Estimation of Direct Groundwater Discharge and Salt (NaCl) Loading to the north shore of Lake Ontario

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By

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1. INTRODUCTION

1.1 Project Outline

Although the Great Lakes have been well studied for decades, there remains considerable uncertainty regarding the direct connection between the lakes and the groundwater flow systems that interact with the lakes. To date groundwater – surface water interaction research has generally focused on investigating localized discharge of groundwater and loadings via groundwater to streams and rivers. In the Great Lakes context this groundwater is referred to as indirect discharge of groundwater to the Great Lakes. Another input of interest is direct discharge of groundwater to the lakes. This refers to groundwater that discharges across the littoral zone. How much groundwater moves directly into the lakes? Are there dissolved parameters in the groundwater discharging directly to the lakes that are having an impact on water quality along the shorelines and in the nearshore areas? A thorough review of road salt issues along the north shore of Lake Ontario is provided in Mackie et al., (2022). A comprehensive presentation of chloride (Cl^-) concentration and trends in surface and groundwater in Ontario is provided in Sorichetti et al., (2022).

The objectives of this project are to provide improved scientific understanding and communication of:

1) Regional direct and indirect groundwater discharge to the northern shore of the western Lake Ontario Basin associated with the groundwater flow system situated between the Oak Ridges Moraine (ORM) south to Lake Ontario, capitalizing on the existing groundwater data and knowledge assembled and managed by the Oak Ridges Moraine Groundwater Program (ORMGP); and
2) Associated Cl^- loadings from the groundwater system to Lake Ontario in this area.

It is anticipated that this knowledge will assist future updates of the Great Lakes Water Quality Agreement (GLWQA) Annex prepared by the United States and Canada (Grannemann and Van Stempvoort, 2016), specifically the estimation of the role of groundwater in influencing the water quality within the Great Lakes.

The Oak Ridges Moraine Groundwater Program (ORMGP) was initiated in 2001 with an overarching goal of consolidating and making accessible groundwater related data, and to make use of this data to understand groundwater flow dynamics more fully within the program study area. This knowledge can then be applied to any number of water resource management initiatives of partner agencies which include municipal level government and conservation authorities. Many consulting companies in the area are also making use of the groundwater data, information, analyses, and knowledge held in the ORMGP. Well underway through the program, and of central importance, is the capture of institutional knowledge and ongoing hydrogeological data collection, management, and analyses (oakridgeswater.ca).

1.2 Physical Setting

The ORMGP study area occurs within the Southern Ontario portion (Sharpe *et al.,* 2014a) of the St. Lawrence Lowlands Hydrogeologic Region (Heath, 1988). Climate is humid continental with warm summers and cold winters influenced by proximity to the Great Lakes

(Brown, 1967, Farvolden and Cherry, 1988; Sharpe *et al*., 2014a, 2014b). Hydrogeologic regions have similar geologic and hydrogeologic characteristics (Brown, 1967; Heath, 1988; Farvolden and Cherry, 1988). The study area is mostly underlain by gently dipping unfolded Paleozoic sedimentary rocks underlying up to 250 m thick unconsolidated Quaternary glacial and interglacial sediments (Figure 1). Thicker glacial sediments are found associated with moraines (e.g., Oak Ridges and Oro) as well as deep bedrock valleys (e.g., Laurentian valley or trough). In the United States Quaternary aquifer systems (Meinzer, 1923) are subdivided into hydrogeologic terranes of "lower" to "higher" complexity based on relative sediment thickness (Haj *et al*., 2018; Yager *et al*., 2019). The Oak Ridges Moraine area would fall into a "higher" complexity Quaternary hydrogeologic terrane based on a thick stratified moraine sediment package. Stratified moraines are rare in glaciated terrain yet are common in Southern Ontario. The stratified Waterloo and Oak Ridges moraines are also very unusual in that they contain extensive, high-capacity aquifers consisting of sands and gravels, surrounded by low hydraulic conductivity sediment (Farvolden and Cherry, 1988).

The Oak Ridges Moraine (ORM) is a west-east ridge of sandy land extending approximately 160 km parallel to, and just north of the Lake Ontario shoreline, within south-central Ontario (Figure 2). The ridge rises to a maximum elevation of approximately 400 metres above sea level (masl) which is 325 m above the average water level of Lake Ontario (approximately 75 masl). The ORM area, home to some 5 to 6 million people, has extensive rural farmlands as well as densely populated urban centres across low relief to hilly terrain. Aquifers associated with the ORM serve as important groundwater sources of drinking water and they also maintain baseflow for the many headwater streams that emanate from the moraine.

The ORM aquifer system functions as an elevated reservoir that distributes water from sandy uplands, via surface and subsurface flow, to Lake Simcoe (to the north) and Lake Ontario (to the south; Figure 3). The simplified hydrogeologic model reflected in Figure 3, consists of three main aquifer and aquitard elements that control the ORM groundwater flow system, with shallow and deep aquifers separated by the regional Newmarket Till aquitard, deposited during the last glacial maximum ~20k years ago. The major shallow aquifer includes the ORM ridge landform and associated higher permeability ORM channels. The ORM landform and the underlying ORM channels form an integrated aquifer system consisting of 80 cubic km of stratified sediment (Sharpe *et al.,* 2007). Downward vertical flow to the deeper Lower Sediments (LS) is inhibited by the Newmarket till coupled with a semi-continuous Thorncliffe Formation mud layer, with vertically downward flow estimated to average approximately 50 mm/year on a regional basis (Gerber and Howard, 2000).

Two regionally interpreted deep aquifers occur within the Thorncliffe and Scarborough Formations of the Lower Sediment lacustrine and fluvial deposits. Higher permeability zones occur within Thorncliffe channels which serve as important water supply aquifers (Gerber et al., 2018). An extensive deep bedrock valley, the Laurentian valley or trough, stretches some 200 km between Georgian Bay and Lake Ontario (Figure 1) and forms a multi-tiered sediment package containing these three main aquifers (Sharpe et al., 2018). Other minor units within Lower Sediment provide heterogeneity that influences the groundwater flow system.

Three important aquitards control flow to the identified aquifer systems (Figure 3): Halton Till and surficial glaciolacustrine deposits, Newmarket Till, and Sunnybrook Drift. When combined with the extensive and thick glaciolacustrine Thorncliffe and Scarborough Formation muds, the entire sediment package is found to contain considerable thicknesses of low permeability sediment. Along the south flank of the moraine, the Halton Till laps onto and partly confines flow in the ORM landform, helping to produce springs at the topographic break in slope.

The Quaternary sediment succession is underlain by shale and limestone (Ontario Geological Survey, 2006) characterized as having low hydraulic conductivity. The regional bedrock is largely considered to also function as an aquitard. Figure 4 illustrates the interpreted thickness of Quaternary sediments along the Lake Ontario shoreline. Two areas, the Scarborough Bluffs and the Bowmanville-Port Granby bluffs, have Quaternary sediment thickness that exceeds 50m. Note that bedrock valleys have been mapped extending to the Lake Ontario shoreline, with the deepest one being the Laurentian valley system in the Toronto area where sediment thickness occurs up to 100 m. The exact location and morphology of bedrock valleys, along with their hydraulic interaction with the lake, remains inexact, and continues to be investigated and refined.

Understanding how this multi-tiered aquifer system functions is paramount to water management and the development of sustainable water resources management policies for this part of Ontario. And in turn, effective water management within the broad Oak Ridges Moraine area is enabled by utilizing the high-quality ORMGP hydrogeological database.

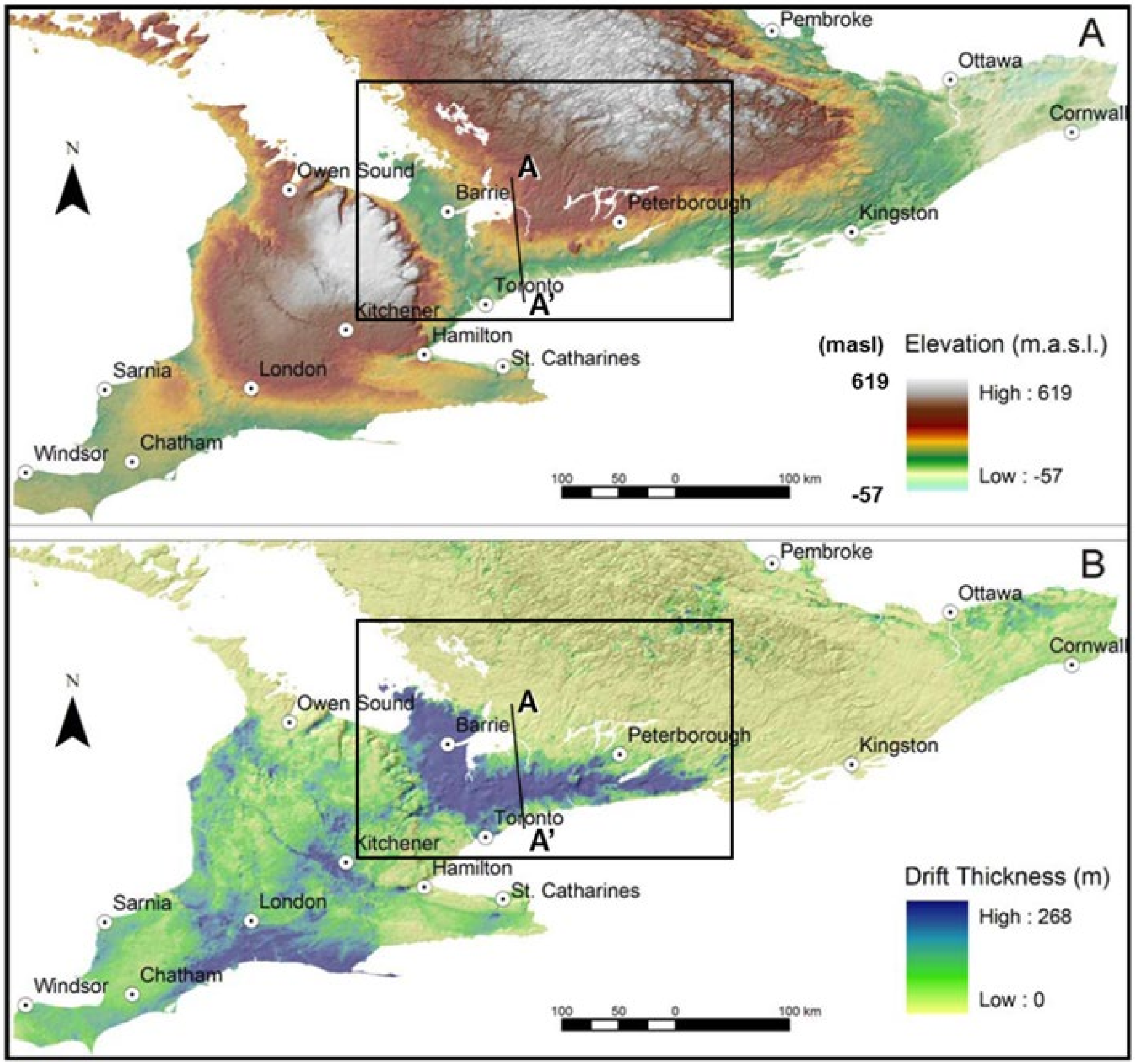

Figure 1: Interpreted southern Ontario a) bedrock topography and b) Quaternary drift thickness (figure from Gao et al., 2006). ORMGP study area occurs within rectangle. Detailed Quaternary sediment thickness for the study area shown in Figure 2. The Laurentian bedrock valley trends northwest to southeast from Lake Huron, through Barrie to the Toronto area.

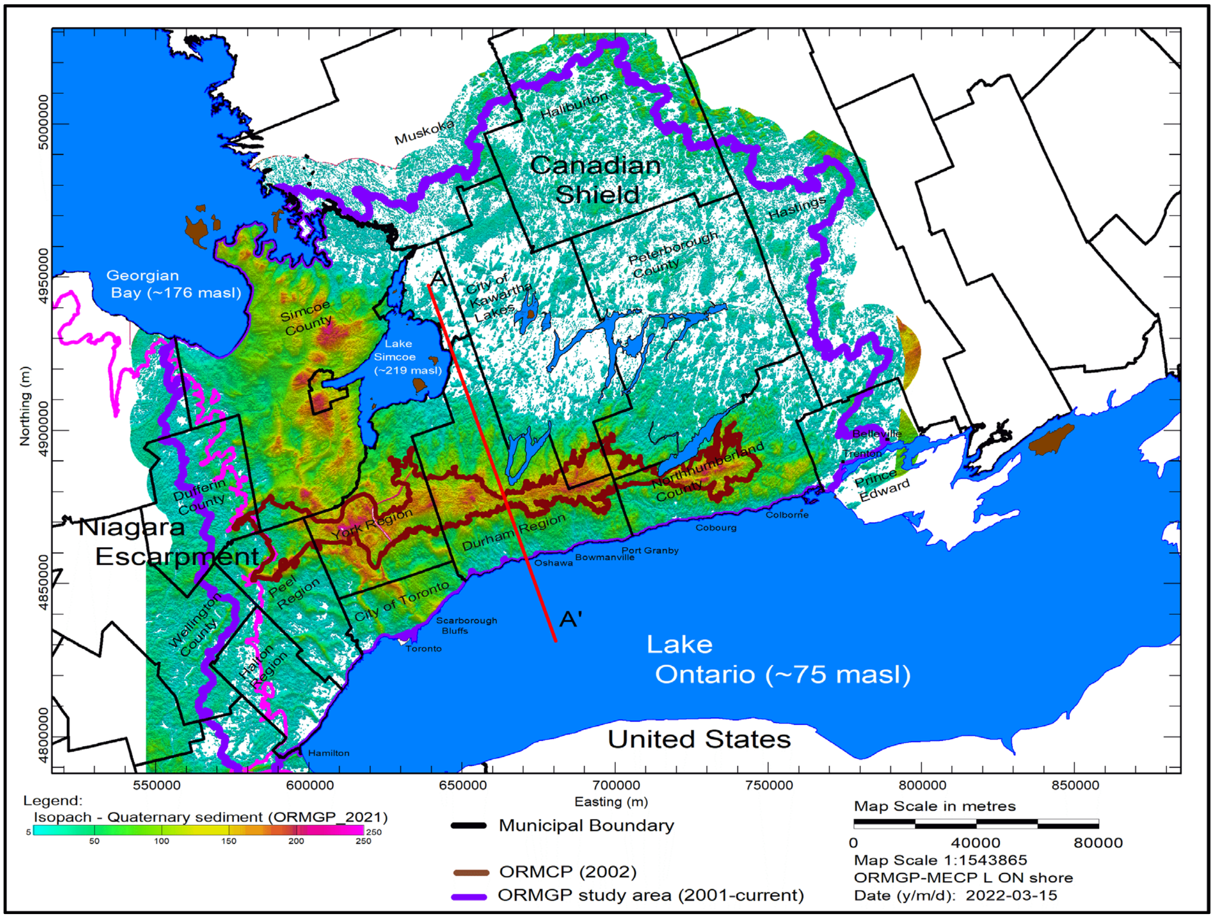

Figure 2: Interpreted Quaternary sediment thickness (m). Interpretation conducted by the ORMGP for the study area. Edge of Niagara Escarpment shown as pink line.

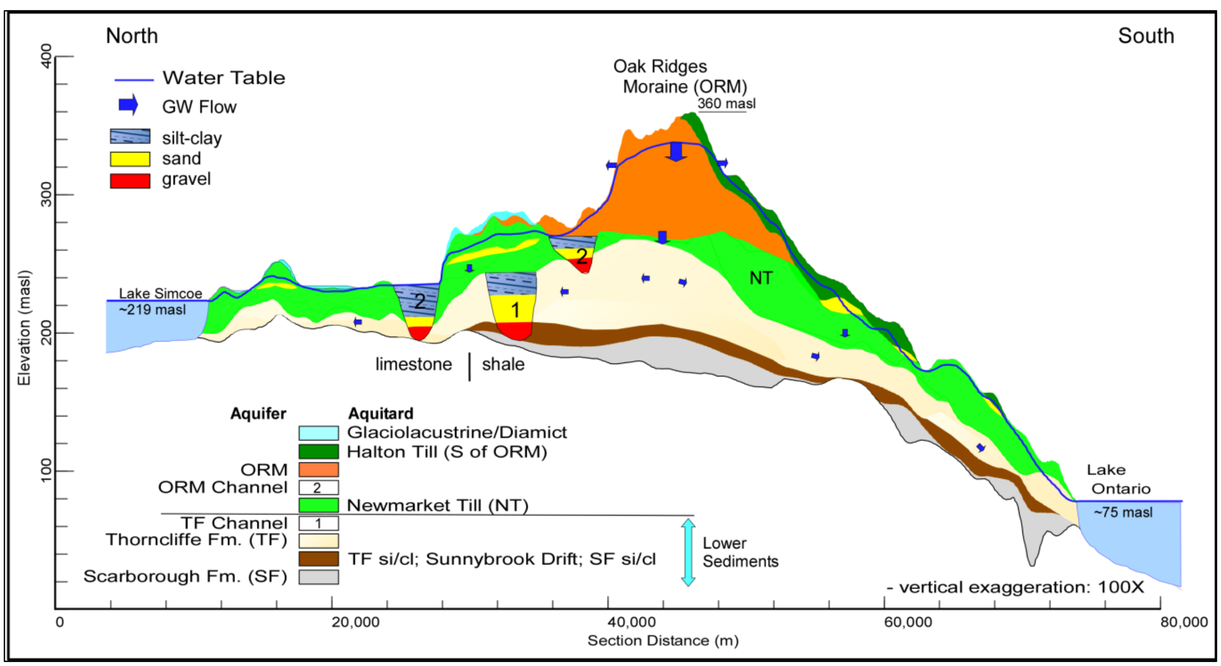

Figure 3: Hydrogeologic conceptual model. Cross-section location A (North) - A' (South) shown on Figure 1 and Figure 2.

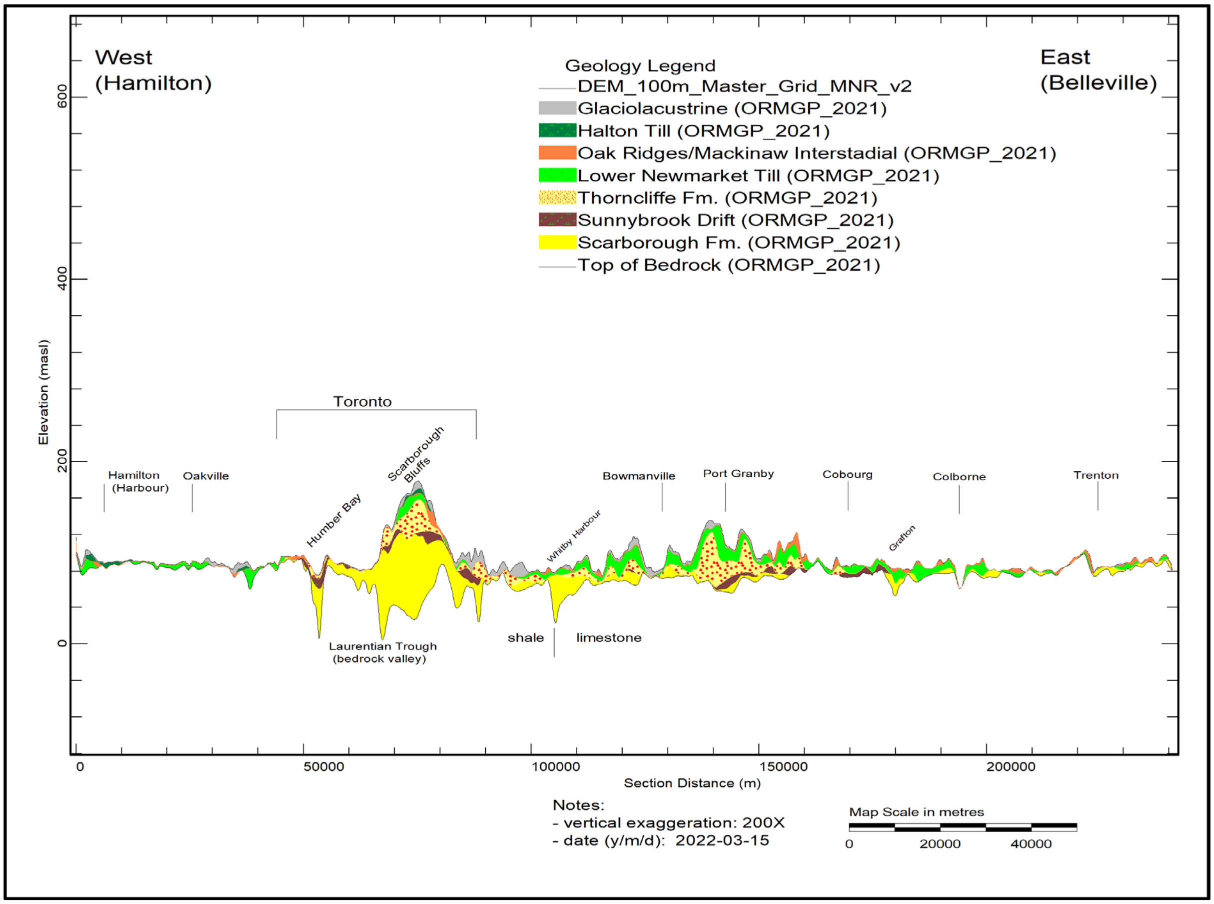

Figure 4: Cross section along the Lake Ontario north shore within the study area. Lake Ontario water level maintained at ~75 masl.

1.3 Historical Investigations

For the purposes of this report the term *direct* groundwater discharge to Lake Ontario refers to groundwater emerging from subsurface geological units directly into the lake; whereas groundwater discharging to Lake Ontario via tributary streams is deemed *indirect*. There have been numerous historical investigations within the study area (north shore of Lake Ontario) regarding either estimates of direct groundwater discharge to Lake Ontario and/or groundwater, stream, and lake water quality, especially with respect to road salting. Few, if any studies, have attempted to combine both aspects (direct groundwater discharge and groundwater quality) into a direct salt loading from groundwater directly to Lake Ontario. Howard and Livingstone (2000) provided a contaminant audit and transport from groundwater to streams and to Lake Ontario for the Don River watershed, however, the quantities of groundwater discharge to rivers and Lake Ontario were not differentiated. In this section we will look at the historical literature to summarize previous estimates of the quantities of direct groundwater discharge to Lake Ontario, followed by investigations regarding reported concentrations of sodium (Na^+) and Cl^- within groundwater along the north shore of Lake Ontario.

1.3.1 Indirect Groundwater Discharge to Canadian shore of Lake Ontario

Some of the earliest investigations regarding regional groundwater flow and estimates of groundwater discharge directly into Lake Ontario were conducted by the federal (Haefeli, 1970; 1972) and the provincial (Singer, 1974; Ostry 1979a; 1979b; Ostry and Singer, 1981) governments as part of numerous investigations for the International Field Year for the Great Lakes (IFYGL; McCulloch, 1973; Hodge, 1978). Haefeli (1970) determined that a groundwater flow divide within both Quaternary sediments and bedrock followed the topographic divide that occurs along the Oak Ridges Moraine. Subsequent work (Haefeli, 1972) estimated direct groundwater discharge to the Canadian Lake Ontario shoreline utilizing various methodologies including cross sectional Darcy fluxes, flow net analysis, and baseflow analyses. These investigations were conducted at various locations along the Canadian shore of Lake Ontario. All estimates of direct groundwater flow into Lake Ontario were less than 715 m^3/d/km of shoreline. Two key conclusions from Haefeli (1972) were that error for direct groundwater discharge estimates could approach 100%, and that direct groundwater discharge to Lake Ontario is low, and on the order of two orders of magnitude lower than streamflow discharge to Lake Ontario. This low estimate of direct discharge to Lake Ontario was also arrived at in subsequent investigations that also addressed the topic (Coulibaly and Kornelsen, 2013; Kornelsen and Coulibaly, 2014). Haefeli (1972) also noted that the permeability of bedrock beneath the Lake Ontario shore area decreases dramatically below a depth of 30m, which along with the local presence of gas, precludes significant groundwater flow. Estimates of groundwater discharge directly to Hamilton Harbour at the west end of Lake Ontario, based on measured hydraulic gradients and hydraulic conductivity, are on the order of 2.1×10^7 m^3/year, which comprises approximately 8% of the total surface inflows to the harbour from streams (Harvey et al., 2000). Assuming 20 km of shoreline for Hamilton Harbour (Figure 11 from Harvey et al., 2000), this estimate extends to approximately 2,900 m^3/d/km of shoreline.

Early numerical modelling on a watershed basis was conducted as part of theses work at the University of Toronto for the Highland Creek, Rouge River, Petticoat Creek and Duffins Creek watersheds. These investigations suggested that direct groundwater discharge to Lake Ontario accounted for less than 5% of the total watershed groundwater outflow (and by extension less than 5% of groundwater recharge) with streams, rivers and wetlands collecting much of the groundwater discharge (Gerber and Howard, 2000; 2002; Meriano and Eyles, 2003; 2009). Numerous investigations estimate the groundwater discharge component of total streamflow for north shore streams to exceed 50% (see for example Neff et al., 2005; and streamflow analysis tools available at oakridgeswater.ca). Estimates of direct groundwater discharge were less than 100 m^3/d/km of shoreline for the Petticoat Creek and Duffins Creek watersheds (Gerber and Howard, 2000; 2003; Meriano and Eyles, 2009). Estimates of direct groundwater discharge to Lake Ontario for the Highland Creek and Rouge River watersheds were higher and approached 500 m^3/d/km of shoreline. This higher area of direct groundwater discharge was believed to occur beneath the Scarborough Bluffs (Meriano and Eyles, 2003). This is a similar conclusion to the earlier referenced IFYGL investigations where higher steep shorelines were considered areas of possible greater direct groundwater discharge. Haefeli 1972 attempted to relate lake bottom temperature survey data to the presence of bedrock valleys but concluded that this could not be determined with certainly. There however did seem to be a relationship between high steep shores (e.g., Scarborough Bluffs east of Toronto, and Bouchette Point and Crysler Point east of the Bowmanville-Newcastle area) and temperature anomalies in the lake, perhaps attributed to increased groundwater discharge.

More recent modelling investigations have been conducted on a regional basis including multiple watersheds situated along the north shore of Lake Ontario (Earthfx Inc., 2006; 2013; Papadopulos and GeoProcess, 2021). These efforts also conclude that direct groundwater discharge to Lake Ontario is less than 5% of the total groundwater discharge for each of the study areas. Larger models have also recently been constructed that cover the area beyond Lake Ontario including Southern Ontario (Frey et al., 2019) and the entire Laurentian Great Lakes watershed (Xu et al., 2021). These larger area models, along with the regional models, are analyzed further in subsequent sections of this report.

Streamflow data, groundwater level data and other related hydrogeological information such as the interpreted water table and bedrock topography can be explored further at oakridgeswater.ca. The locations of historical investigations mentioned in this section are shown on Figure 5.

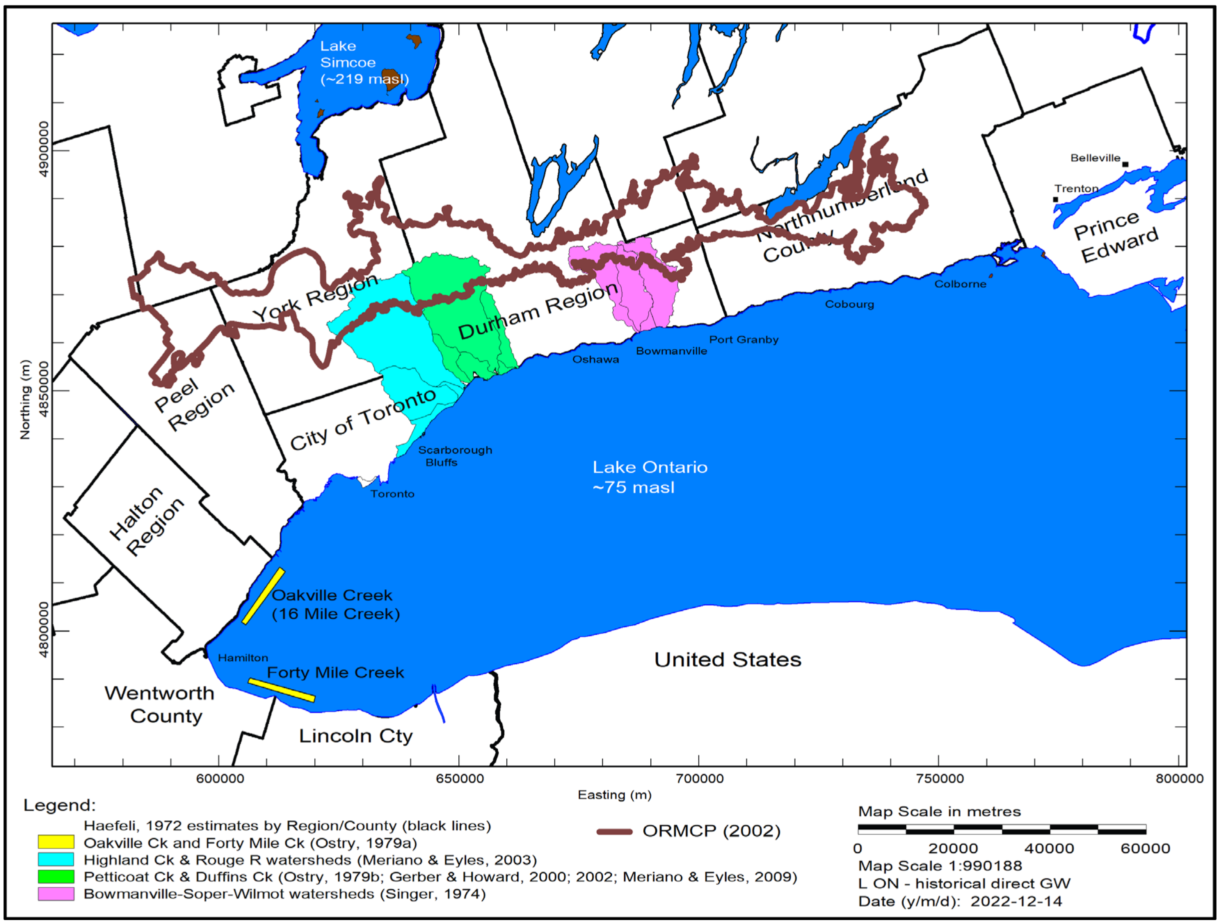

Figure 5: Locations of historical studies that estimated direct groundwater discharge to Lake Ontario. Haefeli (1972) estimated by Region or County which are delineated by black lines on figure.

1.3.2 Water Quality (Road Salt) in the Study Area

A comprehensive summary of road salt issues, literature, and quality impacts on various water reservoirs along the north shore of Lake Ontario is included in Mackie et al., (2022) and Sorichetti et al., (2022). There are general trends regarding Cl^- and Na^+ concentrations within waters of the study area that will be briefly outlined in this section as a lead-up to salt loading estimates provided in the subsequent section. Generally, these are as follows:

- There exists a wide range and variability of water quality depending on location, particularly proximity to contamination sources. For example, in investigations at 15 sites in Canada along urban streams and shorelines, Roy (2019) noted substantial variability in Cl^- concentrations over short distances illustrating a patchy spatial pattern. Salt levels frequently exceed drinking water criteria (250 mg/L) in groundwater and streams;
- Not all annual salt loading flushes out to Lake Ontario every year, rather more than half is estimated to accumulate in the subsurface. This is evidenced by rising groundwater concentrations, and by out of phase stream concentrations (Van Meter et. al., 2019) where high summer salt concentrations are observed in stream flow when the groundwater component is a higher fraction of total streamflow. It is estimated that it will be many decades/centuries before steady state concentrations are reached (Mackie et al., 2022);
- Cl^- and Na^+ concentrations show increasing trends in all water reservoirs (groundwater, streams, lakes) within the study area (Chapra et al., 2009; 2012; Mazumder et al., 2021; Sorichetti et al., 2022); and
- There are many sources of existing information regarding Cl^- and Na^+ concentrations observed in groundwater, streams, and Lake Ontario within the study area. These will be discussed further below.

Na^+ and Cl^- occur naturally at low concentrations within groundwater flow systems of the study area (Howard and Beck, 1986). Shallow groundwater generally has a natural Cl^- concentration of less than 15-20 mg/L, with Na^+ generally being less than 10 mg/L (Howard and Beck, 1986; 1993). Drinking water quality guidelines in Ontario for Cl^- and Na^+ are 250 mg/L and 200 mg/L respectively (Ontario, 2003). Guidelines for Cl^- concentrations for the protection of aquatic life are more stringent at 125 mg/L (CCME, 2011). Na^+ concentrations can naturally increase with groundwater residence time due to cation exchange processes, and Cl^- concentrations can naturally become elevated through interaction with saline bedrock water.

Anthropogenic activities across the wide study area including road salt application and storage (including snow dumps), landfill leachate, septic systems, agricultural fertilizers, and water softeners are sources of elevated Na^+ and Cl^- and these types of activities have led to contamination in groundwater and surface water (Pilon and Howard, 1987; Howard and Beck, 1993; Howard and Livingstone, 2000; Howard and Gerber, 2018; Sorichetti et al., 2022). Road salt application is considered the largest contaminant source (Dugan et al., 2017). Observed Cl^- concentrations in groundwater, spring and stream samples within the study area have sometimes exceeded 100s to 1000s of mg/L (Bowen and Hinton, 1998; Hamilton, 2021; Howard and Taylor, 1998; Howard et al., 1985; Eyles and Howard,1988; Labadia and Buttle, 1996; Lawson and Jackson, 2021; Mazumder et al., 2021; Meriano et al., 2009; Mackie et al., 2022; Sorichetti et al., 2022; Williams et al., 1999). Lake Ontario water quality has also been impacted by contaminant loadings upon the land surface, particularly in nearshore areas. Ultimate concentrations in Lake Ontario are a combination of many factors including tributary discharge, lake circulation and biology, particularly in the nearshore area (Chapra et al., 2009; 2012; Neilson and Stevens, 1986; Howell et al., 2012; Howell and Benoit, 2021).

It is estimated that only 45-60% of the road salt applied annually is flushed from the system by surface runoff processes (Howard and Haynes, 1993; Howard et al., 1993; Perera et al., 2013). The remainder builds up in the shallow subsurface to be released slowly through groundwater recharge and flow processes. It is estimated that steady state concentrations of Cl^- and Na^+ within groundwater and streams will exceed concentrations of approximately 400 – 500 mg/L and 250 mg/L respectively, and that this steady state will take hundreds of years (200-500) to be realized assuming current application rates (Howard et al., 1993; Howard and Livingstone, 2000; Howard and Maier, 2007; Meriano et al., 2009; Perera et al., 2013; Soper et al., 2021).

The incomplete annual flushing of salt loadings is evidenced by the change of seasonality in stream salt concentrations where the concentrations are not necessarily in phase with stream discharge. Increasingly, and particularly in urban areas, elevated salt concentrations in streams are seen in summer months and remain high during periods of both high (spring) and low (summer) discharge periods (Dugan et al., 2021; Van Meter et al., 2019; Nelligan et al., 2021; Lawson and Jackson, 2021; Mazumder et al., 2021). Similar patterns are seen for nutrients within surface waters, with legacy nitrogen accumulation over decades leading to significant time lags in water quality response (Basu et al., 2022).

Numerous publications and/or datasets exist within the study area that contain groundwater quality including Na^+ and Cl^- (Sorichetti et al., 2022 and included references). Specific to the study area (north shore of Lake Ontario) these include:

1) Geological Survey of Canada water supply reports (Caley et al., 1947a; 1947b; Hainstock et al., 1948a-e; 1952);
2) Federal (Haefeli, 1970) and Ontario Ministry of the Environment watershed studies (Sibul et al., 1977; Singer, 1974; Ostry, 1979a; 1979b; Ostry and Singer, 1981) prepared as part of the International Field Year for the Great Lakes program;
3) University Research (e.g., Howard et al., 1993; Howard and Livingstone, 2000; Labadia and Buttle, 1996; Meriano et al., 2009; Pilon and Howard, 1987; Williams et al., 1999;
4) Municipal monitoring networks (Halton, Peel, York, and Durham Regions);
5) Provincial Groundwater Monitoring Network (PGMN; https://data.ontario.ca/dataset/provincial-groundwater-monitoring-network);
6) Provincial (Streams) Water Quality Monitoring Network (PWQMN; https://data.ontario.ca/dataset/provincial-stream-water-quality-monitoring-network);
7) Drinking Water Surveillance Program (DWSP) for municipal groundwater supplies (https://data.ontario.ca/dataset/drinking-water-surveillance-program)
8) Ambient Groundwater Geochemical Database, Ontario Geological Survey (Hamilton, 2021)
9) Miscellaneous site-specific studies (landfills, sewer discharge development reports, etc.).

Groundwater quality data from the municipal monitoring networks, the PGMN (groundwater), PWQMN (streams) and DWSP (municipal drinking water) allow for time-series analysis. The remainder represent ‘snapshots’ of concentrations at one point in time. Within the ORMGP study area, these data sources have mostly (except for IFYGL and University Research studies) been incorporated into the ORMGP database (https://owrc.github.io/databasemanual/Contents/TOC.html). In the case of groundwater wells, the data have been linked to the screened well interval at a specific depth. The consolidation of much of these data allows investigators to undertake comprehensive analyses from the ORMGP database. Further summary and explanation are included in the subsequent section.

2. METHODS

Direct groundwater discharge to Lake Ontario has been estimated using numerical models and baseline groundwater Cl^- concentration ranges have been estimated using data contained within the ORMGP database. Estimates of Cl^- loading along the north shore of Lake Ontario are then compared to salt loading information reported by municipalities and referenced estimates from the literature.

This investigation has utilized Cl^- concentrations only to estimate salt loadings directly to Lake Ontario. Cl^- has been utilized because it is a conservation parameter not subject to reactions within the subsurface other than dilution. Although some Na^+ values are presented below, Na^+ has not been extensively analysed here because Na^+ is subject to subsurface reactions such as cation exchange which can affect contaminant transport behaviour. (Hem, 1985; Lazur et al., 2020).

2.1 Numerical Model Groundwater Discharge Estimates

Twelve existing numerical groundwater models were run to acquire estimates of long-term contributions of groundwater to the Lake Ontario's north shore (Table 1). Groundwater discharge was differentiated as either contributing to Lake Ontario indirectly, via land surface seepage captured by tributary streams, or directly along the Lake Ontario shoreline.

Most the models were built for Source Water Protection in which the investigation of groundwater flow necessitated a concerted effort to provide a detailed interpretation of the Quaternary hydro-stratigraphy. Consequently, ten of the models used in the study typically invoke around 10 numerical layers to represent the complex hydrostratigraphy of the Lake Ontario north shore, including such features as buried channels and bedrock valley systems. The remaining models were necessarily built coarser in resolution to accommodate greater geographic extents, each having Quaternary geology interpolated province-wide to a 5-layer conceptualization.

Spatial model resolution is consistent amongst all models and simulate hydrologic processes at roughly the hectare/plot-scale. Depending on the model code used (MODFLOW, FEFLOW, HydroGeoSphere), the distribution of model "cell" size may vary where finer cell resolutions are found near areas of interest (i.e., boundaries), such as streams, lake shores, municipal wells, etc. (Table 1). Except for the two HydroGeoSphere models, all models were run to a steady state and the results are inferred to represent a long-term average condition. Long term average from the transient HydroGeoSphere models is taken as the total flux accumulated for a year's run with average monthly conditions input. The model boundaries are shown in Figure 6.

2.1.1 Numerical Models

Table 1 contains a brief description of the models used. In all cases, the reader is encouraged to review the models' accompanying reports, most of which can be found on the ORMGP web site (oakridgeswater.ca). The description included on Table 1 includes the following aspects of various models utilized:

1. Model code—the model code is indicative of the capabilities of the groundwater flow model.
2. Time-stepping: either steady-state or average-transient.
3. Number of computational elements (e.g., model cells) is a measure of how large the model is and relates to the time the model takes to run.
4. Indirect discharge type—the output/boundary of the model used to aggregate indirect contributions such as discharge to surface and streams.
5. Direct discharge type—the output/boundary of the model used to aggregate discharge along the Lake Ontario shoreline.

The Laurentian Great Lakes model (Xu et al., 2021) and the Southern Ontario fine model (Frey et al., 2019) are the only transient models applied in this report. These models run effectively on a monthly timestep, where average monthly precipitation and potential evapotranspiration rates are input to the model. The models work on a 10-year loop where the monthly forcings are kept in repetition. Although these are transient models, they are both considered to be long-term average seasonal models. Discharge to the lakes was determined by running the final year of the models' simulation and outputting fluxes for each calendar day. The sum of these 365 daily fluxes was deemed the long-term annual average.

2.1.2 Boundary Conditions

Boundary conditions effectively represent spatial locations in the numerical model where water either enters or exits the model domain. For instance, the land surface can either be a source (recharge) or a sink (seepage/discharge) from the perspective of the groundwater reservoir. Similarly, streams can be groundwater sinks (i.e., gaining water from the groundwater system), however streams can also serve as a source of water to the groundwater system, as in the case of losing reaches. Other boundary conditions that are considered can include pumping wells and exchanges (sources and/or sinks) with larger water bodies (e.g., Lake Ontario).

The greatest difference amongst the model codes are how these boundaries are represented. For instance, the Laurentian Great Lakes Model, the Southern Ontario Model (SOM) and the Durham model allow for seepage anywhere on the land surface, whereas the remaining models tend to restrict surface discharge to delineated stream reaches only.

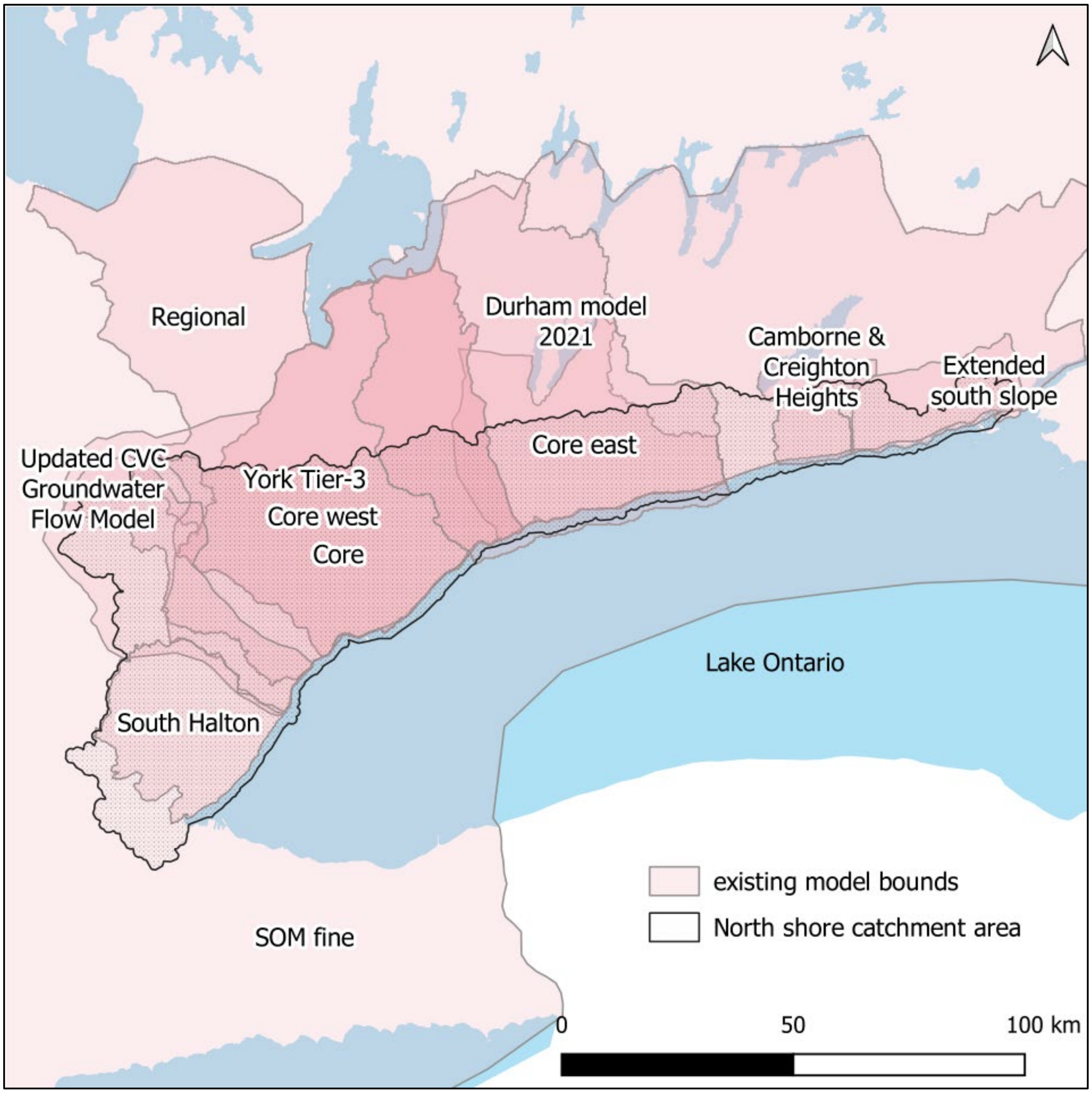

Figure 6: Boundaries of selected numerical models. (Note: deeper the shade signifies greatest model overlap. The Laurentian Great Lakes model not shown as it covers the entire region shown in the figure.) North shore contributing area delineated by black line covers 6,520 km^2. Further information on each numerical model, including reports, is shown in Table 1 and is available at maps.oakridgeswater.ca.

2.2 Chloride (Cl^-) Concentration and Loading

One possible method to look at Cl^- loadings to the system is by applying salt by land use type including road types, parking lots, etc. (Howard and Livingstone, 2000; Howard and Maier, 2007; Betts et al., 2015). This is difficult because different agencies that conduct road maintenance employ different application rates and different sized roads are also treated differently.

2.2.1 Municipal Application Rates

For this study salt loading data by road length that is voluntarily reported to Environment and Climate Change Canada (ECCC, 2021) by various municipalities throughout Ontario was acquired. Although not all municipalities participate in this program, sufficient data is available over the ten-year period of record, to arrive at reasonable road salt application rates. Salt loading information to other types of surfaces during winter months (e.g., private application, parking lots, sidewalks, etc.) have not been incorporated into this analysis as these data are not readily available.

Inspection of Figure 7, which illustrates the density distribution of the amount of salt applied over the municipality's length of serviceable roads, shows that Ontario municipalities apply approximately 11.5 tonnes of salt (NaCl) per road kilometre. This provides a benchmark to compare against Lake Ontario loading estimates given below.

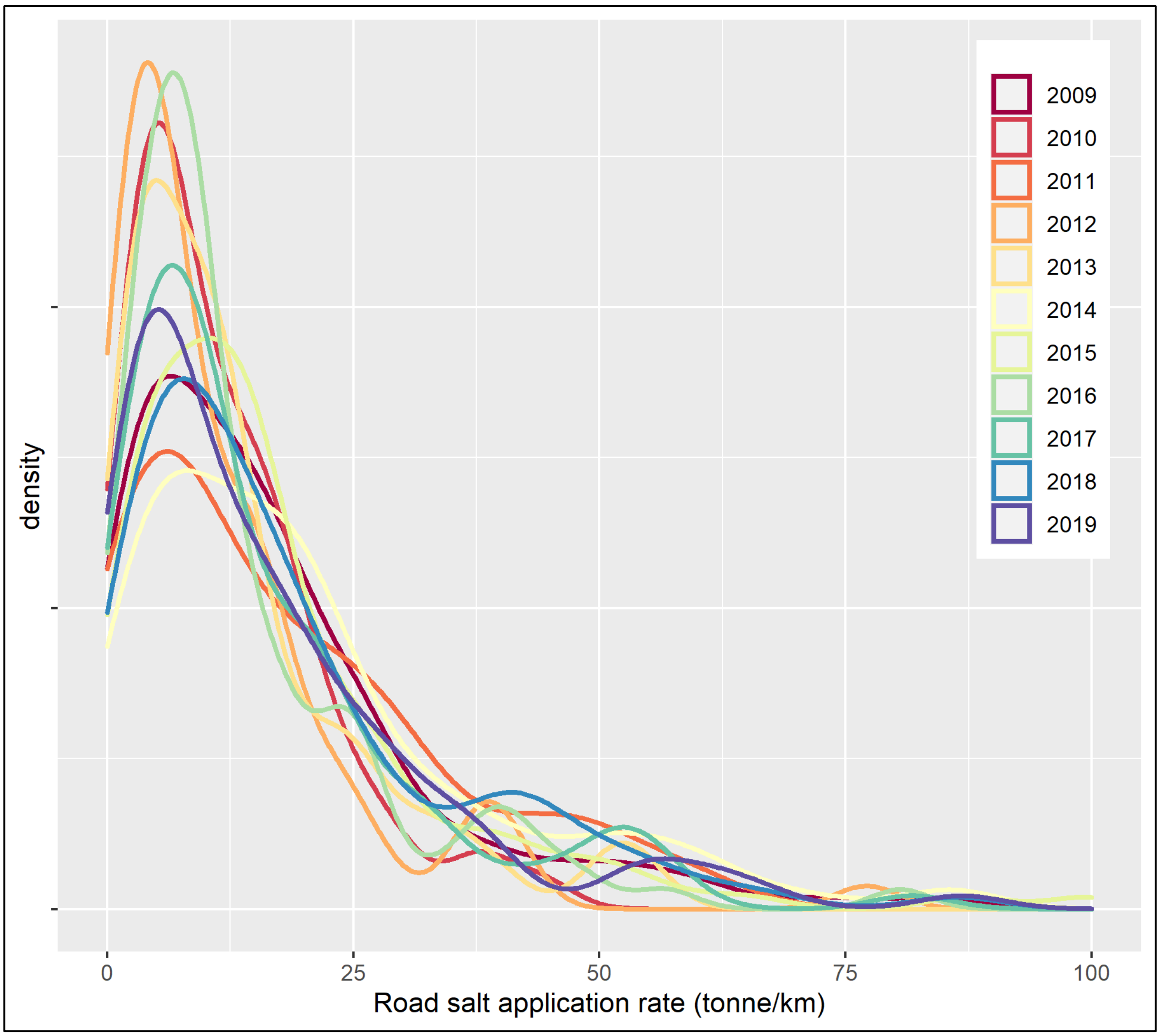

Figure 7: Annual density distributions of Road Salt application rates from approximately 100 municipalities in Southern Ontario (provided by the ECCC, personal communication, 2021). Median application rate overall is 11.5 tonne/km.

2.2.2 Measured Concentrations

To determine the potential loading of road salt to Lake Ontario from groundwater, the background level of road salt (i.e., Cl^- and/or Na^+) in the groundwater discharging to Lake Ontario (and/or its main rivers) must be estimated.

For this, the current study utilizes the wealth of observed sampling data that exist in the ORMGP database. As outlined in section 1.3.2 numerous data sources have been combined into the ORMGP database. The spatial distribution of observed Cl^- and Na^+ in groundwater samples within the database are shown on Figure 8, and Figure 9 respectively. Where wells have been sampled on more than one occasion, the concentrations have been averaged. Statistics related to concentration distributions for over 33,000 readings at approximately 2,000 locations (2,119 locations for Cl^-; 1,900 locations for Na^+) are shown on Figure 10 to Figure 13. Shallow wells (screened less than 20 m deep) exhibit higher mean and median concentrations than the deeper wells (screened greater than 20 m deep) for both Cl^- and Na^+. For Cl^-, greater than 90% of the analyses are less than the Ontario drinking water criteria (aesthetic) of 250 mg/L. 85% of the Cl^- analyses from shallow wells are less than 125 mg/L, the criteria for the protection of aquatic life. 90% of the Cl^- values for deep wells are less than 125 mg/L. For Na^+, greater than 95% of the analyses are less than the Ontario drinking water criteria of 200 mg/L.

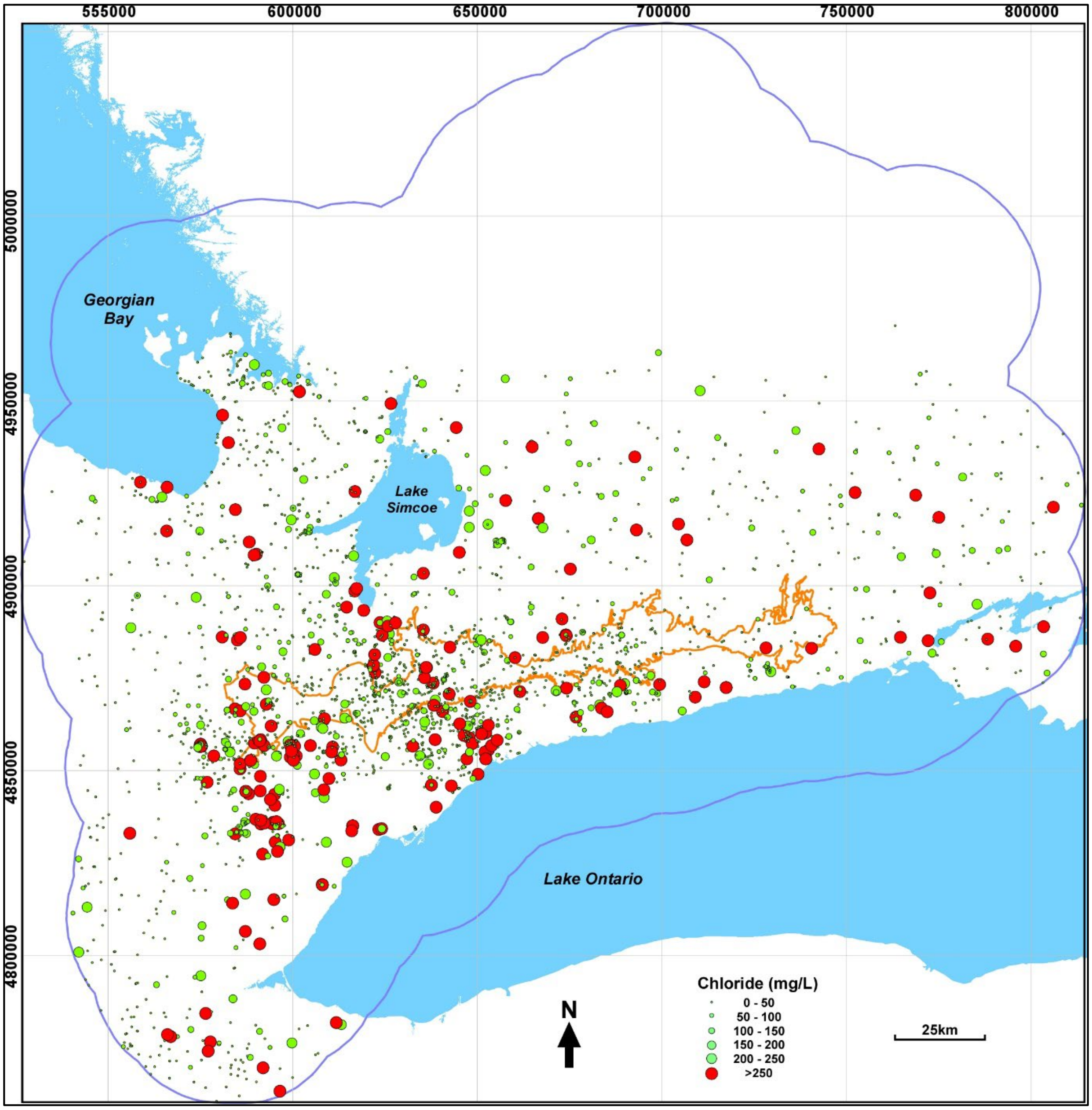

Figure 8: Locations in ORMGP database with Cl⁻ concentrations in groundwater (mg/L). Smallest symbols <50 mg/L and largest symbols >250 mg/L. Oak Ridges Moraine Conservation Plan boundary shown in orange.

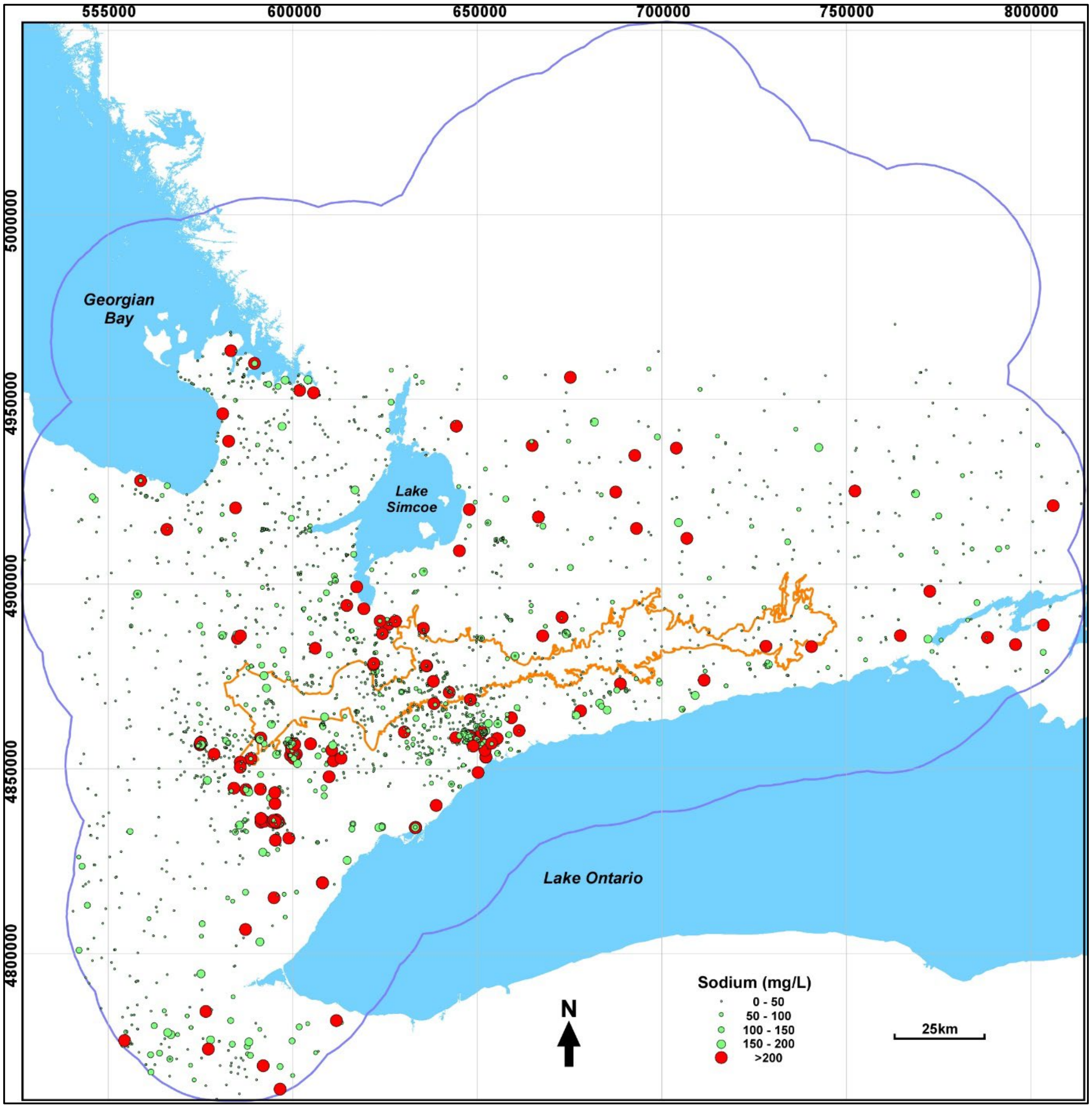

Figure 9: Locations in ORMGP database with Na^+ concentrations in groundwater (mg/L). Smallest symbols <50 mg/L and largest symbols >200 mg/L. Oak Ridges Moraine Planning boundary shown in orange.

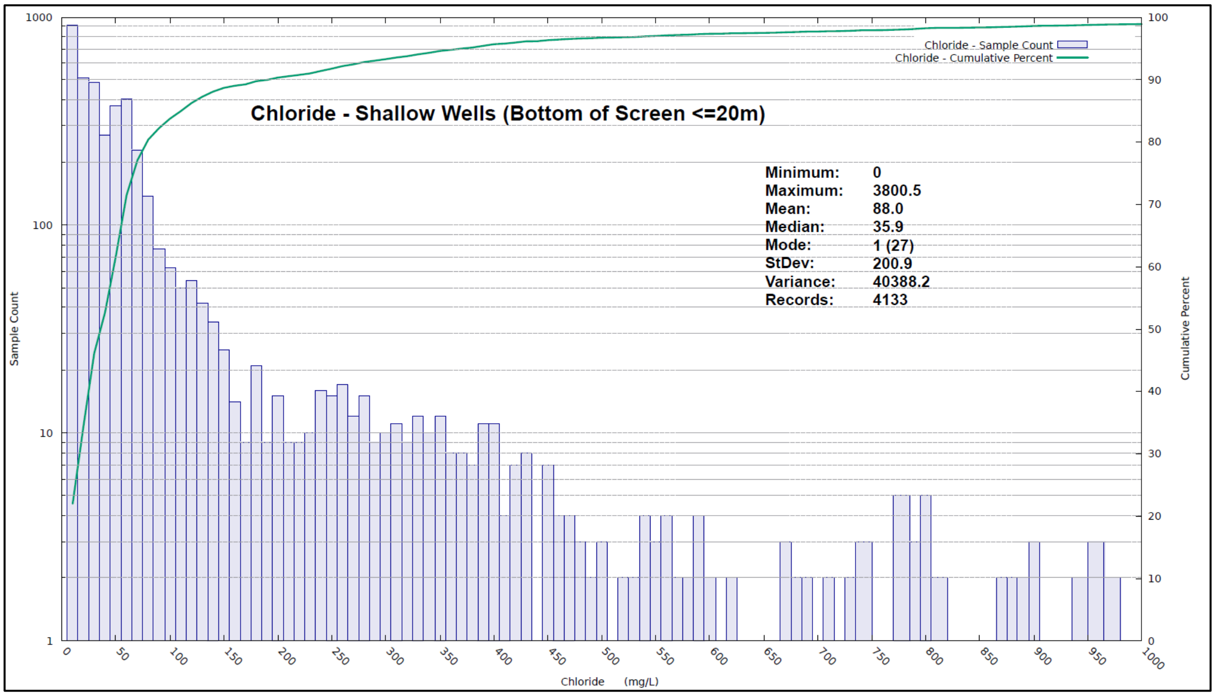

Figure 10: Summary of Cl⁻ concentrations within the ORMGP database for shallow wells. For wells with multiple readings over time, the average concentration has been used.

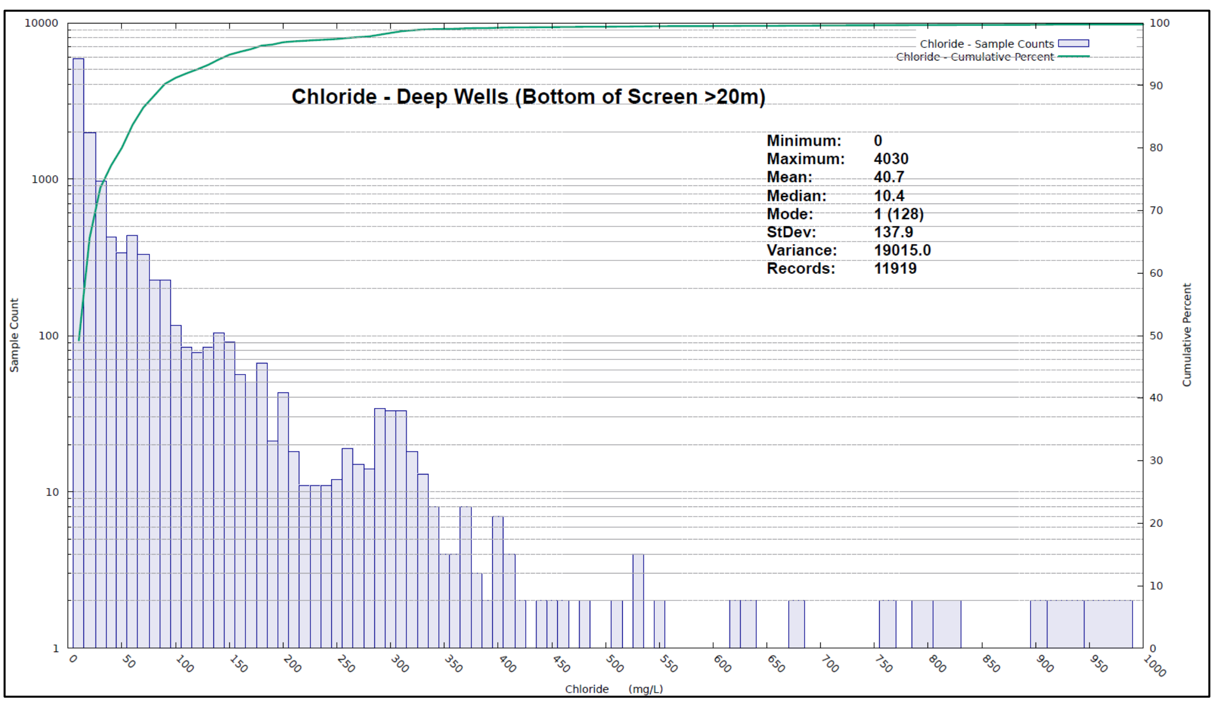

Figure 11: Summary of Cl⁻ concentrations within the ORMGP database for deep wells. For wells with multiple readings over time, the average concentration has been used.

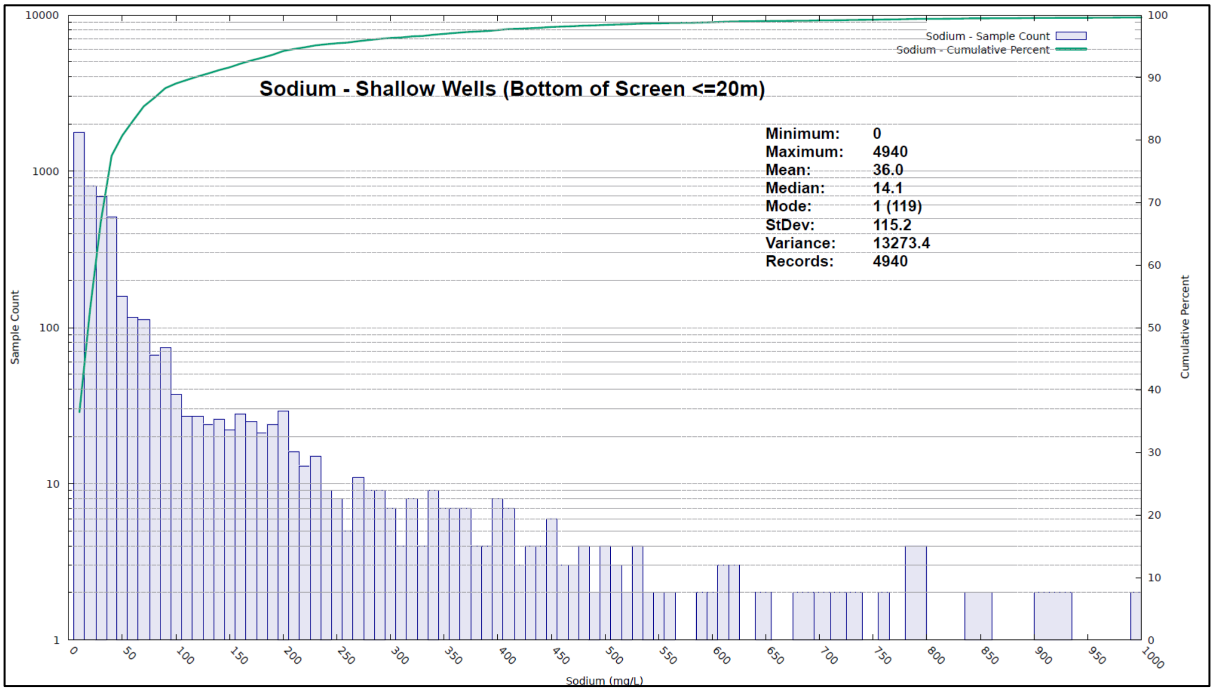

Figure 12: Summary of Na$^+$ concentrations in the ORMGP database for shallow wells. For wells with multiple readings over time, the average concentration has been used.

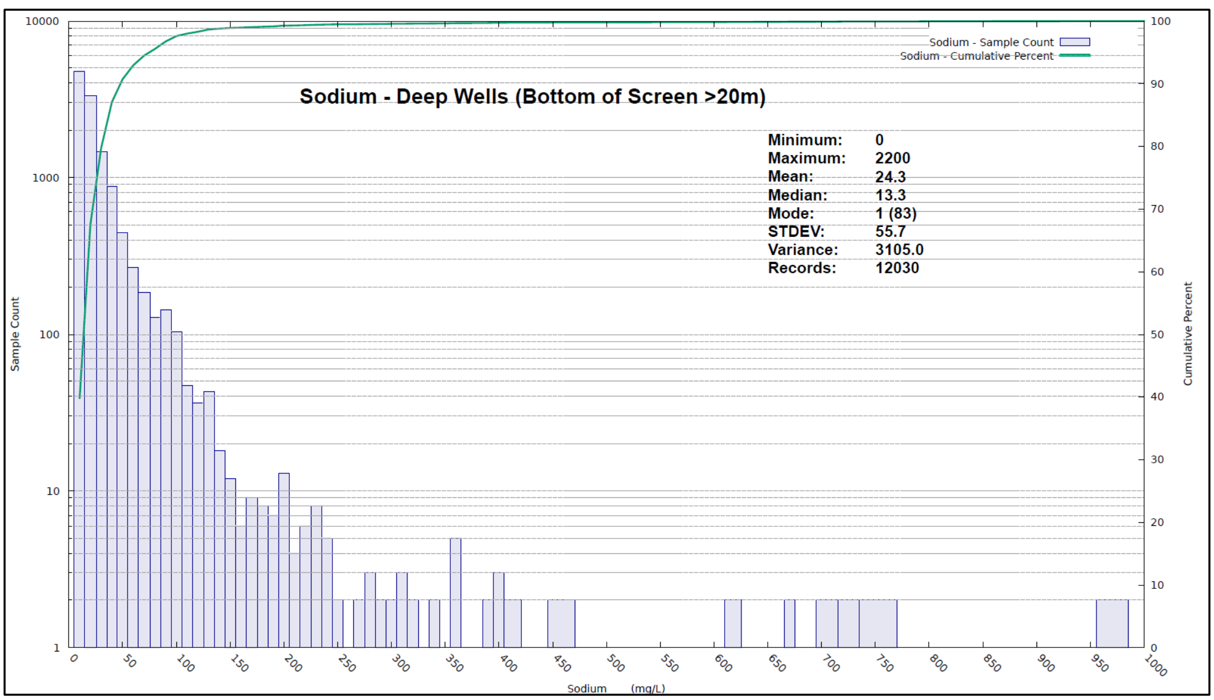

Figure 13: Summary of Na$^+$ concentrations within the ORMGP database for deep wells. For wells with multiple readings over time, the average concentration has been used.

2.2.3 Trending Concentrations

The current background levels of salt in groundwater throughout the study area also exhibit Cl^- and Na^+ trends over time. Figure 14 shows the concentrations over time for both shallow and deep Cl^- (A and B) and shallow and deep Na^+ (C and D). It can be observed that in all cases the concentrations of Cl^- and Na^+ are increasing, with Cl^- and Na^+ in the shallower wells increasing to recent values averaging about 100 mg/L. Examination of the data presented in Figure 10 to Figure 14 suggests that arriving at one number for background Cl^- or Na^+ concentration is difficult given the variability in concentrations: i) between geographically distanced wells; ii) over time; and iii) with depth.

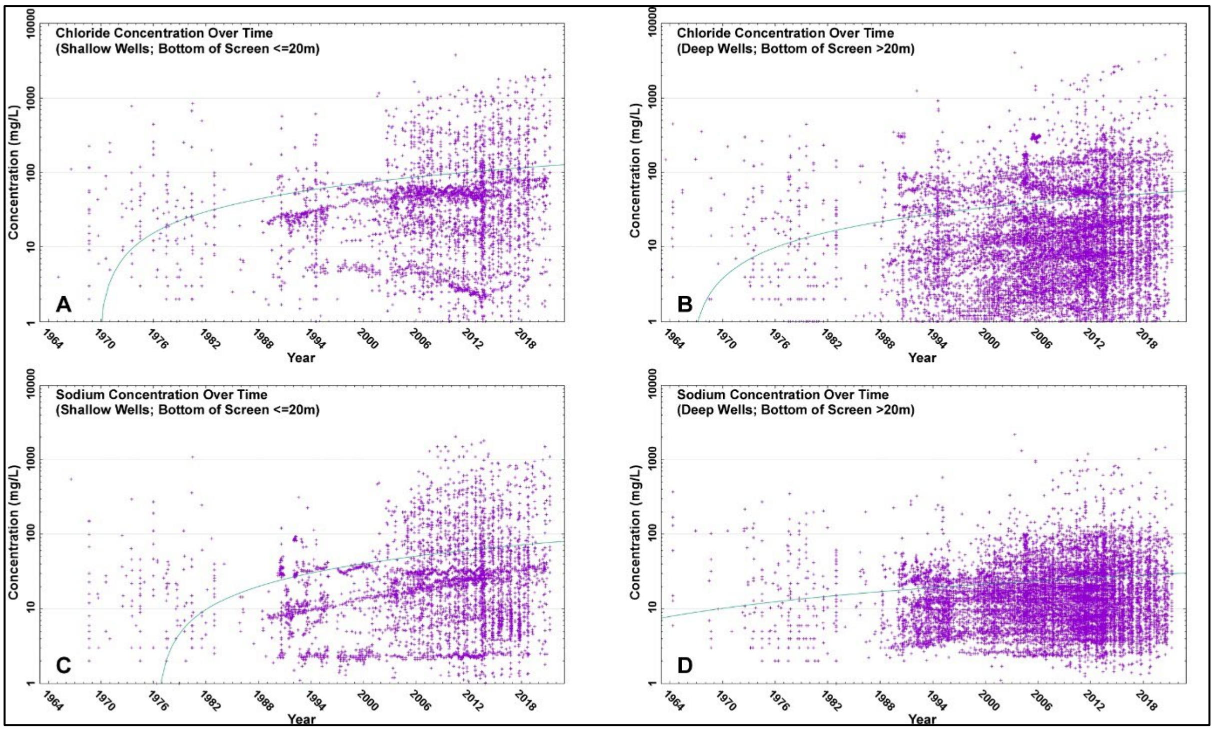

Figure 14: Cl^- and Na^+ versus time for both shallow and deep wells: A – Cl^- vs T - shallow wells; B – Cl^- vs T - deep wells; C – Na^+ vs T - shallow wells; D – Na^+ vs T – deep wells. Trend lines are best fit straight line plotted on log scale.

The distribution of maximum Cl^- measurements queried from the ORMGP dataset can be fitted quite nicely to the lognormal distribution (mean, μ=22.7; standard deviation, σ=5.9 mg/L; Figure 15) for locations within the Lake Ontario north shore contributing area (n=3,295). The previous discussion and portrayal of concentrations used average and other statistical indices to present the existing data set utilized. For loading analysis maximum concentrations will be used for locations with multiple analyses over time. This is done to provide an increased level of conservatism. All Cl^- values, both deep and shallow, are used in this analysis because it is unknown whether groundwater discharge, from either direct or indirect sources, is originating from deep or shallow groundwater systems. To better account for the rising trend in Cl^- as shown on Figure 14, in cases where more than one sample has been obtained from a well, the maximum concentration measured at each well was selected. The log normal distribution reasonably captures the uncertainty in baseline groundwater Cl^- concentrations north of Lake Ontario.

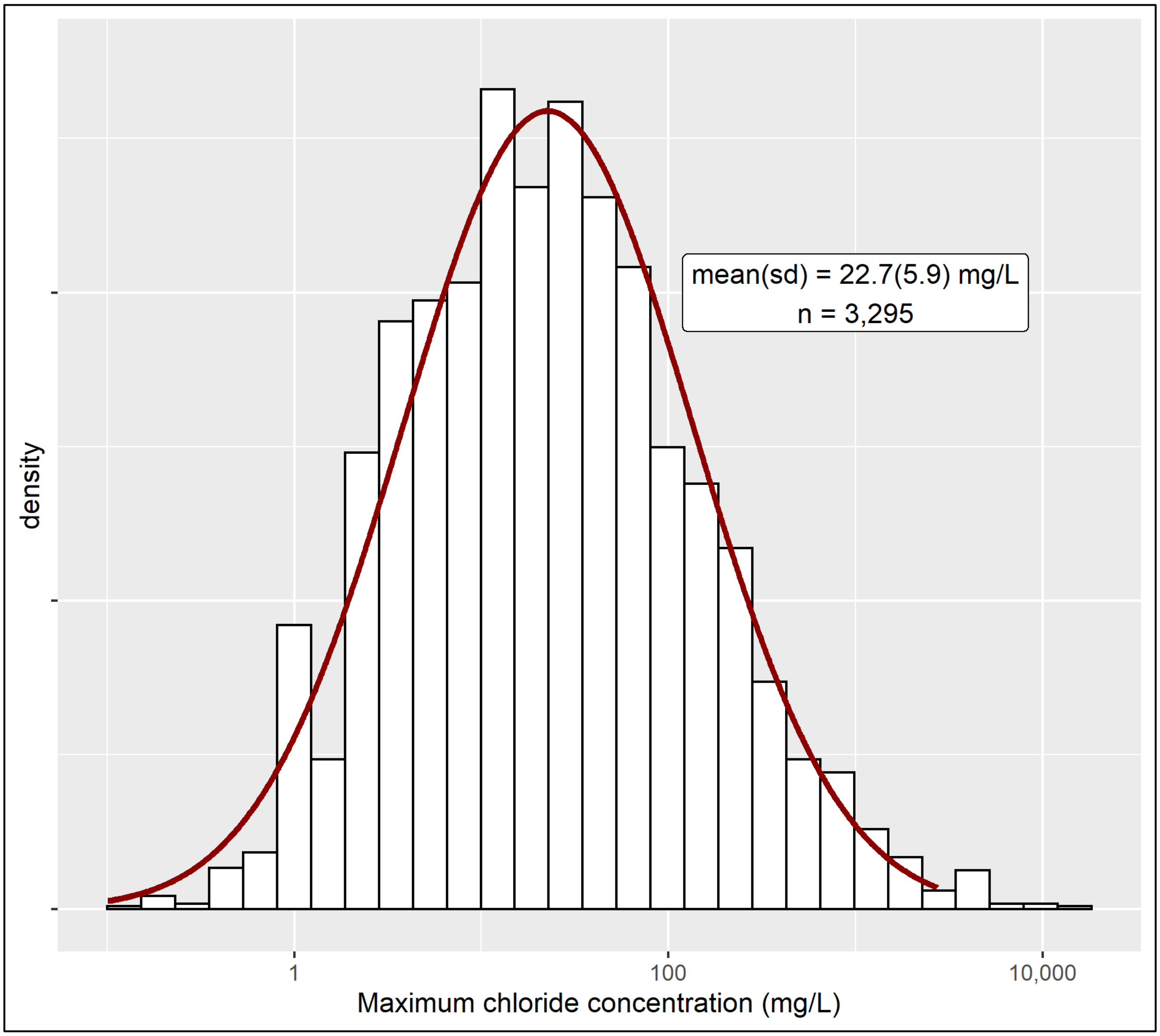

Figure 15: Histogram of maximum Cl⁻ concentrations measured at every well within the Lake Ontario north shore contributing area. Log-normal distribution fitted in red.

2.3 Separated Streamflow to Lake Ontario

The ORGMP database maintains 95 stream gauging stations that have >10 years continuous record within the 6,520 km^2 Lake Ontario north shore contributing area. Hydrograph separation[1] was applied to these stations to separate the total streamflow hydrograph into its "slow" and "quick" flow components. The terms quickflow and slowflow can be loosely regarded like runoff and baseflow, however hydrologists are increasingly concerned that the terms runoff and baseflow can perhaps over-simplify the complex process of water movement in watersheds. The term quickflow simply refers to water that is pushed quickly to streams at the onset of a rainfall or snowmelt event, whereas the term

[1] owrc.github.io/interpolants/modelling/hydrographseparation.html

slowflow is meant to convey a slower push of water following an event. Whether the water comes from groundwater discharge, runoff, or other sources, there is less of an implied link to a particular water source, rather its temporal behaviour.

Total streamflow (= slowflow + quickflow) are normalized to millimeters per year (mm/year) and shown in Figure 16. Reporting in mm/year makes for easier comparisons with annual precipitation, recharge, etc. Approximately 400 mm/year total streamflow is measured at stream gauges in the study area.

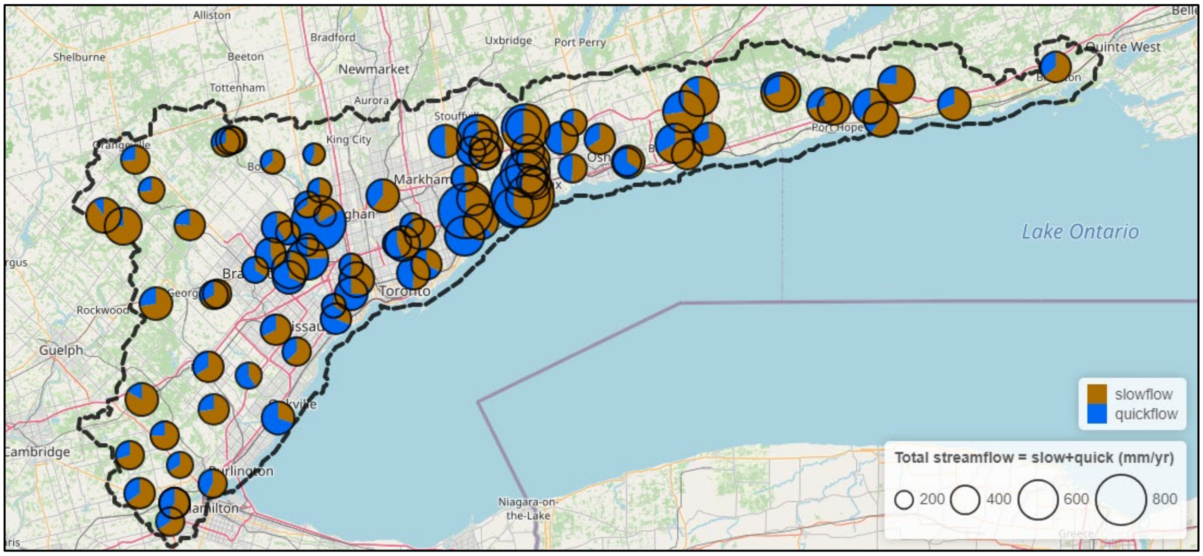

Figure 16: Spatial distribution of total streamflow (mm/year) with estimated proportion of slowflow to quickflow shown in pie charts[2]. North shore contributing or drainage area delineated by dashed black line (6,520 km^2).

Gauging stations in Figure 16 are represented as a pie chart indicating the proportions of slowflow to quickflow that together make up total streamflow. As indicated by the brown proportion of study area streamflow gauges, the gauges are generally dominated by slowflow. The few gauges that are exceptions (circles where blue dominates) are those correlated with increased urbanization (e.g., in the Toronto area), where quickflow is attributed to increased event based overland runoff from impervious surfaces into watercourses.

Mean indirect groundwater discharge to Lake Ontario along its north shore is equivalent to 218 mm/year or 17,200 m^3/d/km along its 226.7 km shoreline (Figure 17A). The median Baseflow Index (BFI: the ratio of slowflow to total flow) is approximately 60% (Figure 17B). If slowflow originates predominantly from groundwater sources, it is noteworthy that, whether direct or indirect, groundwater is the largest contributor of flow to Lake Ontario along the northern shore, greater than overland runoff (i.e., quickflow). A summary of observed mean total streamflow for the stations shown on Figure 16 (mm/year) is also provided on Figure 18 in m^3/d to allow for comparison to direct and indirect groundwater discharge estimates to follow.

[2] Interactive format: owrc.github.io/presentations/2022/220215-GWopenhouse.html#7

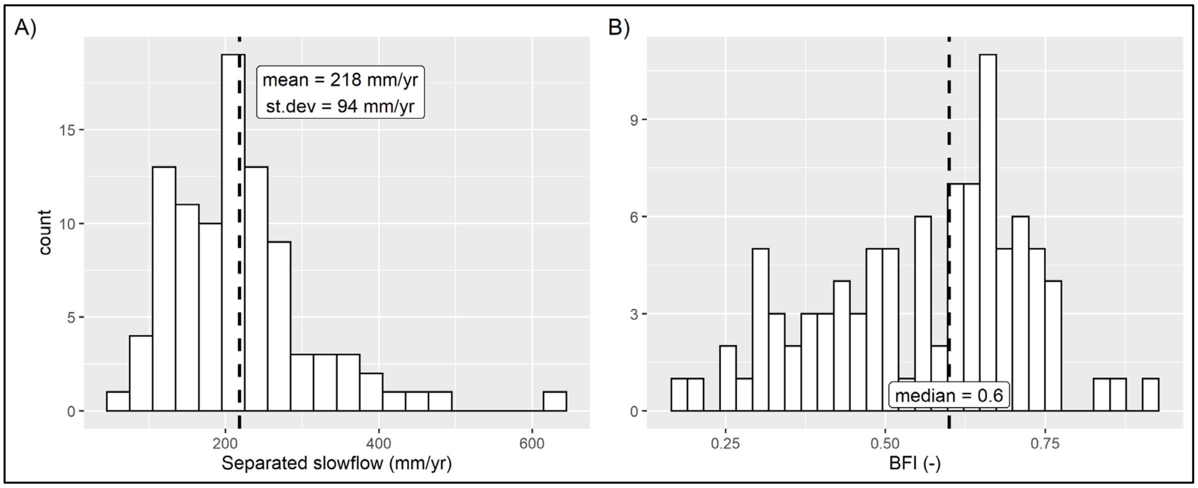

Figure 17: Histogram of A) separated slowflow/indirect discharge; and B) BFI, at the 95 streamflow gauges in the Lake Ontario north shore drainage area shown on Figure 16.

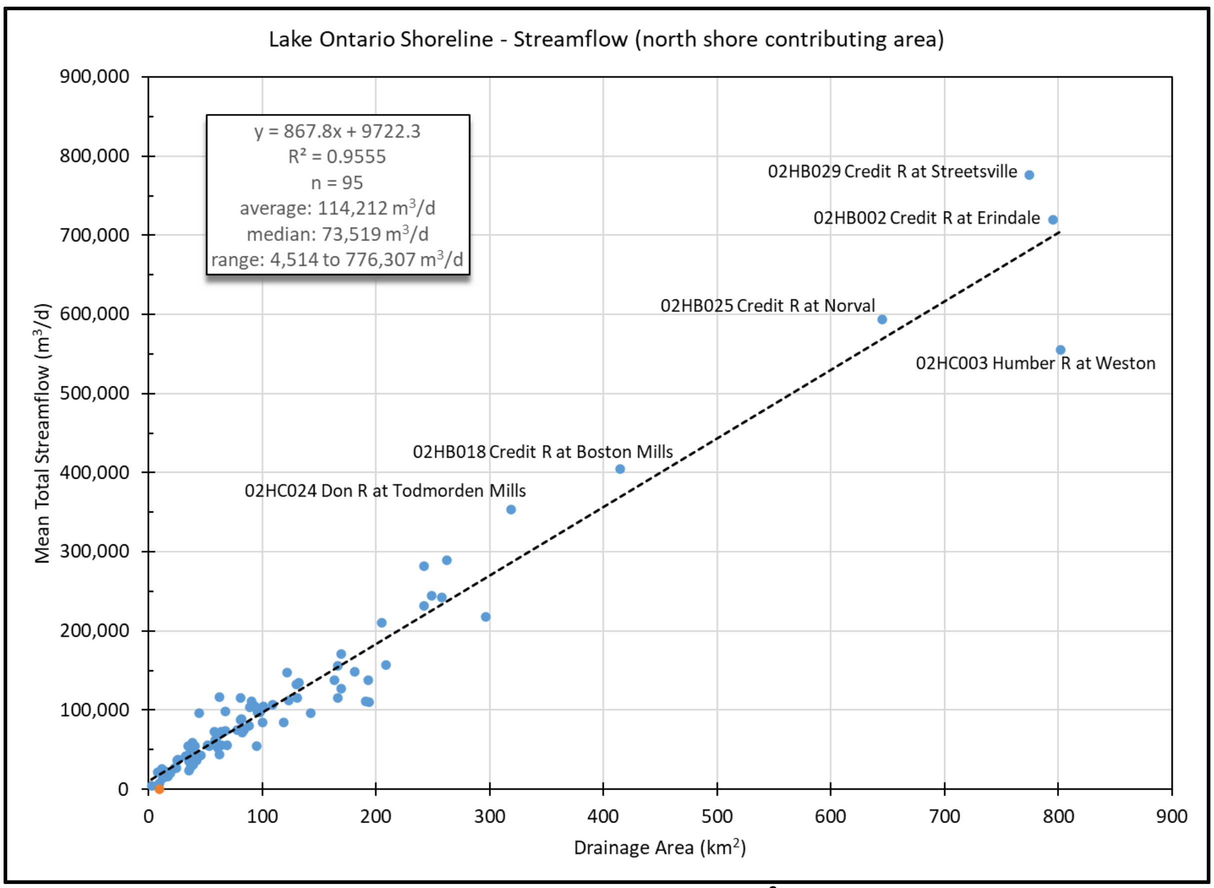

Figure 18: Summary of observed mean total streamflow (m^3/d) versus drainage area, within north shore contributing area. See plan view distribution summary of total streamflow and estimated groundwater discharge (BFI) on Figure 16.

3. RESULTS AND DISCUSSION

3.1 Modelled Groundwater Discharge to Lake Ontario

All models presented in Section 2.1 were run to completion and both indirect and direct groundwater discharge were accumulated. For the steady state models, the fluxes exiting the groundwater system were assumed to be long-term averages. For the transient models, exchange rates reported at 365 consecutive daily snapshots/model states are aggregated to an annual sum. Only the Durham model, the Laurentian Great Lakes model and the Southern Ontario model extended into the lake, the remaining models have their lake boundary condition directly at the shoreline. This didn't appear to affect the results.

Where the models intersect the 6,520 km^2 north shore contributing area, water exchange between the surface water and groundwater domains was captured. Based on a spatial (geographic) analysis, fluxes were separated in three categories (Figure 19):

1. Groundwater recharge,
2. Indirect groundwater discharge (to streams), and
3. Direct groundwater discharge (to Lake Ontario).

For each of the twelve models evaluated for the study, groundwater exchange is normalized to land surface area (mm/year - Figure 19-top) and length of Lake Ontario shoreline (m^3/d/km - Figure 19-bottom). Percentages show the proportion of groundwater discharge to lakes that is of a direct source, along the shoreline. For all models, there is a slight discrepancy between total discharge (direct + indirect) and recharge, owing to factors such as pumping from wells, or cross watershed flow in the subsurface domain. The integrated HydroGeoSphere models (the two right most models in Figure 19)) don't directly account recharge vs. discharge, only the net exchange across ground surface is calculated. Here, exchange from the surface water domain to the groundwater domain less evaporative loss is deemed recharge.

Normalizing the data allows for a more direct comparison of larger area models to smaller area models. Figure 19 presents the results of the modelling analyses in two different ways. The upper bar graph presents the results in terms of mm/year so that these values can be readily compared to other frequently used water budget parameters (e.g., average long-term precipitation to the study area ranges between about 700 to 1100 mm/year). The lower bar graph presents the same results in terms of the length of Lake Ontario shoreline covered by each model. By normalizing both the indirect groundwater discharge to streams as well as the direct Lake Ontario discharge to the length of Lake Ontario shoreline in each model, there is an inherent assumption that each model has a similar ratio of model area to length of shoreline. This assumption does not always hold, for example consider the CVC model where the vast Credit watershed only has a very small length of Lake Ontario shoreline. Nevertheless, this method allows for a comparison of the numerical model derived discharge values to earlier studies that also reported discharge per length of Lake Ontario shoreline using more rudimentary groundwater flow analytical techniques.

As stated previously for the study area, the groundwater discharge to streams is much larger than the groundwater discharge to Lake Ontario directly. Taking the results from twelve numerical models in bulk, direct discharge along the 226.7 km length of the Lake Ontario's north shore accounts for only 7% of the groundwater contribution to the Lake, equivalent to 11 mm/year and 870 m^3/d/km shoreline. Generally, direct discharge is an order of magnitude lower than indirect.

Numerical model results can be verified using Figure 19 by comparing: i) the simulated indirect discharge to the 17,200 m^3/d/km (218 mm/y) mean separated slowflow and ii) the simulated direct discharge to historical estimates of direct discharge (Haefeli, 1972; Singer, 1974; Ostry, 1979a; 1979b; Gerber & Howard, 2000; 2002; Meriano & Eyles, 2003; 2009), set to 715 m^3/d/km, n=21. In both case the numerical models have provided similar results.

Another observation is the noticeable similarity in the estimated discharge to Lake Ontario of about 870 m^3/d/km (ranging from 500 to 1,000 m^3/d/km) and in the indirect discharge to streams of about 10,000 m^3/d/km (ranging from about 4,000 to 40,000 m^3/d/km) in most of the models. This consistency also suggests that the models have arrived at reasonable groundwater flux estimates.

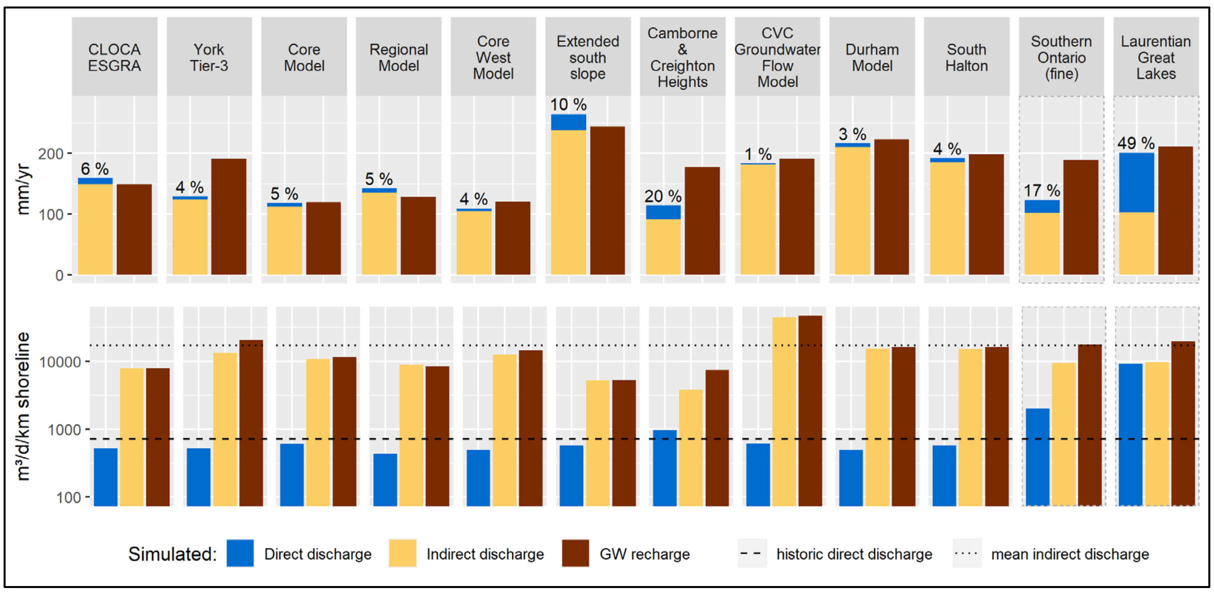

Figure 19: Summary of flux in (recharge) and out (direct and indirect discharge) of the modelled groundwater domain occurring within the Lake Ontario catchment area. Percentages indicate proportion of total direct groundwater discharge contributing to the lake. The dashed line shows maximum of historical estimates (715 m^3/d/km shoreline; n=21), while the dotted line shows separated slowflow (mean indirect groundwater discharge or groundwater discharge to streams).

3.2 Chloride (Cl^-) loading estimate to the north shore of Lake Ontario

Cl^- loading (L) across the 226.7 km length of north Lake Ontario shoreline is simply a function of drainage area (A), groundwater discharge (Q) and background concentration (C):

$$L = AQC$$

Only the contributing area (A) can be known to any certainty, in this case, to the contributing area to the north Lake Ontario shore measures 6,520 km^2 (Figure 6, Figure 16) as per the ORMGP Overland Drainage Model.[3] As presented in section 2, above, groundwater discharges and Cl^- concentrations can only be known with uncertainty.

Uncertainties in Q and C have been propagated to L in the above equation using a joint probability distribution to obtain a posterior uncertainty distribution of Cl^- loading to Lake Ontario. Both Q and C have been fitted to an error model: the concentration fit (C) is shown in Figure 15, while for Q, two prior distributions have been prepared based on the 12 numerical model estimates shown in Table 1. The log normal distribution for the 12 model's direct discharge provides (μ=18; σ=26 mm/year) and for indirect discharge (μ=145; σ=48 mm/year). Using this joint probability approach, uncertainty in loading from indirect and direct groundwater sources is approximated in bulk. Here, the (bulk) modal error is assumed normally distributed, with parameterization specified.

An estimate of mass Cl^- loading to Lake Ontario along its north shore is accomplished using the above equation, where uncertainties in direct and indirect discharge (Q), and Cl^- concentrations (C), are carried through to reveal expected loading (L) with uncertainty (Figure 20). The Cl^- loading projections can be interpreted in two ways:

1. The darkest regions are indicative of where the estimates have the greatest certainty. If we were to accept the inner-most and darkest region as our likely estimate, then given the uncertainty in both loading and the background Cl^- concentration, anywhere from 2-14 kilotonnes of Cl^- currently discharges directly into Lake Ontario from the north shore each year. Indirect groundwater discharge via tributary streams currently adds an additional 10-50 kilotonnes of Cl^- per year.
2. The graphs can be used as a predictive model, for example, one could ask: *"what would be the expected direct loading if background* Cl^- *concentrations approached 100 mg/L?"* Using this plot, one could assume direct loading to increase to between 5-50 kilotonnes Cl^-/year (Please note the y-axis on Figure 20 is in log scale).

From both direct and indirect sources, the range in estimated loadings would be from 12 to 64 kilotonnes per year. Within the north shore contributing area, there is close to 25,000 km of mapped road, based on Provincial road mapping. Assuming all mapped roads are serviced, and 11.5 tonnes of salt (NaCl) are applied per kilometer per year (Figure 7), then approximately 288 kilotonnes NaCl (which translates to ~174 kt Cl^- when the mass ratio of Na^+ to Cl^- is considered) is added to the watershed each year.

[3] owrc.github.io/interpolants/interpolation/overland.html

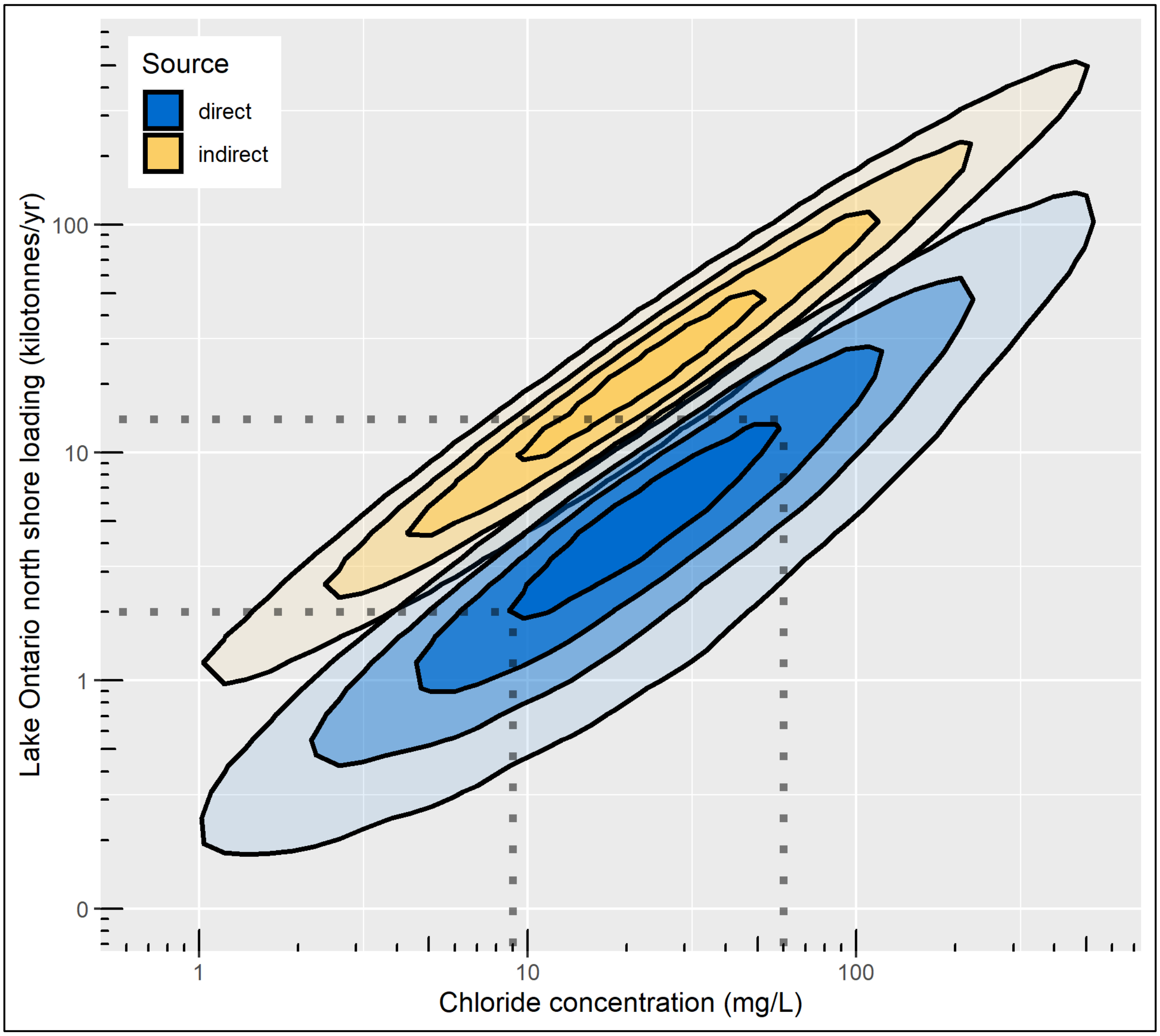

Figure 20: Projected Cl⁻ loadings derived from the joint probability distribution of background groundwater Cl⁻ concentrations and Direct and Indirect groundwater discharge along the north shore of Lake Ontario.

4. SUMMARY AND CONCLUSIONS

Twelve existing numerical groundwater flow models from a wide range of applications using a variety of model codes have been re-run to estimate direct groundwater discharge to the northern shore of Lake Ontario. There exists a wide range of uncertainty in i) the estimation of groundwater discharge to the lake via direct and indirect routes, ii) the value/meaning of a background groundwater Cl^- concentration, and iii) in the estimated road salt application rates to roads within the north shore drainage area. Within the constraints set by this uncertainty, the estimated groundwater Cl^- loading rate (12 to 64 kilotonnes/year) is of the same order of magnitude as the estimated municipal application rates (174 kilotonnes/year). The lower value for the estimated groundwater loading rate versus the application rate might support the predictions mentioned in Section 1, that salt continues to increase in the subsurface and has not yet reached a steady state. Whereas the application of road salt would only take place seasonally in the winter months, the groundwater discharge to Lake Ontario via indirect and direct routes is relatively steady.

Although the rate of groundwater discharge is slow compared to overland runoff events, it is nonetheless continuous and the subsurface is a large temporary repository for much of the salt that is applied to Ontario's landscape (with Lake Ontario being the ultimate repository of the salt applied within the study area). Over the long term, from the Lake's perspective, salt mitigation strategies must be equally, or even more so, focused on groundwater quality in addition to efforts directed to runoff and streams. It is worth highlighting here that there are other significant sources of salt application not being accounted for, for example sidewalk applications as well as private application to the many impervious surfaces associated with parking.

Direct groundwater discharge is but one transport pathway of contaminants to Lake Ontario, along with overland flow and indirect groundwater discharge to streams. While the relative contribution may seem small, it should not be overlooked (Harvey et al., 2000). Relatively shorter time-frame pathways may deliver higher concentration of contaminants via direct discharge owing to shorter groundwater travel times which allow for less time and volume for subsurface reactions (Na^+) and dilution (Cl^- and Na^+) to occur (Howard and Livingstone, 2000).

Cl^- concentrations managed within the ORMGP database showed great variability that nonetheless fitted well to a log-normal error distribution. Numerical model results were also variable and assumed to fit a normal error distribution. Fitting this information into error models allowed for the estimation of direct loading to Lake Ontario, along its northern shore, to be constrained to within 2-14 kt Cl^-/yr.

Combining both indirect and direct groundwater discharge sources, on the order of 12 to 64 kilotonnes of Cl^- is estimated to enter the Lake's north shore. For comparison, the estimated average salt application rate of 11.5 kt NaCl/km serviceable road applied to the roughly 25,000 km of mapped roads within the 6,520 km^2 contributing area, amounts to 288 kilotonnes NaCl (~174 kt Cl^- equivalent) per year. Groundwater loading is therefore considered significant relative to application rates.

4.1 Possible Future Refinements and Studies

As mentioned above there exists a wide range of uncertainty regarding salt loadings to the various water reservoirs that exist within the study area (groundwater, rivers and stream, and lakes). Some of this uncertainly may be reduced by conducting the following possible refinements and investigations:

1) Integrate various water quality data platforms (Persaud et al., 2021). Numerous water quality databases are being developed. Similar to how the ORMGP has moved forward, efforts should be made to integrate these to avoid duplication of efforts and to expand the data coverage;
2) Numerous studies have and are being conducted related to nutrient loading dynamics to the Great Lakes and Lake Ontario (e.g., Van Meter et al., 2019; Nelligan et al., 2021). Perhaps these investigations could be expanded to include regular Cl^- and Na^+ sampling and analyses;
3) Currently many PWQMN (streams) and Conservation Authority stream sampling locations lack winter sampling and analysis (Mazumder et al., 2021). Attempts should be made to include sampling in winter months and include both Cl^- and Na^+. Should physical collection of samples prove to be too difficult during the winter months, perhaps conductivity probes could be installed to collect information that could be related to various ionic concentrations throughout the year as described in Howard and Pilon (1993) and Howard et al., (1993). Perhaps analyses could also include other tracers of watershed dynamics such as contaminants of emerging concern (e.g., pharmaceuticals, PFAS; Baker et al., 2022).
4) Many streams along the north shore of Lake Ontario do not have continuous/regular flow or water quality measurements. Thought should be given to expanding the number of stream gauging stations (flow and quality) as close to river mouths as possible, being careful to avoid nearshore processes such as backflow conditions;
5) Further refine the spatial distribution of estimates of direct groundwater discharge along the north shore of Lake Ontario, emanating from both Quaternary sediments and bedrock (Paleozoic). Haefeli (1972) attempted to correlate lake temperature survey results with bedrock valleys or structures (large fault/fracture networks). This was deemed unsuccessful either due to masking effects of lake currents, or that groundwater discharge creating temperature anomalies are either low or non-existent. Haefeli (1972) did suggest that temperature anomalies do seem to occur near shorelines with steep faces (e.g., Scarborough Bluffs along east end of Toronto, and Bouchette Point east of Bowmanville). Further to this, investigations conducted by the ORMGP at High Park (www.oakridgeswater.ca, /Program Elements/Monitoring Sites/High Park) have discovered flowing aquifer conditions (groundwater levels up to 20 above ground surface) within the Laurentian Trough, a major bedrock valley extending from Georgian Bay to Lake Ontario (Sharpe et al., 2018). The question remains regarding where does this major aquifer system discharge, and why do groundwater pressures remain high so close to the lake shore? These various components could be explored further by utilizing the following possible information sources:
    a. Historical Lake Ontario temperature surveys (Haefeli, 1972) and more recent temperature surveys if they exist;
    b. Updated bedrock valley mapping;
    c. Lake bathymetry along with recently released Paleozoic 3D bedrock geology layer interpretation. If significant groundwater upwelling is occurring along the lake bottom, then certain bedrock units (e.g., shale) may have higher natural salt concentrations; and
    d. Fish spawning and benthic organism surveys. Certain biota or species may have tolerance ranges for water temperature anomalies (possible upwelling), and or water quality ranges;

6) Concentrations and trends within all water reservoirs (groundwater, streams, and lakes) are sensitive to and caused by various stressors including land use practices that increase urbanization. It is expected that climate change will also influence hydrologic processes and phenomena, which by extension may affect salt concentrations within all water reservoirs (Persaud et al., 2020; Costa et al., 2021). Regardless of the various stressors, whether increased urbanization, road salt application changes, climate change or introduction of invasive species, the ecosystem of Lake Ontario has seen significant variability and impacts (Pillsbury et al., 2021). This is similar to global lake investigations (Hebert et al., 2022; Hintz et al., 2022). The estimated impacts of these changing stressors (e.g., land use change, climate change) on salt loadings to Lake Ontario should continue to be investigated further; and
7) The various refinements and analyses suggested in points 5 and 6 above could benefit from selecting one model to use, and/or refine, to further investigate the various factors mentioned above. Likely model candidates for use and refinement have been utilized in the investigation conducted for this report.

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Table 1: Summary of numerical models utilized that cover a portion of the Lake Ontario north shoreline.

	Model Name	Reference	Model Area (km^2)	[1]Drainage Area (km^2)	Cell Size Min (m)	Cell Size Max (m)	#Layers	Shoreline Length (km)	Code	Time-Step	[2]#Elements	[3]Q Type (boundary type) Indirect	Direct
	Models listed roughly west to east along Lake Ontario shoreline												
1	South Halton	Earthfx, 2010b	962	961	12.5	100	10	32.1	MODFLOW-96	steady-state	436,936 x 10 layers	RIV + DRN	Specified head
2	Updated CVC	Matrix Solutions, 2012	1,413	1,199	1.7	180.8	13	13.3	FEFLOW	steady-state	181,477 x 13 layers	Head-dependent specified flux boundary at stream nodes	Specified head
3	Core	Earthfx, 2006	3,575	2,083	100	100	8	58.7	MODFLOW-96	steady-state	358,363 x 8 layers	RIV + DRN	Specified head
4	Regional	Earthfx, 2006	14,525	4,525	240	240	5	187.1	MODFLOW-96	steady-state	252,162 x 5 layers	RIV + DRN	Specified head
5	Core West	Earthfx, 2007	4,722	2,910	100	100	10	65.6	MODFLOW-96	steady-state	471,961 x 10 layers	RIV + DRN	Specified head
6	Core East	Earthfx, 2014	1,509	1,043	100	100	8	54.3	MODFLOW-NWT	steady-state	154,693 x 8 layers	RIV + DRN	Specified head
7	York Tier 3	Earthfx, 2013	3,746	2,252	100	100	10	57.3	MODFLOW-NWT	steady-state	374,723 x 8 layers + 2 quasi-sublayers	UZF + SFR	Specified head
8	Durham 2021	GeoProcess & Papadopulos, 2021	4,106	1,578	100	100	12	59.4	MODFLOW-NWT	steady-state	410,499 x 12 layers	UZF + SFR + LAK	Specified head
9	Camborne & Creighton Heights	Jagger Hims, 2007	401	254	1.6	391.2	9	16.5	MODFLOW-2005	steady-state	47,240 x 9 layers	RIV + DRN	Specified head
10	Extended South Slope (Tier 2)	Earthfx, 2010a	578	336	25	100	6	42.4	MODFLOW-96	steady-state	139,233 x 6 layers	RIV + DRN	Specified head
11	Southern Ontario (Geologic Survey of Canada)	Frey et al., 2019	109,565	7,718	32.5	6832.4	16	226.7	HydroGeoSphere (HGS)	transient (monthly)	132,985 x 16 layers (11 bedrock + 5 Quaternary)	Integrated model: surface exchange is summed over the land surface contributing to Lake Ontario north shore	Specified head boundary with monthly varying lake levels
12	Laurentian Great Lakes	Xu et al., 2021	770,335	7,718	249.1	10415.2	8	226.7	HydroGeoSphere (HGS)	transient (monthly)	107,194 x 8 layers (3 soil + 3 Quaternary + 1 fractured bedrock + 1 competent bedrock)	Integrated model: surface exchange is summed over the land surface contributing to Lake Ontario north shore	Specified head boundary with monthly varying lake levels

Notes:

[1] Drainage area contributing (either directly or indirectly) to the Lake Ontario north shore.

[2] #Elements - number of computational elements.

[3] Q Type - Indirect - The output/boundary of the model used to aggregate indirect contributions such as discharge to surface and streams.

[3] Q Type - Direct - The output/boundary of the model used to aggregate direct discharge along the Lake Ontario shoreline.