to the operation of open-loop geothermal energy systems.

Each criterion has a 5-point rating system, where 1 corresponds to poor conditions for installing GWHP systems for space cooling and 5 is very favorable. A weighting is assigned to each criterion based on professional judgment to reflect their relative importance for this study. The equation for the index is presented below (Equation 2) and the rating system, the selected criteria and their respective weights in the evaluation are summarized in Table 1.

$$I_{CP} = K_R K_W + A_T R A T_W + R_R R_W + S_R S_W + T_R T_W + F_R F_W \quad (2)$$

Table 1. Evaluation tool for assessing the suitability of urban aquifers in large Canadian cities for GWHP cooling system implementation.

Criteria	Aquifer suitability rating for GWHP cooling					Weight final score
	1	2	3	4	5	
Hydraulic conductivity (m/s)	Low $< 1 \times 10^{-7}$	–	Moderate 1×10^{-7} $- 1 \times 10^{-4}$	–	High $> 1 \times 10^{-4}$	25%
Aquifer thickness (m)	< 5	5–10	[10 – 15]	15 – 20	> 20	15%
Mean annual groundwater temperature (°C)	> 15	–	10 – 15	–	< 10	15%
Aquifer recharge (mm/y)	< 10	10–50	[50 – 150]	150 – 300	> 300	15%
Groundwater salinity	–	–	Brackish or saline	–	Fresh	15%
Median iron (Fe) concentration (mg/L)	> 0.5	–	0.2 – 0.5	–	< 0.2	15%

I_{CP} is the index for the cooling potential, the subscripts R and W are for the rating (from 1 to 5) and weight (25% and 15% in our case), respectively.

The hydraulic conductivity criterion is assigned the highest weight (25%) because this hydrogeological characteristic, related to permeability, is widely considered to be the key parameter controlling aquifer behavior and groundwater flow (Freeze and Cherry, 1979; EPA 1990; Sanchez-Vila et al. 2006; Zhu et al. 2016). Therefore, it has a considerable impact on the performance of a GWHP system. Hydraulic conductivity is a property of a geological medium that quantifies its ability to transmit water under a specified hydraulic gradient. This property, in conjunction with the aquifer thickness and recharge rate, is intimately related to the aquifer's capacity to supply water. Good aquifer capacity, and therefore a permeable aquifer with important thickness and a high recharge rate, is desirable because it allows the reinjected warm water to be diluted and move away from the pumping well. Since the parameters AT and R are considered to have less impact than K on the system's performance, they were given a lower weight. It should be noted that arid and even semi-arid regions were not taken into account here. It should also be noted that although groundwater temperature is an important parameter because the greater the contrast with ambient air, the better the cooling performance, the range of values in populated areas of Canada is quite narrow for shallow groundwater (generally between 7 and 14 °C according to Statistics Canada (2022) and even narrower under large cities, see below). Thus, this parameter can only have a limited impact on system performance. Fresh water is preferred over brackish or saline water in order to reduce material or maintenance costs and facilitate pumping and injection (due to its lower density), but GWHP systems are nonetheless viable in any of these conditions. Finally, while elevated iron concentrations can significantly impair system performance, there are ways to limit clogging, including the use of anti-clogging agents such as polymer anti-scalants or oxalic acid, biotechnological interventions such as the use of biocides or enzymes, or conventional disinfection techniques such as chlorination (Shi et al. 2025). The last five criteria are therefore given equal, lower weights (15%) because they are deemed less critical than K , and their ranking is considered too subjective. The points for each city are assigned according to the values from databases and literature, to the best of our knowledge. In cases where multiple aquifers are present in a city, the ratings are based on the aquifer with the largest extent and/or exploitation potential in the urbanized areas of that city.

Benchmark definitions associated with the ratings are based on values considered appropriate for favorable and unfavorable conditions for GWHP systems, according to professional judgment. Benchmarks for 'Median iron (Fe) concentration' are based on those defined in Talbot Poulin et al. (2013) for clogging probability as a function of different chemical parameters. Note that aquifer recharge corresponds to vertical recharge over the selected aquifer and that very dense urban areas where no vertical recharge can occur due to surface impermeabilization are excluded.

The weighted score according to the ratings assigned to each criterion is used to evaluate the potential of Canadian urban aquifers for GWHP cooling. Qualitative interpretations of the scores are made to simplify the results. Scores between 4 and 5 are categorized as high, 3–4 as moderate, and 2–3 as low.

City selection and UHI magnitude evaluation

The magnitude of UHI in Canadian cities is assessed using three criteria: population (P), maximum temperature during daytime (MTD) and minimum temperature during nighttime (MTN), both for the summer period. This identifies cities which would be most in need of low-carbon cooling alternatives. Cities were primarily selected based on their population size in 2022 from Statistics Canada (2023b), with a weight of 50% assigned to this parameter because populous cities are more likely to have UHI of high magnitude and severity. The benchmarks are again defined based on professional judgment. Some cities in Ontario are excluded, such as Hamilton and Oshawa, because they are part of the Greater Toronto Area, as well as London and Windsor, because the aquifers in these regions have similar characteristics to those of the Toronto area. These exclusions result in better spatial coverage across the country, while limiting the number of cities considered to 10. Other cities like Victoria and Halifax are excluded, because their maritime climate prevents them from significant UHI effects. With these considerations in mind, the selection is narrowed down to the following cities (or groupings): Toronto,

Table 2. Evaluation tool for assessing the magnitude of UHI in large Canadian cities.

Criteria	UHI magnitude rating					Weight final score
	1	2	3	4	5	
City population		<500 000	500 000– 1 000 000	1 000 000– 2 000 000	>2 000 000	50%
Maximum temperature of UHI during daytime (°C)	–	–	25–30	–	30–35	25%
Minimum temperature of UHI during nighttime (°C)	–	–	5–10	–	10–15	25%

Montreal, Vancouver, Calgary, Edmonton, Ottawa/Gatineau, Winnipeg, Quebec City, Kitchener/Waterloo/Cambridge, and Saskatoon.

In addition to the city population, both maximum daytime and minimum nighttime temperatures are used because waste heat from air conditioning exacerbates nocturnal UHI (Salamanca et al. 2014). Table 2 presents these three criteria along with their rating, where 1 corresponds to low UHI magnitude and 5 is high. The information on temperature is from a dataset by the Center For International Earth Science Information Network Columbia University (2016) and the benchmarks for the two UHI criteria are also set based on this information: Maximum and minimum UHI temperatures receive an equal weight, together totalling 50%.

The index for the magnitude of UHIs is calculated using Equation 3. Similarly to I_{CP} , scores between 4 and 5 are considered high, those between 3 and 4 moderate, and those between 2 and 3 low.

$$I_M = P_R P_W + MTD_R MTD_W + MTN_R MTN_W \quad (3)$$

I_M is the index for the magnitude of UHI, and the subscripts R and W are again for the rating (from 1 to 5) and weight (50% and 25% in our case), respectively.

The final result corresponds to the combination of the scores of the two indices (I_{CP} and I_M) obtained using equations 2 and 3, which can be interpreted quantitatively or qualitatively (e.g. high-high).

Results

Collected information on the selected cities

Table 3 summarizes the information collected from a literature review for the suitability assessment of aquifers beneath the selected Canadian cities. The first part (Table 3A) presents a geological and hydro-geological description of the most favorable aquifer(s) by city, while the second part (Table 3B) presents their associated values for the six parameters of equation 2. Estimated ground temperature results are also included as a proxy for groundwater temperature. Data in Table 4 provide city data for population, average annual air temperature used to calculate ground temperature, and UHI temperatures during daytime and nighttime.

Index scores for the selected cities

The detailed results of the final evaluation for all the cities are summarized in Tables 5 and 6. Where two aquifers are presented for a given city, the most favorable one is used in Table 5, although it may be the most limited in extent. Nonetheless for Calgary, the Paskapoo Formation was selected because its average values are generally close to those of the Empress Group, while covering a larger area. When a unit is described as highly variable (e.g. having a hydraulic conductivity from low to high), a mid-range value has been assigned. For instance, if hydraulic conductivity was reported as ‘moderate to high’ in Table 3, a rating of 4 was assigned, although it does not actually correspond to a value in Table 1. This approach was intended to yield a more representative value for the index; otherwise, even a relatively good mean K value would have had to be assigned a rating of 3. The same approach was

Table 3A. Compilation of urban aquifer information for the selected Canadian cities in descending order of population for the assessment of GWHP cooling system suitability. Description of the aquifer and references used. The Groundwater Information Network (2024) database was used for many of the cities but was removed from the list of sources to condense the text. GW: groundwater; Fm: Formation.

City	Aquifer name / type	Geological and hydrogeological description	Sources
Toronto	Oak Ridges Moraine (ORM) / Granular	The ORM is a 160 km long and 13 km wide ridge (with a volume using median thicknesses ranging from 42 to 104 km ³) located ~30 km north of Toronto's densely urbanized area. It consists of thick sandy sediments of glaciofluvial and ice-proximal glaciolacustrine origin that are the main recharge zone for two underlying aquifers separated by aquitards (tills). The largest part of the ORM is unconfined and corresponds to the upper unit (called the Oak Ridges Complex). The two aquifers underneath Toronto (Thorncliffe Fm. and Scarborough Fm.) are confined and thought to carry GW from the ORM southward under the city and towards Lake Ontario. The ORM is one of the most productive and high-quality aquifers in Canada and has been well characterized. However, the properties of the Scarborough and Thorncliffe Fms are less well known.	- Howard et al. (1995) - Meriano (1999) - Ontario Ministry of Mines (2024) and pers. commun. with Ms. Laura Colgrove from the Ontario Geological Survey - Sharpe et al. (2003) - Sharpe, Russell, and Logan (2007)
Montreal	Fractured bedrock aquifer system / Fractured rock	This bedrock aquifer is mainly composed of highly fractured limestone, dolostone and sandstone. It is unconformably overlain by sandy silt till, which is in turn overlain by a discontinuous marine clay aquitard. The aquifer is thus generally confined and locally semi-confined. On top of the clay and till aquitards, there are discontinuous unconfined sandy fluvial and littoral units that are only 2–4 m thick.	- Lepage (1996) - Prest and Keyser (1977) - Savard et al. (2013)
Vancouver	Fraser aquifer system / Granular	The Fraser aquifer system is composed of the following hydrogeological units from top to bottom: a glaciofluvial sand and gravel unit that overlies fine sediments (clay and silt), which overlie a till discontinuous unit. Many aquifers are present in the glaciofluvial sediments: mapping has identified more than 200 aquifers in the region.	- Foster and Allen (2015) - Neilson-Welch (1999) - Carmichael, Wei, and Ringham (1995) - Parajulee and Smet (2009)
Calgary	Paskapoo Aquifer System and Empress Group Aquifer / Fractured rock and granular	The Paskapoo Formation consists of a complex succession of interbedded mudstone and siltstone with sandstone channels, making this aquifer system very heterogeneous. This Formation extends over ~65 000 km ² and is the main GW supply in Alberta. In its southern part, it consists mainly of sandstone and is up to 800 m thick, but the active zone (where most of the freshwater flow occurs) is limited to the upper 100–150 m. It is mostly confined to semi-confined. This formation can provide high yields. The Empress Gp., a granular aquifer at the base of the Quaternary pile (see its description and characteristics in the Saskatoon section), has a fairly extensive distribution under the city and may serve locally for geothermal energy.	- Grasby et al. (2008) - Grasby et al. (2004) - Matthews (2011) - Hayashi and Farrow (2014) - Moran (1985)
Edmonton	Prairie buried valleys aquifer system / Granular	Prairie buried valleys tend to be heterogeneous and architecturally complex. Sand, gravel, mud, and till are common; any one can dominate the fill at a given location. This heterogeneity often causes aquifer compartmentalization and makes prediction of aquifer potential difficult prior to drilling. Most of these aquifers are incised into sedimentary bedrock of the Western Canadian Sedimentary Basin (WCSB). Low permeability Quaternary till tends to overlie the buried aquifers. The latter are thus confined to semi confined.	- Cummings, Russell, and Sharpe (2012) - Kehler (2022) - Rubin (2022)
Ottawa/Gatineau	Sand and gravel deposits and fractured bedrock aquifer system / Granular and fractured	The overburden beneath the city centers of Ottawa and Gatineau consists of a relatively continuous till sheet and alluvial sediments with generally low yields. Sand and gravel units with high yield potential are present in the Chelsea/Cantley area and in southern Ottawa. Up to 500	- Allen (1998) - Comeau et al. (2013) - Ontario Ministry of the Environment and Conservation and Parks (2024) - J.L. Richards & Associates Limited

(continued)

Table 3A. Continued.

City	Aquifer name / type	Geological and hydrogeological description	Sources
		meters of fractured bedrock units composed of limestone, dolostone, sandstone and shale of Ordovician age underly the Ottawa/Gatineau urbanized areas at various depths. They are intensely fractured and could be quite permeable. Shallow limestone is expected to be affected by karstic dissolution, enhancing the overall permeability. In particular, the sandstone from the Rockcliffe Fm. and Nepean Fm. below the limestone shows good potential for open-loop geothermal systems. Brackish water and methane can sometimes be found in some of the units. Due to the numerous faults in this region, sites with high potential can be near low potential ones. The faulting and fracturing controls the water yields.	(2021) • Wilson et al. (2009) • Natural Resources Canada (2024) & Natural Resources Canada (2015) • Bélanger (2008) • Pers. comm. with Ms. T. Di Iorio from the City of Ottawa
Winnipeg	Carbonate rock aquifer system / Fractured rock	The carbonate rock aquifer system is comprised of Paleozoic formations ranging in thickness from 76 to 230 m and is separated into three sections: the Upper, Middle and Lower Carbonate aquifers. The highest permeability is found in the Upper aquifer, which is semi confined to confined by overlying glacial deposits (mainly composed of till and clay and having a maximum thickness of 60 m). Open-loop geothermal systems have been used within the City of Winnipeg since the 1940s. The systems extract GW from the Upper Carbonate aquifer and some of it is injected back in this unit, causing an increase in GW temperature in several locations.	• Kennedy and Woodbury (2005) • Susanto (2019) • Ferguson and Woodbury (2006) • Pers. commun. with Dr. G. Ferguson (UofSK)
Quebec City	Limoilou aquifer / Granular	This deltaic aquifer is mainly composed of fine to medium sand and gravel and is part of a buried channel of the Proto St. Lawrence River. It overlies heterogeneous fractured bedrock. This aquifer is variably unconfined and semi confined. It covers about one third of the urbanized area.	• Lamarche et al. (2008) • Talbot Poulin et al. (2013) • Wong et al. (2025)
Kitchener /Waterloo /Cambridge	Waterloo Moraine aquifer system / Granular	The Waterloo Moraine is a multi-layer aquifer system that includes lenticular aquitards and aquifers spanning across an area of about 350 km². The aquifers are all predominantly composed of sand and gravel and have abundant high-quality groundwater. The upper aquifer, located in the core region, is a thick (> 45 m) and laterally broad saturated unit that can supply high yields. Confining layers of till with erosional windows lie between aquifers, which makes the moraine aquifer units confined or semi-confined. High pumping rates from wells completed at the base of the Waterloo Moraine can potentially induce upward flow from the bedrock (Salina Fm.), resulting in increased salinity, sulfate, hardness and iron in the pumped water. While the Waterloo moraine units underly most of Kitchener and Waterloo's urbanized area, it is only present in the western half of Cambridge.	• Bajc, Russell, and Sharpe (2014) • Blackport, Meyer, and Martin (2014) • Martin and Frind (1998)
Saskatoon	Empress Group Aquifer and Upper Floral Formation / Granular	The Empress Group and Upper Floral Formation aquifers are part of the prairie buried valleys aquifer system. They both consist of fluvial sands and gravels and are the most interesting buried valley aquifers in the Saskatoon area. The Empress Gp., which lies at the base of the regional Quaternary succession, is locally very productive and can be expected to yield large volumes. The Upper Floral Fm. lies at shallower depth and may also be quite productive, but it mainly underlies the outskirts of Saskatoon's urbanized area. The Empress Gp is more interesting from a hydrogeological point of view, but it generally lies at depths of more than 50 m. Both aquifers are confined by overlying till units.	• Cummings, Russell, and Sharpe (2012) • MDH (2011) • Sloan, Gillies, and Norum (1991) • Fortin, van der Kamp, and Cherry (1991) • Pers. commun. with Mr. Kei Lo from the Water Security Agency

Table 3B. Values for the different selected parameters. Sources for these values are provided in Table 3B. Mean annual groundwater temperature values were determined with equation 1 (from Ouzzane et al. 2015). For each parameter, a representative range is provided, along with a median / typical value or range displayed in bold when appropriate and available. GW: groundwater; temp: temperature.

City	Aquifer name / type	Hydraulic conductivity	Aquifer thickness	Mean annual GW Temp.	Aquifer recharge	GW salinity	Iron (Fe) concentration
Toronto	Oak Ridges Moraine (ORM) Granular	10^{-6} – 10^{-3} m/s	2–125 m / 20–50 m	13.5 °C	~200–450 mm/y (where unconfined)	Fresh	0–24.5 mg/L / 0.33 mg/L (often exceeds 0.3 mg/L)
	Thorndcliffe Fm. and Scarborough Fm. Granular	10^{-8} – 10^{-4} m/s	0–55 m / ~10–20 m Scarborough Fm.: 0–40 m / ~5–15 m	13.5 °C	Low at regional scale (leakage from the overlying aquitard), but locally 35–200 mm/y	Fresh	Unknown, but considered similar to those of ORM
	Fractured bedrock aquifer system Fractured rock	10^{-8} – 10^{-3} m/s / 5×10^{-5} m/s	1–150 m / 15 m	9.6 °C	~8–376 mm/y / 142 mm/y	Fresh	0–20 mg/L / Generally <0.3 mg/L
Vancouver	Fraser aquifer system Granular	10^{-6} – 10^{-2} m/s	5–40 m	14.4 °C	~253–630 mm/y	Fresh, can locally be brackish to saline	0–17 mg/L / 0.34 mg/L
Calgary	Paskapoo Aquifer System and Empress Group Aquifer/ Fractured rock and granular	Paskapoo Fm: 10^{-6} – 10^{-3} m/s Empress Gr.: can locally be very permeable $\sim 10^{-5}$ – 10^{-3} m/s	Decimetric to metric sandstone and fractured intervals can be found over 150 m Empress Gr.: 0–10 m	8.7 °C	Vertical recharge is regionally low to medium ~10–90 mm/y, but could be higher locally. Some lateral recharge could come from the Rocky Mountain Foothills	Fresh	<0.5 mg/L
Edmonton	Prairie buried valleys aquifer system Granular	10^{-4} – 10^{-3} m/s	0–70 m / Typically <30 m	8.5 °C	Vertical recharge is very low: ~0–2 mm/y. / Lateral recharge comes from adjacent bedrock	Fresh	0–34 mg/L / 1.6 mg/L (as no data were available, the same values as for Saskatoon were used)
Ottawa/ Gatineau	Sand and gravel deposits and fractured bedrock aquifer system Granular and fractured	Sand and gravel deposits: 10^{-5} – 10^{-4} m/s Bedrock: 10^{-8} – 10^{-3} m/s, highly dependent on faults and fractures	Sand and gravel deposits: 0–50 m Bedrock: Nepean Fm.: 0–80 m / 20–50 m Rockcliffe Fm.: 0–51 m	10.8 °C	Sand and gravel deposits: ~0–300 mm/y Bedrock: generally low, but can be locally moderate	Fresh	Sand and gravel deposits: Low (< 0.04 mg/L) Bedrock: 0–14.9 mg/L / 0.09 mg/L
Winnipeg	Carbonate rock aquifer system Fractured rock	10^{-5} – 10^{-3} m/s	15–30 m	7.4 °C	Very low, likely < 50 mm/y	Brackish	Low (no important issues reported in 80 years of operation)
Quebec City	Limolou aquifer Granular	10^{-7} – 10^{-4} m/s	5–30 m	8.5 °C	~140–220 mm/y	Fresh	0.05–22 mg/L / 15.8 mg/L
Kitchener / Waterloo / Cambridge	Waterloo Moraine aquifer system Granular	Upper aquifer: 10^{-6} – 10^{-3} m/s	Upper aquifer: 0–101 m / 30–50 m	11.2 °C	~0 (when confined or heavily urbanized) – 450 mm/y/ 200 mm/y	Fresh	Low (typically < 0.3 mg/L in the Upper aquifer), 43 mg/L in the Lower aquifers, when high pumping rates are used
Saskatoon	Empress Group Aquifer and Upper Floral Formation Granular	Empress and Floral groups: Although highly variable (10^{-9} – 10^{-3} m/s), they can locally be very permeable (10^{-5} – 10^{-3} m/s)	Empress Gp.: 20–60 m / 20–30 m Floral Fm.: 5–10 m	7 °C	Vertical recharge is very low: ~0–2 mm/y. Lateral recharge comes from adjacent bedrock.	Fresh	0–34 mg/L / 1.6 mg/L

Table 4. Population by census metropolitan area and temperature data of the selected Canadian cities.

Cities	Province	Population estimate in 2022 ^a	Average annual air temperature 1981–2010 ^b (°C)	Maximal temperature of UHI during daytime ^c (°C)	Minimal temperature of UHI during nighttime ^c (°C)
Toronto	Ontario	6,685,621	9.4	30–35	10–15
Montreal	Québec	4,378,796	5.3	30–35	10–15
Vancouver	British Columbia	2,842,730	10.4	30–35	10–15
Calgary	Alberta	1,608,342	4.4	25–30	5–10
Edmonton	Alberta	1,516,719	4.2	25–30	5–10
Ottawa/Gatineau	Ontario/Québec	1,498,610	6.6	30–35	10–15
Winnipeg	Manitoba	871,778	3.0	30–35	5–10
Quebec City	Quebec	848,776	4.2	30–35	10–15
Kitchener /Waterloo /Cambridge	Ontario	622,497	7.0	30–35	10–15
Saskatoon	Saskatchewan	347,536	2.6	25–30	5–10

^aStatistics Canada (2023a).^bEnvironment and Natural Resources Canada (2022).^cCenter For International Earth Science Information Network-CIESIN-Columbia University (2016).

taken for iron concentration. For example, when only a limited amount of data was available and all fell below a value close to the lower limit of the range provided for a rating 3, a rating of 4 was assigned. The final evaluation scores from Tables 5 and 6 are represented on a map in Figure 1 using a qualitative classification (high, moderate, and low).

The results in Table 5 show that all the cities obtain scores within a narrow range, between 3.3 and 4.2, thus having moderately to highly favorable conditions for the implementation of open-loop geothermal technology for space cooling (Figure 1). It should be noted, however, that these conditions generally only cover part of the cities (the hydrogeological units represented are described in Table 3) and that relatively optimistic scenarios have been selected for the cities with multiple aquifer systems. The four cities (or city areas) with the highest cooling potential (i.e. with a final score of at least 4 out of 5) are Vancouver, Kitchener/Waterloo/Cambridge, Winnipeg, and Calgary. These cities rank higher, mainly because a permeable aquifer system with high productivity potential is present beneath them, based on their hydraulic conductivity and aquifer thickness. The lowest-ranked city is Saskatoon, with a final score of 3.3 out of 5, which is still considered a moderate cooling potential. In the cases of Toronto, Saskatoon and Ottawa/Gatineau, their hydraulic conductivity ranges are very wide (classified as ‘low to high’) because geological units are heterogenous and/or few values for unit properties are available. Consequently, an average value of 3 has been used for their rating, which can obviously lower the overall score, whereas specific areas within these cities could have a high potential.

With respect to UHI magnitude, all cities scored at least 3.5 out of 5 except for Saskatoon, which scored 2.5 out of 5 (Table 6). This city has the smallest population and one of the coldest climates among those considered here, along with the two other Prairies cities (Edmonton and Calgary). Comparing the scores of both evaluations shows that many cities (or city areas) with high cooling demand also have high suitability for GWHP systems, notably Vancouver, Kitchener/Waterloo/Cambridge and Quebec City (Figure 1). In particular, the three cities with the most intense UHI (Toronto, Montreal, and Vancouver) have GWHP suitability scores of 3.8 out of 5 and higher. These findings show favorable conditions for GWHP to be considered as a viable alternative to traditional air conditioners and an effective way to mitigate UHI.

Discussion

Limitations and future directions

The main limitation of this study is that the results are highly dependent on the current availability of information. This work relied largely on data collected primarily for assessing drinking water resources, hence generally outside the main urbanized areas (which typically use surface water supplied *via* aqueducts).

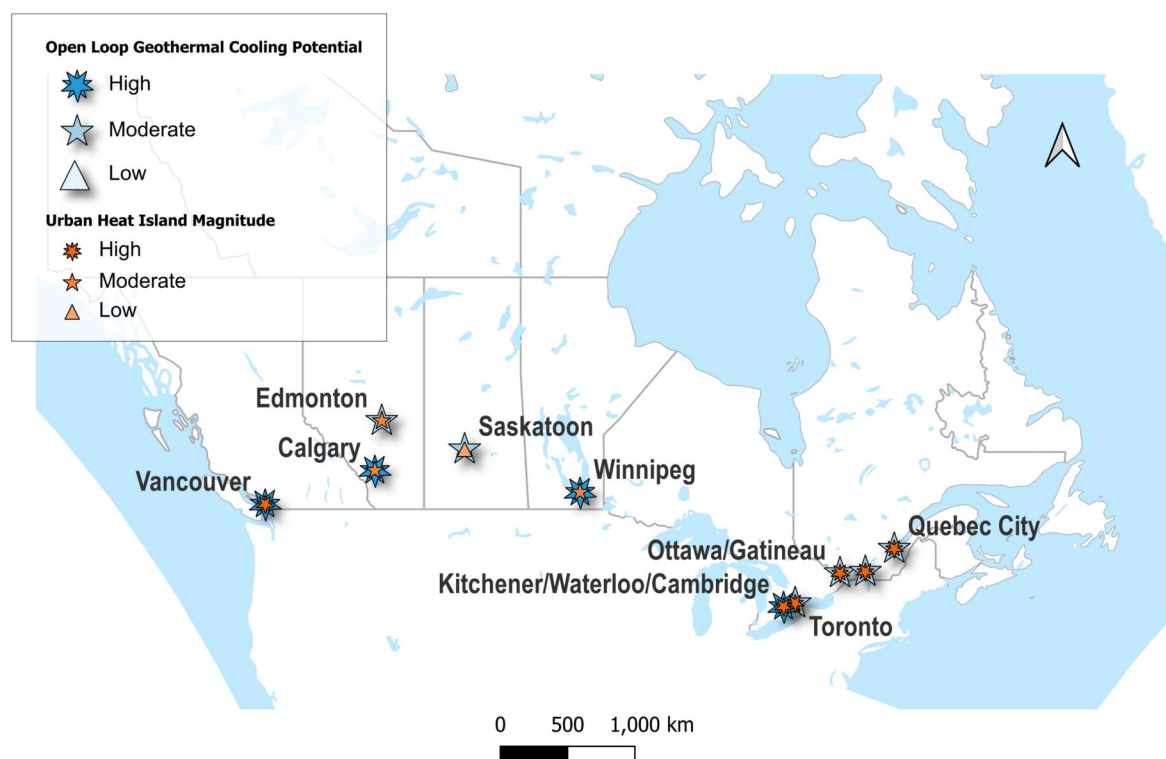
Table 5. Evaluation results and final scores out of 5 for assessing the suitability of urban aquifers in the selected Canadian cities for GWHP cooling system implementation. Cities are listed in descending order of population and the aquifer selected for the evaluation is specified in cases where there are multiple aquifer systems. The scores for individual criterion are presented in parentheses following the result description.

	Hydraulic conductivity (m/s)	Aquifer thickness (m)	Mean annual GW temperature ^a (°C)	Aquifer recharge (mm/y)	Groundwater salinity	Median iron (Fe) concentration (mg/L)	Final score out of 5 (I _p)
Toronto (Thornccliffe Fm.)	Low to High (3)	10 - 20 (4)	13.5 (3)	0 - 200 (3)	Fresh (5)	0.33 (3)	3.5
Montreal	Moderate (3)	15 (4)	9.6 (5)	142 (3)	Fresh (5)	< 0.3 (4)	3.9
Vancouver	Moderate to High (4)	15 - 40 (5)	14.4 (3)	253 - 630 (5)	Fresh (5)	0.34 (3)	4.2
Calgary (Paskapoo Fm.)	Moderate to High (4)	5 - 15 (3)	8.7 (5)	Low vertical (10 - 50) (2)	Fresh (5)	< 0.1 (5)	4.0
Edmonton	High (5)	10 - 30 (3)	8.5 (5)	Very low vertical (0 - 2), mainly lateral (1)	Fresh (5)	1.6 (1)	3.5
Ottawa / Gatineau (Nepean Fm.)	Low to High (3)	20 - 50 (5)	10.8 (3)	Generally low, but can be locally moderate (2)	Fresh (5)	< 0.4 (4)	3.6
Winnipeg	Moderate to High (4)	15 - 30 (5)	7.4 (5)	< 50 (2)	Brackish (3)	Low, no important issues reported (5)	4.0
Quebec City	Moderate (3)	5 - 30 (4)	8.5 (5)	140 - 220 (4)	Fresh (5)	15.8 (1)	3.6
Kitchener /Waterloo	Moderate to High (4)	30 - 50 (5)	11.2 (3)	200 (4)	Fresh (5)	< 0.3 (3)	4.0
Saskatoon (Empress Gr.)	Low to High (3)	20 - 30 (5)	7.0 (5)	Very low vertical (0 - 2), mainly lateral (1)	Fresh (5)	1.6 (1)	3.3
	25%	15%	15%	15%	15%	15%	

^aUndisturbed ground temperature calculated using Equation 1 used as a proxy.

Table 6. Evaluation results and final scores out of 5 for assessing the relative magnitude of UHI in the selected Canadian cities. Cities are listed in descending order of population.

	City population	Maximum temperature of UHI during daytime (°C)	Minimum temperature of UHI during nighttime (°C)	Final score out of 5
Toronto	6,685,621 (5)	30–35 (5)	10–15 (5)	5
Montreal	4,378,796 (5)	30–35 (5)	10–15 (5)	5
Vancouver	2,842,730 (5)	30–35 (5)	10–15 (5)	5
Calgary	1,608,342 (4)	25–30 (3)	5–10 (3)	3.5
Edmonton	1,516,719 (4)	25–30 (3)	5–10 (3)	3.5
Ottawa/Gatineau	1,498,610 (4)	30–35 (5)	10–15 (5)	4.5
Winnipeg	871,778 (3)	30–35 (5)	5–10 (3)	3.5
Quebec City	848,776 (3)	30–35 (5)	10–15 (5)	4
Kitchener /Waterloo /Cambridge	622,497 (3)	30–35 (5)	10–15 (5)	4
Saskatoon	347,536 (2)	25–30 (3)	5–10 (3)	2.5
	50%	25%	25%	

**Figure 1.** Map displaying the open-loop geothermal cooling potential and the UHI magnitude for each Canadian city selected for the evaluation. These qualitative classifications are based on the final scores out of 5 obtained from the evaluation results (4–5 = high, 3–4 = moderate, <3 = Low).

Representativeness is also an important limitation. Our findings are intended as a pre-feasibility assessment that can incentivize further investigations at the site to city scale. We therefore deliberately decided to focus on optimistic scenarios (i.e. most favourable areas) for each city, which are thus not necessarily representative of the whole city. The open-loop geothermal resource assessment study for the City of Ottawa (J.L. Richards & Associates Limited 2021) provides a good illustration of local variations. It revealed that there are many deep (> 150 m) aquifers with high yields, while highlighting significant local variability in hydrogeological conditions. The areas deemed to have high potential were almost all located in the western part of Ottawa and are scattered. The study assessing the heating and cooling potential of a University of British Columbia building in the Vancouver area (Parajulee and

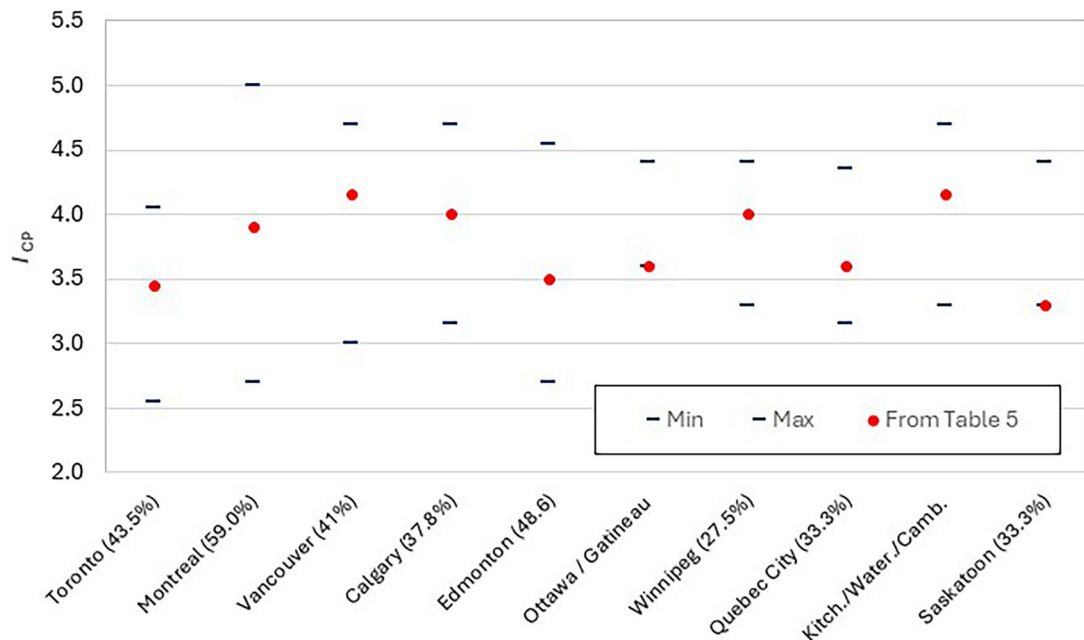


Figure 2. Minimum, average, and maximum values of the cooling potential index for 10 Canadian cities.

Smet 2009) also stressed the great importance of site-scale feasibility studies for the implementation of open-loop systems. Near the proposed site, they found an upper aquifer with freshwater (~ 5 m thick) and a lower aquifer with saline to brackish water (~ 10 m thick), both granular. In our study, the groundwater salinity was considered in Table 5 to be fresh for Vancouver and the mean thickness of the aquifer was also considered higher, based on the other values found in the literature. Therefore, while our study provides useful results for a given city, we acknowledge the need for finer-scale characterization to verify the suitability of local conditions prior to implementation.

In addition, the index developed only takes six parameters into account and could therefore lead to incorrect results for specific areas. For instance, only vertical aquifer recharge from the surface is accounted for in the current index (and not the potential contribution of lateral recharge), which may lead to a negative bias (i.e. underestimation of the potential) in the assessment when the aquifer is confined. A more in-depth examination of hydrogeological conditions and properties would improve the accuracy of suitability assessments, perhaps by using sustainable flow rates in the index. Another limitation stems from groundwater temperature estimation (i.e. using estimated undisturbed ground temperature values as proxy). This most likely underestimates the true value, because the waste heat from urban areas generally increases subsurface temperature (Zhu et al. 2010). Thus, only local studies, ideally including fieldwork with direct temperature measurement in wells, would allow more reliable values to be obtained for a given area.

Moreover, one of the difficulties or challenges lies in assigning a rating to a geological formation when parameter values are widely ranging for that unit beneath the city. The choice of a value (average, or rather pessimistic or optimistic) necessarily leads to biases for specific sites, particularly for hydraulic conductivity, which is given the highest weight in the evaluation. The level of uncertainty increases significantly in these instances. Future data evaluation methods could include a Monte Carlo stochastic analysis to better assess the sensitivity of each parameter.

To provide insight into some of the issues raised above, uncertainty was estimated using the ranges provided in Table 3. Two scenarios were developed based on the minimum and maximum values, and equation 2 and Table 1 were used to estimate a range for the cooling potential index (I_{CP}), reflecting the uncertainty for each city. Several assumptions were made to estimate this uncertainty. When a likely range was available in addition to the general range in Table 3B, the likely range was used for the minimum and maximum values. For hydraulic conductivity, even if the range included values below 10^{-7} m/s, the minimum value assigned to K was 10^{-7} m/s because

below this value, installing such a system would not be worthwhile. For Winnipeg, since no problems have been reported in 80 years but we could not find any values in the literature, the maximum value for iron concentration was set equal to 0.5 mg/L to remain within the limits of ratings 3–5. The I_{CP} results, which include the minimum, average, and maximum values, are presented in Figure 2. Since Table 1 often contains wide ranges of values for a given rating, the minimum and average values are the same for two of the cities. The uncertainty estimated for a given city corresponds to a relative difference ($[\text{max value} - \text{min value}]/\text{mean value}$). Values generally range from 30% to 50%, with an average of 37%; the largest value was obtained for Montreal (59%) and the smallest for Ottawa/Gatineau (22%). Significant uncertainty is thought to reflect a high degree of variability in subsurface conditions.

Other limitations can be highlighted from a more general perspective. For example, our present methodology lacks consideration for current water use in the cities, an important factor to consider when conducting a site-scale study to avoid adding further stress to already water-stressed aquifers. Incorporating this aspect into future studies will help ensure aquifer sustainability beneath large Canadian cities. At present, most cities have limited groundwater withdrawals and/or drawdown regulations in place. However, as geothermal energy systems become more popular, this aspect will need careful consideration, especially since closed-loop systems may also affect groundwater temperature.

The depth to the aquifer was also not factored into our evaluation. This is an influential factor in drilling costs. Future studies should explore this aspect, recognizing that shallower aquifers may offer a more cost-effective option for GWHP or ATEs system implementation.

Assessment of clogging risk may also improve the accuracy of the assessment made. The redox potential and/or oxygen concentration play an important role in iron oxidation and thus in the precipitation of iron oxides. Relatively few data are available in the publications consulted. The iron concentration is not always available either and the values collected from databases or literature do not necessarily specify the valence type. Consequently, in cases where the data correspond to total iron (hence including both soluble Fe^{2+} and insoluble Fe^{3+}), the potential for clogging is likely overestimated.

For all these reasons, the results obtained in this study using the index developed and applied on a city-wide scale should be viewed only as a starting point for more detailed site investigation. In addition, beyond hydrogeological factors, social and political considerations play a pivotal role in GWHP system implementation (Proulx 2023). Future research should encompass these aspects, including public willingness, financial incentives, and subsidies, for a more comprehensive analysis.

Additional considerations

Implementing large-scale open-loop geothermal systems requires careful consideration of various barriers and planning strategies. Several barriers, including regulations, current and projected groundwater use, potential water quality issues including contamination and/or risks of clogging and corrosion due to high iron concentrations, need to be considered for successful implementation (Haehnlein, Bayer, and Blum 2010; Pellegrini et al. 2019). Thermal short-circuiting (when groundwater injected in the aquifer is too rapidly pumped back by the production well, resulting in a gradual decrease of performance) between systems is also a risk that can impact performance and system lifespan. To navigate these challenges effectively, planners must focus on optimizing the spacing between open-loop systems based on hydrogeological conditions and properties (Bloemendal, Jaxa-Rozen, and Olsthoorn 2018). This is especially relevant for dense urban areas, as systems near each other are more susceptible to thermal ‘contamination’.

For the optimal and sustainable use of the subsurface, it is also important to monitor a given system and collect extensive data (e.g. drawdown, groundwater temperature, iron concentration) during its operation so that open-loop systems can operate effectively over the long term (Bloemendal, Olsthoorn, and Boons 2014). For instance, the presence of iron precipitates can be managed by various prevention or treatment methods, such as continuous abstraction and monthly well disinfection (van Beek 2010).

Fujita et al. (2022) have recently shown that low-cost and eco-friendly filtering materials like wood charcoal can effectively adsorb iron and minimize clogging.

Dual-purpose wells, serving as both a drinking water resource and an open-loop geothermal system, present an opportunity for financial viability, provided the well has the capacity to meet both needs. In cases where test drilling reveals insufficient aquifer yield, conversion to a closed-loop system may be a practical solution, although the financial viability would have to be considered. Indeed, close-loop systems can face challenges related to high capital costs and space issues given that several wells are often required since they are less efficient than open-loop systems. Project financing, including government guaranteed loans, can contribute significantly to improving economic performance (Nguyen, Tamasauskas, and Kegel 2022; Proulx 2023).

As decision-makers explore the feasibility of GWHP and ATEs systems in Canada, these considerations offer valuable insights for planning and implementation, contributing to the overarching goal of mitigating UHI.

Conclusions

In this study, we evaluated 10 Canadian cities to assess the implementation potential of open-loop geothermal systems, specifically GWHP technology, for space cooling. The methodology involved the development of an evaluation tool in the form of an index based on six hydrogeological suitability criteria. This index aims to provide a suitability score by establishing threshold values for each criterion on a 5-point rating scale and assigning a weight to each one. Cities were chosen based on population size and their likelihood of encountering UHI estimated from maximum daytime and night-time temperatures. Our conclusions are summarized as follows:

- All selected 10 Canadian cities (Toronto, Montreal, Vancouver, Calgary, Edmonton, Ottawa/Gatineau, Winnipeg, Quebec City, Kitchener/Waterloo/Cambridge, and Saskatoon) exhibit moderately to highly favorable conditions for the implementation of open-loop geothermal technology for space cooling.
- The identified limitations include poor data availability, emphasizing the importance of hydrogeological characterization beneath cities and site-specific assessment.
- While promising, the results obtained with the developed index need to be viewed as a first step, as they used mean values for an entire city. Except for the City of Winnipeg, relatively few projects have been reported in the scientific literature in Canada.
- Comprehensive considerations regarding system and well spacing, water composition and groundwater usage, as well as regulations and social context are needed to pave the way for sustainable and efficient implementation in the Canadian urban landscape.

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Author contributions

CRedit: **Victoria Lee**: Formal analysis, Methodology, Writing – original draft; **Christine Rivard**: Investigation, Supervision, Writing – original draft, Writing – review & editing; **Jasmin Raymond**: Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Writing – review & editing; **Michel Parent**: Investigation, Writing – original draft; **Denis Lavoie**: Investigation, Writing – review & editing; **Félix-Antoine Comeau**: Methodology, Project administration, Writing – review & editing; **Juliet Newson**: Supervision, Writing – review & editing.

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References

- Abesser, Corinna, Melinda A. Lewis, Andrew P. Marchant, and Andrew G. Hulbert. 2014. "Mapping Suitability for Open-Loop Ground Source Heat Pump Systems: A Screening Tool for England and Wales, UK." *Quarterly Journal of Engineering Geology and Hydrogeology* 47 (4): 373–380. <https://doi.org/10.1144/qjegh2014-050>.
- Allen, Diana M. 1998. "Steady-State and Transient Hydrologic, Thermal and Chemical Modelling of a Faulted Carbonate Aquifer Used for Aquifer Thermal Energy Storage, Carleton University, Ottawa, Canada." PhD, Carleton University."
- Aller, Linda, Truman Bennet, Jay H. Lehr, and Rebecca Petty. 1987. "DRASTIC: Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings." Office of Research and Development, Environmental Protection Agency. <http://rdn.bc.ca/cms/wpattachments/wpID3175atID5999.pdf>.
- Bajc, Andy F., Hazen A. J. Russell, and David R. Sharpe. 2014. "A Three-Dimensional Hydrostratigraphic Model of the Waterloo Moraine Area, Southern Ontario, Canada." *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques* 39 (2): 2. <https://doi.org/10.1080/07011784.2014.914794>.
- Bélanger, Randy. 2008. "Urban Geology of the National Capital Area. Geological Survey of Canada, Open File." 5311, Natural Resources Canada. <https://doi.org/10.4095/226165>.
- Blackport, Ray J., Patricia A. Meyer, and Paul J. Martin. 2014. "Toward an Understanding of the Waterloo Moraine Hydrogeology." *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques* 39 (2): 2. <https://doi.org/10.1080/07011784.2014.914795>.
- Bloemendal, Martin, and Theo Olsthoorn. 2018. "ATES Systems in Aquifers with High Ambient Groundwater Flow Velocity." *Geothermics* 75: 81–92. <https://doi.org/10.1016/j.geothermics.2018.04.005>.
- Bloemendal, Martin, Marc Jaxa-Rozen, and Theo Olsthoorn. 2018. "Methods for Planning of ATES Systems." *Applied Energy* 216: 534–557. <https://doi.org/10.1016/j.apenergy.2018.02.068>.
- Bloemendal, Martin, T. N. Olsthoorn, and Frank Boons. 2014. "How to Achieve Optimal and Sustainable Use of the Subsurface for Aquifer Thermal Energy Storage." *Energy Policy* 66: 104–114. <https://doi.org/10.1016/j.enpol.2013.11.034>.
- Bloemendal, Martin, Theo Olsthoorn, and Frans van de Ven. 2015. "Combining Climatic and Geo-Hydrological Preconditions as a Method to Determine World Potential for Aquifer Thermal Energy Storage." *The Science of the Total Environment* 538: 621–633. <https://doi.org/10.1016/j.scitotenv.2015.07.084>.
- Blum, Philipp, Gisela Campillo, Wolfram Münch, and Thomas Kölbl. 2010. "CO₂ Savings of Ground Source Heat Pump Systems – A Regional Analysis." *Renewable Energy* 35 (1): 122–127. <https://doi.org/10.1016/j.renene.2009.03.034>.
- Burté, Luc, Charles A. Cravotta, Lorine Bethencourt, Julien Farasin, Mathieu Pédrot, Alexis Dufresne, Marie-Françoise Gérard, et al. 2019. "Kinetic Study on Clogging of a Geothermal Pumping Well Triggered by Mixing-Induced Biogeochemical Reactions." *Environmental Science & Technology* 53 (10): 5848–5857. <https://doi.org/10.1021/acs.est.9b00453>.
- Carmichael, Vicky, Mike Wei, and Lee Ringham. 1995. "Fraser Valley Groundwater Monitoring Program Final Report." Ground Water Section, Water Management Branch, Ministry of Environment, Province of British Columbia, report 5951. https://a100.gov.bc.ca/pub/acat/documents/r5951/1427_1143661621641_d2e6a53e208f46cfb61ae6eb67fa6741.pdf.
- Center For International Earth Science Information Network-CIESIN-Columbia University. 2016. *Global Urban Heat Island (UHI) Data Set, 2013*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). <https://doi.org/10.7927/H4H70CRF>.
- Comeau, G., Talbot Poulin, M.C., Tremblay, Y., Ayotte, S., Molson, J., Lemieux, J.M., Montcoudiol, N., Therrien, R., Fortier, R., Therrien, P., Fabien-Ouellet, G. (2013). *Projet d'acquisition de connaissances sur les eaux souterraines en Outaouais, Rapport final*. Département de géologie et de génie géologique, Université Laval, juillet 2013, 148 pages, 24 annexes, 25 cartes. https://www.environnement.gouv.qc.ca/_PACES/rapports-projets/Outaouais/OUT-scientif-ULAVAL-201307.pdf.
- Cummings, Don I., Hazen A. J. Russell, and David R. Sharpe. 2012. "Buried-Valley Aquifers in the Canadian Prairies: Geology, Hydrogeology, and Origin", Earth Science Sector (ESS) Contribution 20120131." *Canadian Journal of Earth Sciences* 49 (9): 987–1004. <https://doi.org/10.1139/e2012-041>.

- Environment and Climate Change Canada. 2022. "Canadian Climate Normals—1981-2010 Climate Normals & Averages." https://climate.weather.gc.ca/climate_normals/index_e.html.
- EPA. 1990. "New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers." report EPA/600/2-90/002, 235.
- Ferguson, Grant, and Allan Woodbury. 2006. "Observed Thermal Pollution and Post-Development Simulations of Low-Temperature Geothermal Systems in Winnipeg, Canada." *Hydrogeology Journal* 14 (7): 1206–1215. <https://doi.org/10.1007/s10040-006-0047-y>.
- Ferguson, Grant. 2012. "Characterizing Uncertainty in Groundwater-Source Heating and Cooling Projects in Manitoba, Canada." *Energy* 37 (1): 201–206. <https://doi.org/10.1016/j.energy.2011.11.045>.
- Fortin, G., G. van der Kamp, and J. A. Cherry. 1991. "Hydrogeology and Hydrochemistry of an Aquifer-Aquitard System within Glacial Deposits, Saskatchewan, Canada." *Journal of Hydrology* 126 (3–4): 265–292. [https://doi.org/10.1016/0022-1694\(91\)90160-J](https://doi.org/10.1016/0022-1694(91)90160-J).
- Foster, Simon B., and Diana M. Allen. 2015. "Groundwater—Surface Water Interactions in a Mountain-to-Coast Watershed: Effects of Climate Change and Human Stressors." *Advances in Meteorology* 2015 (October): e861805–22. <https://doi.org/10.1155/2015/861805>.
- Freeze, R. Allan, and John A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice Hall, 604 p.
- Fujita, Claudia, M. Shahbaz Akhtar, Ray Hidaka, and Makoto Nishigaki. 2022. "Mitigation of Groundwater Iron-Induced Clogging by Low-Cost Bioadsorbent in Open Loop Geothermal Heat Pump Systems." *Applied Water Science* 12: 30. <https://doi.org/10.1007/s13201-022-01574-x>.
- Grasby, Stephen E., Anthony Hamblin, Zhuoheng Chen, Arthur Sweet, Glen Stockmal, and Paul Wosniak. 2004. "Regional Groundwater Water Study of the Paskapoo Formation, SW Alberta." Paper presented at 57TH Canadian Geotechnical Conference and 5TH joint CGS/IAH-CNC Conference.
- Grasby, Stephen E., Zhuoheng Chen, Anthony P. Hamblin, Paul, R. J. Wozniak, and Arthur R. Sweet. 2008. "Regional Characterization of the Paskapoo Bedrock Aquifer System, Southern Alberta." *Canadian Journal of Earth Sciences* 45 (12): 12. <https://doi.org/10.1139/E08-069>.
- Groundwater Information Network. 2024. Accessed January 2024. <http://gw-info.net>.
- Haehnlein, Stefanie, Peter Bayer, and Philipp Blum. 2010. "International Legal Status of the Use of Shallow Geothermal Energy." *Renewable and Sustainable Energy Reviews* 14 (9): 2611–2625. <https://doi.org/10.1016/j.rser.2010.07.069>.
- Hayashi, Masaki, and Christopher R. Farrow. 2014. "Watershed-Scale Response of Groundwater Recharge to Inter-Annual and Inter-Decadal Variability in Precipitation (Alberta, Canada)." *Hydrogeology Journal* 22 (8): 1825–1839. <https://doi.org/10.1007/s10040-014-1176-3>.
- Howard, Ken W. F., Nicholas Eyles, Philip J. Smart, et al. 1995. "The Oak Ridges Moraine of Southern Ontario: A Ground-Water Resource at Risk". Geoscience Canada." September 9. <https://journals.lib.unb.ca/index.php/GC/article/view/3878>.
- J.L. Richards & Associates Limited. 2021. "Open Loop Geothermal Resource Scoping Study." 27623–27020.
- Kavanaugh, Steve, and Kevin Rafferty. 2014. *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, 420 p., ISBN 1936504855
- Kehler, Marcus Henry. 2022. *Regional Groundwater Modelling for Flow Analysis and Investigation of Alternative Water Resources in the Edmonton Region*. Alberta: University of Alberta.
- Kennedy, Paula L., and Allan D. Woodbury. 2005. "Sustainability of the Bedrock Aquifer Systems in South-Central Manitoba: Implications for Large-Scale Modelling." *Canadian Water Resources Journal* 30 (4): 281–296. <https://doi.org/10.4296/cwrj3004281>.
- Kranz, Stefan, and Stephanie Frick. 2013. "Efficient Cooling Energy Supply with Aquifer Thermal Energy Storages." *Applied Energy* 109: 321–327. <https://doi.org/10.1016/j.apenergy.2012.12.002>.
- Lamarche, Lise, Michel Parent, René Lefebvre, and Didier Perret. 2008. "3D Geological Model of a Deltaic Aquifer System Formed in a Buried Channel of the St. Lawrence River in Quebec City, Canada." 8.
- Lepage, Nicolas. 1996. "Modélisation Tridimensionnelle Régionale et Locale de L'écoulement de L'eau Souterraine Sur L'île de Montréal et au Centre de Tri et D'Élimination Des Déchets de la Ville de Montréal" Masters." Université du Québec, Institut national de la recherche scientifique. <http://espace.inrs.ca/1841/>.
- Lu, Hongwei, Peipei Tian, Yanlong Guan, and Sen Yu. 2019. "Integrated Suitability, Vulnerability and Sustainability Indicators for Assessing the Global Potential of Aquifer Thermal Energy Storage." *Applied Energy* 239: 747–756. <https://doi.org/10.1016/j.apenergy.2019.01.144>.
- Lund, John W., and Aniko N. Toth. 2021. "Direct Utilization of Geothermal Energy 2020 Worldwide Review." *Geothermics* 90: 101915. <https://doi.org/10.1016/j.geothermics.2020.101915>.
- Magli, Susanna, Chiara Lodi, Luca Lombroso, Alberto Muscio, and Sergio Teggi. 2015. "Analysis of the Urban Heat Island Effects on Building Energy Consumption." *International Journal of Energy and Environmental Engineering* 6 (1): 91–99. <https://doi.org/10.1007/s40095-014-0154-9>.
- Martin, P. J., and E. G. Frind. 1998. "Modeling a Complex Multi-Aquifer System: The Waterloo Moraine." *Groundwater* 36 (4): 679–690. <https://doi.org/10.1111/j.1745-6584.1998.tb02843.x>.

- Matthews, Vance A. 2011. "Stochastic Modeling of the Paskapoo Formation. xvi, 213 Leaves: Ill.; 30 cm. xvi, 213 Leaves: Ill.; 30 cm." <https://doi.org/10.11575/PRISM/22504>.
- McGeehin, Michael A., and Maria Mirabelli. 2001. "The Potential Impacts of Climate Variability and Change on Temperature-Related Morbidity and Mortality in the United States." *Environmental Health Perspectives, Ahead of Print* 109: 185. <https://doi.org/10.2307/3435008>.
- MDH. 2011. "Hydrogeology Mapping of NTS Map Sheet Saskatoon 73B." M1890-1030109. <https://www.wsask.ca/wp-content/uploads/2021/08/Hydrogeology-Mapping-Saskatoon.pdf>.
- Menberg, Kathrin, Hannes Hemmerle, Peter Bayer, Christoph Bott, Asal Bidarmaghz, Grant Ferguson, Martin Bloemendal, and P. Philipp Blum. 2025. "Opportunities, Benefits and Impacts of Shallow Geothermal Energy." *Nature Reviews Earth & Environment* 6 (12): 808–823. <https://doi.org/10.1038/s43017-025-00736-0>.
- Meriano, Mandana. 1999. "Hydrogeology of a Complex Glacial System, Rouge River." Highland Creek watershed, Scarborough, Ontario, MSc thesis, University of Toronto, 99 pages.
- Minea, Vasile. 2022. "Heating and Cooling with Ground-Source Heat Pumps in Cold and Moderate Climates: Fundamentals and Basic Concepts." First edition. 1 online resource (xv, 379 pages): illustrations. CRC Press. <https://www.taylorfrancis.com/books/9781003032540>.
- Mohanta, A., N. Nandkeolyar, B. Banerjee, S. Rajput, A. Baldaniya, N. Nimavat, S. Kundu, S. K. Saha, and H. S. Kumar. 2025. "Advanced Optimization Techniques for Parameter Calibration in the DRASTIC Model: A Multi-Criteria Decision Analysis Approach to Groundwater Vulnerability Assessment." In *Progress in Multicriteria Decision Making Models. Advances in Geographic Information Science*, edited by Das, J., Halder, S. Cham: Springer. https://doi.org/10.1007/978-3-031-89246-2_16.
- Moonen, Peter, Thijs Defraeye, Viktor Dorer, Bert Blocken, and Jan Carmeliet. 2012. "Urban Physics: Effect of the Micro-Climate on Comfort, Health and Energy Demand." *Frontiers of Architectural Research* 1 (3): 197–228. <https://doi.org/10.1016/j.foar.2012.05.002>.
- Moran, S. 1985. "Surficial Geology of the Calgary Urban Area. ARC/AGS Bulletin 53." Alberta Geological Survey. <https://ags.aer.ca/publication/bul-053>.
- National Energy Use Database (NEUD). 2021. "The Office of Energy Efficiency, Natural Resources Canada." https://oe.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/databases.cfm.
- Natural Resources Canada. 2015. "Surficial Geology Index Map." <https://open.canada.ca/data/en/dataset/5887347a-f64d-c5e6-b983-8cace169313b>.
- Natural Resources Canada. 2022. <https://oe.nrcan-nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB§or=res&juris=00&rn=14&year=2020&page=4>
- Natural Resources Canada. 2024. "Bedrock Geology Index Map." <https://open.canada.ca/data/en/dataset/cebc283f-bae1-4eae-a91f-a26480cd4e4a>.
- Neilson-Welch, Laurie A. 1999. "Saline Water Intrusion from the Fraser River Estuary: A Hydrogeological Investigation Using Field Chemical Data and a Density-Dependent Groundwater Flow Model." M.Sc. thesis, University of British Columbia, Vancouver, BC, 209 p. <http://hdl.handle.net/2429/9050>
- Nguyen, A., J. Tamasauskas, and M. Kegel. 2022. "A Method for Fast Economic Optimization of Large Hybrid Ground Source Heat Pump Systems." *Geothermics* 104: 102473. <https://doi.org/10.1016/j.geothermics.2022.102473>.
- Ontario Ministry of Mines. 2024. "Ontario Ministry of Mines Database." <https://www.hub.geologyontario.mines.gov.on.ca/>.
- Ontario Ministry of the Environment, Conservation and Parks. 2024. "Provincial Groundwater Monitoring Network." <https://data.ontario.ca/dataset/provincial-groundwater-monitoring-network>.
- Ouzzane, Mohamed, Parham Eslami-Nejad, Messaoud Badache, and Zine Aidoun. 2015. "New Correlations for the Prediction of the Undisturbed Ground Temperature." *Geothermics* 53: 379–384. <https://doi.org/10.1016/j.geothermics.2014.08.001>.
- Parajulee, Abha, and Kim Smet. 2009. "A Pre-Feasibility Study to Assess the Potential of Open Loop Ground Source Heat to Heat and Cool the Proposed Earth Science Systems Building at the University of British Columbia." <https://doi.org/10.14288/1.0053585>.
- Pellegrini, M., M. Bloemendal, N. Hoekstra, G. Spaak, A. Andreu Gallego, J. Rodriguez Comins, T. Grotenhuis, et al. 2019. "Low Carbon Heating and Cooling by Combining Various Technologies with Aquifer Thermal Energy Storage." *The Science of the Total Environment* 665: 1–10. <https://doi.org/10.1016/j.scitotenv.2019.01.135>.
- Possemiers, Mathias, Marijke Huysmans, and Okke Batelaan. 2014. "Influence of Aquifer Thermal Energy Storage on Groundwater Quality: A Review Illustrated by Seven Case Studies from Belgium." *Journal of Hydrology: Regional Studies* 2: 20–34. <https://doi.org/10.1016/j.ejrh.2014.08.001>.
- Prest, Victor Kent, and Joseph Hode Keyser. 1977. "Geology and Engineering Characteristics of Surficial Deposits: Montreal Island and Vicinity, Quebec." (75–27): 29–pages25. Geological Survey of Canada, Paper, 75-27, 29 p., Energy, Mines and Resources Canada, ISBN 0660008106
- Proulx, Myriam. 2023. "Une Transition Enfouie Sous Terre? L'énergie Géothermique Partagée en Milieu Urbain au Québec: Le Parcours de Cinq Projets Entre Émergence, Motivations et Contraintes." MSc thesis,

- Université du Québec, Institut national de la recherche scientifique, Centre Urbanisation Culture Société, Montréal, QC, 144 p.
- Rubin, Allison D. 2022. "Pre-Laurentide and Deglacial History of the Edmonton Region, Alberta, Canada." MSc thesis, University of Alberta, <https://doi.org/10.7939/r3-s73c-6n29>, <https://ualberta.scholaris.ca/items/c3bedb0f-ca26-4e0a-ac50-c95f6b9a762e>
- Salamanca, F., M. Georgescu, A. Mahalov, M. Moustauoui, and M. Wang. 2014. "Anthropogenic Heating of the Urban Environment Due to Air Conditioning." *Journal of Geophysical Research: Atmospheres* 119 (10): 5949–5965. <https://doi.org/10.1002/2013JD021225>.
- Sanchez-Vila, Xavier, Alberto Guadagnini, and Jesus Carrera. 2006. "Representative Hydraulic Conductivities in Saturated Groundwater Flow." *Reviews of Geophysics* 44 (3): 1–46. <https://doi.org/10.1029/2005RG000169>.
- Savard, M. M., M. Nastev, D. Paradis, et al. 2013. "Canadian Inventory of Groundwater Resources." *Integrated Regional Hydrogeological Characterization of the Fractured Aquifer System of Southwestern Quebec Geological Survey of Canada, Bulletin* 587 (114), 102 p.
- Schibuola, Luigi, and Chiara Tambani. 2022. "Environmental Impact and Energy Performance of Groundwater Heat Pumps in Urban Retrofit." *Energy and Buildings* 261 (April): 111964. <https://doi.org/10.1016/j.enbuild.2022.111964>.
- Sciakovelli, A., E. Guelpa, and V. Verda. 2014. "Multi-Scale Modeling of the Environmental Impact and Energy Performance of Open-Loop Groundwater Heat Pumps in Urban Areas." *Applied Thermal Engineering, Special Issue: MICROGEN III: Promoting the Transition to High Efficiency Distributed Energy Systems* 71 (2): 780–789. <https://doi.org/10.1016/j.applthermaleng.2013.11.028>.
- Sharpe, D. R., A. Pugin, S. E. Pullan, and G. Gorrell. 2003. "Application of Seismic Stratigraphy and Sedimentology to Regional Hydrogeological Investigations: An Example from Oak Ridges Moraine, Southern Ontario, Canada." *Canadian Geotechnical Journal* 40 (4): 711–730. <https://doi.org/10.1139/t03-020>.
- Sharpe, David R., Hazen A. J. Russell, and C. Logan. 2007. "A 3-Dimensional Geological Model of the Oak Ridges Moraine Area, Ontario, Canada." *Journal of Maps* 3 (1): 239–253. <https://doi.org/10.1080/jom.2007.9710842>.
- Shi, Min, Yuesuo Yang, Dianlong Wang, Yuhui Wu, Xi Zhang, and Ying Lu. 2025. "Iron Clogging Mechanism around Injection Wells during Groundwater Recharge in Shallow Iron-Rich Aquifer: Insight from Spatiotemporal Evolution." *Water Research* 283: 123778. <https://doi.org/10.1016/j.watres.2025.123778>.
- Sloan, M., J. A. Gillies, and D. I. Norum. 1991. "Using Poor Quality Groundwater for Irrigation in Saskatchewan, Canada." *Canadian Water Resources Journal* 16 (1): 45–64. <https://doi.org/10.4296/cwrj1601045>.
- Statistics Canada. 2022. "Environmental Thematic Maps and Graphics: Average Annual Temperature, by Ecoprovince." 1979 to 2016. <https://www150.statcan.gc.ca/n1/pub/38-20-0001/2021001/102-eng.htm>.
- Statistics Canada. 2023a. "Air Conditioning: More Canadians Keep Cool, but Costs Heat up." <https://www.statcan.gc.ca/o1/en/plus/4034-air-conditioning-more-canadians-keep-cool-costs-heat>.
- Statistics Canada. 2023b. "Table 17-10-0135-01 Population Estimates, July 1, by Census Metropolitan Area and Census Agglomeration, 2016 Boundaries." <https://doi.org/10.25318/1710013501-eng>.
- Statistics Canada. 2025. "A Heated Discussion: Who Uses Air Conditioning in Canada in 2025?" <https://www150.statcan.gc.ca/n1/daily-quotidien/250708/dq250708a-eng.htm>
- Stemmle, Ruben, Philipp Blum, Simon Schüppler, Paul Fleuchaus, Melissa Limoges, Peter Bayer, Kathrin Menberg, et al. 2021. "Environmental Impacts of Aquifer Thermal Energy Storage (ATES)." *Renewable and Sustainable Energy Reviews* 151: 111560. <https://doi.org/10.1016/j.rser.2021.111560>.
- Susanto, Sylvia. 2019. "Assessment of Geothermal Energy Extracted from Upper Carbonate Aquifer beneath the City of Winnipeg." <https://mspace.lib.umanitoba.ca/xmlui/handle/1993/33819>.
- Talbot Poulin, M. C., G. Comeau, Y. Tremblay, R. Therrien, M. M. Nadeau, J. M. Lemieux, J. Molson, et al. 2013. *Projet D'acquisition de Connaissances Sur Les Eaux Souterraines du Territoire de la Communauté Métropolitaine de Québec, Rapport Final*. Département de géologie et de génie géologique, Université Laval, Québec, QC, mars 2013, 172 p., 19 annexes, 28 cartes. <https://cmquebec.qc.ca/wp-content/uploads/2018/11/2013-09-01-paces-cmq-rapp-fin.pdf>
- Uejio, Christopher K., Olga V. Wilhelmi, Jay S. Golden, David M. Mills, Sam P. Gulino, and Jason P. Samenow., 2011. "Intra-Urban Societal Vulnerability to Extreme Heat: The Role of Heat Exposure and the Built Environment, Socioeconomics, and Neighborhood Stability." *Health & Place* 17 (2): 498–507. <https://doi.org/10.1016/j.healthplace.2010.12.005>.
- van Beek, C. G. E. M. 2010. "Cause and Prevention of Clogging of Wells Abstracting Groundwater from Unconsolidated Aquifers." PhD thesis, Vrije Universiteit Amsterdam. <https://research.vu.nl/en/publications/cause-and-prevention-of-clogging-of-wells-abstracting-groundwater/>.
- Vujovic, Svetlana, Bechara Haddad, Hamzé Karaky, Nassim Sebaibi, and Mohamed Boutouil. 2021. "Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements." *CivilEng* 2 (2): 459–484. <https://doi.org/10.3390/civileng2020026>.

- Wilson, Stephen, Anthony West, Jaime Oxtobee, and Brian Stratton. 2009. "Groundwater Vulnerability Study - March/Nepean Formation Aquifer."
- Wong, C. S. Y., J. Comte, J. Raymond, C. Rivard, and G. Bordeleau. 2025. "Spatiotemporal Geochemical Evolution of Groundwater through an Open Loop Geothermal System – a Pilot Field Study, Submitted to." *Groundwater for Sustainable Development* 31: 101525. <https://doi.org/10.1016/j.gsd.2025.101525>.
- Zhu, Ke., Philipp Blum, Grant Ferguson, Klaus-Dieter Balke, and Peter Bayer. 2010. "The Geothermal Potential of Urban Heat Islands." *Environmental Research Letters* 5 (4): 044002. <https://doi.org/10.1088/1748-9326/5/4/044002>.
- Zhu, Lin, Huili Gong, Yun Chen, Xiaojuan Li, Xiang Chang, and Yijiao Cui. 2016. "Improved Estimation of Hydraulic Conductivity by Combining Stochastically Simulated Hydrofacies with Geophysical Data." *Scientific Reports* 6: 22224. <https://doi.org/10.1038/srep22224>.
- Zuurbier, Koen G., Niels Hartog, Johan Valstar, Vincent E. A. Post, and Boris M. van Breukelen. 2013. "The Impact of Low-Temperature Seasonal Aquifer Thermal Energy Storage (SATES) Systems on Chlorinated Solvent Contaminated Groundwater: Modeling of Spreading and Degradation." *Journal of Contaminant Hydrology* 147 (April): 1–13. <https://doi.org/10.1016/j.jconhyd.2013.01.002>.

Annex A

Summary of most influential factors determined by Bloemendal, Olsthoorn, and van de Ven (2015) and Lu et al. (2019).

- a. Occurrence and type of aquifer
 - i. Major granular aquifer (with high hydraulic conductivity)
 - ii. Local and shallow (less than 50 m deep)
 - iii. Complex hydrological structure (e.g. fractured or karstified rock aquifers with highly variable conditions)
- b. Aquifer yield
- c. Groundwater recharge rate
- d. Groundwater salinity (fresh, brackish or saline)
- e. Water quality (chemical composition and pollution level)
- f. Amount of stress on the groundwater supply
- g. Average annual outside air temperature (to assess the energy balance between cooling and heating demand)
 - i. $> 25^{\circ}\text{C}$: Only cooling demand, no heating demand
 - ii. $[20\text{--}25]^{\circ}\text{C}$: Predominant cooling demand, low heating demand
 - iii. $[15 - 20]^{\circ}\text{C}$: Heating and cooling demand (more or less) balance
 - iv. $[10\text{--}15]^{\circ}\text{C}$: Predominant heating demand, low cooling demand
 - v. $< 10^{\circ}\text{C}$: Only heating demand, no cooling demand