

Development and Evaluation of an
Aquifer Capability Screening Tool
Pilot Study: Clarence-Rockland, Ontario

by

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Abstract

Increased development pressure led the United Counties of Prescott and Russell to seek development of a GIS-based Aquifer Capability Screening Tool (ACST). A Pilot ACST, developed by a project partner within this study, was made for the City of Clarence-Rockland, Ontario, and consists of several maps showing delineated areas where there may be groundwater limitations in terms of quality or quantity. This study gathered the chemistry data needed for the Pilot ACST from 127 domestic dug and drilled wells. The results showed exceedances of provincial health and aesthetic standards, which were then used to delineate maps for the Pilot ACST. An evaluation of the necessary data source and sampling scale for ACST development revealed that data gathered from existing reports was inadequate for various reasons and sampling scale should be on a grid $2 \times 2 \text{ km}^2$ or smaller. Further recommendations were provided for future ACST development studies.

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1 Introduction

1.1 Background

Approximately 25% of Canadians rely on groundwater as a source of drinking water (Statistics Canada, 2010). While many residents live in cities which can produce potable water from surface waters or municipal wells and distribute that water via pipelines and waterworks, millions of Canadians live in rural settings and need to obtain their water from private wells.

In Ontario, prior to the creation of any new lot it is the Approval Authority's responsibility to ensure that the lot can be serviced with respect to water and wastewater. In Eastern Ontario, the Approval Authority is currently the Municipality. The Ontario Ministry of the Environment and Climate Change (MOECC) published a series of Guidelines to assess the suitability of proposed development sites for development on private services. These documents include: "MOEE Hydrological Technical Information Requirements for Land Development Applications" (April 1995); "Procedure D-5-5 Technical Guideline for Private Wells: Water Supply Assessment" (August 1996); and "Technical Support Document for Ontario Drinking Water Standards, Objectives and Guidelines" (June 2006). Many Municipalities in Ontario still rely on these Guidelines to evaluate the suitability of development where private wells are proposed.

Procedure D-5-5 (1996) recommends that a hydrogeological study be conducted and a report submitted prior to the recommendation of draft approval for the proposed development. A hydrogeological study must show that: *"Future owners of lots or homes have a high probability of being able to obtain adequate quantities of potable water for domestic consumption over both the short and long term."* (Section 1.0 Statement of Principles, Procedure D-5-5, MOE, 1996). Site-specific studies are necessary to ensure that development is safe and sustainable in the long-term. A hydrogeological study may reveal that a proposed development site is not suitable for development on private water wells based on lack of sufficient water quantity or suitable water quality, which may come at a loss of time and money to the developer.

In the past decade, Municipalities in the United Counties of Prescott and Russell (UCPR), located east of Ottawa, Ontario, have experienced growth in rural communities, causing an increased need for potable groundwater supplies. Since natural groundwater quality is a persistent issue limiting development on private services within the UCPR, the UCPR sought the development of an Aquifer Capability Screening Tool (ACST)—a mapping tool that can be used to pre-screen potential development sites where private wells are proposed. The ACST would be developed based on the groundwater quantity and quality found in pre-existing wells in the area and knowledge of the local geological and hydrogeological setting. The ACST would not replace the need for a hydrogeological study, but would provide a broad 'first glance' showing areas where water quantity or quality concerns may be anticipated.

Within the UCPR, the City of Clarence-Rockland ("the City") was selected for the development of the first ASCT as a pilot study. The City was chosen for the pilot study because

of increased development pressures as well as persistent problems with groundwater quality limiting potential development. According to supporting letters from the City, each year more than 200 residential building permits are approved and 35 new consents for rural residential lot development are granted. Municipal water service is provided to some portions of the City, but 13% of new developments are in rural or community policy areas that are not serviced and must rely on private wells to supply domestic water. The development of an ACST will benefit city planning by predicting areas which may be less suitable for development due to groundwater availability and quality.

This Thesis focused on supporting the ACST development by identifying areas of poor groundwater quality throughout the City. This was done by collecting groundwater chemistry data and comparing that data to Provincial drinking water standards. An evaluation has also been made of the sampling data requirements necessary for ACST development, and is intended to assist the planning of future ACST mapping projects in other municipalities.

While the ACST involves both groundwater quality and quantity, this Thesis focussed solely on aspects related to groundwater quality. Groundwater quantity ACST maps were developed independently by a project partner using data from the Ministry of Environment Water Well Information System and are not discussed herein.

1.2 Thesis Objectives

The objectives of this thesis were: (1) to collect and analyze groundwater samples throughout the City to be used to develop an ACST; (2) to investigate groundwater quality exceedances of Provincial drinking water standards for possible links to local geology and hydrogeology; and (3) to provide an evaluation of the sampling data requirements necessary for ACST development. Further details on these objectives are provided below.

The first objective involved conducting a Groundwater Sampling Program (GSP) throughout the City and producing a groundwater chemistry database. Groundwater samples were collected from existing privately owned overburden and bedrock wells at regularly spaced intervals following a 2 km² sampling grid. The groundwater from each well was thoroughly chemically analyzed, both on site and at laboratories, following the protocols used by the Ontario Geological Survey (OGS) in the Ontario Ambient Groundwater Geochemistry Project (OAGGP). The methods and results of the GSP are described in **Sections 3.1 to 3.4**. A series of maps which visually depict the groundwater chemistry results at each sampled location are presented in **Appendix 2**.

The second objective involved identifying differences in groundwater chemistry based on well type and depth setting, and comparing the data at each well to the Ontario Drinking Water Standards, Objectives and Guidelines (ODWSOG) described by the MOECC (2006). Investigating the groundwater chemistry type in **Section 3.5** helped to identify differences between shallow overburden groundwater and deeper groundwater, allowing the distinction of

wells into dug well and drilled well categories. The dug wells and drilled wells were then compared to the ODWSOG in **Section 4** order to identify exceedances throughout the City and examine their sources. The locations of these exceedances were used by a project partner to delineate areas of potentially poor groundwater quality, which comprise the ACST maps. Their methodology for ACST development is summarized in **Section 5.1**.

The third objective involved a Data Source Evaluation and a Data Scale Evaluation, which are discussed in **Sections 5.2** and **5.3**, respectively. The purposes of these two evaluations were: (1) to evaluate whether existing groundwater chemistry data could be used as an alternative to collecting new data from field sampling; and (2) to evaluate if data collected using coarser sampling grids would be sufficient for ACST mapping. In the Data Source Evaluation, existing groundwater chemistry data was gathered from available reports and documents and the resulting dataset was compared to the GSP dataset in terms of its spatial coverage, data quality and resulting ACST groundwater quality maps. In the Data Scale Evaluation, correlation scales were determined for each delineated parameter and a visual demonstration was made by comparing ACST maps produced from datasets re-selected from the GSP dataset using 2 km², 2.5 km², 3 km² and 4 km² sampling grids. In **Section 6** conclusions are drawn from these evaluations and recommendations are provided for what should be done in future ACST projects.

1.3 Project Partners

This project was part of a collaborative partnership between the University of Ottawa (UOttawa), the South Nation Conservation Authority (SNC), the Ontario Geological Survey (OGS) and Geofirma Engineering Limited (Geofirma). The project was funded by The United Counties of Prescott and Russell, the City of Clarence-Rockland, the Eastern Ontario Water Resources Committee and many in-kind contributions from the project partners (OGS, SNC, UOttawa and Geofirma). Project management and communications were led by SNC. The field program was carried out by UOttawa and SNC, and sample analyses were performed by OGS GeoLabs and UOttawa. OGS provided field training to UOttawa prior to the field season. The database for this project was managed by UOttawa with audits from OGS, who published the dataset inclusively with the results of the Ontario Ambient Groundwater Geochemistry Project (OAGGP) in MRD283-REV (Hamilton, 2014). Geofirma developed the methodology to produce the ACST (maps of expected groundwater quantity and groundwater quality) for the City, in consultation with SNC and UOttawa. The ACST produced by Geofirma was peer reviewed by OGS, UOttawa and SNC.

2 Study Area: The City of Clarence-Rockland, ON

2.1 Description of Study Area

The City of Clarence-Rockland (“the City”) lies directly east of Ottawa, Ontario, and is situated along the southern shore of the Ottawa River. The City is one of eight municipalities that make up the United Counties of Prescott and Russell (UCPR), shown in **Figure 2-1**. Geographically, the City is situated in Zone 18N of the Universal Transverse Mercator (UTM) coordinate system, between latitudes of N45°21’52” and N45°35’15”, and between longitudes of W075°20’29” and W075°04’46”. The datum used to display spatial data in this thesis is the 1983 North American Datum (NAD83).

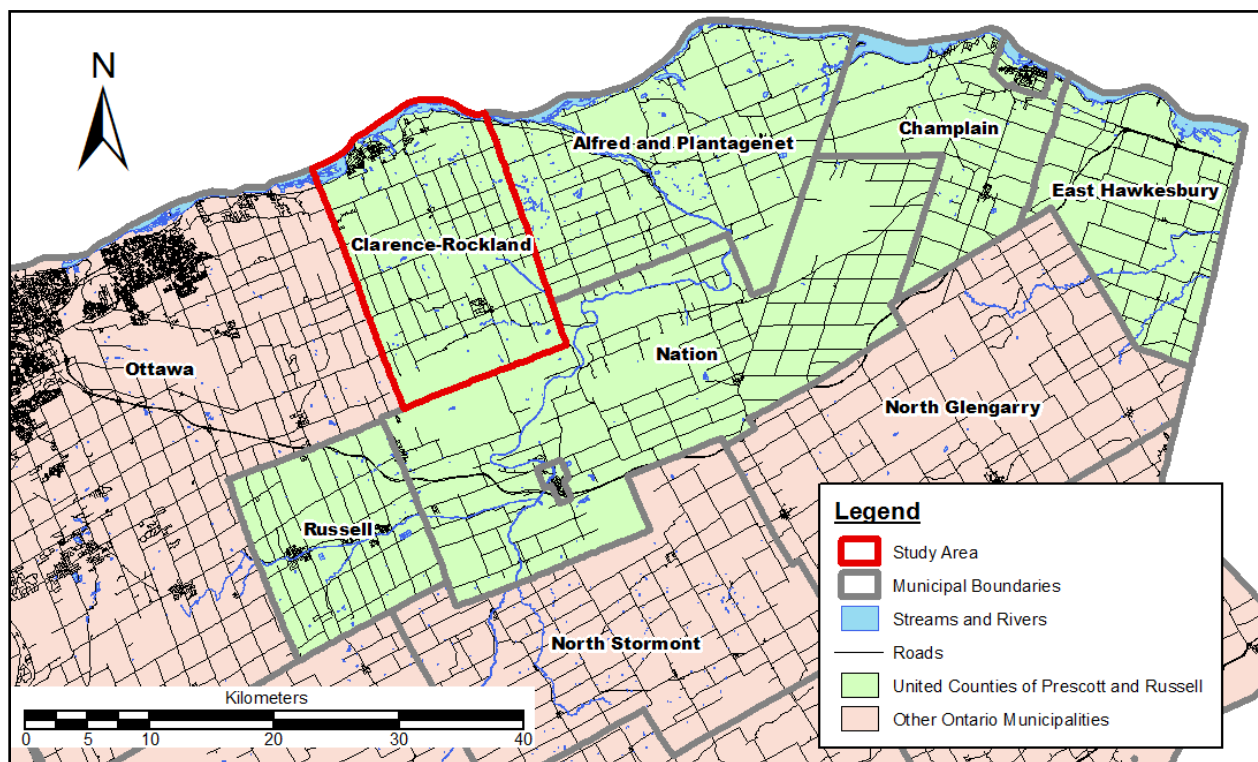


Figure 2-1. Overview map of the United Counties of Prescott and Russell showing the study area: The City of Clarence-Rockland, ON. *Map data for municipal boundaries, water bodies and roads were acquired from NRCan (2010) and OMNR (2012a; 2012b).*

The total land area in the City is 297.86 km², and in 2011 the population density was 77.8 people/km² (Statistics Canada, 2012). The City itself includes several smaller villages including Rockland, Clarence, Clarence Creek, Saint-Pascal-Baylon, Hammond, Bourget and Cheney; the locations of these villages are shown in **Figure 2-2** along with the network of drivable roads. The Larose Forest, also shown in **Figure 2-2**, is a restored natural environment that is protected and managed by the UCPR. According to Statistics Canada (2012), in 2011 the City had a

population of 23,185 people, showing an 11.5% increase from the 2006 population of 20,790. This has been the largest growth experienced throughout the United Counties of Prescott and Russell, whose total population rose 6.5% from 80,184 to 85,381 during that time.

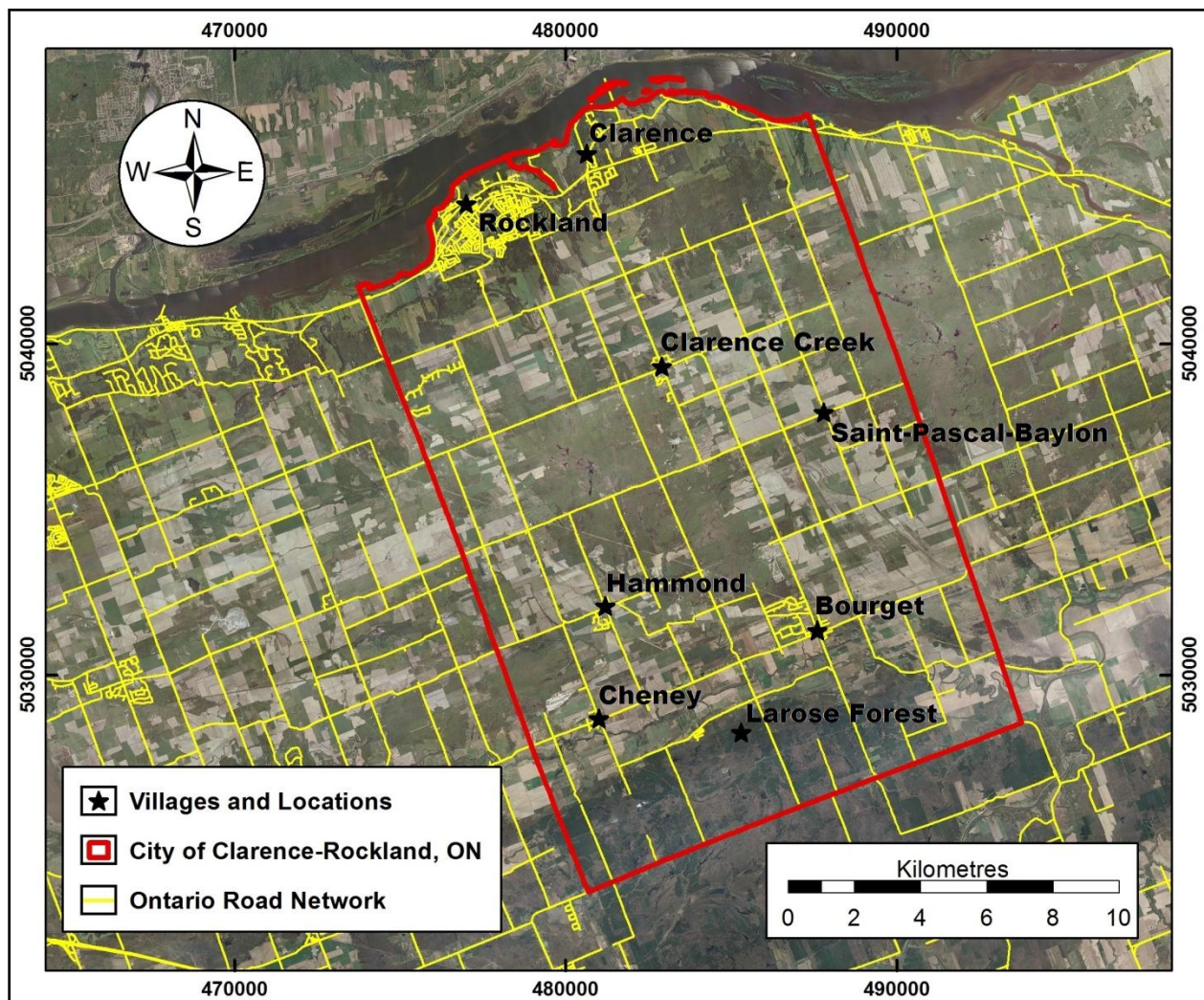


Figure 2-2. Map of the City of Clarence-Rockland, Ontario, showing the city boundaries, locations of villages and major forests, the Ontario Road Network and satellite imagery. *Map data for city boundaries and roads were acquired from NRCan (2010) and OMNR (2012b).*

The villages in the City are serviced by municipal water distributed from the treatment plant at Rockland, which draws from the Ottawa River. Outside of these areas are rural homes which either obtain potable water from private wells or use alternatives such as bottled water. There are exceptions to this along some major roads where municipal water pipelines are run to connect to the villages.

The ground surface elevation across the City and its surroundings is shown in **Figure 2-3** with elevation expressed as meters above sea level (m a.s.l.). The highest elevations in the City are around 100-110 m a.s.l. and consist of forested hills located a short distance south of

Rockland and Clarence on the east and west portions of the City. Between these hills there is a wide valley or channel with low elevation (42-50 m a.s.l.) running through the City southeast from the Ottawa River. In the southeast, that channel is joined by another of low elevation (50-60 m a.s.l.) which decreases in elevation along its west-east span, and is connected to a third channel with slightly higher elevation (60-70 m a.s.l.). Today, these channels mark what were once flow or drainage paths of the Proto Ottawa River.

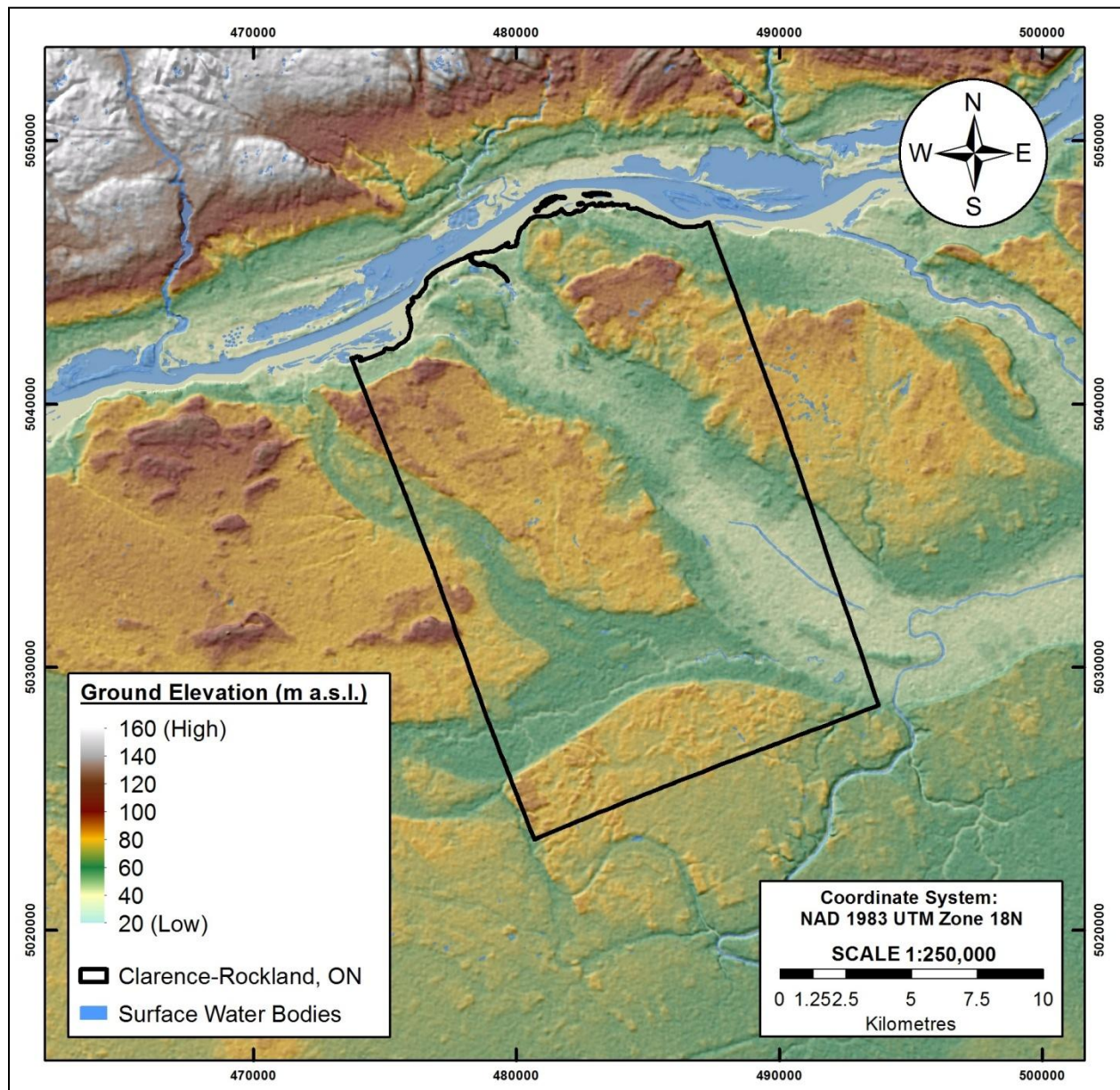


Figure 2-3. Digital Elevation Model (DEM) showing ground surface elevation across the City of Clarence-Rockland, ON. *DEM and hillshade raster datasets were acquired from NRCan (2013).*

The villages within the City are situated at slightly elevated topography relative to their surroundings. Low lying areas, particularly to the southeast of the City are sparsely populated and may be prone to flooding, as was seen with road closures in July 2013. The hilly areas are mostly forested with some development, and much of the land throughout the City is used for agriculture.

For historic climate data, the nearest source of information is a climate station located 35 km west of the City at the Ottawa Macdonald-Cartier International Airport. The temperature and precipitation data at that station were obtained from Environment Canada (2014) and have been averaged based on 30 years of monthly data from July 1981 to June 2011. The average annual temperature is 6.4°C, with average monthly temperatures of 21.0°C in July and -10.2°C in January. The highest precipitation occurs in August, and the annual average is 944 mm/yr with 758 mm/yr from rain and 226 mm/yr from snow. The average annual potential evapotranspiration is estimated at 649 mm/year in the surrounding area of the City (RRCA-SNC, 2006), which leaves a minimum of 295 mm/year in water surplus that can infiltrate the ground or become runoff.

2.2 Local Bedrock Geology

The bedrock geology found beneath the City consists of Precambrian igneous and metamorphic rock that is overlain unconformably by numerous Paleozoic sedimentary rock layers deposited from the Late Cambrian to Upper Ordovician periods. This section and subsections serve to summarize the origin and stratigraphy of the bedrock geology found within the City.

A map of the bedrock geology formations found nearest to the ground surface in the City is shown in **Figure 2-4**. Extending southeast from the Ottawa River at the northwestern city boundary, the surficial bedrock geology formations range from sandstones and dolostones (Upper Cambrian to Middle Ordovician Periods) to limestones, siltstones and shales (Middle to Upper Ordovician Periods). The bedrock surface throughout most of the City belongs to the Ottawa Group carbonates, with younger more shaly and organic bedrock formations at the southeastern edge underlying the Larose Forest and older more sandy bedrock formations in the northwestern portion where the main city centers (Clarence and Rockland) are located.

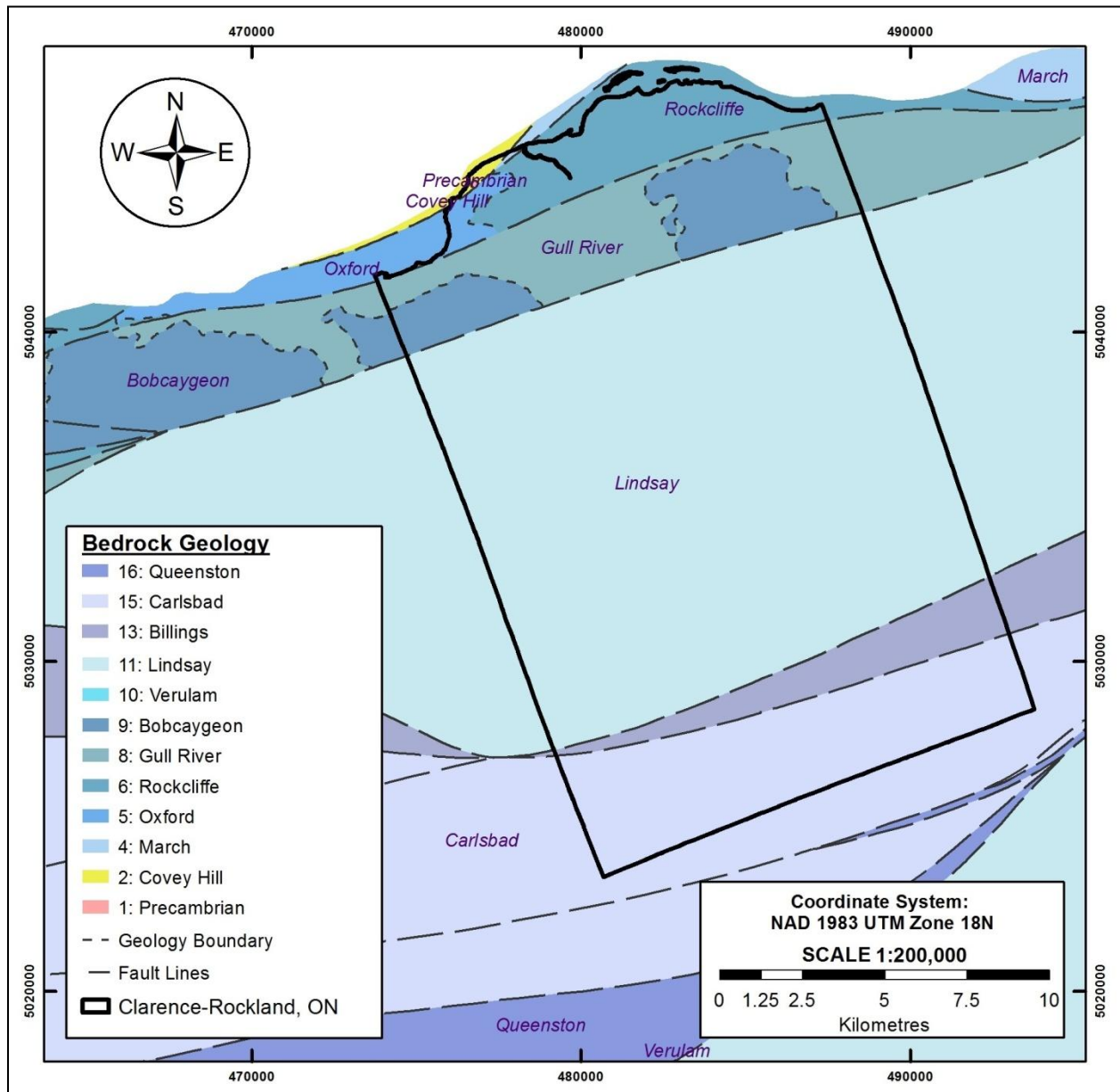


Figure 2-4. Paleozoic bedrock geology map for Clarence-Rockland, ON. Map data acquired from OGS Miscellaneous Release Data 219 (Armstrong & Dodge, 2007).

The Geological Survey of Canada (GSC) have many borehole records throughout Canada revealing the stratigraphy and approximate thickness of geological units. **Figure 2-5** shows the depth and stratigraphy of a GSC borehole in Russell, ON, located approximately 20 km southwest of the City. The stratigraphy in that borehole is largely representative of Eastern Ontario and can serve as a guide, however the March Formation and Queenston Formation portrayed are not encountered in the City. GSC borehole records do not exist for the City, but the approximate thicknesses of each unit can be inferred from three surrounding GSC boreholes, whose formation thicknesses are described in **Table 4-1**.

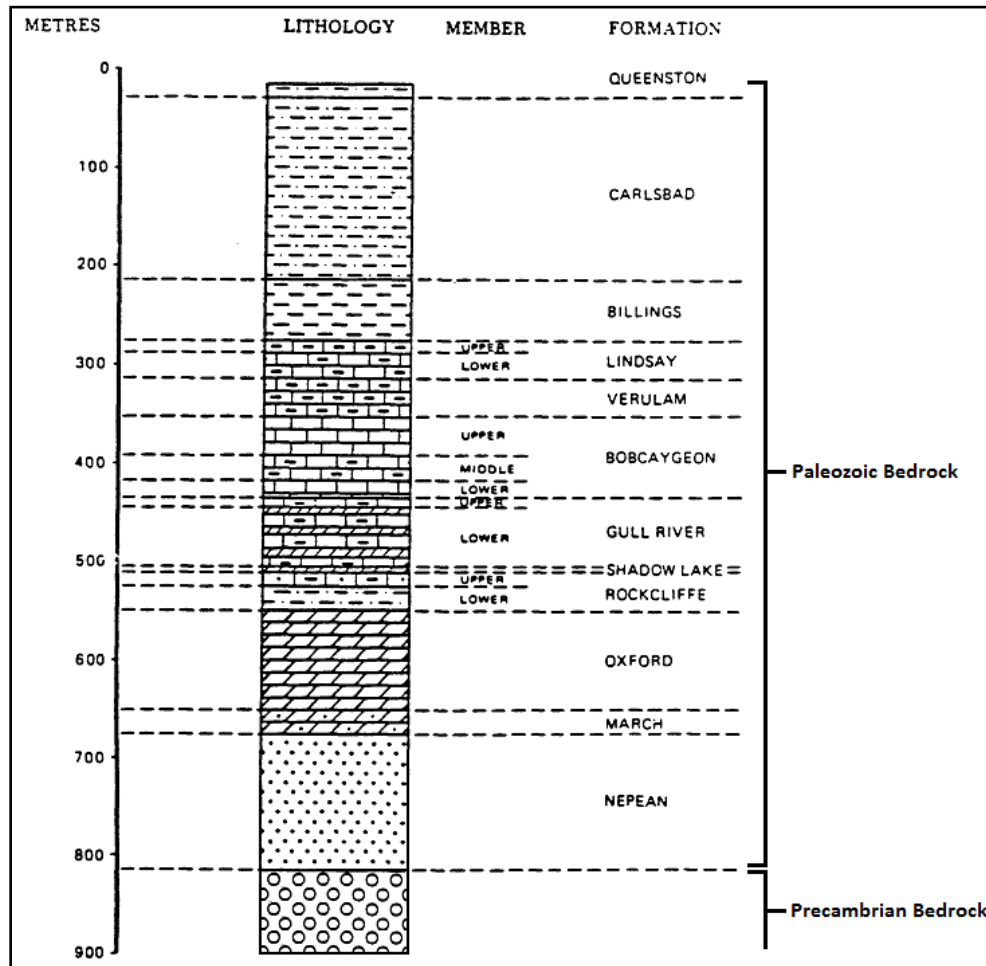


Figure 2-5. Stratigraphy of a Geological Survey of Canada well located in Russell, Ontario. Modified from Williams (1991).

Table 2-1. Bedrock unit thicknesses reported by Williams (1991) from borehole records for Ottawa, Russell and Hawkesbury, ON, that were produced by the Geological Survey of Canada.

<u>Bedrock Formation</u>	<u>Thicknesses of Bedrock Formations in Boreholes (m)</u>		
	Ottawa, ON (447360m E, 5025840m N)	Russell, ON (469400m E, 5017600m N)	Hawkesbury, ON (514360m E, 5042560m N)
Queenston	Not present	>13.0	Not present
Carlsbad	Not present	186.9	Not present
Billings	Not present	62.0	>56.7
Lindsay	25.0	32.7	24.6
Verulam	32.0	39.7	65.4
Bobcaygeon	83.6	83.3	51.2
Gull River	54.1	71.4	42.7
Rockcliffe	52.1	47.9	65.9
Oxford	62.2	102.1	129.1
March	17.6	20.1	26.3
Nepean	60.4	>159.3	>10.9
Covey Hill	0.0 – 8.8	Unknown	Unknown

2.2.1 Precambrian Bedrock Geology

The Precambrian Era basement rocks underlying the sedimentary layers in the City are part of the Grenville Province and were formed between 1.3-1.0 billion years ago during the Grenville Orogeny (Bélanger, 2008). The Grenville Orogeny was a mountain building event that occurred when the North American craton, known as Laurentia, was merging with other continents to form the supercontinent, Rodinia. Today, the Grenville Province Precambrian rocks cover half of Canada spanning North and East from Central Canada, and are better known as the Canadian Shield.

The Canadian Shield is mainly a combination of metamorphic gneiss and marble with igneous dike intrusions of pegmatite. These rocks underlie the entire region, forming a basement complex, and can be found outcropping near Ottawa, ON, as the Gatineau Hills and the Carp Ridge (Bélanger, 2008). Throughout the rock are transition zones where the original sedimentary rocks have been partially metamorphosed due to their proximity to the igneous intrusions; carbonate sedimentary rocks such as limestone have metamorphosed into marble and other lime silicate rocks, whereas non-carbonate rocks such as shale and sandstone have metamorphosed into gneiss and quartzite (Bélanger, 2008). Some contact zones along the intrusions contain a mixture of igneous and metamorphic rock and are considered magmatic.

2.2.2 Paleozoic Bedrock Geology

Resting above the Precambrian Canadian Shield are several sedimentary rock formations that were deposited, buried and lithified between the Late Cambrian and Late Ordovician periods during the Paleozoic Era (Williams, 1991). The age of these deposits range approximately from 523 to 443 million years before present (Bustros-Lussier, 2008). The supercontinent Rodinia had split at the beginning of the Paleozoic Era, and seawater began to transgress inward from the Iapetus Ocean, gradually submerging the Eastern portion of Laurentia (Bélanger, 2008).

The first preserved marine deposits were the high energy conglomerates and sandstones known as the Covey Hill Formation and the Nepean Formation. These formations, each separated by an unconformity, make up the Potsdam Group and were deposited from Late Cambrian to Early Ordovician roughly between 523 and 500 million years ago (Gall, 2010). These formations were non-calcareous and feldspathic, with matrices of fine to coarse quartz sand and angular feldspar grains (Williams, 1991).

Throughout the Early Ordovician the sea levels continued to rise, lowering the energy of the environment and allowing the deposition of finer grained material. The March Formation, deposited above the Nepean formation, is an example of this gradual transgression with its quartz sandstone layers that are intermixed with dolostone (Williams, 1991). Following the March formation is the Oxford formation, containing interbeds of finely crystalline dolostone with shaly dolostone and some sandstone, with a general fining upward sequence hinting again at the rising water level (Bélanger, 2008). Together, the March and Oxford Formations make up the

Beekmantown Group, which was deposited approximately 500 to 478 million years ago (Gall, 2010).

In the Early to Middle Ordovician, the sea level fluctuated considerably (Bélanger, 2008). The initial regression caused erosion and exposure to much of the Early Ordovician rocks, which was followed by a new transgression resulting in the Rockcliffe Formation (Bélanger, 2008). The Rockcliffe Formation consists mainly of interbedded quartz sandstone and shale, beginning with deposits of conglomerates and green quartz sandstone which had eroded from uplifted sections of Precambrian rock, and gradually depositing finer material to end with layers of sandy shale with some shaly bioclastic limestone in its upper member (Bélanger, 2008; Williams, 1991).

Throughout the Middle Ordovician there were numerous low energy deposits of shale, dolostone and carbonate which collectively now make up the Ottawa Group (Bélanger, 2008; Wilson, 1956). The Ottawa Group began deposition approximately 458 million years ago and is lithologically and stratigraphically equivalent to the Simcoe Group (Gall, 2010; Hersi and Dix, 1997). From bottom to top, it includes 5 bedrock formations: the Shadow Lake, Gull River, Bobcaygeon, Verulam and Lindsay Formations.

The Shadow Lake Formation, at the base of the Ottawa Group, includes non-calcitic to calcitic sandy and silty dolostone with thin interbeds of calcareous quartz sandstone (Williams, 1991). The Gull River Formation begins with interbedded limestone and silty dolostone at its base and grades upwards into finely crystalline limestone, with shaly partings all throughout. The Bobcaygeon formation contains thin to massively bedded limestone ranging in grain size from lithographic to coarsely crystalline fossiliferous limestone in which cross-bedding and stylolites are also commonly observed. The Verulam Formation consists of very thin to medium thickness fossiliferous limestone which can be sublithographic to coarse in grain size, with 15 cm interbeds of calcareous shale. The Lindsay Formation two members: a lower member which makes up most of its thickness and contains interbedded sublithographic to coarsely crystalline fossiliferous limestone; and a relatively thin upper member also known as the Eastview Formation has a very high organic carbon content and consists of calcareous shale and finely crystalline petroliferous fossiliferous limestone.

Throughout the Ottawa Group, there was an increasing abundance of vegetation and marine life, particularly evident in the Lindsay formation which is abundant with fossils and contains pockets of natural gas (Hamblin, 1998). Because of this, the Ottawa Group can be characterized by a general increase in CaO content from its base layer (Williams, 1991). Despite the general increase of CaO content in the Ottawa Group, the Bobcaygeon Formation sees a decrease from 54% near its base to 45% at its surface, though multiple rises and falls occur (Williams, 1991). These sudden changes in CaO indicate dissolution and removal of calcite from the system, hinting at fluid transport from underlying shale or sandstone layers which may also explain the stylolites which form through pressure dissolution (Kennedy & Logan, 1998).

In the Late Ordovician there were much deeper waters and shelf-like conditions, resulting in low energy shale deposits which became the Billings, Carlsbad and Queenston Formations (Bélanger, 2008). The Billings formation consists of dark brown to black calcareous to non-

calcareous shale with thin laminations of finely crystalline limestone and calcareous siltstone near the bottom (Williams, 1991). Towards the end of the Billings deposition, there was major crustal uplift causing the sea level to drop and resulting in a reverse upward grading from the Billings into the Carlsbad Formation above (Bélanger, 2008). The Carlsbad Formation consists of interbedded dark grey calcareous to non-calcareous shale, fossiliferous calcareous siltstone and silty bioclastic limestone (Williams, 1991). The younger Queenston Formation consists of slightly calcareous siltstone and shale of varying colour (Bélanger, 2008), but is not encountered in the City.

2.2.3 Faulting in the Late Paleozoic and Mesozoic Eras

Following the Late Ordovician, a large section of geological history is absent from the region due to major erosional events dating from the Silurian Period to the Quaternary Period. It is estimated that as many as 1000 meters of rock have been removed from certain areas, which greatly smoothed the landscape following the rifting and faulting events that occurred between the Late Paleozoic and Mesozoic Eras (Bélanger, 2008).

In the Late Paleozoic Era the supercontinent Pangea formed, and in the Mesozoic Era Pangea broke up. The convergence and separation caused major rifting to occur, and as a result, numerous faults of major and minor scale exist throughout Ontario. The Ottawa River Valley was in fact formed by extensional rifting, which produced the Ottawa-Bonnechere Graben (Rimando & Benn, 2005). An overview of the Ottawa-Bonnechere Graben is depicted in grey in **Figure 2-6a**, and **Figure 2-6b** shows the known and predicted fault lines throughout the Ottawa region with the City's boundaries in red. The position of mapped faults in the City are shown in **Figure 2-4**.

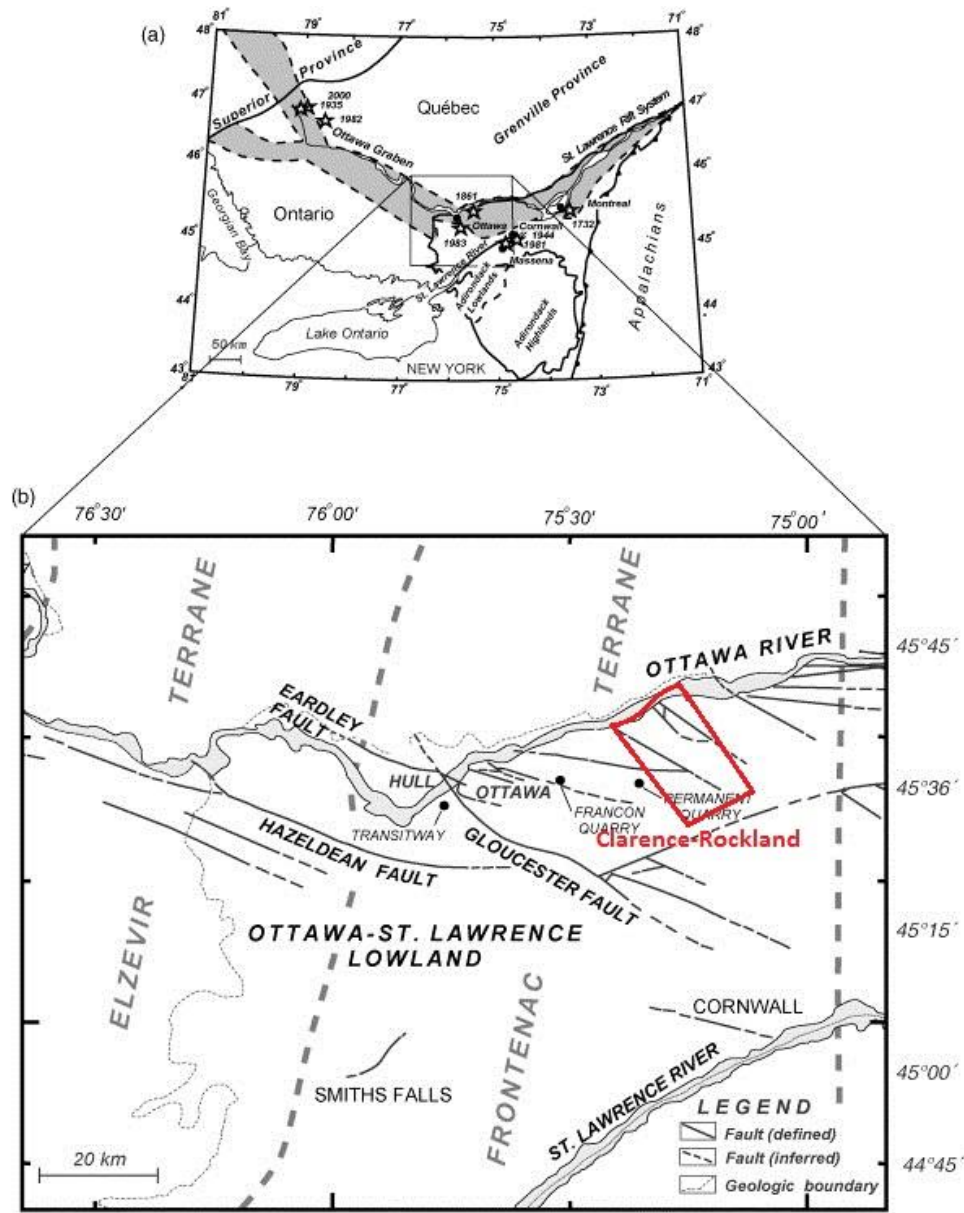


Figure 2-6. (a) Map showing the location of the Ottawa-Bonnechere Graben. **(b)** Regional structures of the Ottawa graben in the Ottawa Valley region. Shown in red are boundaries of the City of Clarence-Rockland, Ontario. *Modified from Rimando & Benn (2005).*

In a study of the paleo-stress field within the Ottawa-Bonnechere Graben, there were found to be three typical fault orientations: Northwest to Southeast, West-Northwest to East-Southeast, and East-Northeast to West-Southwest (Rimando & Benn, 2005). Four known faults extend into the City. One is a West-Northwest orienting fault which extends westward from Hammond. The other three are Northwest orienting faults that are located between Cumberland and Clarence, and span as far southeast as Bourget. Two of those Northeast orienting faults, located at the edge of Rockland and at the midpoint of Rockland and Clarence, appear to connect at Saint-Pascal-Baylon and feature younger bedrock geology than their adjacent units, indicating that the rifting caused the inner portion to sink as a minor failed graben. Due to their orientation, it is speculated that the three Northwest orienting faults in the City would have originated in the

Late Paleozoic during the closing of the Iapetus Ocean, whereas the West-Northwest orienting fault would have originated later during the opening of the Atlantic Ocean in the Mesozoic Era (Rimando & Benn, 2005).

The uppermost bedrock units found along each of the fault margins throughout the City are Ottawa-Group formations on both sides (Wilson, 1946). With the approximate thickness of the Ottawa Group being 215 meters (Wilson, 1946) and the vertical displacement being contained within those units, we see that the faults throughout the City were relatively minor. It is likely that these faults did not exceed a displacement of 150 meters; however considering the thickness of each bedrock unit (**Table 2-1**) such a displacement would greatly affect the local aquifers and groundwater movement would be facilitated along the fault margins, resulting in possibly complex groundwater geochemistry.

2.3 Local Overburden Geology

Within the context of this thesis, the term “overburden” refers to any sediment or deposit that exists between the topsoil and the uppermost bedrock unit. Surficial geology refers to the upper layer of overburden geology.

The overburden geology throughout the City, shown in **Figure 2-7**, consists mainly of silt and clay, some sand and gravel. The study area is predominantly overlain by marine offshore deposits left by the Champlain Sea. High-standing areas contain sands and gravels which were beaches of the Champlain Sea, and some fluvial and glaciofluvial deposits are present at the southern edge of the city where the Proto-Ottawa River flowed.

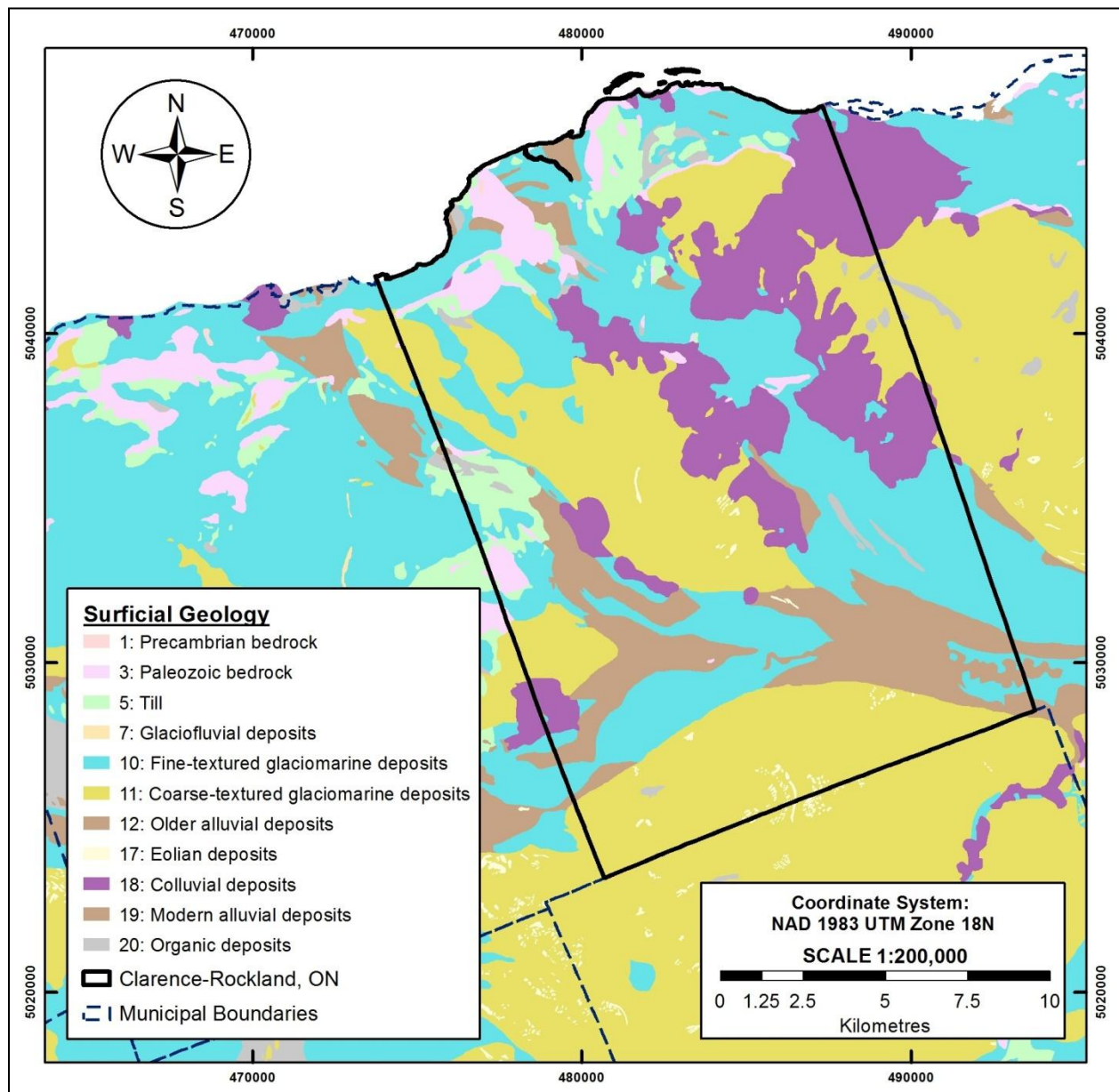


Figure 2-7. Surficial geology map for the City of Clarence-Rockland, Ontario. *Map data acquired from OGS Miscellaneous Release Data 128 (OGS, 2010).*

2.3.1 History and Depositional Setting

Throughout Eastern Ontario, all of the sediments that exist on top of bedrock have originated within the Quaternary Period, which started 1.8 million years ago (Bélanger, 2008). Surface material that previously existed on top of bedrock, as well as many bedrock layers that are no longer present, were removed by the passing of numerous glacial ice sheets in recent geological time. It is the Laurentide ice sheet from the most recent glaciation, the Wisconsinan, which is responsible for all surficial geology deposits throughout the City. Deposits of gravelly till from the bottom of the glacier overlay the bedrock, along with other glacial deposits with widely ranging grain sizes. As the Laurentide ice sheet retreated, the proglacial lakes Agassiz

and Ojibway formed along its Western and Eastern fronts, respectively, which eventually drained to form the Great Lakes that we know today.

Approximately 12,000 years ago, the weight of the glaciers on the land had caused enough subsidence for the North Atlantic Ocean to flow into the Ottawa Valley (Bélanger, 2008). With the ocean water from the Atlantic and the freshwater drainage from Lake Ojibway, a brackish body of water known as the Champlain Sea then occupied the inlet. The Champlain Sea existed for approximately 2,500 years, and blanketed the region in a thick layer of sodium-rich clays (Bélanger, 2008). With ice retreating from the area, there was less weight on the land and isostatic rebound occurred, causing the Champlain Sea to gradually drain back into the Atlantic. With this, Lake Ojibway was granted a flow path through the Ottawa Valley, which formed the Proto-Ottawa River. The high flow rates of the Proto-Ottawa River were enough to carve out the marine clays, replacing them with freshwater fluvial deposits of sands and gravels directly onto the bedrock surface and overlying till. The paths of the Proto-Ottawa River can be seen in the low elevation areas of the City shown in the digital elevation model in **Figure 2-3**.

2.3.2 Surficial Deposits

The surficial deposits throughout the City vary greatly both spatially and with depth and are shown in **Figure 2-7**. The overburden geology can largely be summarized into different categories based on the materials origins. They are glacial till, glaciofluvial sediments, marine offshore sediments, marine nearshore sediments and fluvial deposits.

Glacial till unconformably overlies the bedrock throughout the region (Bélanger, 2008). Till describes poorly sorted sediments which have come from a glacier that have either been released from their suspension within the ice upon glacial retreat and deglaciation, or have been deposited as lodgement till beneath the glacier. Because till has been contained within the ice, the sediments can originate from any rocks that the glacier has passed over. Throughout the Ottawa Region till deposits are loose near the surface and very compact at depth (Bélanger, 2008). Due to the eroded rocks in the region being mostly soft carbonates, there is a high silt and clay content in these tills compared to other regions, which provides a matrix for the otherwise stony and sandy material (Bélanger, 2008). In most parts of the City, the uppermost unit of bedrock is covered in 10-20 feet of gravelly till; this gravel section is hydraulically connected to the underlying bedrock units and would expectedly yield similar types of groundwater.

Glaciofluvial sediments lie at the bottom and sides of valleys that existed during the deglaciation. These sediments have been transported by the freshwater rivers that flow within and beneath the glaciers themselves, and as a result their grains are typically less angular and better sorted than glacial till. Their grain sizes consist of coarse to medium grained sand and gravel (Bélanger, 2008; Williams, 1991), and are quite permeable to groundwater flow.

There are two types of marine sediment deposits throughout the City: marine offshore sediments and marine nearshore sediments. Much of the City's bedrock and gravelly till are overlain by tens of meters of marine offshore silt and clay deposits. These thick low permeability deposits alternate in layers and make poor aquifers despite the occurrences of sand

and gravel pockets that can be found scattered throughout. Adding to that, these clays have a high salt content, due to their marine depositional setting, making them potentially unstable and susceptible to landslides and subsidence.

Marine nearshore sediments, consisting of sand, gravelly sand and gravel, occupy the areas of higher elevation where there would have been beaches, and overly the thick clays in many parts due to beach formation during the gradual regression of the Champlain Sea. These deposits are highly permeable and can make great groundwater aquifers when underlain by impermeable/semi-permeable marine clay deposits. Due to their proximity to the surface and their semi-continuous occurrence throughout the region, these aquifers are placed at high risk for potential contamination.

2.4 Hydrogeology and Groundwater Flow

There are numerous aquifers throughout the City, and their flow paths can be difficult to identify due to the complex variety and arrangement of surficial quaternary deposits and underlying bedrock units. It is important to consider where those aquifers recharge and discharge their water. Their composition, depth, thickness, permeability and surroundings all play critical roles in the physical hydrogeology of an aquifer and influence the chemistry of the groundwater that can be encountered.

Between the underlying bedrock formations and overlying overburden formations, there is an interface several to tens of meters in thickness which is commonly referred to as the **contact zone aquifer**. This contact zone aquifer is found throughout the City and is an important aquifer for the South Nation River watershed due to its accessible depth (via drilling) and high groundwater yield. The actual thickness of the contact zone aquifer at any given location is difficult to discern because it is found at the interface between bedrock and overburden materials and serves as a hydraulic connection between them. Its vertical span typically includes the fractured and weathered upper layers of Paleozoic bedrock and the overlying deposits of gravelly and bouldery glacial till, and it can be hydraulically connected to smaller aquifers scattered throughout the thick marine clays deposited above. The marine clays vary up to 60 meters in thickness throughout the City resulting in total overburden thicknesses up to 96 meters (Logan et al., 2009).

The potentiometric surface and some interpreted groundwater flow directions for the upper bedrock and contact zone aquifer are shown in **Figure 2-8**. Potentiometric surface shows hydraulic head, which is the water level relative to a datum, usually sea level. Effectively, water will flow from high to low hydraulic head. In **Figure 2-8** we see that there are high hydraulic head areas southwest of Rockland, northeast of Rockland, and east of Clarence Creek.

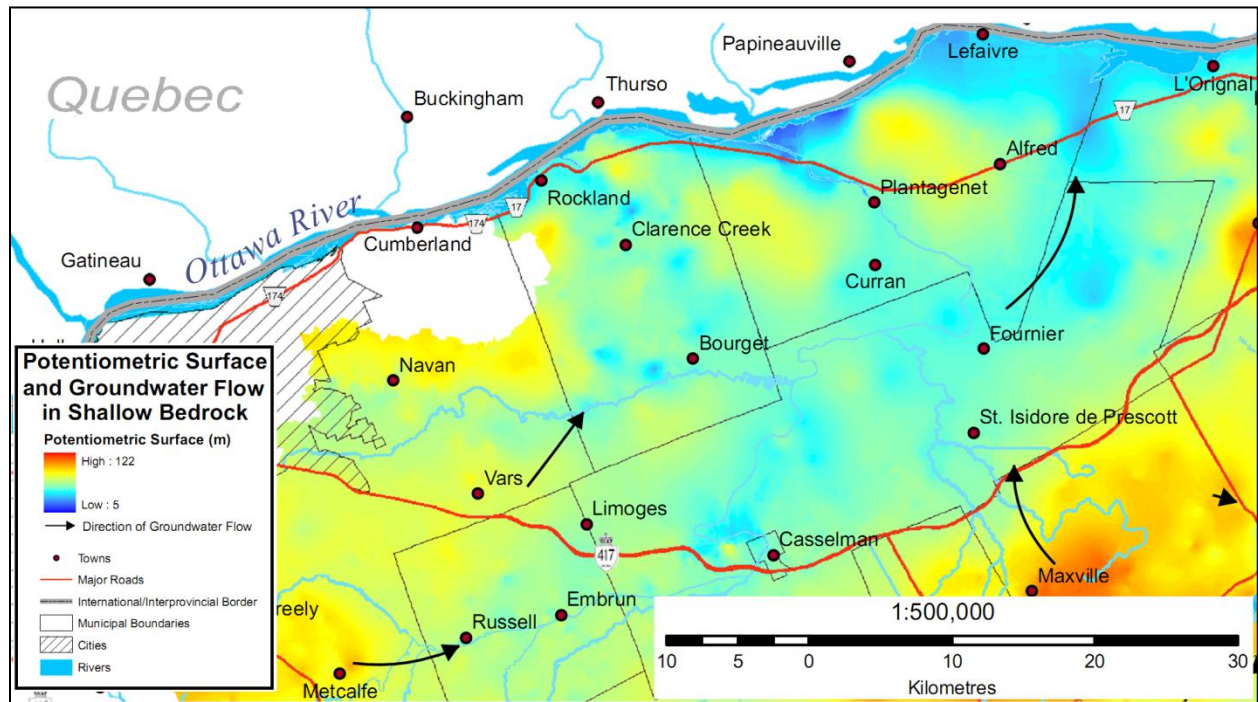


Figure 2-8. Map of potentiometric surface and groundwater flow for shallow bedrock in the City of Clarence-Rockland, Ontario, and its surrounding area. *Modified from Map 3-16 of the Source Protection Watershed Characterization Report (RRCA & SNC, 2008).*

In most sediments, the horizontal permeability is greater than the vertical permeability. This inhibits vertical water movement and allows groundwater in horizontally continuous deposits to develop chemical characteristics that are very different from groundwater in deposits situated above or below (USGS, 1985). However, in the City this is not always the case. The overburden geology in the City is highly complex due to the depositional environment of marine and fluvial deposits overlying glacial till. The clay layers are discontinuous, allowing vertical movement into underlying layers where more permeable material exists within the clays. In addition to this, Farah et al. (2012) used tritium measurements to demonstrate that deep vertical fractures exist within the clayey aquitards of the surrounding Ottawa Valley; the permeable openings are understood to be abundant and widespread in the area, but are still unpredictable in modelling. Where the clay is continuous, water may move slowly and have longer residence times within and below marine clays.

3 Groundwater Sampling Program

In the summer of 2013, a Groundwater Sampling Program (GSP) was conducted throughout the City of Clarence-Rockland (“the City”), Ontario. A total of 127 private wells surveyed and sampled following a 2x2 km² sampling grid; in an attempt to obtain one overburden and one bedrock sample per grid block. Field parameters were recorded at each site, and samples were analyzed for major ions, dissolved gases, dissolved carbon, bacteria, nitrogen parameters, environmental isotopes, trace anions and 56 trace metals. Additional sites with identical sample and analysis procedures from the Ontario Ambient Groundwater Geochemistry Project (OAGGP) were compiled into the GSP database, giving a total of 136 sampled well locations. With the chemical analysis performed for each well, it was possible to identify trends in the data and make comparisons to the Ontario Drinking Water Standards (later discussed in **Section 4**) for the ultimate goal of delineating areas of potentially poor groundwater quality for the Aquifer Capability Screening Tool (ACST).

3.1 Sampling Methodology

In order to gather groundwater chemistry data for producing maps of groundwater quality to be used as the Aquifer Capability Screening Tool (ACST), a groundwater sampling program (GSP) was conducted throughout the City. During the planning stages, it was agreed that 150 sample sets would be analyzed, which included 8 duplicates, 3 blanks and 13 standards, allowing for 127 private wells to be sampled. The locations of these 127 sampled wells and 9 additional wells are presented in detail in **Section 3.3.2**.

The sampling methodology applied in the field followed the methodology documented for the Ontario Ambient Groundwater Geochemistry Project (OAGGP) by the Ontario Geological Survey (OGS) (Hamilton et al., 2007; Hamilton and Brauneder, 2008). Training was provided by OGS prior to field sampling to ensure that similar protocols were applied and, while there were some minor differences in sampling equipment, the datasets obtained from these studies are comparable and of equal quality.

Field measurements were made at each site and include: temperature (°C), specific conductance (µS/cm), pH, oxidation-reduction potential (ORP; mV), alkalinity (mg/L as CaCO₃), dissolved oxygen (DO; % saturation) and hydrogen sulphide (H₂S; mg/L as S²⁻; not measured if DO was present). Temperature, specific conductance, pH, ORP and DO were measured using a YSI 650 data logging multi-parameter probe, which was calibrated daily for pH (using a three point calibration of pH 4, 7 and 10 buffer solutions) and DO and checked daily for specific conductance. For pH, three-point calibrations were performed with buffer solutions at 4, 7 and 10 pH, and the meter was then checked for accuracy within 0.02. Alkalinity was measured by titrating 1.6 N H₂SO₄ into a 100 mL sample containing bromocresol green indicator

using a HACH 16900-01 digital titrator, and bicarbonate (HCO_3^- , mg/L) was estimated from alkalinity using a linear conversion. H_2S was measured using the methylene-blue method using a HACH model 2238-01 test kit; if oxidizing conditions were present, H_2S was assumed to be zero.

Groundwater samples were collected from private residential water supply wells that extend to either bedrock formations or overburden deposits throughout the City. During the sampling program, it was presumed that dug wells extract groundwater from overburden deposits and drilled wells extract groundwater from bedrock formations. Examples of drilled and dug wells are shown in **Figure 3-1**.



Figure 3-1. Photos of a drilled well (left) and a dug well (middle) with a side by side comparison for scale (right).

Prior to sampling, a consent form was signed by the well owner and a brief interview was conducted in order to establish the following: age and depth of the well, types of treatment options used, history of water quality and quantity issues, and the locations of the well, the pressure tank and a connection point that would bypass any treatment systems. An inspection of plumbing was often required to locate a non-treated connection point. Homeowners also provided a copy of the Ministry of Environment (MOE) Well Record, if available. The homeowner consent form and groundwater sampling form are shown in **Figure A1-1** and **Figure A1-2** of **Appendix 1**.

UTM coordinates for each well were recorded using a Garmin® GPSMAP® 60Cx global positioning system (GPS) handheld unit. With consent from the homeowners, wells were opened and the well depths and static water levels were measured from the top of the casing using a water level tape. The height of the well above ground surface (or ‘stickup’) was measured using a tape measure; stickup was later subtracted from all depths and the depths were subtracted from the ground surface elevation to determine the well bottom elevation and

hydraulic head of each well in meters above sea level. Ground surface elevations were first recorded using the GPS, but later the values extracted at each location from a digital elevation model were used instead as they were considered to be more accurate. If a well was buried or inaccessible, or if homeowners did not consent to the opening of their well, then the well depth and static water level were obtained from an MOE Well Record.

A sampling apparatus, shown in **Figure 3-2**, was used to divert pumped water from the connection point towards (1) a 75 L bucket which would be filled three times to purge water prior to sampling, (2) a flow cell used to pass water through a YSI 650 data logging multi-parameter probe, and (3) a tube which could be used to collect samples. The lines diverting water to the flow cell and sampling tube had switch valves to help control the flow rate. Approximately 225 L of water were purged at each site, with lesser amounts purged if historic water quantity issues were indicated in the interview. The flow cell was placed inside a white 10 L bucket, which also served as a backdrop for qualitatively identifying water colour. Sampling commenced once stable temperatures readings were observed on the YSI, as per OAGGP protocol.



Figure 3-2. Sampling apparatus used to collect groundwater samples from privately owned wells.

Eleven sample bottles were filled at each site. These included: metals (60 mL), anions (60 mL), mercury (60 mL), iodide (60 mL), isotopes (120 mL), tritium (180 mL), dissolved organic/inorganic carbon (45 mL), total Kjeldahl nitrogen + ammonia/ammonium (45 mL), nitrate/nitrite (45 mL), bacteria (120 mL) and methane (1 L). Sample bottles were filled to a meniscus to ensure minimal headspace with the exception of methane bottles which were filled to 600 mL. Sample bottles for metals, anions and mercury were passed through a 0.45 μm filter prior to filling to prevent suspended solids and large colloids from influencing the water

chemistry prior to analysis, and the metal samples were later acidified using 1% HNO₃. Bacteria samples were obtained directly from the faucet following disinfection by scrubbing the faucet with an antibacterial wipe for 20 seconds and rinsing the faucet to remove the suds.

Some sample bottles contained preservatives prior to sampling, and others were acidified after to sampling. The preservatives used for the TKN+ammonia bottles, iodide bottles and bacteria bottles were added prior to sampling and were respectively 1:1 H₂SO₄, 0.2 M nickel acetate, and sodium thiosulphate. Metals and mercury samples were acidified after sampling using 1% HNO₃ and 2% HCl, respectively. The other samples did not require preservatives.

At the end of each sampling day, the four carbon, nitrogen and bacteria sample bottles from each sample set were placed in a cooler with ice packs and shipped to SGS Environmental Laboratories for analysis. Methane samples were stored in an indoor cupboard with stable temperature and were measured the following morning. Iodide samples were refrigerated and analyzed within five days of collection and the remaining sample bottles were refrigerated and later delivered to the Ontario Geological Survey laboratory for analysis.

There were some minor differences between the field sampling probes used in this project and those used by the Ontario Geological Survey. The OGS 2013 field crew made use of an archer and sonde for the onsite measuring and logging of pH, conductance, temperature and ORP, and used a YSI "oDO" optical probe for measuring dissolved oxygen. The archer, as a miniature field computer interface, enabled the crew to track probe readings using graph displays in real time, which allowed accurate determination of when temperature conditions were stable. The YSI used in this study did not have such capabilities; instead the temperature was frequently monitored for stability prior to sampling.

One difference between the OAGGP protocol and the method applied in this study was the measurement of DO. This study used a rapid-pulse sensor Clark cell for measuring DO; however, the OGS uses an optical DO probe which offers increased reliability with less maintenance and no risk of damage in the presence of H₂S, at the small cost of a slightly slower response time (Priebe et al., 2012). There were some issues related to the reliability of the DO probe during the 2013 field season and, as a result, some sites were revisited to obtain a second reading of DO with the OGS optical DO probe in September 2013.

3.2 Analysis of Collected Groundwater Samples

3.2.1 Overview of Analytical Methods

In this study, groundwater samples from 127 different wells in the City were collected and analyzed. The analysis was very thorough as it followed the protocols of the Ontario Ambient Groundwater Geochemistry Project (OAGGP), whose project focus was to analyze as much as possible to improve the understanding of groundwater chemistry throughout the province. Seven chemistry parameters were measured in the field and a total of 77 different laboratory analyses were performed including bacterial analysis, cations, anions, trace elements, rare earth elements and environmental isotopes.

Alkalinity, dissolved oxygen and hydrogen sulphide had been measured in the field and bicarbonate was determined linearly from alkalinity. For the analysis of time-sensitive parameters, samples were shipped to SGS Environmental Laboratories at the end of each sampling day; their analyses measured total Coliform bacteria, fecal Coliform bacteria, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), total Kjeldahl nitrogen (TKN), ammonia (NH_3) + ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) and organic nitrogen. The dissolved methane gas content and dissolved iodide concentrations were measured at the University of Ottawa and more details are provided in **Section 3.2.2**.

All remaining major cations, major anions, trace metals, isotopes and rare earth elements were analyzed by the OGS GeoLabs in Sudbury, ON. Each major cation and anion were analyzed using two different methods so that their values could be compared to ensure accuracy and optimize charge balance results. The major cations Ca, Mg, Na and K, as well as B and Zn, were measured using both inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma emission spectrometry (ICP-ES). Si and Mn were measured using ICP-ES. The remaining metals and trace elements were all measured using ICP-MS. All anions were measured using Ion Chromatography (IC), and secondary measurements of chloride, sulphate and total sulphur were made using ICP-ES.

The detection limits of all parameters measured in laboratories (except for isotopes tritium, deuterium and oxygen-18) are shown in **Table 3-1**.

Table 3-1. Detection limits for chemistry parameters that were analyzed in laboratories.

Parameter	Detection Limit	Parameter	Detection Limit	Parameter	Detection Limit
Total Coliforms	0 Counts/100 mL	Ba	0.02 µg/L	Ta	0.0003 µg/L
Fecal Coliforms	0 Counts/100 mL	Au	0.004 µg/L	Ti	0.1 µg/L
DIC	0.1 mg/L	Ag	0.005 µg/L	Tl	0.001 µg/L
DOC	0.5 mg/L	Al	5 µg/L	V	0.003 µg/L
NO ₃ ⁻	0.1 mg/L as N	As	0.03 µg/L	W	0.01 µg/L
NO ₂ ⁻	0.1 mg/L as N	B	0.003 mg/L	Y	0.0005 µg/L
TKN	0.05 mg/L as N	Bi	0.05 µg/L	Zr	0.1 µg/L
NH ₃ /NH ₄ ⁺	0.1 mg/L as N	Cd	0.01 µg/L	Zn	0.1 µg/L
Organic N	0.65 mg/L as N	Co	0.005 µg/L	La	0.001 µg/L
F ⁻	0.02 mg/L	Cr	0.2 µg/L	Ce	0.002 µg/L
Cl ⁻	0.03 mg/L	Cu	0.2 µg/L	Pr	0.0004 µg/L
Br ⁻	0.1 mg/L	Fe	0.003 mg/L	Nd	0.003 µg/L
I ⁻	5 µg/L	Ga	0.002 µg/L	Sm	0.001 µg/L
SO ₄ ²⁻	0.05 mg/L	Hf	0.004 µg/L	Eu	0.0004 µg/L
PO ₄ ²⁻	0.1 mg/L	Hg	1.5 ng/L	Gd	0.001 µg/L
H ₂ S	0.01 mg/L as S	Mn	0.002 mg/L	Tb	0.0001 µg/L
Li	0.01 µg/L	Mo	0.01 µg/L	Dy	0.001 µg/L
Na	0.2 mg/L	Nb	0.001 µg/L	Ho	0.0001 µg/L
K	0.2 mg/L	Ni	0.1 µg/L	Er	0.001 µg/L
Rb	0.005 µg/L	Pb	0.05 µg/L	Tm	0.0001 µg/L
Cs	0.0005 µg/L	Sc	0.1 µg/L	Yb	0.001 µg/L
Be	0.01 µg/L	Sb	0.01 µg/L	Lu	0.0001 µg/L
Mg	0.1 mg/L	Se	0.2 µg/L	Th	0.001 µg/L
Ca	0.1 mg/L	Si	0.076 mg/L	U	0.0002 µg/L
Sr	0.0001 mg/L	Sn	0.01 µg/L	Tritium	0.8 TU

For quality assurance, duplicate sample sets, laboratory blanks and laboratory standards were submitted for analysis alongside the sample sets filled in the field. Duplicates were filled at random locations with one for approximately every 10 samples collected, bearing 13 duplicates in total. Laboratory blanks, 3 in total, were filled with de-ionized water by OGS prior to sampling. Laboratory standards, 12 in total, were also prepared by OGS prior to sampling and consisted of 3 types referred to as BLK, GRN and BLU. The BLK standard was the OGS internal Bulk standard (BLK-1) used for anions. The GRN standard was for NO₃ and NO₂ and contained BLK-1 spiked with NaNO₃ (5 mg/L as N). The BLU standard was for TKN and ammonia/ammonium and contained BLK-1 spiked with NH₃ (5 mg/L as N). The standard used for cations, metals and mercury was not submitted alongside the samples like the others and was instead used in-house by the OGS; this was the CANMET certified reference standard SLRS-4.

3.2.2 Methane and Iodide Sample Analysis

Methane samples collected in the field were analyzed the following morning. Methane was measured from the headspace of methane samples using an RKI Eagle 2 Portable Gas

Monitor. The exact volume of the headspace was not measured, so there is no estimate of the error on these measurements. The Eagle 2 also measured oxygen and carbon dioxide gases, and a HANNA[®] hand probe was used to measure the water temperature in the methane bottles afterwards. Methane measurements were made using an Eagle 2 Gas Monitor equipped with two methane sensors: a low-level catalytic sensor capable of measuring from 0 to 25 000 ppm CH₄, and a high-level infrared sensor capable of measuring up to 50 volume% CH₄. The low level sensor was calibrated daily, while the high level sensor was calibrated every 3-5 days since the process left residual methane in the lines and took much longer.

Measurements were made in units of milligrams of methane gas per litre of headspace air. A conversion was made by the OGS using Henry's Law to estimate the aqueous content of methane in the water; for more information the process has recently been well documented by McIntosh et al. (2014). Although the conversion performed by OGS is critical, the process and factors involved is beyond the scope of this study. The OGS units of mg_{methane(aq)}/L_{water} needed to be converted to L_{methane(aq)}/m³_{water} in order to compare to drinking water standards. To do this conversion, all methane was assumed to be aqueous, and the drinking water standard was assumed to be representative of standard ambient temperature pressure (SATP) conditions (such that a mole of gas occupies 22.4 L of volume according to Avogadro's Law). The conversion used is as follows:

$$\frac{\text{L CH}_4}{\text{m}^3 \text{ water}} = \frac{\text{mg CH}_4}{\text{L water}} \times \frac{1000 \text{ L}}{\text{m}^3} \times \frac{1 \text{ mmol CH}_4}{16.0425 \text{ mg CH}_4} \times \frac{1 \text{ mol}}{1000 \text{ mmol}} \times \frac{22.4 \text{ L}}{\text{mol}}$$

The methane measurements differed slightly from OAGGP protocols; this project used an Eagle 2 rather than an Eagle 1, and temperature was measured independently for all samples. OAGGP protocols assume the same temperature for each sample; however it was found early in the sampling season that bottles stored in the same location could still vary by up to 1°C at the time of measurement, so individual temperatures were kept and were not pooled.

Iodide samples collected in the field were measured within 5 days of their collection. Measurements were made using an iodide ion-selective electrode (ISE) probe that was connected and operated through a Thermo Orion Star[™] A324 pH/ISE portable meter. Each day it was used, the ISE meter was calibrated and checked before any measurements were made.

The iodide samples were placed in a warm water bath one hour before their measurement to bring them to room temperature. Afterwards, the 2 cm headspace of each sample was discarded and replaced with 1 mL of ionic strength adjuster and one magnetic stir bar. The probe of the ISE meter was then inserted into the sample bottle over top of a magnetic stirring plate, and a measurement was taken after 15 minutes. Measurements for iodide were in units of µg/L.

3.2.3 Determination of Hardness and Total Dissolved Solids

The water hardness and total dissolved solids (TDS) concentration were calculated for each well using the analytical chemistry data. The procedures for these calculations are as follows:

Hardness

Hardness was calculated for each sample as the sum of the equivalent concentrations of the following divalent cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), strontium (Sr^{2+}), zinc (Zn^{2+}) and iron (Fe^{2+}). The calculation was made by converting each to molarity units, summing the equivalent concentrations of these cations in meq/L, and converting to units of mg/L as CaCO_3 which are standard for hardness measurements. All iron present in the chemical analysis was assumed to be ferrous and not ferric, because the samples were filtered prior to collection which would remove any ferric iron precipitates larger than 0.45 μm in diameter. Furthermore, the metals were acidified after collection and filtered again with a 0.1 μm filter prior to analysis.

Total Dissolved Solids

Traditionally, TDS was measured in a laboratory by evaporating the liquids out of solution and weighing the solid remains of a sample. With a complete analysis, TDS can be calculated rather than measured by summing the dissolved components of a sample. The results are not always comparable between different studies due to the inclusion of different parameters in sample analysis, but with a more thorough analysis comes a better approximation of TDS that is closer to the truth.

In this study the chemical analysis was extensive, so nearly all of the measured constituents were included in the calculation of TDS. For any parameter concentrations that were reported as less than their respective detection limits, the half detection limit values were included in the summation. The detection limits for each parameter were shown **Table 3-1** in **Section 3.2.1**.

TDS was calculated in units of mg/L as the sum of all dissolved non-gaseous chemical constituents. This sum included the following parameters: DOC, HCO_3^- , NO_3^- , NO_2^- , TKN, SO_4^{2-} , PO_4^{3-} , F^- , Cl^- , Br^- , I^- , Li, Na, K, Be, Mg, Ca, Sr, Ba, Rb, Au, Ag, Al, As, B, Bi, Cd, Co, Cr, Cs, Cu, Fe, Ga, Hf, Hg, Mn, Mo, Nb, Ni, Pb, Sc, Sb, Se, Si, Sn, Ta, Ti, Tl, V, W, Y, Zr and Zn.

Gaseous parameters such as methane, hydrogen sulphide and oxygen were excluded from the TDS sum. Lanthanides and actinides were also not used in the summation of TDS. All of the dissolved bicarbonate was included, which is standard in the methods of the Ambient Groundwater Geochemistry Project. Alkalinity and dissolved inorganic carbon were excluded because they were accounted for in the concentration of bicarbonate. Similarly, Total Kjeldahl nitrogen (TKN) was used instead of organic nitrogen and ammonia/ammonium, since it encompasses all nitrogen in the +3 oxidation state.

All of the dissolved bicarbonate was included, which is standard in the methods of the Ambient Groundwater Geochemistry Project. When calculating TDS, some organizations may choose to multiply bicarbonate by 0.4917 to account for the evaporative loss which occurs during a traditional TDS measurement (USGS, 1985), but that was not done in the OAGGP nor in this study.

3.3 Locations of Sampled Wells and their Physical Settings

In order to protect the privacy of homeowners who voluntarily took part in our study, the spatial coordinates of wells at each site have been removed from the database of this Thesis and are not available. Any well locations will herein only be referred to by their site numbers, indicated in **Figure 3-6** and **Figure 3-7** of **Section 3.3.3**, or described in context to their surrounding features.

3.3.1 Site Selection

Site selection and communications were managed by the South Nation Conservation Authority (SNC). Site selection generally followed the methodology developed for the Ontario Ambient Groundwater Geochemistry Project (OAGGP) (Hamilton et al., 2007). The OAGGP applied a grid of 10 km x 10 km blocks across the province for their regional study, whereas this project applied a grid of 2 km x 2 km blocks across the study area for city-wide coverage. The smaller grid spacing used in this study allowed for a higher spatial resolution of groundwater chemistry data to be collected. The 2x2 km² scale used in this study was selected to optimize the total number of sample analyses provided by the Ontario Geological Survey (OGS), as determined in the project planning stage. The 2x2 km² sampling grid followed in this study is shown in **Figure 3-3** along with satellite imagery and the municipal boundaries for the City.

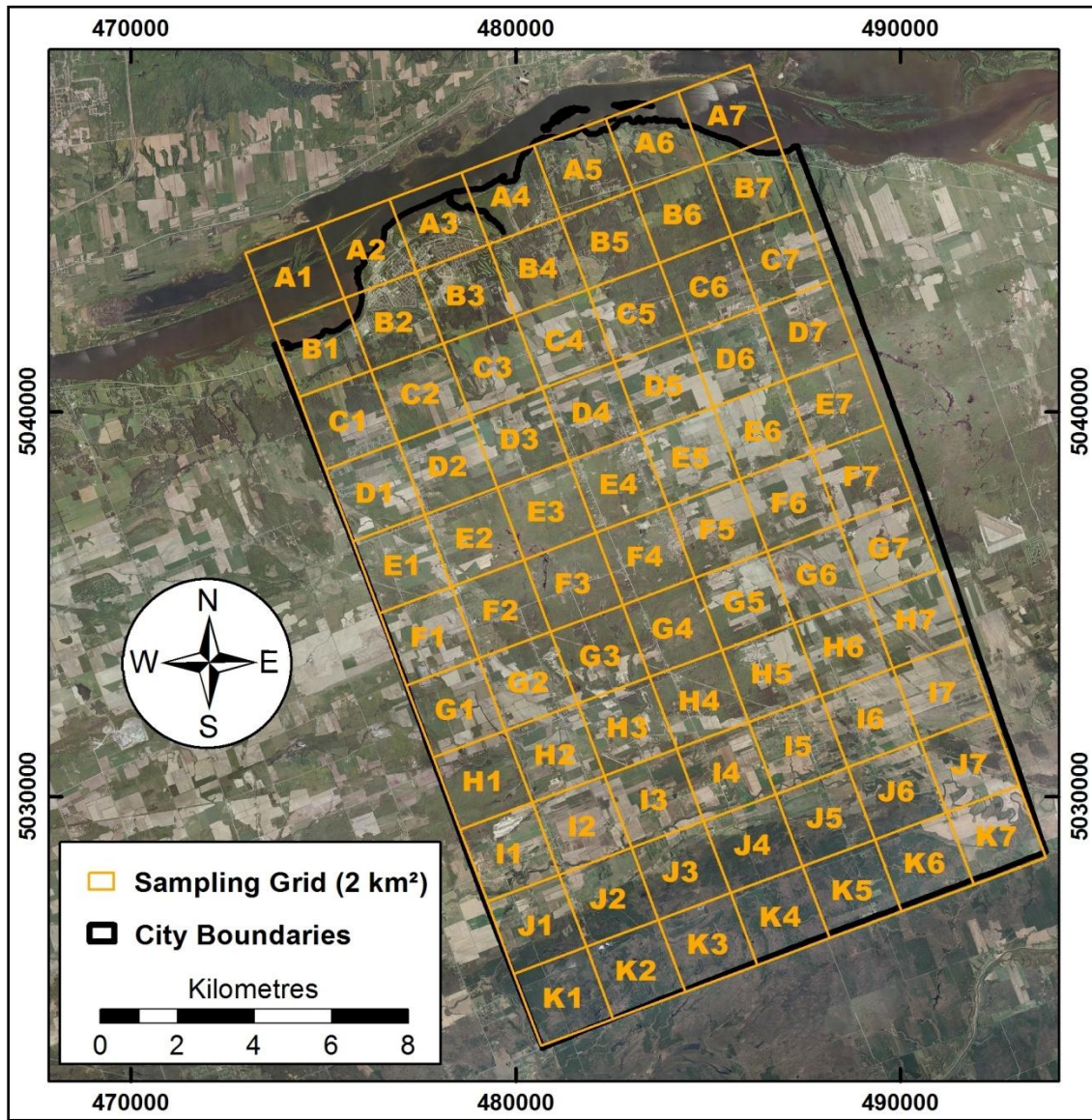


Figure 3-3. Sampling grid of 2 x 2 km grid blocks used in this study for collecting groundwater samples from homeowner wells throughout the City of Clarence-Rockland, Ontario.

Site selection and public communications were managed by SNC. Site selection was initiated prior to the commencement of sampling in order to expedite the sampling season (8 weeks in July and August) and to foster communication about the project within the community. The project was advertised in June and July through presentations and printed ads. A one page advertisement was designed to introduce the project and solicit volunteers for well sampling across the Municipality (English and French). The advertisement was displayed as posters in public areas across the Municipality and delivered as a directed mail drop to nearly 8,000 residents. In addition, the ad was issued as a press release and run in local newspapers throughout the summer.

Prior to advertising, site scheduling protocols were developed. First, a sampling schedule was established for the 8 week field season, with two grid blocks (4 samples) scheduled per day.

If the well was deemed suitable to sample (criteria listed below), then the volunteer was told what date the field team would visit their residence. Next, the sampling grid was added to Google Maps and each grid block was given a unique identifier consisting of a letter (A to K, running north to south) and a number (1 to 7, running west to east). When a volunteer contacted SNC, their address was entered into Google Maps to determine which grid block the well was located. Once the grid location was determined, the volunteer was asked the type of well (drilled or dug) and if they had a copy of the well record. In order to simplify site scheduling, it was assumed that drilled wells were bedrock wells and dug wells were overburden wells. This assumption holds true for overburden wells and, based on local MOE water well records, is generally true for bedrock wells. If the volunteer responded that they did not have a copy of the well record, then geology could be inferred from proximal well records in the MOE Water Well Information System as long as well depth could be measured. However, if the well could not be accessed (i.e. buried wells), and there was no well record, then the well was not sampled. Site scheduling was done on a first-come-first-served basis for suitable wells. If a volunteer phoned and someone had already been scheduled for that well type and grid block, then the well was not sampled; however, their address and contact information were added to a waiting list for future consideration.

203 residents volunteered in response to the project advertising and 82 of their wells were sampled in this project. The remaining 45 wells of the 127-well allotment were found by going door to door throughout the City in grid blocks where volunteers were still needed for overburden or bedrock groundwater samples. Grid blocks still missing samples were searched thoroughly for wells and willing participants. Navigation was assisted using a GPS connected to a field laptop running ArcMap, which showed the current location as well as the sampling grid, Ontario Road Network, surficial and bedrock geology maps, satellite imagery and the MOE Well Record Database shapefile. Soliciting volunteers door to door was time consuming and sometimes unsuccessful resulting in grid blocks without samples, discussed in **Section 3.3.2**. Residents who had prior knowledge of the project were more likely to participate when approached.

3.3.2 Well Locations and Spatial Gaps

In July and August of 2013, the Groundwater Sampling Program (GSP) for this project was completed, during which 127 privately owned groundwater wells were sampled. The locations of each of these wells, categorized into dug well and drilled wells, are shown in **Figure 3-4**. The 127 sampled wells included 59 dug wells and 68 drilled wells. The locations and sample data collected from nine additional wells were contributed from the OGS, indicated in **Figure 3-4** by green outer circles. The nine additional wells were located within 5 km of the City and were sampled and analyzed in 2012 as part of the Ontario Ambient Groundwater Geochemistry Project, which used methods and protocols identical to the GSP. The nine additional wells consisted of three dug wells and six drilled wells, resulting in a total of 136 wells to be used in this study (62 dug wells and 74 drilled wells).

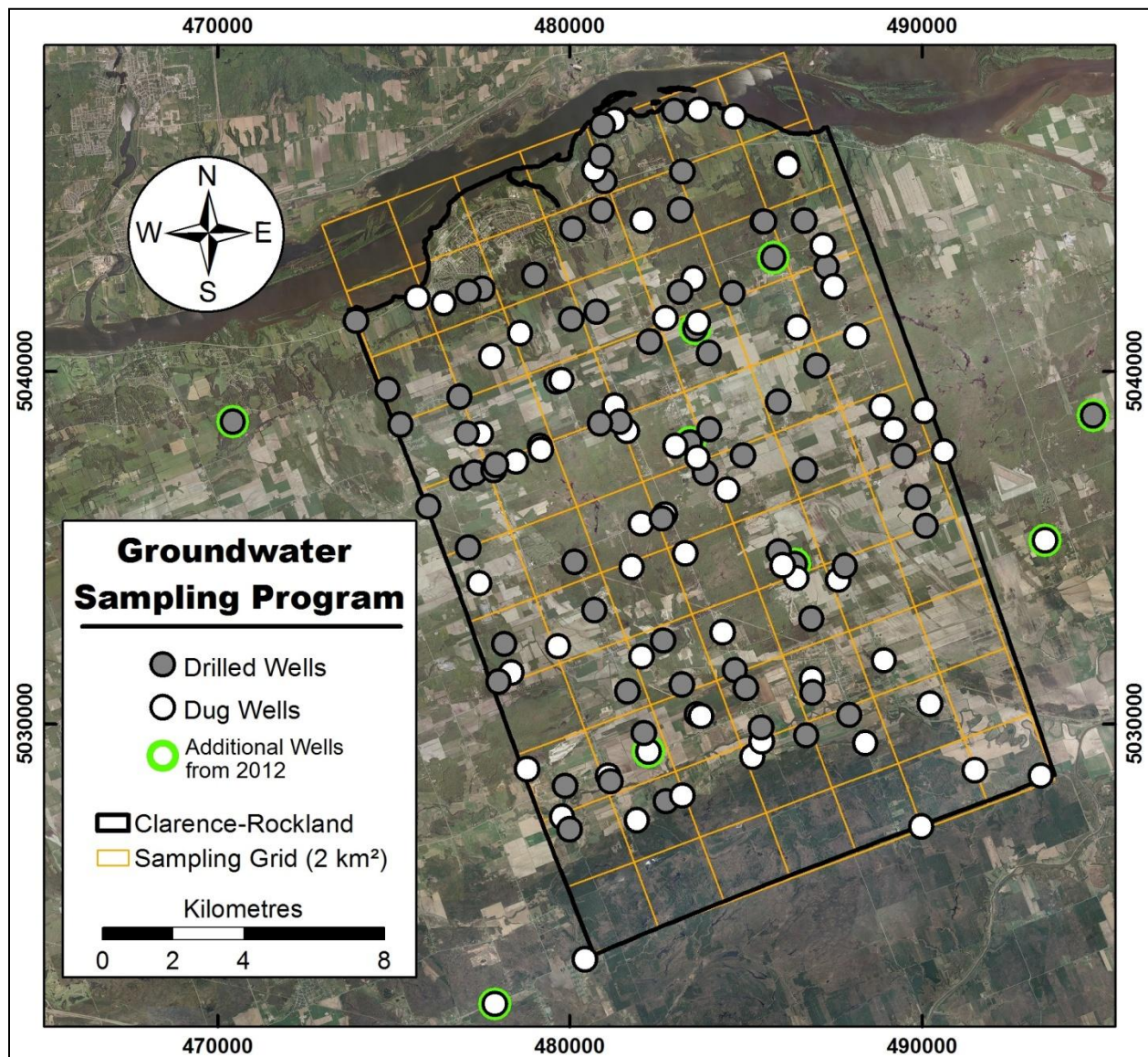


Figure 3-4. Locations of 127 wells sampled (2013), categorized as dug wells and drilled wells, and 9 additional wells sampled by the Ontario Geological Survey (2012).

The objective during the field season was to sample two wells per grid block; one drawing water from overburden aquifers and one drawing water from bedrock aquifers. To simplify the field program and well selection, it was assumed that dug wells draw water from overburden aquifers and drilled wells draw water from bedrock aquifers. Dug wells were typically cased in concrete and 36" to 58" in diameter, while bedrock wells were typically cased in steel and 5.5" to 6.5" in diameter; however there were many instances where drilled wells were encased in concrete bearing similar appearance to dug wells. Two surface wells were dug into shallow bedrock outcrops, however these were still classified as overburden wells due to their proximity to the ground surface. Well Records obtained from homeowners or the MOE Water Well Information System, when available, revealed that some drilled wells did not extend

into bedrock and instead were completed in the deep overburden clays or gravels near the bedrock surface; these wells were referred to as deep overburden wells instead of bedrock wells.

Following the field season, a detailed audit was performed by Dr. Stewart Hamilton (OGS) to verify whether each well was physically representative of shallow overburden, deep overburden, or bedrock geological settings. The audit made use of well completion information within the MOE well records, ground surface elevation, bedrock surface elevation, measured well depth and background knowledge of local geology. For wells with well completion information available, the classification of bedrock or deep overburden was inferred by comparing the measured depth of the well to the ground surface elevation and bedrock surface elevation for the well location. In addition to revealing the aquifer type for each well, this inspection also indicated the representative geological unit for drilled wells, from which water was likely being supplied.

As a result of the audit, many drilled wells initially presumed to be bedrock wells were reclassified as deep overburden wells. Of the 74 drilled wells, there were 64 bedrock wells and 10 deep overburden wells. Under this classification the 62 dug wells were listed as shallow overburden wells. The locations of the 62 shallow overburden wells, 10 deep overburden wells and 64 bedrock wells are shown in **Figure 3-5**.

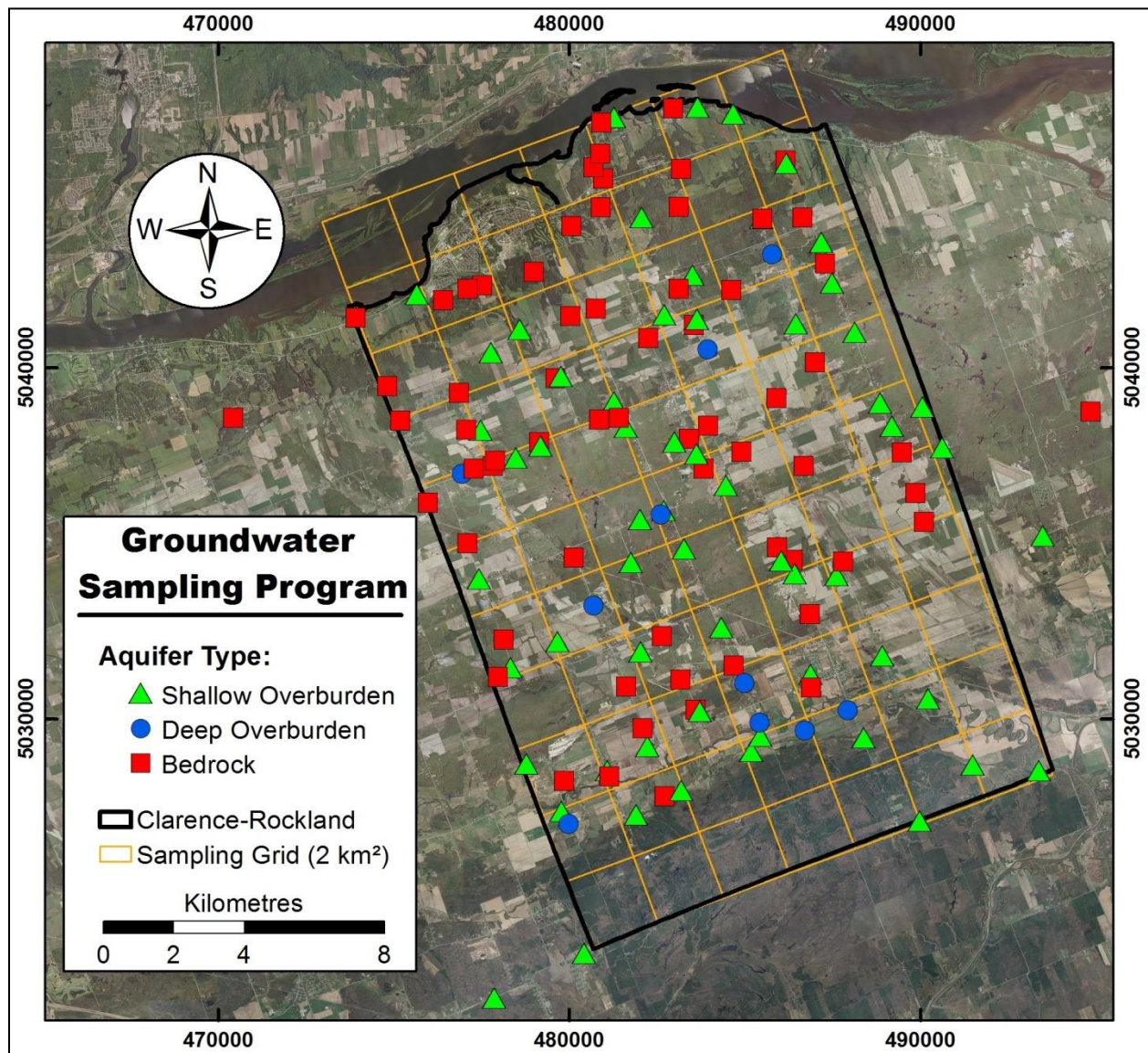


Figure 3-5. Locations of 136 wells included in this study, differentiated by geological completion.

Samples could not be obtained from some grid blocks throughout the City, and as a result there are spatial gaps. Bedrock aquifers are known to produce poor quality groundwater in some parts of the City; in these areas, dug wells are predominant. Similarly, there are areas where the overburden is either too thin to install a dug well, or a surface well would not produce sufficient water quantity due to a lack of aquifer material (i.e. marine clay at surface). Hence, there are also areas of the City where drilled wells are predominant.

There were also some parts of the City where wells did not exist, either due to available Municipal water supply or in unpopulated areas (i.e. Larose Forest). When municipal water lines were established in the City most homeowners had their existing wells decommissioned, either by choice or regulation, depending on the area, and although some of those wells still exist

mainly for outdoor use, they were uncommon. As a result, there were many areas throughout the City where wells could not be located.

In this study, there will have been an inherent sampling bias involved in estimating areas of poor water quality, and predictive maps may be more optimistic than reality. This is because wells that could be sampled were for the most part located in areas known for good water production. In unpopulated areas or areas known for poor water quality or quantity, fewer wells may exist, making it more difficult to foresee problems that may be encountered. While unpopulated areas could also produce great water quality, in the end it will remain inevitable that areas of poor water quality will exist that have not been discovered.

3.3.3 Site Numbers and Physical Well Settings

In both this study and the OAGGP, wells were assigned a Station ID and Sample ID to identify the well location and sample set. The two ID numbers are identical except for duplicate sample sets. Each ID is formatted as “13-AG-###”; where 13 indicates the sampling year 2013, AG indicates Ambient Groundwater, and ### is a number between 601 and 750. The 9 additional points of data provided by the OGS have Station IDs of 12-AG-### since they were collected in 2012; note that these 9 are considered part of this study.

Throughout this thesis, stations and samples are sometimes referred to by their formal ID (eg. 13-AG-624), but more often they are referred to as site numbers (eg. Site 624). The site numbers for all drilled wells and dug wells are shown in **Figure 3-6** and **Figure 3-7**.

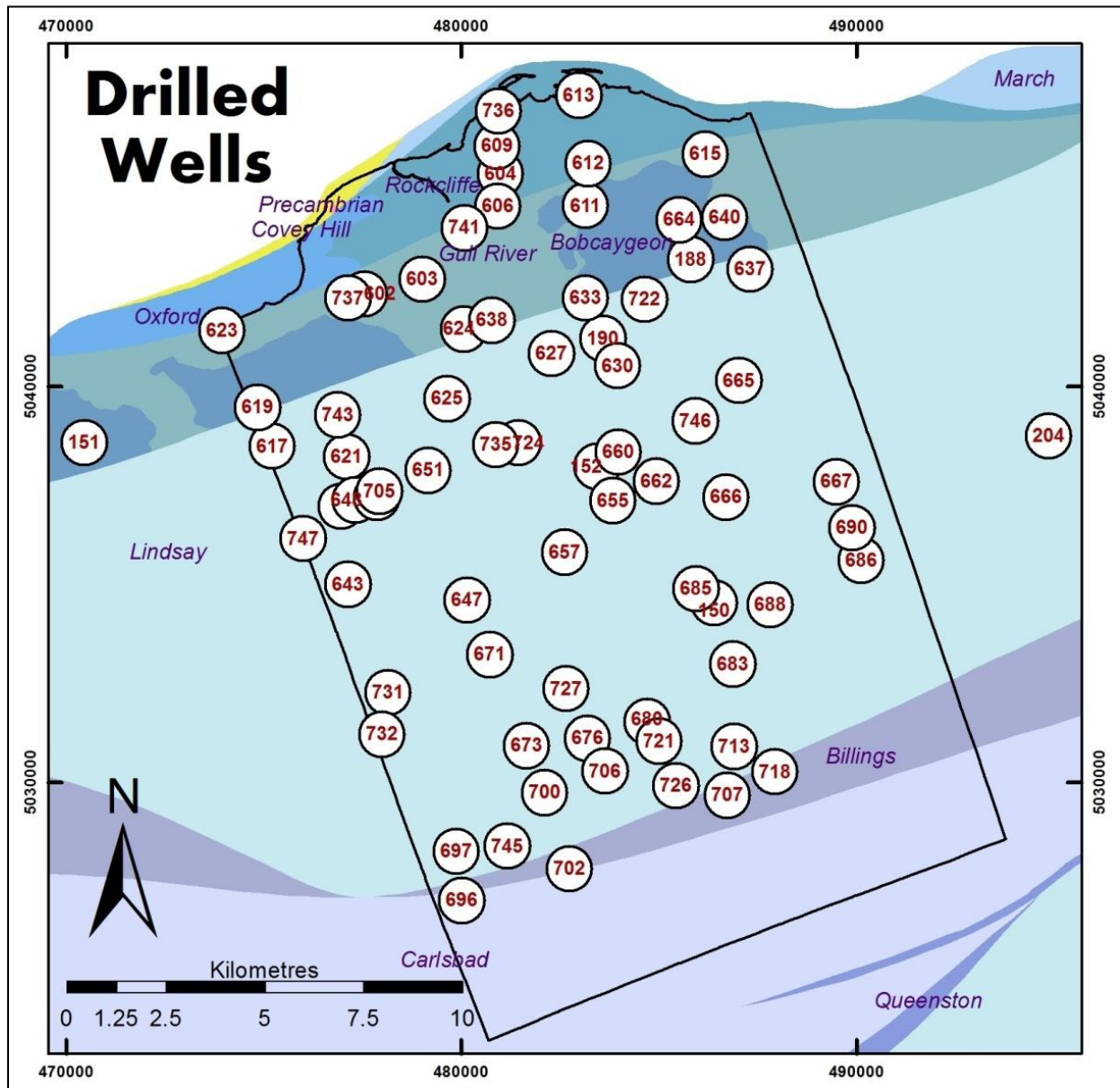


Figure 3-6. Site numbers for all 74 drilled wells sampled in this study. The background shows the city boundaries for the City of Clarence-Rockland and the Paleozoic geology map (See *Figure 2-4* for legend).

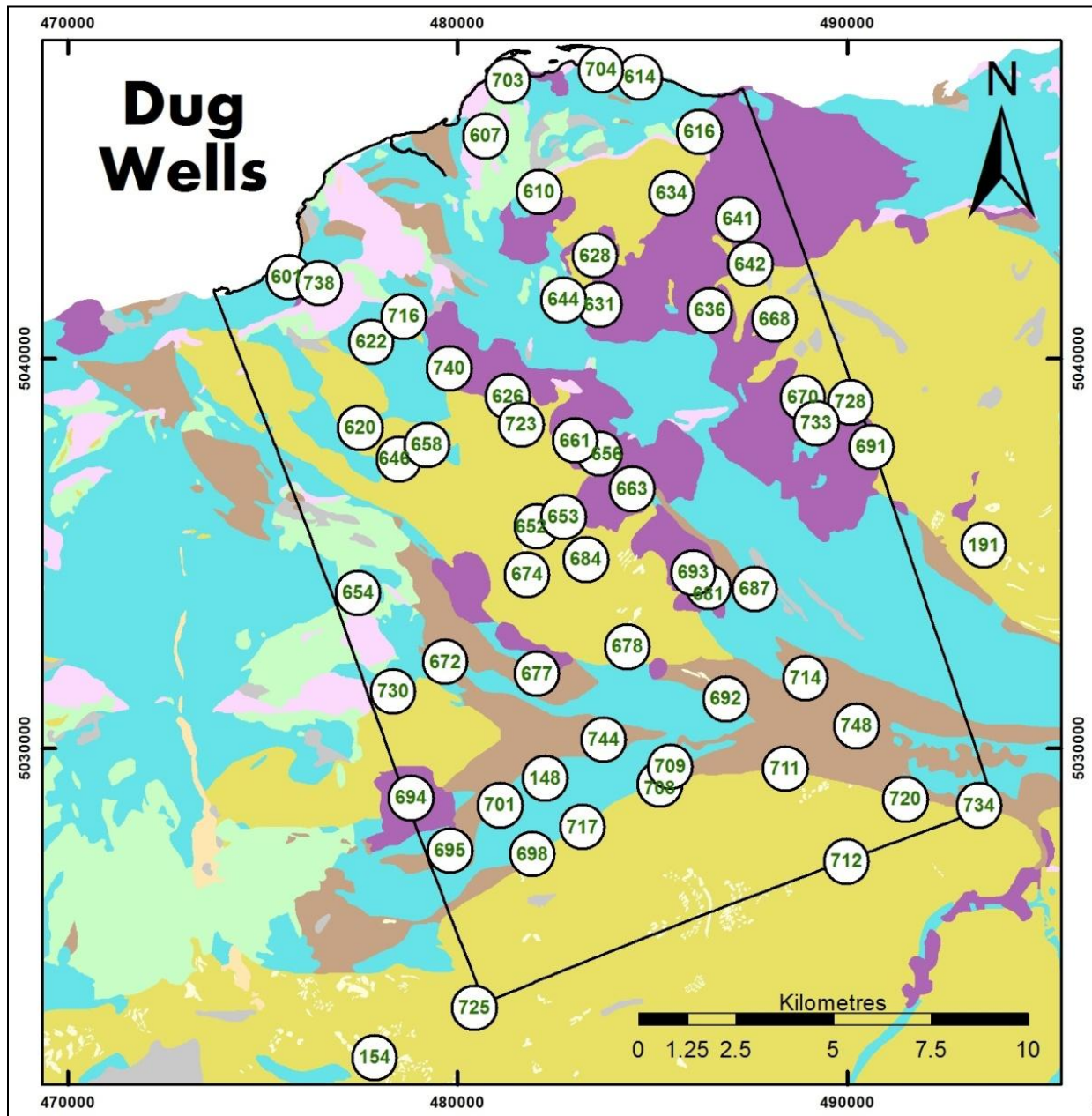


Figure 3-7. Site numbers for all 62 dug wells sampled in this study. The background shows the city boundaries for the City of Clarence-Rockland and the surficial geology map (See **Figure 2-7** for legend).

The depths of all drilled wells and dug wells are shown in **Figure 3-8** and **Figure 3-9**. In **Figure 3-8**, the representative geological unit of each drilled well is also indicated. The representative geological units, identified by OGS for this study, indicate the geological formation to which the bottom of each well corresponds; this identification is based on the measured well depth and available models and records of overburden and bedrock geology. The depth of drilled wells throughout the City ranged from 13.4 to 97.5 m below ground surface (bgs) with an average depth of 37.2 m ($n=74$, $\sigma=17.0$ m bgs). Dug wells ranged in depth from 2.4 to 8.6 m bgs, averaging 5.5 m ($n=62$, $\sigma=1.9$ m bgs). While dug wells had a short range and

standard deviation in well depth, drilled wells varied considerably in depth and were often finished in different bedrock units compared to other nearby wells. These differences in aquifer setting could result in different groundwater chemistry being produced at nearby locations; hence it was important to identify the different representative geological units shown in **Figure 3-8**.

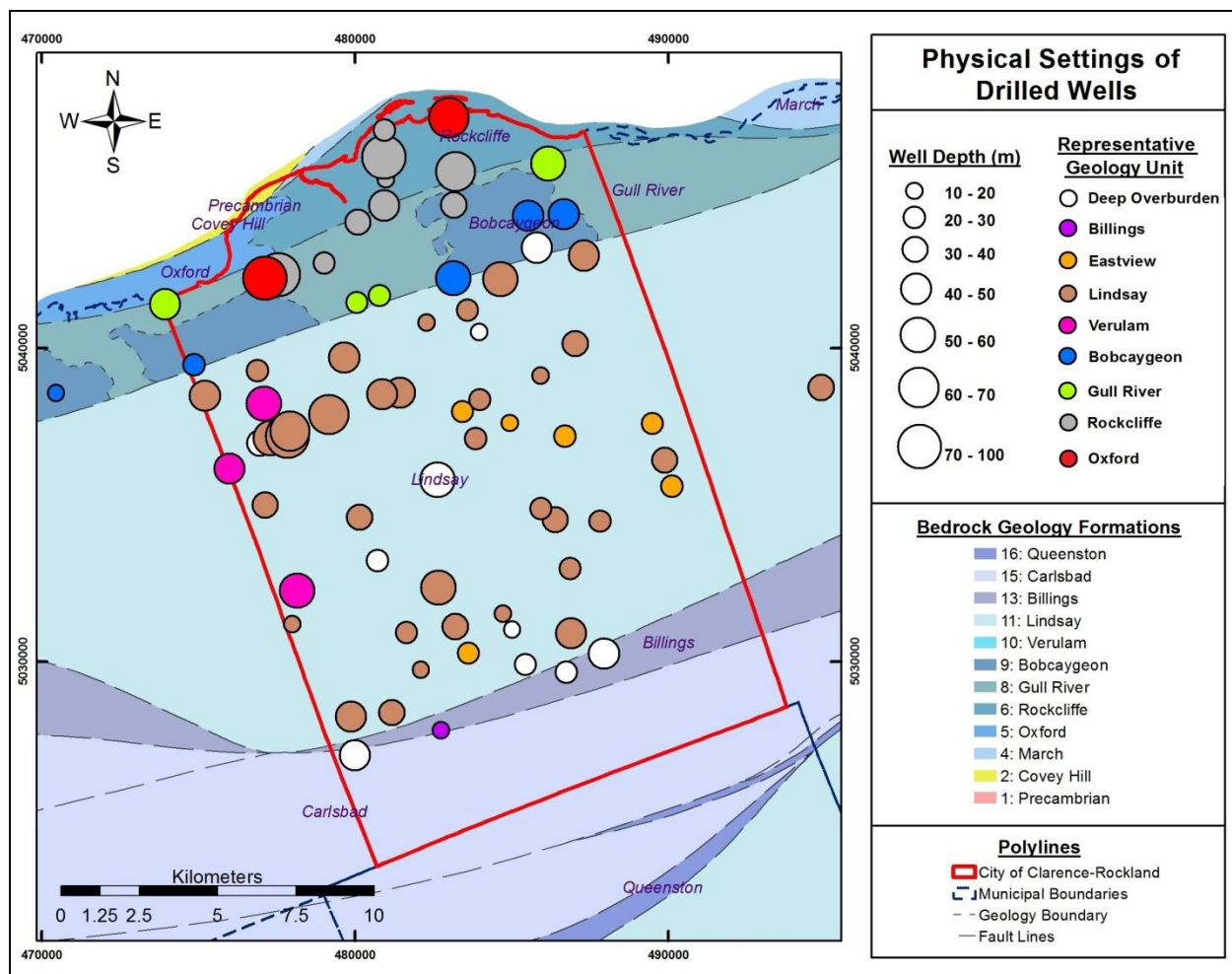


Figure 3-8. Map showing the well depths (below ground surface) and representative geological units of all 74 drilled wells sampled in this study.

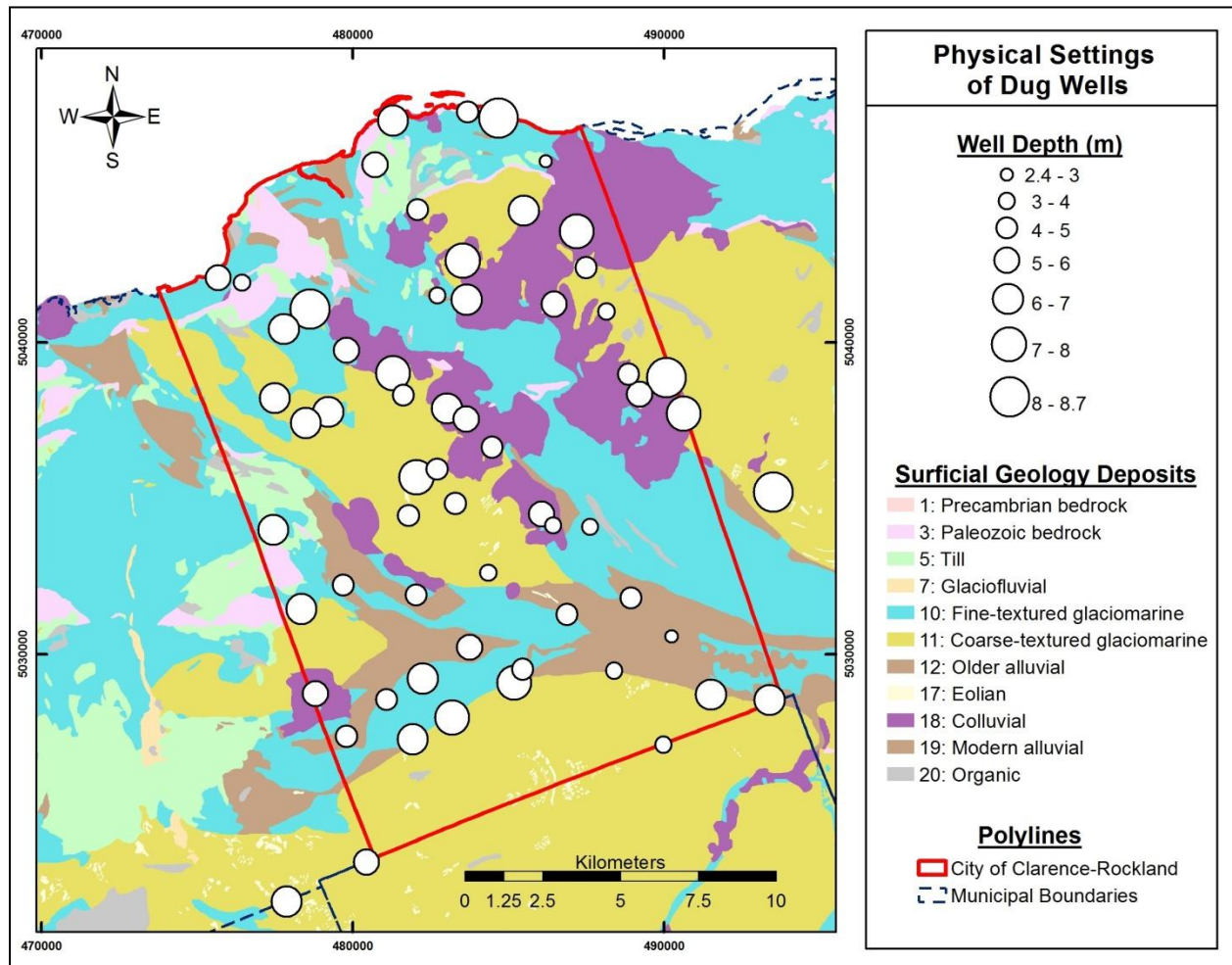


Figure 3-9. Map showing the depths (below ground surface) of all dug wells sampled in this study.

3.4 Groundwater Chemistry Results

All groundwater chemistry data and physical well measurements (except spatial coordinates) for each of the 136 wells can be found in the Microsoft Access Database titled “**GSP_Database.mdb**”, which can be obtained by contacting the South Nation Conservation Authority located in Finch, Ontario. The full dataset has also been published inclusively with the results of the Ontario Ambient Groundwater Geochemistry Project (OAGGP) in MRD283-REV (Hamilton, 2014).

The chemistry results of the GSP are visually expressed as bubble plot concentration maps, which are found in **Appendix 2**. All maps shown in this study were prepared using ArcMap. Each map of a parameter corresponding to an Ontario Drinking Water Standard (discussed in **Section 4**) contains a colour scheme which indicates which concentrations are exceedances to help visually identify exceedances when looking at the maps.

Table 3-2 reports the data range, mean and standard deviation for each parameter, grouped into drilled wells and dug wells. Many parameters were below the detection limits; for the calculation of means and standard deviations, non-detect values were replaced with values equal to half the detection limits, as is done in the OAGGP. For instances where a significant portion of the data were below detection limits, the detection limit is reported instead.

Table 3-2. Summary of groundwater chemistry data for drilled and dug wells in this study showing the mean, standard deviation, minimum and maximum concentrations or values with units for each chemistry parameter.

Chemistry Parameters	Units	Drilled Wells (n = 74)			Dug Wells (n = 62)		
		Mean ± St.Dev.	Min	Max	Mean ± St.Dev.	Min	Max
<u>FIELD CHEMISTRY</u>							
Temperature	°C	10.22 ± 0.83	8.64	12.58	11.95 ± 2.16	8.46	19.51
Specific Conductance	µS/cm	1953 ± 2486	379	13781	778 ± 576	94	3603
pH	pH Units	8.07 ± 0.63	6.57	9.24	7.05 ± 0.42	6.05	9.11
Oxidation Reduction Potential	mV	-146 ± 118	-341	223	20 ± 91	-140	287
Alkalinity	mg/L as CaCO ₃	455 ± 233	146	1242	238 ± 98	29	488
Dissolved Oxygen, DO	%Sat.	5.75 ± 14.89	0.00	74.30	9.97 ± 15.84	0.00	77.90
Hydrogen Sulphide, H ₂ S	mg/L as S	0.08 ± 0.40	0.00	3.00	0.00 ± 0.02	0.00	0.12
<u>CALCULATED PARAMETERS</u>							
Hardness	mg/L as CaCO ₃	149.35 ± 160.77	4.68	704.70	278.40 ± 126.80	11.16	765.57
Total Dissolved Solids	mg/L	1372.08 ± 1458.26	307.20	8007.96	564.34 ± 334.72	69.36	2053.01
<u>BACTERIA</u>							
Total Coliforms	Count/100mL	13.1 ± 23.3	0	120	38.2 ± 44.8	0	231
Fecal Coliforms	Count/100mL	0.9 ± 4.0	0	29	10.4 ± 38.8	0	292
<u>CARBON SPECIES</u>							
Bicarbonate, HCO ₃ ⁻	mg/L	555 ± 285	178	1514	293 ± 116	35	595
Dissolved Inorganic Carbon, DIC	mg/L as C	111.1 ± 65.2	11.0	297.0	61.9 ± 28.4	5.6	143.0
Dissolved Organic Carbon, DOC	mg/L as C	9.59 ± 8.04	<1	29.00	4.79 ± 2.55	<1	12.70
Methane, CH _{4(aq)}	Litres/m ³	11.34 ± 18.17	0.00	81.26	0.47 ± 2.77	0.00	21.54
<u>NITROGEN SPECIES</u>							
Nitrate, NO ₃ ⁻	mg/L as N	0.362 ± 1.886	<0.006	15.400	1.205 ± 1.855	<0.006	7.590
Nitrite, NO ₂ ⁻	mg/L as N	0.004 ± 0.013	<0.003	0.094	0.009 ± 0.017	<0.003	0.087
NO ₃ ⁻ + NO ₂ ⁻	mg/L as N	0.366 ± 1.885	<0.009	15.400	1.214 ± 1.859	<0.009	7.594
Total Kjeldahl Nitrogen, TKN	mg/L as N	1.34 ± 1.42	<0.05	6.87	0.39 ± 0.36	<0.05	2.63
NH ₃ /NH ₄ ⁺	mg/L as N	0.98 ± 1.17	<0.04	5.19	0.13 ± 0.33	<0.04	2.59
Organic Nitrogen	mg/L as N	0.37 ± 0.44	<0.05	2.39	0.27 ± 0.22	<0.05	0.86
<u>HALIDES AND OTHER ANIONS</u>							
Fluoride, F ⁻	mg/L	1.095 ± 0.899	0.028	3.208	0.146 ± 0.130	0.032	0.878
Chloride, Cl ⁻	mg/L	353.77 ± 761.31	0.19	4511.00	71.49 ± 156.65	0.75	837.25
Bromide, Br ⁻	mg/L	1.098 ± 2.543	<0.02	15.693	0.073 ± 0.153	<0.02	1.146
Iodide, I ⁻	µg/L	259.9 ± 453.5	<5	2530.0	14.6 ± 17.7	<5	88.9
Phosphate, PO ₄ ³⁻	mg/L	1.146 ± 1.992	<0.05	9.021	0.033 ± 0.075	0.020	0.482
Sulphate, SO ₄ ²⁻	mg/L	20.69695 ± 41.27942	<0.04	228.120	34.816 ± 30.122	0.130	158.59

Table 3-2. (Continued)

Chemistry Parameters	Units	Drilled Wells (n = 74)			Dug Wells (n = 62)		
		Mean ± St.Dev.	Min	Max	Mean ± St.Dev.	Min	Max
<u>ALKALI METALS</u>							
Lithium, Li	µg/L	22.300 ± 31.910	1.107	168.80	3.585 ± 5.471	0.153	28.82
Sodium, Na	mg/L	360.88 ± 479.27	4.26	2420.0	46.61 ± 85.39	2.556	435.94
Potassium, K	mg/L	11.269 ± 13.131	0.504	65.200	5.445 ± 6.188	0.796	38.500
Rubidium, Rb	µg/L	5.264 ± 6.363	0.376	32.100	3.596 ± 3.578	0.303	20.490
Cesium, Cs	µg/L	0.0656 ± 0.0630	0.0028	0.3553	0.0153 ± 0.0136	0.0008	0.0761
<u>ALKALINE EARTH METALS</u>							
Beryllium, Be	µg/L	<0.01	<0.01	0.031	<0.01	<0.01	0.025
Magnesium, Mg	mg/L	18.940 ± 22.883	0.627	133.561	18.141 ± 11.815	1.643	53.454
Calcium, Ca	mg/L	27.568 ± 44.299	0.823	234.551	80.992 ± 36.318	1.388	224.549
Strontium, Sr	mg/L	1.717 ± 3.698	0.038	30.435	0.416 ± 0.550	0.052	3.515
Barium, Ba	µg/L	323.99 ± 345.38	17.8	1830.000	69.830 ± 43.712	14.7	190.000
<u>TRANSITION METALS</u>							
Cadmium, Cd	µg/L	<0.01	<0.01	0.083	0.013 ± 0.016	<0.01	0.115
Chromium, Cr	µg/L	0.356 ± 0.302	0.032	1.330	0.306 ± 0.528	0.029	3.991
Cobalt, Co	µg/L	0.09 ± 0.09	<0.005	0.44	0.51 ± 1.12	<0.005	7.05
Copper, Cu	µg/L	1.74 ± 4.28	<0.2	30.30	8.12 ± 13.63	<0.2	84.33
Gold, Au	µg/L	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Hafnium, Hf	µg/L	<0.004	<0.004	0.005	<0.004	<0.004	0.023
Iron, Fe	mg/L	0.312 ± 0.713	<0.0015	5.270	0.539 ± 2.016	<0.0015	15.363
Manganese, Mn	mg/L	0.031 ± 0.087	<0.002	0.600	0.270 ± 0.561	<0.002	3.430
Mercury, Hg	µg/L	<0.0015	<0.0015	0.0063	<0.0015	<0.0015	0.0031
Molybdenum, Mo	µg/L	1.045 ± 1.351	0.037	7.324	0.850 ± 0.680	0.052	4.256
Niobium, Nb	µg/L	0.0088 ± 0.0094	<0.001	0.0404	0.0075 ± 0.0119	<0.001	0.0879
Nickel, Ni	µg/L	0.80 ± 0.93	<0.1	6.21	1.84 ± 1.66	<0.1	6.75
Scandium, Sc	µg/L	0.118514 ± 0.190054	<0.1	1.44	<0.1	<0.1	0.40
Selenium, Se	µg/L	2.84 ± 5.36	<0.2	29.020	0.294 ± 0.49	<0.2	3.750
Silver, Ag	µg/L	<0.005	<0.005	0.03	<0.005	<0.005	0.0025
Tantalum, Ta	µg/L	<0.0003	<0.0003	0.0009	<0.0003	<0.0003	0.0019
Titanium, Ti	µg/L	3.37 ± 3.69	<0.1	14.75	0.34 ± 0.93	<0.1	7.03
Tungsten, W	µg/L	1.337 ± 1.356	<0.01	5.223	0.040 ± 0.107	<0.01	0.798
Vanadium, V	µg/L	0.9088 ± 1.0207	0.0142	3.8500	0.6849 ± 0.8202	0.0195	4.6200
Yttrium, Y	µg/L	0.0579 ± 0.0608	0.0119	0.3354	0.2942 ± 0.6373	0.0032	4.7600
Zinc, Zn	µg/L	1.458108 ± 2.902762	<1	19.9	5.9 ± 9.3	<1	58.4
Zirconium, Zr	µg/L	0.243581 ± 0.304067	<0.1	1.96	0.12 ± 0.17	<0.1	0.99

Table 3-2. (Continued)

Chemistry Parameters	Units	Drilled Wells (n = 74)			Dug Wells (n = 62)		
		Mean ± St.Dev.	Min	Max	Mean ± St.Dev.	Min	Max
<u>OTHER METALS</u>							
Aluminum, Al	µg/L	<5.0	<5.0	45.8	7.0 ± 11.3	<5	79.0
Bismuth, Bi	µg/L	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Gallium, Ga	µg/L	0.030 ± 0.035	<0.002	0.185	0.043 ± 0.050	<0.002	0.211
Lead, Pb	µg/L	0.0677 ± 0.2352	<0.002	1.9899	0.1663 ± 0.1948	0.0073	0.8922
Thallium, Tl	µg/L	0.001928 ± 0.006835	<0.001	0.0548	0.0135 ± 0.0195	<0.001	0.1427
Tin, Sn	µg/L	0.018655 ± 0.089316	<0.01	0.7740	0.0084 ± 0.0086	<0.01	0.0545
<u>METALLOIDS</u>							
Antimony, Sb	µg/L	0.034 ± 0.066	<0.01	0.561	0.052 ± 0.054	<0.01	0.301
Arsenic, As	µg/L	0.190 ± 0.135	<0.03	0.901	0.336 ± 0.327	0.041	1.588
Boron, B	mg/L	0.474 ± 0.346	0.007	1.539	0.038 ± 0.049	0.005	0.293
Silicon, Si	mg/L	6.434 ± 2.633	2.335	16.930	6.143 ± 2.135	2.070	11.423
<u>RARE EARTH ELEMENTS</u>							
Lanthanum, La	µg/L	0.0677 ± 0.1383	<0.001	0.7149	0.5029 ± 2.0215	0.0015	15.1100
Cerium, Ce	µg/L	0.13 ± 0.29	<0.002	1.48	0.30 ± 0.93	<0.002	6.46
Praseodymium, Pr	µg/L	0.015 ± 0.030	<0.0004	0.152	0.087 ± 0.287	<0.0004	2.035
Neodymium, Nb	µg/L	0.065 ± 0.107	<0.003	0.564	0.341 ± 1.030	<0.003	7.23
Samarium, Sm	µg/L	0.011 ± 0.016	<0.001	0.085	0.053 ± 0.131	0.001	0.881
Europium, Eu	µg/L	0.000831 ± 0.002159	<0.0004	0.0148	0.0082 ± 0.0206	<0.0004	0.1395
Gadolinium, Gd	µg/L	0.0113 ± 0.0132	<0.001	0.0640	0.0504 ± 0.1183	<0.001	0.8298
Terbium, Tb	µg/L	0.00106 ± 0.00164	<0.0001	0.00828	0.00596 ± 0.01220	<0.0001	0.08317
Dysprosium, Dy	µg/L	0.007 ± 0.009	<0.001	0.045	0.034 ± 0.061	<0.001	0.3999
Holmium, Ho	µg/L	0.00152 ± 0.00189	<0.0001	0.01041	0.00762 ± 0.01203	<0.0001	0.07593
Erbium, Er	µg/L	0.0056 ± 0.0069	<0.001	0.0426	0.0252 ± 0.0350	<0.001	0.205
Thulium, Tm	µg/L	0.00102 ± 0.00115	<0.0001	0.00764	0.00386 ± 0.00488	<0.0001	0.02284
Ytterblum, Yb	µg/L	0.0084 ± 0.0096	<0.001	0.0624	0.0292 ± 0.0363	<0.001	0.1802
Lutetium, Lu	µg/L	0.00234 ± 0.00246	<0.0001	0.01337	0.00606 ± 0.00826	<0.0001	0.05027
Thorium, Th	µg/L	0.0119 ± 0.0228	<0.0001	0.1446	0.0109 ± 0.0284	<0.0001	0.1867
Uranium, U	µg/L	0.10364 ± 0.21595	0.00078	1.41546	1.32263 ± 1.79977	0.00726	9.25000
<u>ENVIRONMENTAL ISOTOPES</u>							
Oxygen-18, δ ¹⁸ O	‰	-10.623 ± 0.486	-12.374	-9.818	-10.952 ± 0.701	-13.383	-9.288
Deuterium, δ ² H	‰	-70.744 ± 3.592	-84.422	-63.774	-73.331 ± 5.209	-93.483	-61.892
Tritium, ³ H	Tritium Units	3.66 ± 4.13	<0.8	12.66	Not analyzed		

The quality of the chemical analysis performed for each site was assessed by conducting a charge balance test. According to Freeze and Cherry (1979), Aqueous solutions are electrically neutral because the total charge contributed by cations in a solution is balanced by an equal charge contributed from anions. Comparing charge balance is an effective means of assessing the quality of an analysis for major ions, because a significant charge balance error (CBE) can indicate that some constituents were not accounted for or that some measurements were inaccurate. The quality of the analyses for neutral or non-charged species was ensured by the OGS OAGGP protocols.

In this study, charge balances errors were calculated for all samples using the following equation:

$$\text{Charge Balance Error, CBE} = \frac{\sum(z \cdot m)_{\text{cations}} - \sum(z \cdot m)_{\text{anions}}}{\sum(z \cdot m)_{\text{cations}} + \sum(z \cdot m)_{\text{anions}}} \times 100\%$$

In the above equation, z is the absolute value of the ion's charge expressed in equivalents per mole (eq/mol), and m is the molality in mol/kg. Positive CBE indicates cation excess and negative CBE indicates anion excess. The cations used for CBE included Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , Fe^{2+} , Mn^{2+} and NH_4^{+} , and the anions used included HCO_3^{-} , SO_4^{2-} , Cl^{-} , F^{-} , NO_3^{-} and NO_2^{-} .

The charge balance errors for all 136 wells are shown in **Figure 3-10**. Of the 136, 124 (91.2%) had $\text{CBE} < \pm 5\%$. 12 (8.8%) had $\text{CBE} > \pm 5\%$, and of those 12, 2 (1.5%) had $\text{CBE} > \pm 10\%$. The site numbers corresponding to analyses exceeding $\pm 5\%$ CBE are indicated in **Figure 3-10**. The 124 wells within $\pm 5\%$ are considered to be of high quality, and the 10 sites between ± 5 -10% are considered acceptable according to OAGGP protocols and have an equal proportion of sites with cation excess and anion excess.

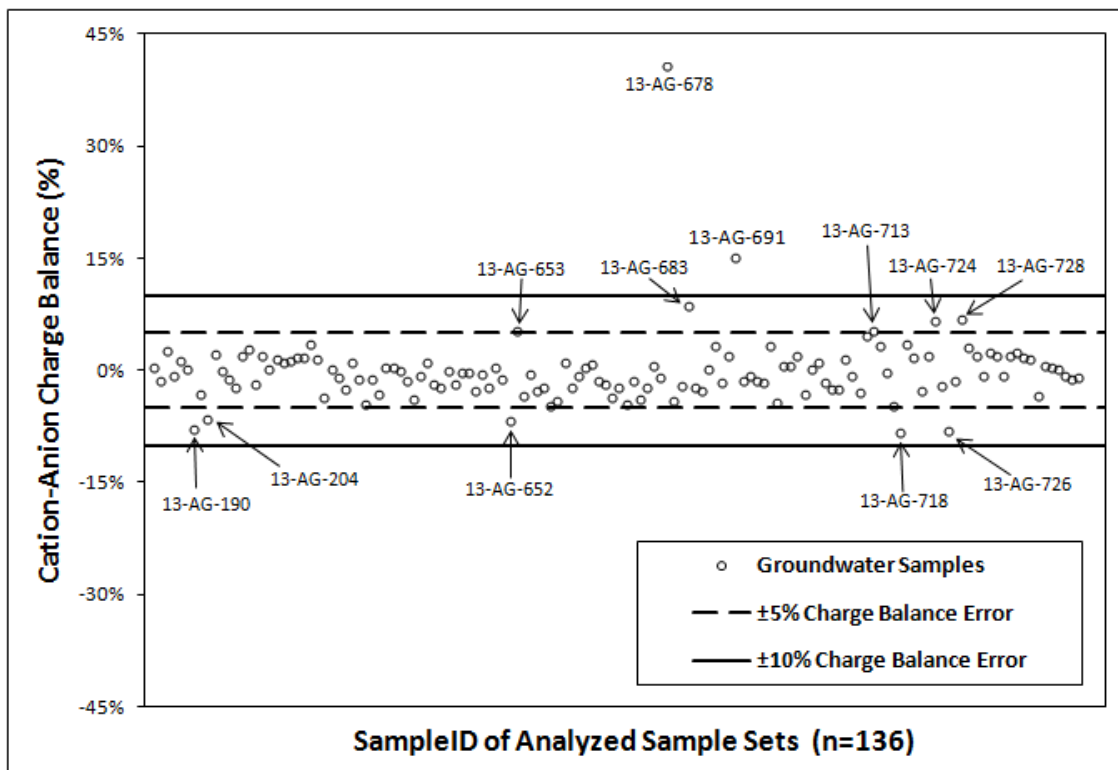


Figure 3-10. Charge balance error (CBE) calculated for all well samples gathered throughout the City of Clarence-Rockland during the Groundwater Sampling Program and the Ontario Ambient Groundwater Geochemistry Project.

Of the 2 sites with > 10% cation excess, one was moderately high at 15.4% (13-AG-691) and the other was very high at 40.8% (13-AG-678). The groundwater from these two sites came from shallow dug wells, and in both wells Ca^{2+} was the main contributor for cation excess, which presumably should have been balanced by higher readings of HCO_3^- . Site 13-AG-678 had an extremely low alkalinity of 40 mg/L as CaCO_3 , which was likely the cause of its high CBE. In future studies, better accuracy can be obtained on an alkalinity titration of low alkalinity water by doubling the titration volume of 100 mL to 200 mL. Calcium concentrations in dug wells are commonly very high, especially in shallow sand/gravel aquifers in the Ottawa Valley since the material is ~20% calcium carbonate. Regardless, because the analyses for sites 13-AG-678 and 13-AG-691 yielded $\text{CBE} > \pm 10\%$, the results at those sites are considered to be of poor quality compared to the analyses at the other 134 sites.

3.5 Discussion of Groundwater Types in Dug and Drilled Wells

In order to identify major differences between groundwater chemistry in overburden wells, deep overburden wells and bedrock wells, the water types for each well were determined and plotted in a piper plot, shown in **Figure 3-11**. This was done using AquaChem software

provided by Schlumberger Water Services. The chemistry data for all 136 points were filled into a template which was then imported into AquaChem. AquaChem automatically converted the concentrations of Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , HCO_3^- , CO_3^{2-} and SO_4^{2-} into milliequivalents per litre (meq/L) and determined water types based on percentage meq/L ratios. The percentage ratios are expressed in the Piper plot generated in AquaChem in **Figure 3-11**.

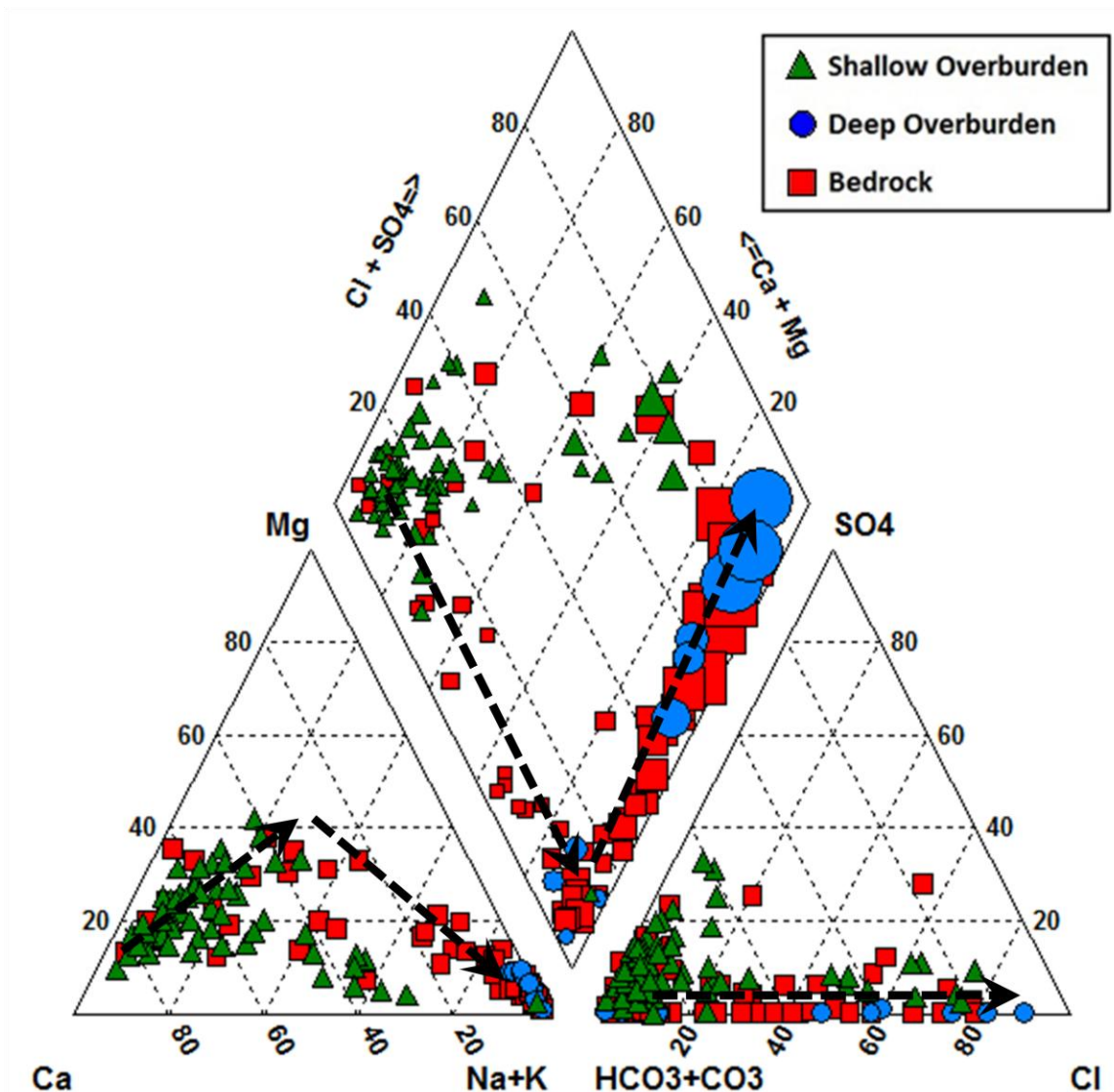


Figure 3-11. Piper plot of major element compositions (in % milliequivalents) for groundwater in the City of Clarence-Rockland sampled from wells situated in shallow overburden (dug), deep overburden (drilled), and bedrock (drilled). Symbols in the central diamond are scaled proportionately to TDS. Arrows indicate the typical progression of groundwater chemistry described by Macpherson & Townsend (1998) (see text for further explanation).

From **Figure 3-11**, we see that shallow overburden wells in the City produced mainly calcium bicarbonate water and that bedrock wells produced mainly sodium bicarbonate and sodium chloride water. We also see that deep overburden wells behave similarly to bedrock

wells in both composition and total dissolved solids. Because there was such a clear similarity between deep overburden and bedrock wells, the remainder of this study divided wells into groups of dug and drilled wells instead of shallow overburden, deep overburden and bedrock.

The water types and TDS of drilled wells in **Figure 3-11** resemble the typical changes in groundwater chemistry with time and distance along a flow path described by Macpherson & Townsend (1998). In a typical progression, groundwater in recharge areas will begin as calcium bicarbonate water, change to sodium bicarbonate water by natural softening processes as it is recharged, and gradually become sodium chloride water, all while increasing in TDS concentration due to increased mineral exposure and residence time (Macpherson & Townsend, 1998; Boyle et al., 1998; Clark, 2015).

In the upper portion of the diamond, we see a deviation from the usual trend in both dug wells and drilled wells, where the groundwater chemistry has evolved directly towards sodium chloride water. That cluster contains 9 dug wells and 4 drilled wells. The dug wells were Sites 191, 607, 656, 672, 677, 711, 712, 714 and 717. The drilled wells were Sites 606, 609, 737 and 741. With the exception of Site 737 which plotted there due to its sulphate content, an analysis of chloride to bromide ratios later discussed in **Section 4.3.7** revealed all of these to be due to halite dissolution, which is likely from anthropogenic road salt. On a side note, there was one dug well (Site 693) which produced Na-HCO₃ water; this likely resulted from anthropogenic water softening processes which use Na-HCO₃ salts.

In **Figure 3-12** the major anion component of the piper plot for drilled wells was colour-coded, as per Peeters' (2014) methodology for displaying hydrochemical data, and is shown overlaying the digital elevation model from **Figure 2-3**. This map shows a good correspondence between surface topography, groundwater discharge areas and the water types that are produced. As one would expect from the typical groundwater progression, areas of higher topography are often recharge zones which will produce bicarbonate water, and areas of low topography are often discharge zones that will produce groundwater that has had longer residence times and is more enriched with natural chloride. It is important to stress that elevation itself is not a controlling factor on groundwater chemistry, but rather, the groundwater residence time is.

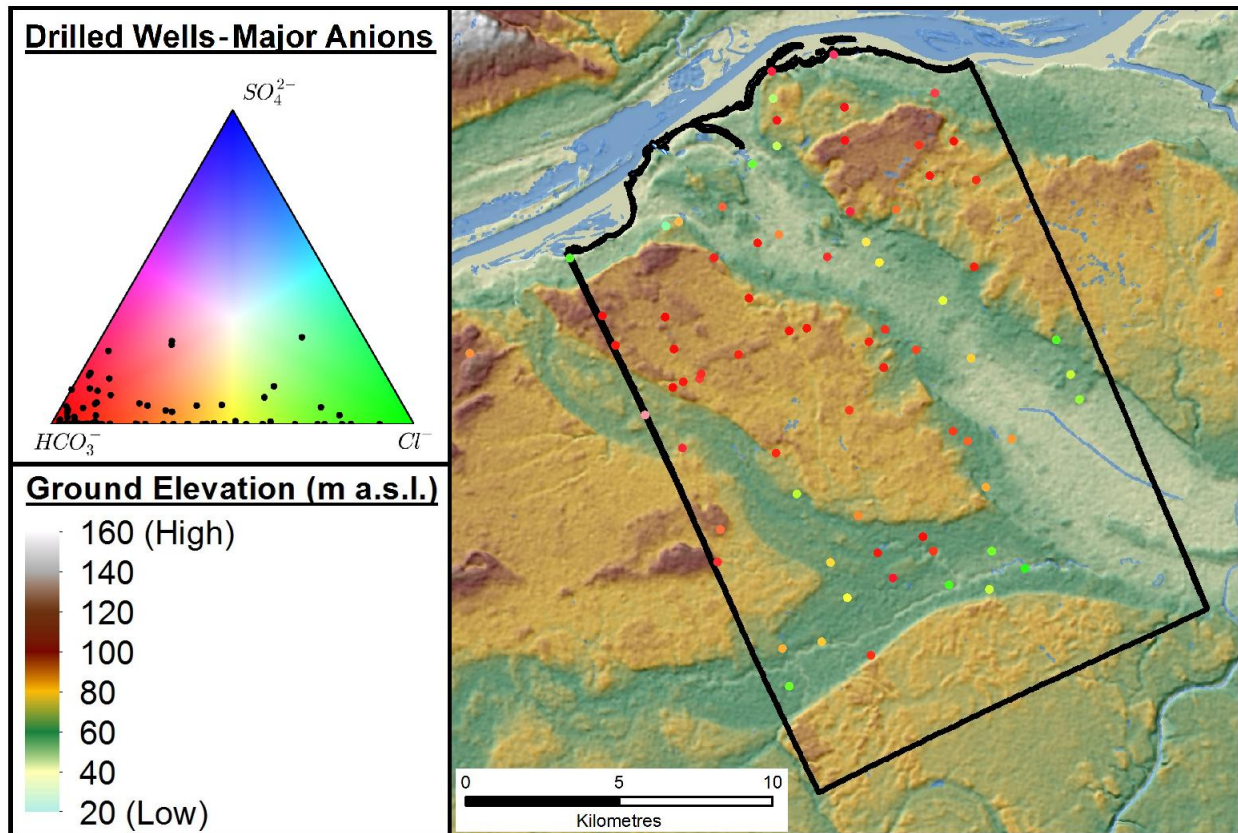


Figure 3-12. Map showing drilled well locations colour coded by their major anion type from the Piper plot overlain across the digital elevation model for the City of Clarence-Rockland. Colour-coding method used was developed by Peeters (2014).

3.6 Discussion of Tritium Contents in Drilled Wells

The ambient content of tritium in groundwater has changed worldwide since the atomic bomb testing that began in 1952, and to this day the tritium content of precipitation in Ottawa, ON, is still approximately 15 Tritium Units (Drimmie, 2011). Considering that the atmospheric tritium contents prior to the 1950s were much closer to zero, Clark & Fritz (1997) provided a general classification scheme for tritium in groundwater to indicate whether the groundwater was sub-modern or modern. Sub-modern groundwaters have <0.8 TU, modern waters have 4-15 TU, and 0.8-4 TU indicate mixing of modern and sub-modern water. Higher tritium contents can indicate bomb residue from the nuclear tests at the end of World War II and the beginning of the Cold War.

The groundwater tritium content was measured for all bedrock wells in this study, including some deep overburden wells. The mean tritium content was 2.83 TU ($n = 72$) with a standard deviation of 0.81. Of the 72 measured wells, 26 (36%) were below the detection limit of 0.8 TU (sub-modern water), 20 (28%) were between 0.8 and 4.0 TU (mix of sub-modern and

modern water), and 26 (36%) had tritium contents above 4.0 TU to a maximum of 13.9 TU (modern water). None of the sampled wells exceeded 15 TU.

The bedrock areas, easiest for recent water to enter, correspond to recharge zones with higher bedrock topography. In **Figure 3-13**, the tritium content in drilled wells are shown overtop the bedrock topography layer included in the GSC Overburden model by Logan et al., (2009). Tritium contents were generally highest in areas of high bedrock topography, but the opposite could not be identified from **Figure 3-13**. Instead, the locations of wells with sub-modern tritium contents seemed to coincide with groundwater discharge areas with low surface elevation and higher chloride percentages, discussed in **Section 3.5**. This further supports that those areas are generally preserved and do not have groundwater mixing with the overburden aquifers.

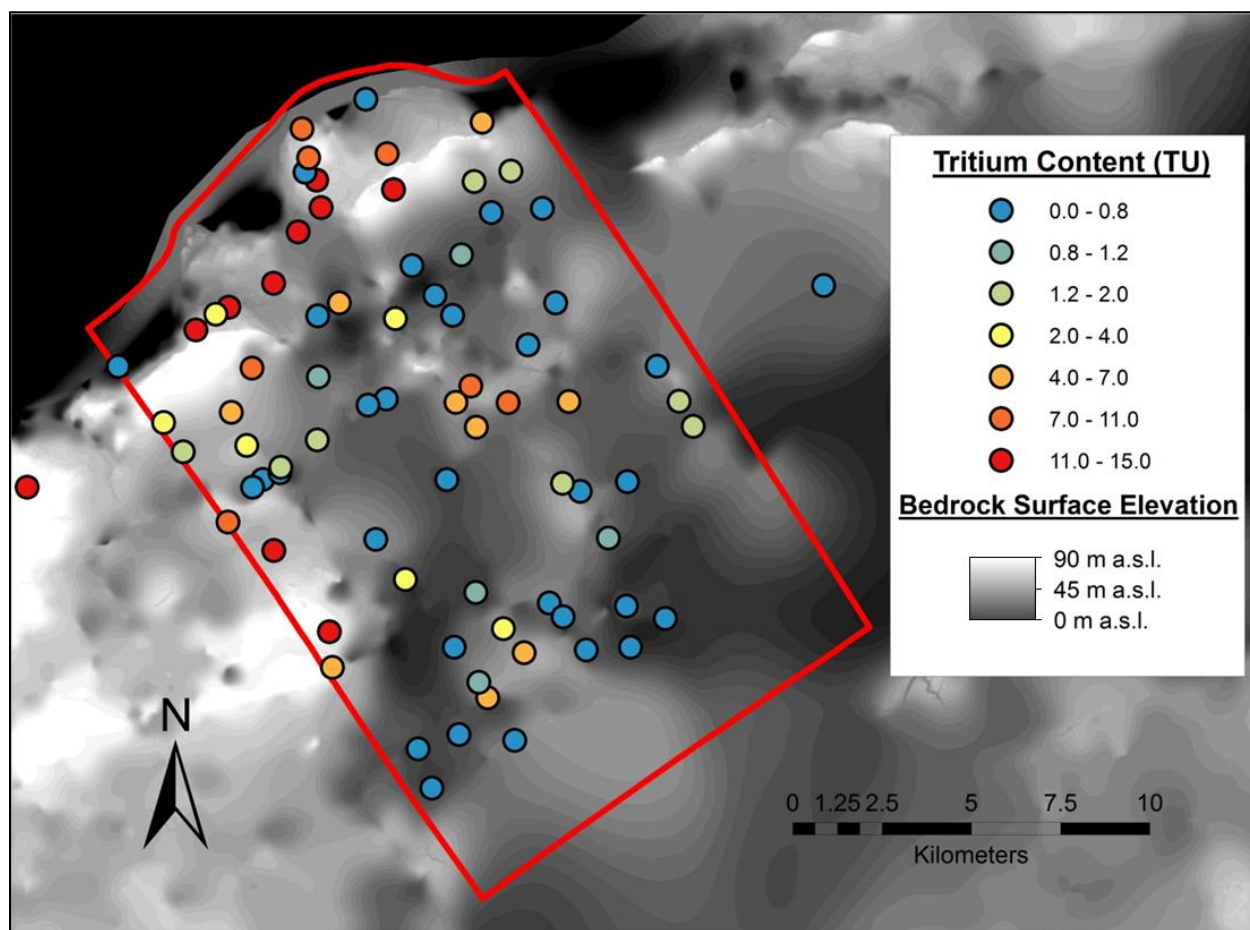


Figure 3-13. Tritium content of bedrock wells in the City of Clarence-Rockland shown with bedrock topography from the Geological Survey of Canada 3D Overburden Model produced by Logan et al. (2009). The City boundaries are shown in red.

4 Exceedances of Drinking Water Standards

This section compares the groundwater chemistry results obtained in the Groundwater Sampling Program (GSP) to the Ontario Drinking Water Standards, Objectives and Guidelines (ODWSOG) in order to help identify areas of poor groundwater quality for the Aquifer Capability Screening Tool. **Section 4.1** provides an overview of the ODWSOG as they relate to the chemistry parameters analyzed in this study, and outlines the exceedance criteria for each parameter. The ODWSOG (MOE, 2006) group parameters into three main classes based on Health Standards, Aesthetic Objectives and Operational Guidelines. Exceedances of parameters in these three classes are reported and discussed in **Sections 4.2, 4.3 and 4.4**, respectively.

4.1 Ontario Drinking Water Standards

In 2002, the province implemented the Safe Drinking Water Act under Ontario Regulation 169/03. The Ministry of the Environment (MOE) document titled “Ontario Drinking Water Quality Standards” accompanied that act, and was revised and republished in 2006 as the “Ontario Drinking Water Standards, Objectives and Guidelines” (ODWSOG). The ODWSOG provide information for the protection of public health through the provision of safe drinking water (MOE, 2006). Numerous criteria are defined in the ODWSOG including, but not limited to, microbiological, chemical, physical, radioactive and aesthetic characteristics.

MOE Procedure D-5-5 (MOE, 1996) presents water quality guidelines to be applied when assessing development proposals where private wells are proposed as the source of domestic water in Ontario. The Guideline identifies a minimum set of parameters which should be analyzed, and also identifies that additional parameters should be analyzed as identified by specific site conditions.

For a well to supply water to private residences, the water produced should be safe and aesthetically suitable for human consumption (MOE, 1996). Criteria for safe and aesthetically suitable water are referred to as Health Standards and Aesthetic Objectives. Additionally, for long term use the water should be within a certain operational range to prevent corrosion or encrustation of pipes; these ranges are referred to as Operational Guidelines. Health Standards, Aesthetic Objectives and Operational Guidelines are discussed in **Sections 4.1.1, 4.1.2 and 4.1.3**, respectively.

Some water quality exceedances can be resolved by implementing various treatment systems and methods. In Procedure D-5-5, the MOE (1996) outlines a Maximum Concentrations Considered Reasonably Treatable (MCCRT) for various aesthetic parameters and provides comments on possible treatment methods. The MCCRTs as they relate to this study are

indicated in **Section 4.1.4**. Exceedances of MCCRTs are reported with aesthetic exceedances in **Section 4.3**.

4.1.1 Health Standards

There are two types of limits associated with health standard parameters: Maximum Acceptable Concentrations (MAC) and Interim Maximum Acceptable Concentrations (IMAC). MACs are established for parameters which, when present above a certain concentration, are known or suspected to cause adverse health effects. IMACs are established as a precaution for parameters whose toxicological data are insufficient to determine a precise MAC. Under the Safe Drinking Water Act (Service Ontario, 2002), water intended for drinking in Ontario should not exceed any of the MAC and IMAC limits. As such, it is considered a potential health risk for water to be consumed if it exceeds the established MAC or IMAC limits in any chemical parameters.

The list of MACs described in the ODWSOG contains numerous complex chemical compounds ranging from pesticides to toxic pollutants, however many such analyses go beyond the scope of this study and are not typically analyzed unless a specific contaminant is suspected at a given location. The Health Standard parameters assessed in this study include plate counts of total Coliform and fecal Coliform bacteria and concentrations of nitrate, nitrite, fluoride, arsenic, boron, barium, cadmium, chromium, lead, antimony, selenium, uranium and mercury. The MACs and IMACs for these Health Standard parameters are shown in **Table 4-1**.

Table 4-1. Health standards for parameters involved in this study. Source: MOE (2006).

Parameter	Health Standard	MAC/IMAC
Total Coliform Bacteria	Zero counts per 100 mL of water	MAC
Fecal Coliform Bacteria	Zero counts per 100 mL of water	MAC
Nitrate, NO ₃ ⁻	Less than 10 mg/L as Nitrogen	MAC
Nitrite, NO ₂ ⁻	Less than 1.0 mg/L as Nitrogen	MAC
Nitrate + Nitrite	Less than 10 mg/L as Nitrogen	MAC
Fluoride, F ⁻	Less than 1.5 mg/L	MAC
Antimony, Sb	Less than 0.006 mg/L	IMAC
Arsenic, As	Less than 0.0025 mg/L	IMAC
Barium, Ba	Less than 1.0 mg/L	MAC
Boron, B	Less than 5.0 mg/L	IMAC
Cadmium, Cd	Less than 0.005 mg/L	MAC
Chromium, Cr	Less than 0.05 mg/L	MAC
Lead, Pb	Less than 0.01 mg/L	MAC
Mercury, Hg	Less than 0.001 mg/L	MAC
Selenium, Se	Less than 0.01 mg/L	MAC
Uranium, U	Less than 0.02 mg/L	MAC

4.1.2 Aesthetic Objectives

Aesthetic Objective parameters have been set within the ODWSOG to identify drinking water as aesthetically acceptable and pleasant to drink in terms of taste, odour and colour. The aesthetic-related chemistry parameters measured in this study include water temperature and concentrations of total dissolved solids, sodium, chloride, sulphate, dissolved organic carbon, iron, copper, manganese, zinc, methane gas and hydrogen sulfide. During the GSP, turbidity, colour and odour were described qualitatively at each site but were not quantitatively measured. Turbidity and odour cannot be compared to the aesthetic objectives, but colour can be used as any visible colouration is above the acceptable criteria. Taste was not tested at any of the sites in the GSP, so aesthetic exceedances in that regard cannot be discussed either. Aesthetic Objectives for each parameter are shown in **Table 4-2**.

Table 4-2. Aesthetic Objectives for parameters involved in this study. Source: MOE (2006).

Parameter	Aesthetic Objective
Temperature	Below 15°C
Colour	Less than 5 True Colour units
Taste	Must be inoffensive
Odour	Must be inoffensive
Turbidity	Less than 5 Nephelometric Turbidity units
Total Dissolved Solids, TDS	Less than 500 mg/L
Dissolved Organic Carbon, DOC	Less than 5.0 mg/L as Carbon
Chloride, Cl ⁻	Less than 250 mg/L
Sulphate, SO ₄ ²⁻	Less than 500 mg/L
Copper, Cu	Less than 1.0 mg/L
Iron, Fe	Less than 0.3 mg/L
Manganese, Mn	Less than 0.05 mg/L
Sodium, Na	Less than 200 mg/L
Zinc, Zn	Less than 5.0 mg/L
Methane gas, CH ₄	Less than 3 L/m ³
Hydrogen sulphide, H ₂ S	Less than 0.05 mg/L as Sulphide

Aesthetic exceedances do not necessarily indicate that water is unsafe for human consumption, but rather that it may be unpleasant. However, in terms of the use of private wells as drinking water supplies, Provincial Guidelines (MOE, 1995: Sections 1 and 4.1) state that both health and aesthetic considerations provide the basis for drinking water suitability. For example, it is not uncommon or necessarily unhealthy for people to drink water that is coloured or smells of sulfur, and though high sulphate concentrations may cause laxative effects this is not considered a health risk. Similarly, concentrations of iron and manganese may be of concern for the staining of sinks and clothes, while the high chloride imparts a salty taste to drinking water without any associated health risk. Sodium, on the other hand, can have potential health implications; sodium concentrations above 200 mg/L are considered too salty to be palatable, but

there is a health-related warning level of 20 mg/L which may be of concern to people who are on sodium-reduced diets.

4.1.3 Operational Guidelines

Operational Guidelines are suggested by the ODWSOG to help improve the operation of the water system by reducing the possibility of corrosion or material buildup within the pipes (encrustation). The ODWSOG warns that if Operational Guidelines are not met, the efficiency and effectiveness of treatment, disinfection and distribution of the water maybe impacted. Operational Guideline parameters include pH, water hardness and alkalinity, and concentrations of dissolved aluminum and organic nitrogen in the water. The requirements for meeting each operational guideline are outlined in **Table 4-3**.

Table 4-3. Operational Guidelines for parameters involved in this study. Source: MOE (2006).

Parameter	Operational Guideline
pH (acidity)	Between 6.5 and 8.5
Alkalinity	Between 30 and 500 mg/L as CaCO ₃
Hardness	Between 80 and 100 mg/L as CaCO ₃
Aluminum	Less than 100 µg/L
Organic Nitrogen	Less than 0.15 mg/L as Nitrogen

4.1.4 Maximum Concentrations Considered Reasonably Treatable

There are many different options available to homeowners for water treatment. Treatment systems are often individually implemented for the purposes of neutralizing bacteria, removing certain metals, resolving water hardness issues, and removing colour and odour from groundwater before it reaches the tap. Although they come at a price and may require additional maintenance over time, many homeowners rely on treatment technology to optimize their plumbing and produce drinking water that is aesthetically pleasing. Some examples of water treatment systems that are used in Ontario include: Water softeners, UV filters, Iron filters, Aerators, Reverse-osmosis units, chlorine injectors, sediment filters and charcoal filters.

MOE Procedure D-5-5 (1996) provides comments on some treatment options for private wells, as well as upper concentration limits for several parameters, above which it is not reasonable for a private well owner to treat. The upper concentration limits for treatment are denoted as Maximum Concentrations Considered Reasonably Treatable (MCCRT). MCCRTs are specified for several Aesthetic Objective parameters, and are set in order to outline concentrations that if encountered will not be economically feasible to correct using common treatment options. The MCCRTs for relevant aesthetic parameters outlined in D-5-5 are summarized in **Table 4-4**.

Table 4-4. MCCRTs for aesthetic parameters involved in this study. Source: MOE (1996).

Parameter	MCCRT	Comments on Treatment
Chloride	250 mg/L	Not considered reasonably treatable above the limit
Colour	7 TCU	Carbon filter treatment systems; cause of colour should be determined
DOC	10.0 mg/L as C	Carbon filter treatment systems
Iron	Up to 5.0 mg/L	Water softeners or manganese greensand filters
Iron	5.0 to 10.0 mg/L	Oxidation with filtration through proprietary filter media or chlorination followed by sand or multimedia filtration
Manganese	1.0 mg/L	Water softeners or manganese greensand filters
Sodium	200 mg/L	Not considered reasonably treatable above the limit
Sulphate	500 mg/L	Not considered reasonably treatable above the limit

Although more advanced options may exist to treat exceedances, this Thesis focuses on the D-5-5 Guideline values. Additional analyses and groundwater mapping may be necessary in the future when the MCCRT limits are re-evaluated by the MOECC.

4.2 Discussion of Health Standard Exceedances

The numbers of sampled drilled and dug wells with health standard exceedances are shown in **Table 7.2.1**. Exceedances were detected for total Coliform bacterial, fecal Coliform bacteria, nitrate, fluoride, barium and selenium. No exceedances were detected for nitrite, antimony, arsenic, boron, cadmium, chromium, lead, mercury or uranium. There were many bacterial exceedances in drilled wells and dug wells, however the remaining health exceedances were only encountered in drilled wells. In total, out of 136 sampled wells, there were 77 total Coliform bacteria exceedances (32 drilled wells, 45 dug wells), 34 fecal Coliform bacteria exceedances (8 drilled wells, 25 dug wells), 1 nitrate exceedance, 23 fluoride exceedances, 5 barium exceedances and 6 selenium exceedances.

Table 7.2.1 – Exceedances of drinking water health standards detected in the groundwater samples collected from drilled and dug wells throughout the City of Clarence-Rockland during this study.

Health Standard Exceedances				
Parameter	Exceedance Criteria	Drilled Wells (n = 74)	Dug Wells (n = 62)	All Wells (n = 136)
Total Coliform Bacteria	> 5 Counts/100 mL	32 (43%)	45 (73%)	77 (57%)
Fecal Coliform Bacteria	> 0 Counts/100 mL	8 (11%)	25 (40%)	34 (25%)
Nitrate, NO₃⁻	> 10.0 mg/L as N	1 (1%)	0 (0%)	1 (1%)
Nitrite, NO ₂ ⁻	> 1.0 mg/L as N	0 (0%)	0 (0%)	0 (0%)
Nitrate + Nitrite	> 10.0 mg/L as N	1 (1%)	0 (0%)	1 (1%)
¹ Fluoride, F⁻	> 1.5 mg/L	23 (31%)	0 (0%)	23 (17%)
Antimony, Sb	> 0.006 mg/L	0 (0%)	0 (0%)	0 (0%)
Arsenic, As	> 0.025 mg/L	0 (0%)	0 (0%)	0 (0%)
Barium, Ba	> 1.00 mg/L	5 (7%)	0 (0%)	5 (4%)
Boron, B	> 5.00 mg/L	0 (0%)	0 (0%)	0 (0%)
Cadmium, Cd	> 0.005 mg/L	0 (0%)	0 (0%)	0 (0%)
Chromium, Cr	> 0.050 mg/L	0 (0%)	0 (0%)	0 (0%)
Lead, Pb	> 0.010 mg/L	0 (0%)	0 (0%)	0 (0%)
Mercury, Hg	> 0.001 mg/L	0 (0%)	0 (0%)	0 (0%)
Selenium, Se	> 0.010 mg/L	6 (8%)	0 (0%)	6 (4%)
Uranium, U	> 0.020 mg/L	0 (0%)	0 (0%)	0 (0%)

¹ Fluoride concentrations exceeding 2.4 mg/L may be toxic and potentially hazardous to humans if consumed regularly.

4.2.1 Coliform Bacteria

From a health standpoint, certain bacteria can be indicative of contamination or potential contamination in drinking water. Coliform bacteria are rod-shaped Gram-negative non-spore forming and motile bacteria, which are easy to culture, and can indicate that pathogens of fecal origin may be present (APHA, 1995). Among the different genera of Coliforms are Fecal Coliforms and *Escherichia coli* (*E. coli*) which directly indicate contamination and can be harmful to humans depending on their strain. Total Coliform counts include the Fecal Coliforms (which include *E. coli*), however non-fecal Coliforms may not cause health-related effects.

Each well sampled in this study was analyzed for Total Coliforms and Fecal Coliforms, but not *E. coli*. Both measurements were expressed by their total counts of bacterial colonies per 100 mL of sample (Counts/100 mL). The Ontario Drinking Water Standards for Fecal Coliforms and Total Coliforms are each 0 Counts/100 mL; however MOE Procedure D-5-5 allows <6 Counts/100 mL for privately serviced developments. This study has used 0 Counts/100 mL and <6 Counts/100 mL as safe criteria for Fecal Coliforms and Total Coliforms, respectively, and any higher amounts are considered exceedances.

Maps of the bacterial counts from all drilled wells and dug wells in this study are shown from **Figure A2-17** to **Figure A2-20** in **Appendix 2**. In general, there were more Total Coliform exceedances in the bedrock wells of the northern half of the city compared to the southern half of the city, whereas overburden wells showed no distinction with exceedances scattered throughout the City. Fecal Coliform exceedances were also scattered, though there were few detections in bedrock wells compared to overburden wells.

It is suspected that the occurrence of bacteria in a private homeowner well depends more on the integrity and construction of the well rather than its physical location. In **Table 4-5**, the 127 drilled and dug wells that were sampled during the Groundwater Sampling Program in 2013 are compared based on their type of well cap. There are five major categories that can be used to describe the well caps encountered in the City: standard steel, concrete, vermin-proof, buried/well pit and other. **Standard steel** (**Figure 4-1**) and **concrete** (**Figure 4-2**) well caps were most common for drilled wells and dug wells, respectively, followed by **vermin-proof** (**Figure 4-1, Figure 4-2**) caps which provide a tight fitting seal to keep out pests. Some wells were **buried** (**Figure 4-3**) or situated in a **well pit** (**Figure 4-3**) beneath the ground surface level, and there were a few **other** (**Figure 4-4**) wells whose caps had been improvised or were old and exposed at the surface.

Table 4-5. Bacteriological sampling results for 2013 sampling, showing the number of exceedances of Total Coliform (>5 Counts/100 mL) and Fecal Coliforms (>0 Counts/100 mL) for all wells, drilled wells and dug wells, differentiated by their type of well cap.

		Type of Well Cap					Total
		<u>Standard Steel</u>	<u>Concrete</u>	<u>Vermin-Proof</u>	<u>Buried/Well Pit</u>	<u>Other</u>	
<u>All Wells</u>	Sample Size	33	37	42	9	6	127
	Total Coliform Exceedances	18 (55%)	29 (78%)	20 (48%)	4 (44%)	6 (100%)	77 (61%)
	Fecal Coliform Exceedances	5 (15%)	19 (51%)	7 (17%)	0 (0%)	3 (50%)	34 (27%)
<u>Drilled Wells</u>	Sample Size	33	0	25	9	1	68
	Total Coliform Exceedances	18 (55%)	---	9 (36%)	4 (44%)	1 (100%)	32 (47%)
	Fecal Coliform Exceedances	5 (15%)	---	2 (8%)	0 (0%)	1 (100%)	8 (12%)
<u>Dug Wells</u>	Sample Size	0	37	17	0	5	59
	Total Coliform Exceedances	---	29 (78%)	11 (65%)	---	5 (100%)	45 (76%)
	Fecal Coliform Exceedances	---	19 (51%)	5 (29%)	---	2 (40%)	26 (44%)



Figure 4-1. Drilled Wells encountered with standard steel caps (left and middle) and vermin-proof caps (right).



Figure 4-2. Dug wells encountered with concrete caps (left) and vermin-proof caps (right).



Figure 4-3. Wells encountered that were buried (left) or located in a well pit (right).



Figure 4-4. Wells encountered with improvised or otherwise old and damaged well covers.

In the City, 61% of all 127 wells analyzed had Total Coliform exceedances and 27% had Fecal Coliform exceedances. For the 68 drilled wells, 47% had Total Coliform exceedances and

12% had Fecal Coliform exceedances. For the 59 dug wells, 76% had Total Coliform exceedances and 44% had Fecal Coliform exceedances. From these numbers alone we see that the dug wells in the City were much more prone to bacterial contamination.

Separating the drilled and dug wells into the categories shown in **Table 4-5** was a good way of showing that the presence of bacteria could be related to the type of well cap. Drilled wells that were fitted with vermin-proof caps had the fewest exceedances compared to the other well caps, followed by drilled wells that had been buried or were located in a well pit. The next lowest were drilled wells with standard steel caps, which insects could freely enter due to the looseness of their fitting; it was not uncommon for bugs such as earwigs and spiders to be found under the steel caps, whereas the vermin-proof caps are securely fastened with a rubber gasket between the cap and the casing. Many homeowners were unaware of the importance of their well caps, and some admitted to opening their wells on a regular basis, which can allow unwanted foreign material to enter the well if not done carefully.

Nearly half of the wells buried beneath the ground or in well pits showed bacterial exceedances, indicating that they had not been properly installed. If a well head is not properly sealed and is then buried or situated in a pit surrounded by material or water, then there is a high risk for contamination.

The ages of drilled wells also varied considerably, with records dating as far back as 1954, and it is possible that the grout seals around the wells have been compromised over time. It is also possible that some of the wells had not been grouted at all, and these situations may have contributed to the Coliform occurrence throughout the drilled wells.

Compared to drilled wells, dug wells had a much higher occurrence of bacterial Coliforms, and much of this can likely be attributed to the well cover at the surface of the well. Concrete block lids were often loosely placed on top of the well and were sealed only by their own weight, allowing for small gaps where debris, bugs and rainfall could easily enter the well. Most often, there was a stiff layer of dirt or decomposing organic matter forming a makeshift seal between the concrete well and concrete well cap. Dug wells that were fitted with plastic Vermin-Proof caps which were bolted on and securely fitted showed a lower occurrence of bacteria (65%) than dug wells with standard concrete lids (78%).

From this, it is evident that vermin-proof well caps provide a better level of security compared to traditional well caps, and will help protect against contamination by Coliform bacteria. The occurrence of bacteria in wells with vermin-proof caps remains alarming however, and hints at other entry points for bacterial presence. The annulus of the well, which is the area between the well casing and the borehole wall, is grouted at the time of well construction with cement and/or bentonite to provide a seal. In many wells throughout the City, including those brought up to code and fitted with vermin-proof caps, the integrity of the well seals may have been compromised over time or may have been poor to begin with due to past grouting procedures being primitive or unregulated. In such wells, the annulus itself may be a pathway for bacteria to enter the well.

While compromised well integrity can introduce greater risk of bacterial contamination, there is also a natural risk for bacteria depending on well settings in general. Compared to

drilled wells which draw from deep and typically confined aquifers, shallow wells are expected to have higher incidences of bacteria. This is because water drawn from phreatic (surficial) aquifers have a higher chance of being contaminated by surface water, which may contain bacteria and nutrients for bacterial growth.

For drilled wells in bedrock, karstic bedrock units which contain air pockets can be breeding grounds for bacteria and may provide a natural source of bacteria to groundwater in areas where karst is present. Karst aquifers are extremely susceptible to contamination by pathogens (Mahler et al., 2000). In the City, the Gull River and Rockcliffe Formations have been mapped by the OGS in GRS005 as potential and inferred karst locations due to their carbonate layers being highly vulnerable and susceptible to karstification (Brunton & Dodge, 2008). Comparing the bacterial presence shown in **Figure A2-17** to their representative geological units identified in **Figure 3-8**, we observe that all 13 drilled wells that were situated in the Gull River and Rockcliffe Formations measured exceedances of Total Coliforms (Sites 602, 603, 604, 606, 609, 611, 612, 615, 623, 624, 638, 736 and 741). This correlation between karst and bacterial presence supports the hypothesis that bacterial exceedances may be ambient to the natural groundwater obtainable in those areas.

4.2.2 Fluoride

Fluoride was found to be one of the main health concerns with groundwater from drilled wells in the City. Maps of fluoride concentration in groundwater samples collected from drilled wells and dug wells are shown in **Figure A2-37** and **Figure A2-38**, respectively. Of 72 drilled well samples collected, there were 23 wells exceeding the drinking water health standard of 1.5 mg/L, and 7 of those contained more than 2.4 mg/L. No exceedances of fluoride were found in dug wells. While it is important to have some fluoride in drinking water, concentrations beyond 2.4 mg/L have been linked with increased risk of developing the bone condition known as fluorosis.

Almost all of the wells with fluoride concentrations higher than the half exceedance limit of 0.75 mg/L were drawing water from limestone formations according to MOE well records. Comparing to the representative geological units of each well shown in **Figure 3-8**, none of the drilled wells situated in the Rockcliffe Formation (n=9) measured exceedances of fluoride. Likewise, the wells situated in the Gull River Formation (n=4) and Verulam Formation (n=3) did not contain fluoride exceedances either. The Bobcaygeon, Lindsay and Eastview Formations contained many wells with fluoride exceedances. Of these wells, records indicating a shale substrate rather than limestone at the bottom of the well generally contained lower fluoride concentrations. There were some exceptions to this, however it is uncertain that all MOE records indicating shale are accurate, considering that darkly coloured limestone was sometimes misidentified as shale in areas where shales should not have been present. Of the wells situated in the Late Ordovician Billings and Carlsbad Formations (n=4), which are composed mainly of shale, there were no fluoride exceedances.

From this, it seems that the gradual rise in biotic life throughout the Ottawa Group depositional period was linked to a rise in fluoride content as well. The fluoride has likely been stored over long periods of time in the form of fluorite. Fluorite, CaF_2 , is a relatively low solubility mineral with a K_{sp} of $10^{-10.51}$ (Garand & Mucci, 2004).

A study by Saxena & Ahmed (2001) found that the dissolution of fluorite in groundwater can be favorable within a pH range of 7.6–8.6, a bicarbonate range of 350–450 mg/L and a specific conductance range of 750–1750 $\mu\text{S}/\text{cm}$. The fluoride concentrations observed in drilled wells in this study are plotted against those three parameters in **Figure 4-5**. Fluoride concentrations did persist beyond the ranges reported by Saxena & Ahmed (2001), though an effective range may differ from an optimal range and there would be notable differences in temperature and ionic strength conditions compared to their experiments. Regardless, the plots of **Figure 4-5** show that the favorable conditions for fluorite dissolution are met by the groundwater found in drilled wells in the City, allowing the low solubility mineral to dissolve.

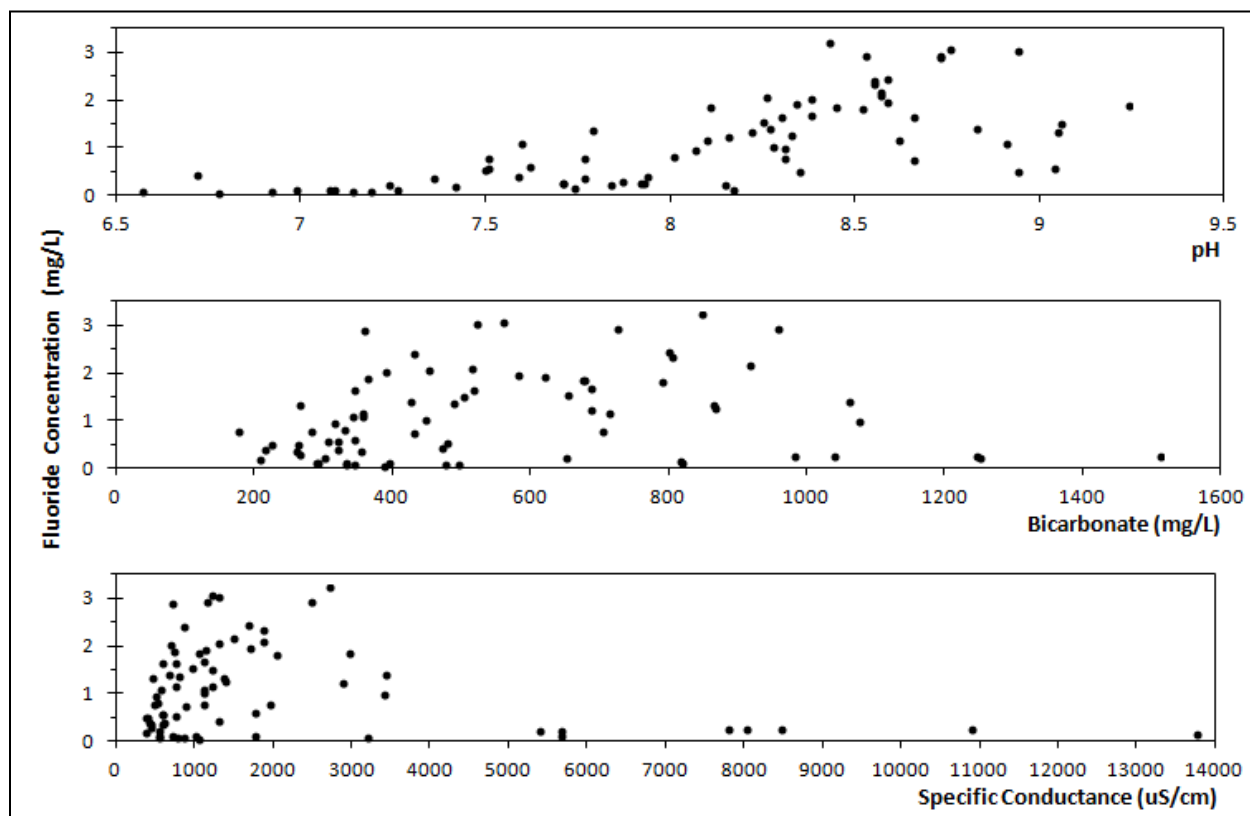


Figure 4-5. Fluoride concentration in drilled wells (n=74) plotted against pH, bicarbonate concentration and specific conductance.

To verify that the necessary dissolution conditions were met, saturation indices for fluorite were calculated at each well using the geochemical model PHREEQC. These saturation indices, which are defined as the log of the ratio of the ion activity product to the solubility constant, are plotted against fluoride concentration in **Figure 4-6**. Each of the drilled and dug

wells contained water with a negative saturation index for fluorite, indicating that dissolution would be possible.

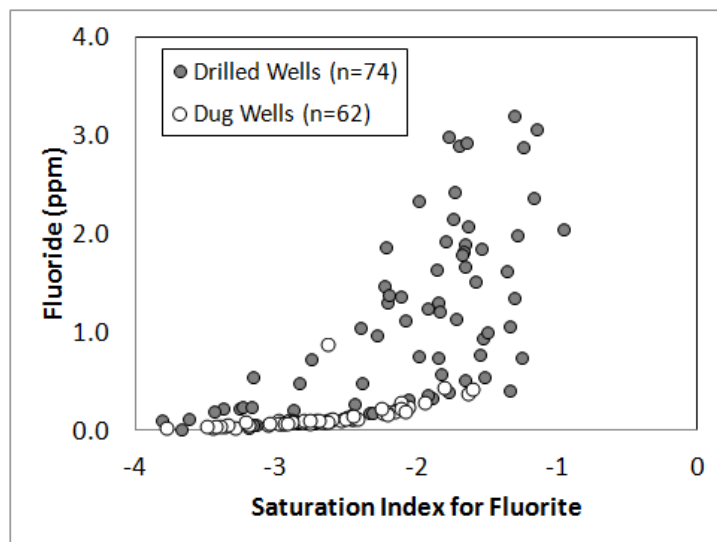


Figure 4-6. Fluoride concentration in drilled wells (n=74) plotted against pH, bicarbonate concentration and specific conductance.

In **Figure 4-7**, fluoride concentration was found to negatively correlate with hardness and calcium concentration, indicating that fluoride is most abundant in softer waters where calcium is absent. If the source of fluoride is the dissolution of a calcium based mineral, then the continued presence of fluoride in solution implies that the calcium is re-precipitated as another mineral following dissolution. An example may be calcite, as its precipitation would be supported by the same alkaline bicarbonate-rich conditions that support fluorite dissolution.

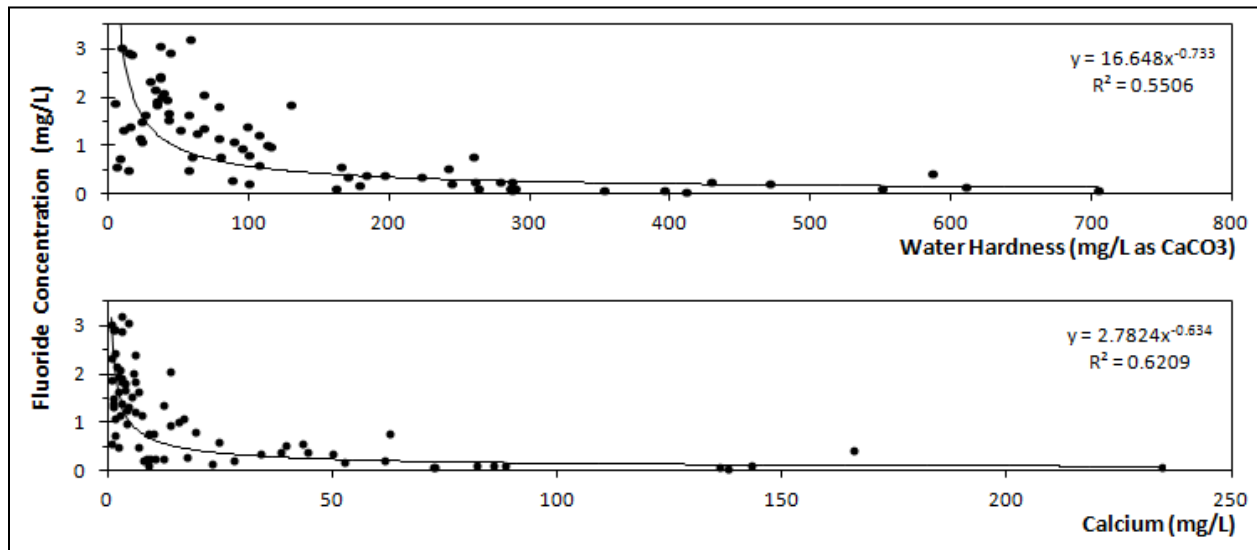


Figure 4-7. Fluoride concentration in drilled wells (n=74) plotted against water hardness and calcium concentration.

Another available source of fluoride in these bedrock units is the mineral apatite, which was found in nearby carbonatite dikes by Williams (1991). Apatite is a calcium phosphate mineral with the formula $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$. High phosphate concentrations up to 9 mg/L were found in drilled wells throughout the City with 20 wells higher than 1 mg/L PO_4^{3-} , which was alarming at first because high phosphate can indicate contamination from septic systems. However, a plot of phosphate against fluoride in **Figure 4-8** revealed that high phosphate concentrations only occurred in areas also high in fluoride, suggesting that the phosphate is likely occurring naturally from mineral dissolution and not from septic systems. Due to 101 of the 136 wells sampled having phosphate concentrations below the detection limit of 0.04 mg/L, saturation indices for apatite could not be calculated.

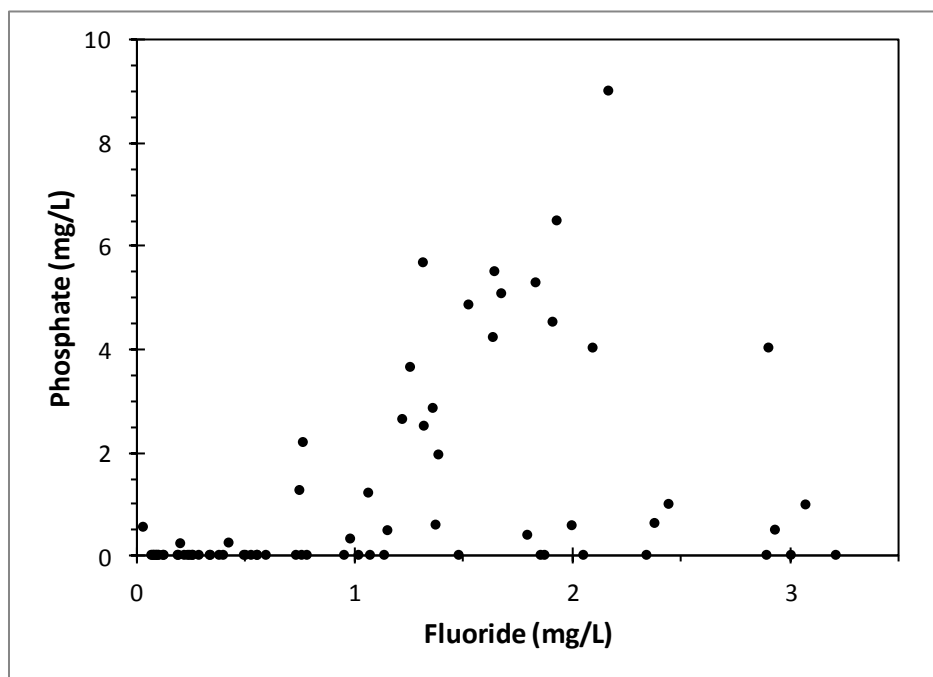


Figure 4-8. Phosphate concentrations in drilled wells (n=74) plotted against fluoride concentrations.

4.2.3 Barium

The locations of the 5 barium exceedances found in drilled wells sampled in the City are shown in **Figure A2-51**. Compared to the maximum acceptable concentration of 1.0 mg/L, barium exceedances were mild ranging from 1.04 to 1.83 mg/L. The exceedances were mostly located along fault margins, and drilled well concentrations were moderately high throughout the City compared to the dug wells that are shown in **Figure A2-52**.

A negative correlation ($r = -0.32$) was found between the concentrations of barium and sulphate in drilled wells, shown in **Figure 4-9**. The negative correlation between barium and sulphate in solution suggests that sulphur bearing minerals such as barite, BaSO_4 , may be a source. Because barite has a relatively low solubility in water ($K_{sp} = 1.1 \times 10^{-10}$; Speight, 1999), any significant barium present would precipitate out in the presence of sulphate; the absence of sulphate in these samples where barium was present indicates that there is an alternate sink for the sulphate as it is dissolved from the barite. Barite is not the only possible source, however, as barium can also be substituted into carbonate minerals in the place of calcium due to its divalence and can be adsorbed and bound to carbonate minerals (Astilleros et al., 2000; Dymond et al., 1992).

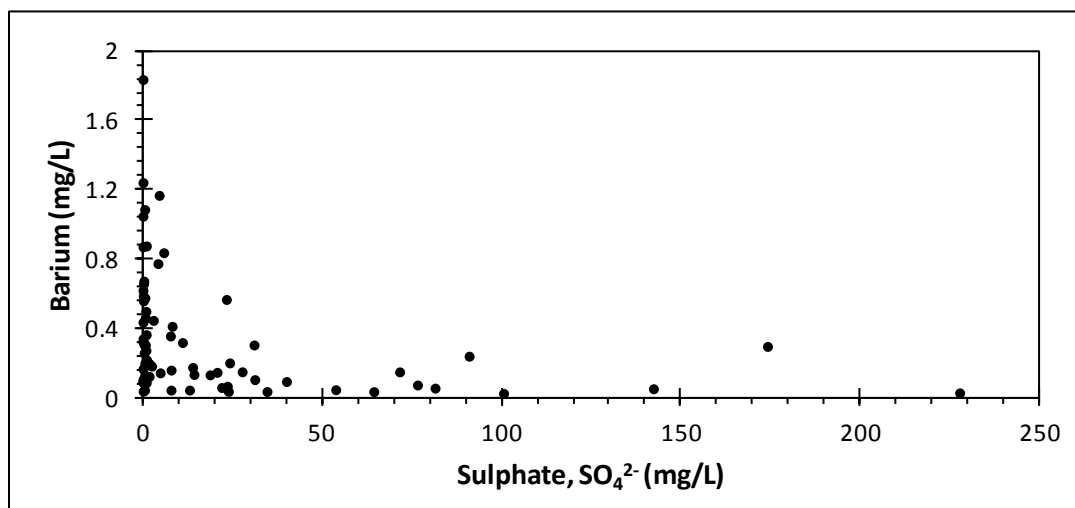


Figure 4-9. Barium concentration in drilled wells (n=74) plotted against sulphate concentration.

In deep sea sediments barium enrichments closely coincide with regions of upwelling and high productivity (Schmitz, 1987). In those conditions, barite forms in microenvironments which contain decaying organic matter and siliceous plankton (Bishop, 1988). During the deposition of the Paleozoic limestones, dolostones and shales, the Ottawa area was located offshore in a deep sea environment. The increasing biotic activity throughout the Ottawa Group (except for the Bobcaygeon Formation which had a drop in biotic activity) combined with upwelling currents from the offshore position at their time of deposition would give the right environment for increased sedimentation of barite and barium-enriched carbonates. In fact, Williams (1991) identified barite within faults in the Ottawa area. These faults, serving as a hydraulic connection between the Ottawa Group carbonate layers, may have accumulated barite over time and would be a potent source of barium to the groundwater.

In addition to the negative correlation with sulphate, barium concentrations in drilled wells were found to correlate positively with TDS ($r = 0.66$), Na ($r = 0.66$), Cl ($r = 0.63$), HCO_3^- ($r = 0.53$), hardness ($r = 0.66$), alkalinity ($r = 0.53$) and selenium ($r = 0.74$). The relationship of barium and selenium in drilled wells is shown in **Figure 4-10**. All wells with barium exceedances also measured exceedances of selenium, and both parameters appear to scale upwards with increasing TDS. Due to this, the occurrences of selenium and barium are both believed to be fault-related.

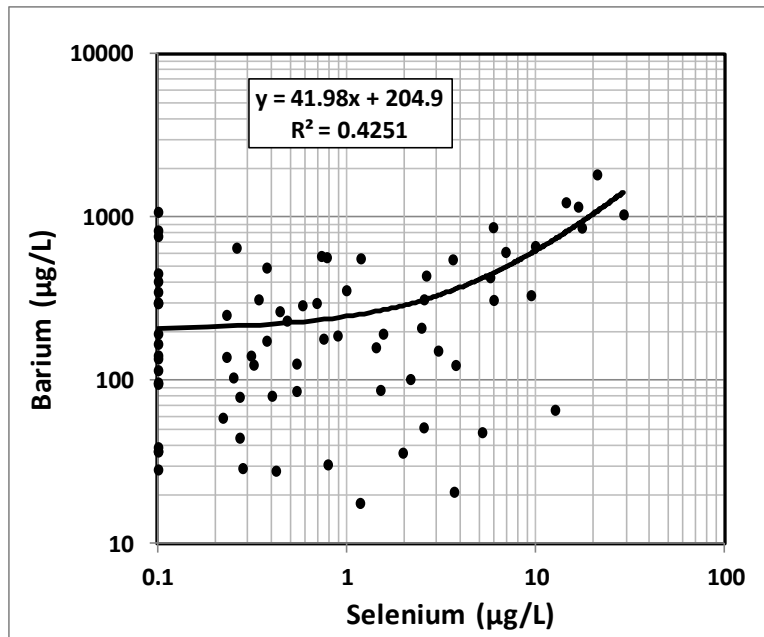


Figure 4-10. Barium concentration in drilled wells (n=74) plotted against selenium concentration.

4.2.4 Selenium

The locations of the 6 selenium exceedances found in drilled wells sampled in the City are shown in **Figure A2-53** and indicated by pink circles. Higher concentrations were observed in the south and southeast portions of the City compared to the rest. As an element, selenium behaves similar to sulphur, commonly substituting into pyrite as iron selenide, FeSe_2 , which can be oxidized to produce selenate, SeO_4 . As a result of geochemical processes such as mineral weathering, selenium occurs naturally in waters at trace levels as seen in the dug wells in **Figure A2-54**. In the City, it is suspected that the source of elevated selenium concentrations is shale components of bedrock formations since shales typically have higher sulphide contents compared to limestones (Geofirma, 2015). Comparing the exceedance locations to the representative geological units of each well shown in **Figure 3-8**, we see three exceedances in deep overburden overlying the Billings and Carlsbad shale Formations, two exceedances in the Lindsay Formation with one in the upper Eastview member, and one in the Gull River Formation.

According to the MOE ODWSOG (2006) the maximum acceptable concentration for selenium in drinking water is 0.01 mg/L, however selenium is an essential trace element in the human diet and a daily multivitamin contains about 0.05 mg. Though it is difficult to discern that high selenium wells pose a health risk, the wells containing high selenium groundwater would not be drinkable for other aesthetic reasons. As shown in **Figure 4-11**, selenium exceedances only occurred in samples with a total dissolved solids concentration greater than 3000 mg/L, which is huge compared to the aesthetic objective of 500 mg/L. With the main TDS

contributors being sodium and chloride, these waters would be very salty to taste and would not be suited for human consumption.

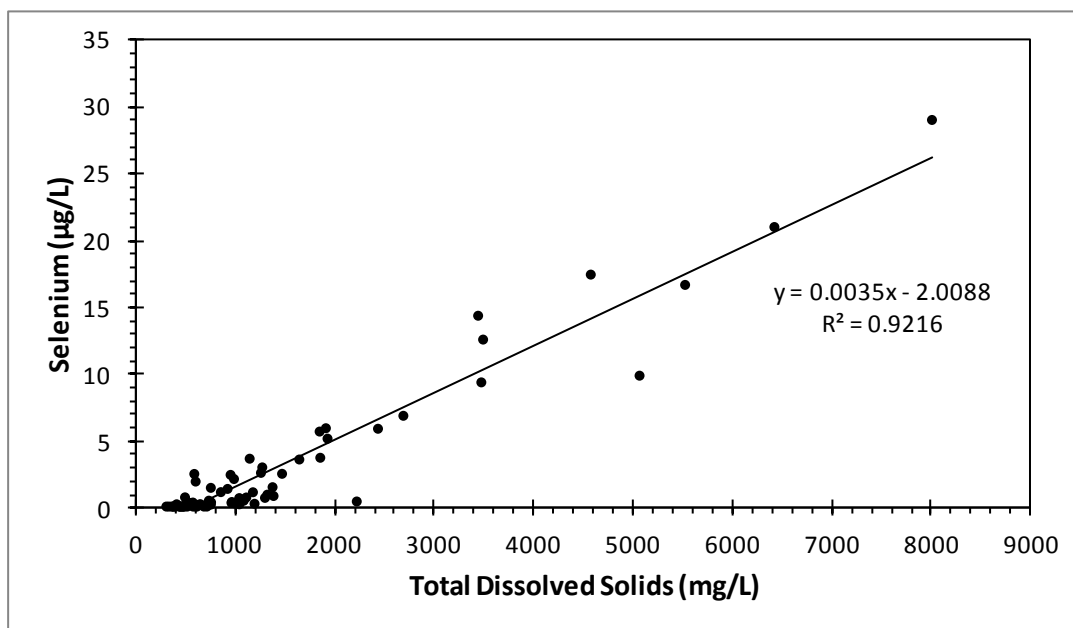


Figure 4-11. Selenium concentration in drilled wells (n=74) plotted against total dissolved solids.

4.2.5 Nitrate

One well was found in the City with a nitrate exceedance (>10 mg/L as N); the drilled well at Site 602 had a nitrate concentration of 15.4 mg/L as N. The concentrations of nitrate found in drilled wells and dug wells are shown in **Figure A2-27** and **Figure A2-28** of **Appendix 2**. Many dug wells had concentrations greater than 2 mg/L as N, but none were higher than 7.6 mg/L as N.

Site 602 is located in the northwestern portion of the City just south of Rockland. The surficial bedrock geology there is mapped as Gull River, however the representative geological formation at the well bottom was estimated to be of the Rockcliffe Formation. Comparing the nitrate concentrations (**Figure A2-27**) to the representative geological formations (**Figure 3-8**), we see that drilled wells with nitrate concentrations above 0.5 mg/L as N were mostly situated in the Rockcliffe Formation. The Rockcliffe Formation also had the highest occurrences of bacteria compared to the other units (discussed in **Section 4.2.1**), and that formation is known to potentially contain karst (Brunton & Dodge, 2008). Nitrate is a short-lived contaminant due to natural processes, so its presence is often indicative of a local or point source of contamination. The karst may be playing a role in this, but the exceedance could also be related to the well seal integrity and location of septic tanks, which were not assessed in this study.

4.3 Discussion of Aesthetic Objective Exceedances

The numbers of sampled drilled and dug wells with different aesthetic objective exceedances are shown in **Table 7.2.2**. Exceedances were detected for temperature, colour, total dissolved solids, dissolved organic carbon, chloride, iron, manganese, sodium, methane gas and hydrogen sulphide. No exceedances were detected for sulphate, copper or zinc.

Table 7.2.2 – Exceedances of drinking water aesthetic objectives detected in the groundwater samples collected from drilled and dug wells throughout the City of Clarence-Rockland during this study.

Aesthetic Objective Exceedances				
Parameter	Exceedance Criteria	Drilled Wells (n = 74)	Dug Wells (n = 62)	All Wells (n = 136)
Temperature	> 15°C	0 (0%)	4 (6%)	4 (3%)
Colour	Colourless	54 (73%)	18 (29%)	72 (53%)
Total Dissolved Solids	> 500 mg/L	59 (80%)	30 (48%)	89 (65%)
Dissolved Organic Carbon	> 5.0 mg/L as C	41 (55%)	22 (35%)	63 (46%)
Chloride, Cl ⁻	> 250 mg/L	21 (28%)	5 (8%)	26 (19%)
Sulphate, SO ₄ ²⁻	> 500 mg/L	0 (0%)	0 (0%)	0 (0%)
Copper, Cu	> 1.00 mg/L	0 (0%)	0 (0%)	0 (0%)
Iron, Fe	> 0.30 mg/L	16 (22%)	14 (23%)	30 (22%)
Manganese, Mn	> 0.050 mg/L	7 (9%)	31 (50%)	38 (28%)
Sodium, Na	> 200 mg/L	39 (53%)	3 (5%)	42 (31%)
Zinc, Zn	> 5.00 mg/L	0 (0%)	0 (0%)	0 (0%)
Methane gas, CH ₄	> 3.0 Litres/m ³	36 (49%)	2 (3%)	38 (28%)
Hydrogen sulphide, HS ⁻	> 0.05 mg/L as S ⁻	8 (11%)	2 (3%)	10 (7%)

The exceedances of maximum concentrations considered reasonably treatable (MCCRT) are summarized in **Table 4-6**. MCCRT exceedances were more frequent in drilled wells compared to dug wells, especially with chloride, dissolved organic carbon, and sodium. Colour MCCRT exceedances were common to both well types, but were more prevalent in drilled wells. Iron and manganese MCCRT exceedances were few in number, and iron and manganese MCCRT exceedances were exclusive to dug wells. There were no exceedances of sulphate.

Table 4-6. Exceedances of aesthetic parameter MCCRTS detected in the groundwater samples collected from drilled and dug wells throughout the City of Clarence-Rockland during this study.

Exceedances of Maximum Concentrations Considered Reasonably Treatable (MCCRT)				
Parameter	Exceedance Criteria	Drilled Wells (n = 74)	Dug Wells (n = 62)	All Wells (n = 136)
Chloride, Cl⁻	> 250 mg/L	21 (28%)	5 (8%)	26 (19%)
¹Colour	7 TCU	54 (73%)	18 (29%)	72 (53%)
Dissolved Organic Carbon	> 10.0 mg/L	26 (35%)	4 (6%)	30 (22%)
Iron, Fe	> 10.0 mg/L	0 (0%)	1 (2%)	2 (1%)
Manganese, Mn	> 1.0 mg/L	0 (0%)	5 (8%)	5 (4%)
Sodium, Na	> 200 mg/L	39 (53%)	3 (5%)	42 (31%)
Sulphate, SO₄²⁻	> 500 mg/L	0 (0%)	0 (0%)	0 (0%)
²Hardness	> 500 mg/L as CaCO ₃	4 (5%)	4 (6%)	8 (6%)

¹ Any visible appearance of a colour is assumed to exceed the 7 TCU requirement.

² There is no MCCRT limit for hardness, however values exceeding 500 mg/L as CaCO₃ are excessive and considered to be unacceptable.

4.3.1 Temperature

For palatability, there is an aesthetic objective for groundwater temperature to be cooler than 15°C. There were four dug wells which produced water warmer than this: sites 709, 738, 677 and 644 had temperatures of 15.04°C, 15.55°C, 15.70°C and 19.51°C, respectively. There were also a number of other dug wells with temperature above 14°C, and the mean temperature in dug wells was 11.95°C (n=62, σ=2.16°C). As one would expect, drilled wells had lower and more consistent temperatures, averaging 10.22°C (n=74, σ=0.83°C). The sampling was performed during the warmest months of the year, July and August, and it is likely that the groundwater was influenced by this. The fact that 15°C is nearly within the standard deviation of temperature in dug wells, however, indicates that dug wells may have a tendency to occasionally produce warm water. In drilled wells, water is pulled from depths tens of meters below the surface and temperature is not of concern.

4.3.2 Colour

In the Groundwater Sampling Program (GSP), visual observations of groundwater colour were made at every well. The drinking water objective for colour is 5 True Colour units (TCU) with a MCCRT of 7 TCU. A True Colour measurement is made after filtering the groundwater to remove turbidity from colloids or suspended particulates which affect the observed colour. The colour observations at each site were of Apparent Colour and not True Colour, because the turbidity was not removed for the colour observation and turbidity was not quantitatively measured. Nonetheless colour ranges from 0 to 500 TCU and 7 TCU is relatively invisible to the untrained eye, so it is reasonable to assume that any visually non-colourless water was in exceedance of 7 TCU.

In the City, groundwaters were observed to be colourless, grey/black, pale (slightly) yellow, dark yellow and brown. Pictures of these waters are shown in **Figure 4-12**. The number of wells with each colour are indicated in **Table 4-7**. Of all 136 wells, 65 contained colourless water, 8 had grey or black water, 34 had slightly yellow water, 23 had dark yellow water, and 6 had brown water.



Figure 4-12. Photos of colourless, grey, black, pale yellow, deep yellow and brown groundwater that were encountered throughout the City of Clarence-Rockland.

Table 4-7. Frequency of different apparent colours observed in groundwater sampled from drilled and dug wells throughout the City of Clarence-Rockland, ON.

Apparent Colour of Groundwater	Drilled Wells (n = 74)	Dug Wells (n = 62)	All Wells (n = 136)
Colourless	21 (28%)	44 (71%)	65 (48%)
Grey	4 (5%)	0 (0%)	4 (3%)
Black	4 (5%)	0 (0%)	4 (3%)
Pale Yellow	20 (27%)	14 (23%)	34 (25%)
Dark Yellow	20 (27%)	3 (5%)	23 (17%)
Brown	5 (7%)	1 (2%)	6 (4%)

The grey and black waters were found exclusively in bedrock wells, accounting for 10% of the bedrock wells sampled. The apparent colours of grey and black were likely caused by black manganese oxides, which were accidentally stirred up in some wells during the depth

measurements prior to sampling. When the water level tape was lowered to the well bottom to measure depth, it would run the risk of scraping manganese oxides which over time would accumulate on the metal casing of some wells via bacterial processes. We realized this partway through the field season and instead would then measure well depth last. The dark waters were not seen again after that.

Yellow groundwater was surprisingly common in the City. There were two distinct shades of yellow that were encountered, pale and dark yellow. Pale yellow was common to both well types as it was found in 27% of drilled wells and 23% of dug wells. Dark yellow groundwater was found in 27% of drilled wells and only 5% of dug wells, making it almost exclusive to drilled wells. The cause of the yellow water in the City has not been determined in previous studies, but may be related to the presence of humic substances, tannin and lignin. Humic substances, tannin and lignin can impart a characteristic yellowish to brownish colour in water and are most common in surface water, wetlands, and shallow groundwater due to the dissolution of tree stumps, bark and other buried organic debris (Nova Scotia Environment, 2009). Occasionally they can also be found in deep groundwater aquifers that are either in close proximity to coal or carbonaceous shale or are hydraulically connected to enriched surface waters (Nova Scotia Environment, 2009). Unfortunately, this study cannot confirm the relation of yellow water colour to the presence of humic substances, tannin and lignin, as they were not analyzed.

Brown and orange-brown waters were observed in 4% of all wells with 5 occurrences in drilled wells and one occurrence in dug wells. These darker colours are suspected to either be caused by iron oxides or be more concentrated colours of similar origin to the dark yellow.

The locations of drilled wells and dug wells where different colours were observed are shown in **Figure A2-15** and **Figure A2-16** of **Appendix 2**. Coloured groundwater was a widespread occurrence in the City. A spatial trend for colour in dug wells was not apparent. For drilled wells yellow water was most common in parts of the City overlain by the Lindsay Formation, but was also found elsewhere.

In drilled wells, fluoride may be contributing to the deep yellow colour observed. In a study aimed at identifying a sensitive detection method for fluoride, Black et al. (1999) demonstrated that increasing fluoride concentrations can turn light-yellow organic solutions to an orange dark-yellow by reacting to available NH bonds in amine groups. In **Figure 4-13**, we see that for drilled wells the yellow water mostly occurred when there were also high concentrations of fluoride. Of the 41 drilled wells with fluoride concentrations higher than 0.75 mg/L (half exceedance limit), 12 had pale yellow water and 19 had dark yellow water. The chelating agents required for the colour change are most likely organic compounds, indicated by the particularly high dissolved organic carbon concentrations also observed in the deep yellow water, shown in **Figure 4-14**. The light yellow colour is probably also caused by organic compounds, however a closer analysis of organic compounds is required to validate this claim.

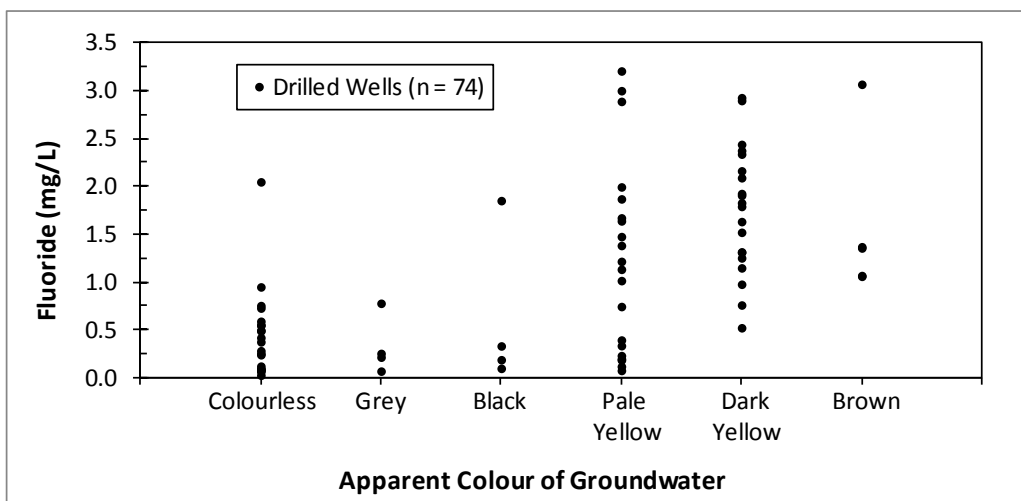


Figure 4-13. Comparison between apparent colour and dissolved fluoride concentration in groundwater obtained from drilled wells throughout the City of Clarence-Rockland, Ontario.

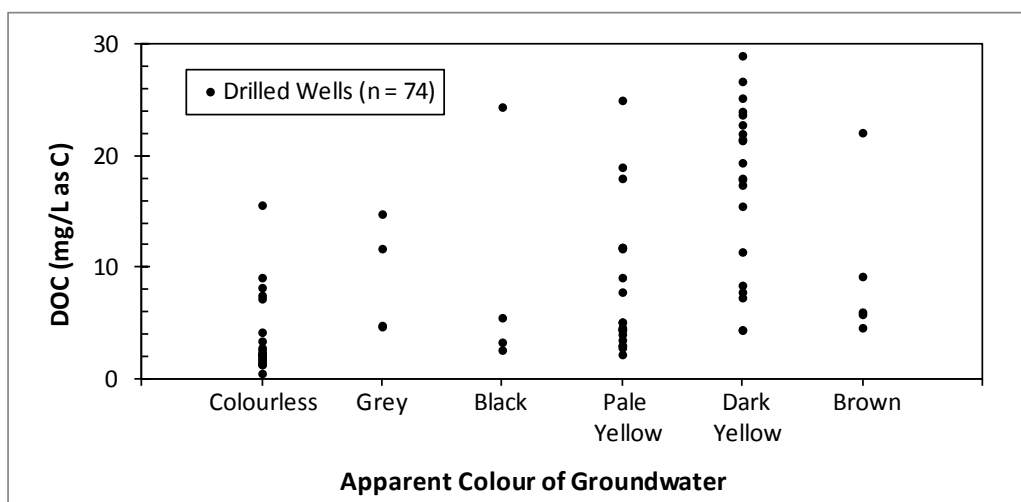


Figure 4-14. Comparison between apparent colour and dissolved organic carbon concentration of groundwater obtained from drilled wells throughout the City of Clarence-Rockland, Ontario.

For treating the colour, some well owners in the City demonstrated that standard water softening can be effective in removing the yellow colour. For organic compounds, this would be effective against chelating agents, which form strong bonds with polyvalent metal ions and are often responsible for the colours observed in organic matter (eg. Chlorophyll is a chelate whose colour is caused by magnesium bonds). In such cases, colour would be removed by separating the polyvalent metal ion from the organic ion during softening. Being able to treat the colour via softening further suggests that the yellow colour found in the City is related to organic material. Alternatively, if the colour is caused by high iron instead of organic material, an iron filter can be used to remove the colour.

Overall, due to the widespread distribution of colour in the groundwater of the City, it is presumed that when installing a well in the City there is a chance of encountering coloured water regardless of location. Drilled wells are more likely to have coloured water than dug wells, but both types can produce coloured water that is aesthetically unacceptable.

4.3.3 Dissolved Organic Carbon

The aesthetic objective for dissolved organic carbon (DOC) is 5 mg/L as C. The ODWSOG (MOE, 2006) state that high DOC can indicate potential chlorination by-product problems and is an indicator of possible water quality deterioration during storage and distribution due to the carbon being a growth nutrient for biofilm dwelling bacteria. Coagulation treatment or high pressure membrane treatment can be used to reduce DOC up to the MCCRT of 10 mg/L as C.

The DOC concentrations and exceedance locations for drilled wells and dug wells in the City are shown in **Figure A2-23** and **Figure A2-24** of **Appendix 2**. DOC aesthetic exceedances were detected in 55% of drilled wells and 35% of dug wells. DOC MCCRT exceedances were detected in 35% of drilled wells and only 6% of dug wells. In drilled wells, the MCCRT exceedances occurred mainly within the area mapped as the Lindsay Formation, whereas the lower aesthetic exceedances were spread out across the City. For the dug wells there were no observable trends. The high DOC concentrations in drilled wells are likely due to biotic marine origins of the bedrock, whereas the high DOC in dug wells may be due to land use or natural features such as forested areas or wetlands. The high DOC throughout the City may also be contributed from organic material in the thick Champlain Sea clay deposits.

4.3.4 Manganese and Iron

For aesthetic reasons relating to groundwater color and staining of laundry and plumbing fixtures, aesthetic objectives of 0.3 mg/L and 0.05 mg/L have been set for iron and manganese (MOE, 2006). Beyond those concentrations, there are MCCRTs of 10 mg/L for iron and 1 mg/L for manganese, above which the water is considered untreatable by the MOE.

Aesthetic iron and manganese exceedances were fairly common throughout the City, respectively occurring in 22% and 28% of all wells. Iron aesthetic exceedances were balanced between drilled and dug wells (22% each), while manganese exceedances occurred mostly in dug wells (50%) compared to drilled wells (9%). There were no MCCRT exceedances of iron or manganese in drilled wells, but in dug wells there was one for iron and 5 for manganese.

In drilled wells there was a strong positive linear correlation between iron and manganese ($r = 0.90$). Dissolved iron concentrations in groundwater from drilled wells correlated positively with water hardness ($r = 0.47$), calcium ($r = 0.58$) and sulphate ($r = 0.50$); manganese behaved similarly.

In dug wells the correlation between iron and manganese was also positive, but it was much weaker ($r = 0.39$). In dug wells iron showed weak negative correlations to hardness ($r = -0.08$), calcium ($r = -0.14$) and sulphate ($r = -0.22$), while manganese showed weak positive correlations with hardness ($r = 0.22$) and calcium ($r = 0.23$) but not sulphate ($r = 0.03$). In dug wells, iron showed very strong positive correlations with ammonia ($r = 0.96$) and methane ($r = 0.85$), while manganese had a weaker correlation with ammonia ($r = 0.43$) and did not correlate with methane ($r = 0.03$).

In **Appendix 2**, maps of iron concentrations in drilled and dug wells are shown in **Figure A2-55** and **Figure A2-56**, and maps of manganese concentrations in drilled and dug wells are shown in **Figure A2-57** and **Figure A2-58**. There were no obvious patterns for the distributions of aesthetic exceedances in drilled or dug wells. Reducing conditions are required to keep iron and manganese from precipitating, and seemed to determine whether exceedances would occur in dug wells judging by the positive correlations to methane and ammonia which, when present, indicate reducing environments. Each of the dug wells with iron or manganese MCCRT exceedances had very high concentrations compared to the rest of the wells sampled in this study and were near wells with low concentrations, which indicates that these exceedances may have been site-specific anomalies.

4.3.5 Methane Gas

From an aesthetic perspective, methane accumulation can be of concern in confined spaces due to its potential as an explosive hazard. Methane gas is produced naturally through the reduction process of methanogenesis. In methanogenesis, methanogenic bacteria reduce available carbon to the -4 oxidation state and feed off of the reaction energy. For methane to accumulate in large amounts there needs to be an abundant source of decaying organic material, such as former plant biomass. Areas where trapped methane gas accumulates in vast quantities are often sought after for fuel sources by the oil and gas industry.

In the City, methane gas in groundwater is a major aesthetic concern. Comparing to the drinking water aesthetic objective of 3 L/m^3 , there were 38 exceedances total: 36 in drilled wells and 2 in dug wells. The locations of wells with methane gas exceedances are shown in **Figure A2-21** and **Figure A2-22** of **Appendix 2**. Looking at **Figure A2-21**, there is general trend of increasing methane content going from the northwest of the City where no methane was encountered to the southeast of the City where high methane was common. Methane contents as high as 81.3 L/m^3 (8.13%) were measured, which is above the lower explosive limit of 5% by volume. In the Ottawa area, the Billings and Carlsbad shale Formations are known to have oil and gas potential (Wilson, 1946); these Formations are presumed to be high sources of methane, and methane may be travelling northward from these formations in the general groundwater flow direction.

In dug wells, methane was not a concern. There were two dug wells with methane exceedances, but they were spatially isolated and are likely site-specific.

4.3.6 Hydrogen Sulphide

Hydrogen sulphide (H_2S) occurs naturally in soil and groundwater via anaerobic digestion in certain reducing environments and imparts a rotten egg odour that makes water aesthetically unpleasant. There were 8 drilled wells and 2 dug wells which measured above the aesthetic objective of 0.05 mg/L as S^{2-} . Maps displaying the H_2S concentrations in drilled wells and dug wells are shown in **Figure A2-25** and **Figure A2-26** of **Appendix 2**. Throughout the City, exceedances were sporadically located and spatial patterns could not be determined.

4.3.7 Total Dissolved Solids, Sodium and Chloride

The drinking water aesthetic objectives for sodium and chloride are 200 mg/L and 250 mg/L, respectively. Above the aesthetic objectives, sodium and chloride are known to impart a salty taste to water that may be considered unpalatable (MOE, 2006). The aesthetic objectives for sodium and chloride are also the maximum concentrations considered reasonably treatable (MOE, 1996). Sodium and chloride are often the main contributors to total dissolved solids (TDS), which is the sum of all dissolved constituents in groundwater and has an aesthetic objective of 500 mg/L.

In drilled wells, there were 21 chloride exceedances, 39 sodium exceedances and 59 TDS exceedances. In **Appendix 2**, maps of chloride, sodium and TDS concentrations in drilled wells are shown in **Figure A2-39**, **Figure A2-43** and **Figure A2-13**, respectively. Nearly perfect positive correlations ($r > 0.97$) were observed between TDS, sodium and chloride. The high concentrations of sodium observed in drilled wells throughout the City may partially result from ion exchange processes occurring between the groundwater and the salty Champlain Sea clay sediments that blanket the bedrock throughout much of the City. The clays perform cation exchange by trapping polyvalent cations and releasing sodium and lithium ions into the water instead, but leaving the anions (mostly bicarbonate) unaltered. Because of this process, it is suspected that areas where thick clay deposits overlie the bedrock topography will often produce sodium water and, in all likelihood, that water will exceed the sodium aesthetic objective. Conversely, in deeper wells Champlain Sea water originally present, which is high in chloride and sodium, gets displaced by incoming carbonate water and produces concentrated sodium chloride water, resulting in a slight chloride excess. This hypothesis is supported by the 99% correlation between sodium and chloride in the drilled wells.

The drilled wells in the City located along the southeastern edge of the city had excessively high sodium, chloride and TDS even compared to the exceedances encountered throughout the rest of the City. These waters were very salty (TDS up to 8000 mg/L) and are thought to originate in shale deposits that are segregated by marine clays; some remnant water from the Champlain Sea may even be present. These high concentrations were also identified in the south of the City along a fault line between the Lindsay Formation and the Billings shale Formation. Highly concentrated groundwater may be moving along this fault.

In dug wells, there were 5 chloride exceedances, 3 sodium exceedances and 30 TDS concentrations. In **Appendix 2**, maps of chloride, sodium and TDS concentrations in dug wells are shown in **Figure A2-40**, **Figure A2-44** and **Figure A2-14**, respectively. Despite the low chloride and sodium concentrations in dug wells, there were many TDS exceedances. This is due to the water type in dug wells being calcium bicarbonate instead of sodium chloride and sodium bicarbonate like the drilled wells, which was shown in Piper Plots and discussed in **Section 3.5**.

In order to differentiate wells where chloride exceedances were naturally occurring or were anthropogenic, molar chloride to bromide ratios were calculated for all wells. This method has become increasingly popular in recent years and is very effective since bromide is a conservative tracer in groundwater (Davis et al, 1998; Alcala & Custodio, 2008). The plot of molar chloride to molar bromide is shown in **Figure 4-15**. From it, we see that most of the drilled wells produced groundwater with a similar ratio to seawater (655 Cl:Br), while dug wells did not.

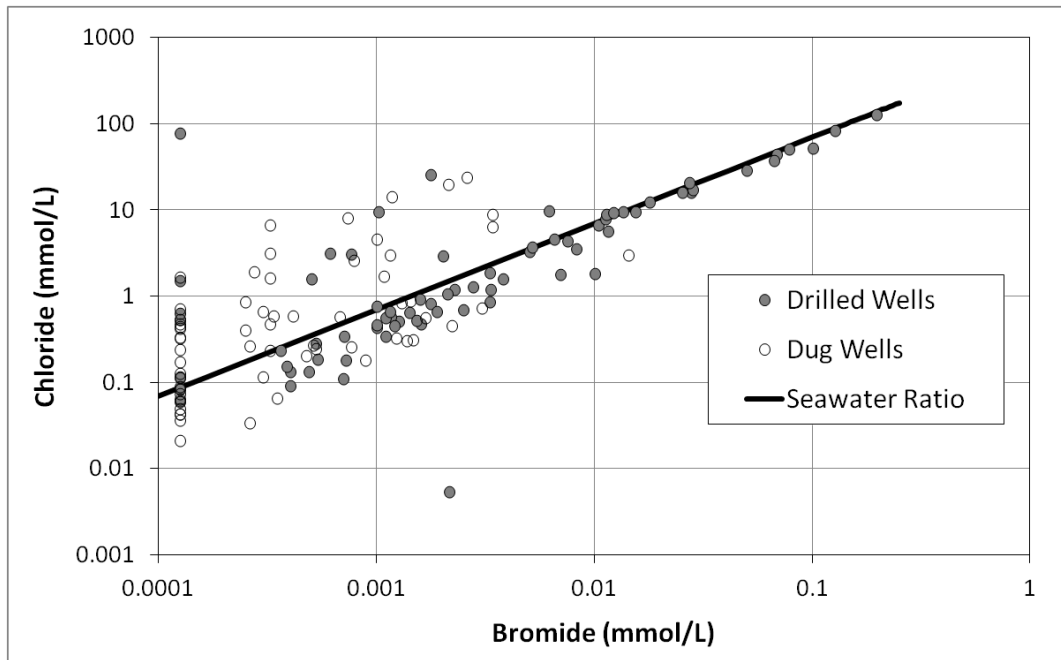


Figure 4-15. Molar chloride to bromide ratios in groundwater samples compared to the seawater ratio of 655 reported by Alcala and Custodio (2008).

In **Section 3.5**, **Figure 3-11** showed 9 dug wells that contained Na-Ca-Cl-HCO₃ water; these wells were at Sites 191, 607, 656, 672, 677, 711, 712, 714 and 717. Those 9 wells include each of the dug wells with chloride concentrations above the half exceedance criteria of 125 mg/L, and all 9 had Cl:Br ratios between 1850 and 20,000. Ratios this high are far above what can occur from natural, marine, organic or septic influences and can only have been caused by halite dissolution (ie. road salt) (Davis et al., 1998). Hence it is likely that the chloride exceedances observed in dug wells have been contributed from road salt.

In drilled wells the Cl:Br ratios had first and third quartiles of 405 and 695, however there were 11 wells with ratios greater than 1000. These were Sites 151, 152, 602, 603, 606, 609, 660, 662, 726, 741 and 747. Of those, only 4 sites had chloride concentrations greater than 125 mg/L. From this it is evident that chloride exceedances in drilled wells have not been caused by anthropogenic road salt and instead are likely naturally occurring.

4.4 Discussion of Operational Guideline Exceedances

The numbers of sampled drilled and dug wells with different operational guideline exceedances are shown in **Table 7.2.3**. Exceedances were detected for pH, alkalinity, hardness and organic nitrogen. No exceedances were detected for aluminum. For pH, alkalinity and hardness, whose operational guidelines are ranges, exceedances below (low) and above (high) the suggested range are indicated.

Table 7.2.3 – Exceedances of drinking water operational guidelines detected in the groundwater samples collected from drilled and dug wells throughout the City of Clarence-Rockland during this study.

Operational Guideline Exceedances				
Parameter	Exceedance Criteria	Drilled Wells (n = 74)	Dug Wells (n = 62)	All Wells (n = 136)
pH (<i>Low</i>)	< 6.5	0 (0%)	3 (5%)	3 (2%)
Alkalinity (<i>Low</i>)	< 30 mg/L as CaCO ₃	0 (0%)	1 (2%)	1 (1%)
Hardness (<i>Low</i>)	< 80 mg/L as CaCO ₃	36 (49%)	2 (3%)	38 (28%)
pH (<i>High</i>)	> 8.5	22 (30%)	1 (2%)	23 (17%)
Alkalinity (<i>High</i>)	> 500 mg/L as CaCO ₃	27 (36%)	1 (2%)	28 (21%)
Hardness (<i>High</i>)	> 100 mg/L as CaCO ₃	33 (45%)	60 (97%)	93 (68%)
Organic Nitrogen	> 0.15 mg/L as N	44 (59%)	39 (63%)	83 (61%)
Aluminum, Al	> 0.10 mg/L	0 (0%)	0 (0%)	0 (0%)

4.4.1 pH

An operational guideline for pH to be between 6.5 and 8.5 is set in order to that water is non-corrosive and does not produce incrustations (MOE, 2006). Above 8.5, mineral incrustations and bitter tastes can occur; below 6.5, pipes can corrode and undesirable chemical parameters may result depending on the pipes. The pH in sampled drilled wells and dug wells are shown in **Figure A2-5** and **Figure A2-6** of **Appendix 2**.

Drilled wells mostly had basic pH above 7.0, with a mean pH of 8.07 up to a maximum of 9.24, and 30% of the drilled wells had operational exceedances with pH above 8.5. There were 5 drilled wells with slightly acidic pH below 7.0 but none were below the operational guideline of 6.5. Comparing the representative geological units of each well shown in **Figure**

3-8, we see that wells situated in the Rockcliffe Formation had lower pH values between 6.57 and 7.94. Higher pH were encountered in each of the other formations. There was a cluster of pH exceedances (pH > 8.5) located in the southwest corner of the City spanning slightly northeast, and exceedances were also found in the northeast corner.

Dug wells had an even mix of slightly acidic and slightly basic waters with a mean pH of 7.05. There was one dug well with pH above the operational guideline and there were 3 wells below it. There was no visible trend between pH and the surficial geology. Because there were so few exceedances, pH is not believed to be a concern in dug wells.

4.4.2 Alkalinity

Alkalinity is a measure of a water's capacity to resist changes in pH by buffering bicarbonate into either carbonate or carbonic acid. The operational guideline for alkalinity is between 30 and 500 mg/L as CaCO₃, though it should be noted that this guideline exists mainly for coagulant-treated drinking water and does not apply to most domestic treatment processes (MOE, 2006). Low alkalinity waters may accelerate corrosion while high alkalinity waters may produce scale incrustations.

In the GSP, alkalinity was measured in the field at each site to ensure that degassing of CO₂ would not be a factor affecting the results. The alkalinity in sampled drilled wells and dug wells are shown in **Figure A2-9** and **Figure A2-10** of **Appendix 2**. There were no drilled wells below the operational guideline for alkalinity, but 36% of drilled wells were above it. In dug wells there was only one well below the guideline and one well above it. Comparing the alkalinity of drilled wells in **Figure A2-9** to the representative geological units of each well identified in **Figure 3-8**, we see that the alkalinity exceedances were exclusive to wells situated in deep overburden and the Lindsay Formation (with one exception in the northwest corner of the City).

4.4.3 Hardness

Hard waters have a tendency to form scale deposits in pipes and water heaters and will produce soap scum when mixed with chelating agents found in most soaps, shampoos and detergents. For water hardness, the operational guideline between 80 and 100 mg/L as CaCO₃ indicates the optimal range considered to provide an acceptable balance between corrosion and incrustation. Water with hardness between 200 and 500 mg/L as CaCO₃ is considered poor but also acceptable. Water with hardness exceeding 500 mg/L as CaCO₃ is considered unacceptable for most domestic purposes and will produce sodium concentrations in exceedance of the 200 mg/L aesthetic and MCCRT limits when treated by water softening (MOE, 1996; MOE, 2006).

The water hardness in drilled wells and dug wells sampled in the City are shown in **Figure A2-11** and **Figure A2-12** of **Appendix 2**. The calculation of hardness for each groundwater sample was discussed in **Section 3.2.3**. There were only five wells that were within the operational range for hardness and they were all drilled wells. Of the 74 drilled wells, 36 had hardness lower than 80 mg/L and 33 had hardness above 100 mg/L. For the 62 dug wells, two

had hardness below 80 mg/L and the remaining 60 were above 100 mg/L with varying levels of hardness. Four drilled wells and three dug wells contained hardness greater than 500 mg/L as CaCO₃.

4.4.4 Organic Nitrogen

The operational guideline for organic nitrogen in drinking water is 0.15 mg/L as N. Above 0.15 mg/L as N, poor tasting water can result if chlorine treatment is used, as it results in the production of chlorophenol (MOE, 2006). The ODWSOG also note that organic nitrogen can interfere with chlorine disinfection and reduce its effectiveness (MOE, 2006). Of the 127 wells sampled in the City in 2013, 13 had chlorine injection systems installed in the plumbing. However, many residents stated that they ‘shock’ their wells few to several times per year by pouring chlorine solutions into their wells to kill bacteria.

Organic nitrogen exceedances were very common in the City, occurring in 61% of all wells, 59% of drilled wells and 63% of dug wells. The concentrations in sampled drilled wells and dug wells are mapped in **Figure A2-31** and **Figure A2-32** of **Appendix 2**. There were no apparent spatial patterns for organic nitrogen in either map, and no areas seemed to be free of exceedances. Thus, when installing a well of any kind in the City, an operational exceedance for organic nitrogen can be anticipated and should be expected.

4.5 Summary of Findings

In this section the groundwater chemistry data obtained from drilled and dug wells throughout the City were compared to the Provincial drinking water standards listed in ODWSOG (MOE, 2006) and Procedure D-5-5 (MOE, 1996). Comparisons were made with parameters grouped by Health Standards, Aesthetic Objectives and Operational Guidelines. Discussions were provided for the exceedances of each parameter, and MCCRT exceedances were also discussed where applicable. Maps showing the exceedance locations for each parameter can be found in **Appendix 2**.

Health Standard exceedances were found for Coliform bacteria, fluoride, barium, selenium and nitrate. Coliform bacteria exceedances were numerous and widespread throughout the City in both dug and drilled wells; their presence may be naturally occurring but might also be promoted by poor well maintenance or faulty well caps which compromise well security. Fluoride exceedances were common among drilled wells situated in the Bobcaygeon, Lindsay and Eastview Formations, and may be caused by dissolution of fluoride and fluoro-apatite minerals contained therein. Barium or selenium exceedances occurred in some drilled wells with high TDS; the exceedances are located near faults of shale layers and may be related to the presence of barite, BaSO₄. Selenium behaves similarly to sulphur and may be coming from barite dissolution, as well as the dissolution of other sulphur-bearing minerals contained along

the fault margins. There was only one exceedance of nitrate; it appeared to be anomalous and possibly site specific. Groundwater from dug wells did not exceed Health Standards for fluoride, barium, selenium or nitrate, and no wells sampled throughout the City exceeded the Health Standards for nitrite, antimony, arsenic, boron, cadmium, chromium, lead, mercury or uranium.

Aesthetic Objective exceedances were found for temperature, colour, DOC, manganese, iron, methane gas, hydrogen sulphide, TDS, sodium and chloride. Temperature exceedances were observed in some dug wells. Yellow groundwater was common among dug drilled wells and drilled wells often produced darker yellows; the colour appears to be linked to decaying or dissolved organic material and the darker yellows in drilled wells corresponded with elevated fluoride concentrations. DOC exceedances were found in more than half of drilled wells (many of which exceeded the MCCRT) and more than a third of dug wells; some possible sources include the Champlain Sea clay deposits, decaying remnants of previous forests and wetlands, and carbonates of the Ottawa Group that were deposited in biotic marine environments. Manganese exceedances occurred in half of the dug wells and iron exceedances occurred in nearly a quarter of dug and drilled wells; the presence of slightly elevated iron and manganese reflects the reducing environments of the aquifers and there were a few anomalies that exceeded MCCRTs. Methane exceedances were a major concern for drilled wells (but not dug wells) and increasingly high concentrations were found towards the southeast corner of the City where shales of the Lindsay/Eastview, Billings and Carlsbad Formations were present. Hydrogen sulphide exceedances were found at some wells throughout the City and are also a natural product of reducing conditions, though they may also indicate growth of sulphur bacteria within the pipes. Exceedances of TDS occurred in most drilled wells and nearly half of dug wells. About half of the drilled wells had sodium exceedances and a quarter had chloride exceedances, which contributed to the high TDS in many drilled wells. Very few sodium and chloride exceedances were found in dug wells and the few chloride exceedances were anomalies likely of anthropogenic cause. None of the wells sampled throughout the City measured exceedances of Aesthetic Objectives for sulphate, copper or zinc.

Operational Guideline exceedances, high and low, were found for pH, alkalinity, hardness and organic nitrogen. No drilled wells and very few dug wells were below the operational ranges for pH or alkalinity. Nearly all dug wells were within the operational ranges for pH and alkalinity, and nearly all dug wells exceeded the hardness range with slightly hard to very hard groundwater. Nearly half of the drilled wells were above the operational range and the other half were beneath it; this was due to the Operational Guideline range for hardness being very narrow (80-100 mg/L as CaCO_3). Most of the drilled wells with soft water were located in portions of the City mapped as Lindsay Formation, where the overlying marine clay deposits were very thick; natural water softening in these areas is suspected as a contributing factor. Similarly, a third of drilled wells had alkalinity exceedances and were also located in these areas. Organic nitrogen exceedances were prevalent in nearly two thirds of all wells, with equal percentages among dug and drilled wells; neither well type had any spatial patterns for the exceedances and the occurrence of elevated organic nitrogen may be the result of chlorine treatments (regular or irregular) by well owners. Throughout the City there were no exceedances of the Operational Guideline for aluminum.

5 The Aquifer Capability Screening Tool (ACST)

The Aquifer Capability Screening Tool (ACST) is a tool for pre-screening development applications for privately-serviced lots, which was developed in order to identify areas where future land acquisition and property development may be less appropriate due to foreseeable problems related to groundwater quality or quantity. The tool is intended to be used by municipal planners to help make informed decisions about where to direct future development and expansion projects.

The ACST consists of a series of maps that show delineated areas where limited water quantity or poor water quality may be encountered. The ACST was created in a GIS program (ArcGIS) and has the advantage of being made up of layers of spatial data. When an area of interest is selected in the GIS program, the ACST is designed to identify a list of the quantity and quality problems that may be encountered and provide recommendations for sample analysis and well development.

As with any map, the ACST is only as good as the available data allows it to be and should be considered only as a guideline to pre-screen areas for land development potential. Conditions experienced locally may differ from the predictions of the ACST, and having this tool does not replace the need for a hydrogeological study to be performed at a site of interest prior to development.

This thesis section outlines the methods used to develop an Aquifer Capability Screening Tool (ACST) for the City of Clarence-Rockland (“the City”) and provides an evaluation of the groundwater sampling data requirements that are necessary for ACST development. The ACST was developed and produced alongside this study by a project partner, Geofirma Engineering Ltd. (Geofirma), as a pilot study for the United Counties of Prescott and Russell (UCPR). In development, Geofirma used the groundwater chemistry data obtained from the Groundwater Sampling Program (GSP), discussed in **Section 3**, to delineate areas of potentially poor groundwater quality based on locations with exceedances of Provincial drinking water standards, which are shown in **Appendix 2** and discussed in **Section 4**. The development methods used by Geofirma to make the ACST maps are described in **Section 5.1** and the resulting ACST maps of groundwater quality are shown.

Since the GSP was very thorough both in spatial coverage and in parameter analysis, the evaluation focussed on determining whether less expensive alternatives could be considered suitable for ACST development. This thesis made two evaluations: (1) a data source evaluation to determine whether existing geochemistry data could be used instead of collecting new data; and (2) a data scale evaluation to determine what level of sampling is necessary and if larger scales can be used. These evaluations can be found in **Section 5.2** and **Section 5.3**. The overall conclusions of these evaluations and recommendations for future ACST development projects are provided in **Section 6**.

To avoid confusion, the remainder of this thesis will refer to the ACST produced by Geofirma (2015) as the “**Pilot ACST**”.

5.1 Development of the ACST

The ACST development methods have been outlined by Geofirma (2015) in four basic steps:

- Step 1:** Acquire and inspect the data available for the study area.
- Step 2:** Refine the data based on the quality of each dataset.
- Step 3:** Identify wells with lower water quantity and lower water quality.
- Step 4:** Map the wells with lower water quantity and quality to delineate areas that may potentially have lower water quantity and water quality.

As mentioned earlier in **Section 1**, the groundwater quantity aspects of the Pilot ACST were addressed solely by Geofirma (2015) through use of the MOE Water Well Information System (WWIS), whereas this Thesis focussed on chemical groundwater quality and was not involved in the determination of areas with poor groundwater yield. Hence, this Thesis does not discuss the physical yield components and focuses only on aspects related to groundwater quality. Any information pertaining to the data acquisition and mapping of delineated areas with potentially poor groundwater quantity for drilled and dug wells can be found in the report by Geofirma (2015), titled “*Clarence Rockland Groundwater Study: Development of an Aquifer Capability Screening Tool*”.

The groundwater quality data used to develop the Pilot ACST were the dataset obtained from the Groundwater Sampling Program (GSP) performed in this thesis, described in **Section 3**. The collection of groundwater chemistry data and assessment of its quality completed **Step 1** and **Step 2** of ACST development.

Step 3 of ACST development had been to identify areas of poor groundwater quality. Poor quality in the case of this study referred to exceedances of the Ontario Drinking Water Standards, Objectives and Guidelines (ODWSOG). In **Section 4**, the chemistry of all 74 drilled wells and 62 dug wells sampled in the GSP were compared to the ODWSOG and any exceedances of health standards, aesthetic objectives and operational guidelines were identified and discussed.

For **Step 4** of ACST development, hand drawn delineations were made to identify areas where drilled wells may potentially produce groundwater with elevated concentrations (exceedances) of health and aesthetic parameters. Exceedances of operational guidelines were not considered for the ACST because the common exceedance parameters (alkalinity, organic nitrogen and pH) were considered unlikely to impact private water supplies.

Geofirma delineated areas by hand using the available point data and professional judgement. Once the delineations were completed, the paper copies were scanned and georeferenced into ArcMap. New polygon shapefiles were then made, and the ‘Create Features’

tool was used to make polygons by tagging points along the hand drawn lines. The edges of the polygons were smoothed by a factor of 0.5 and the shapefiles were clipped to the city boundaries.

The main health parameters with exceedances of the Maximum Allowable Concentrations (MACs) included Coliform bacteria, fluoride, selenium and barium. Areas of bacterial exceedance were not delineated in the ACST because exceedances were prevalent all throughout the city and may have been partially related to well integrity (See **Section 4.2.1**). The Pilot ACST maps (Geofirma, 2015) showing delineated areas of potentially elevated fluoride, selenium and barium in drilled wells are presented in **Figure 5-1**, **Figure 5-2** and **Figure 5-3**, respectively.

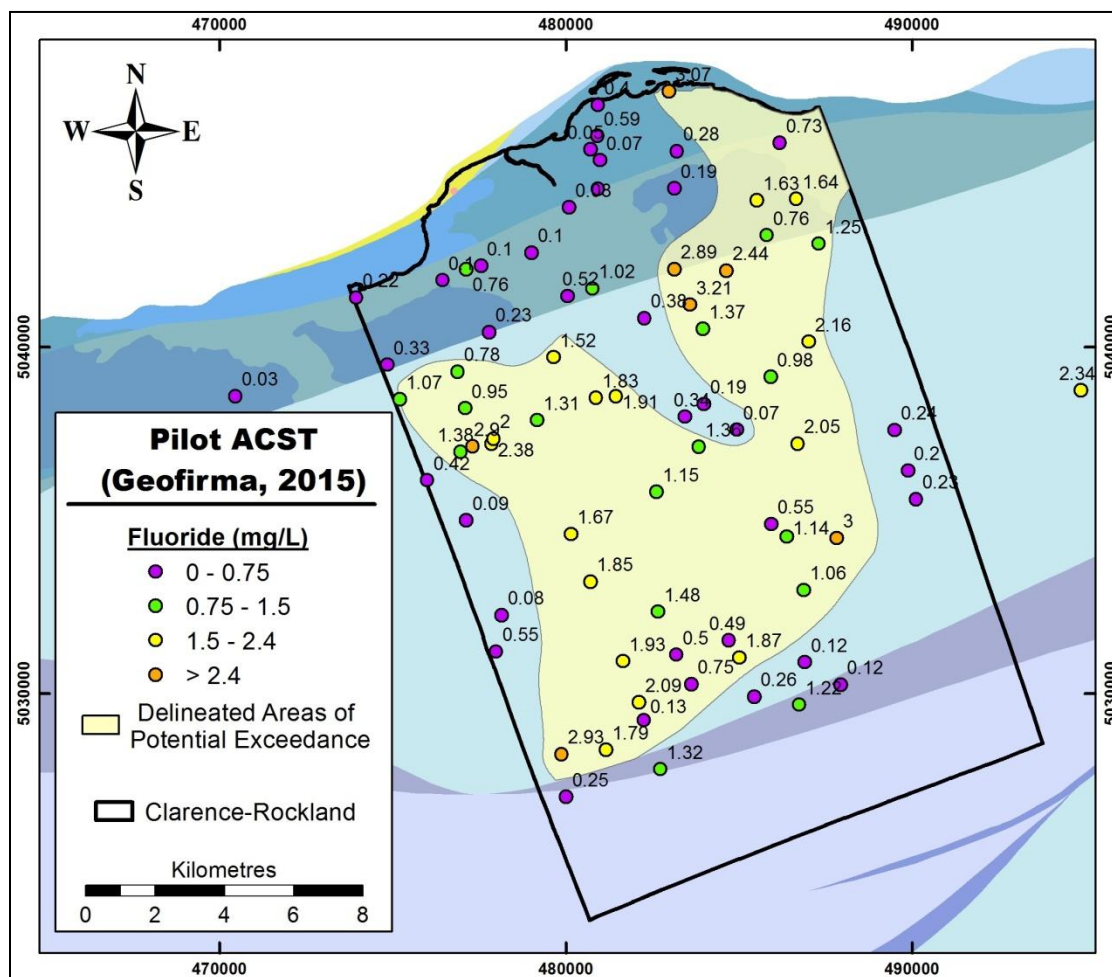


Figure 5-1. ACST groundwater quality map showing delineated areas of potentially elevated fluoride in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and orange dots indicate exceedances of the Health Standard for fluoride, and green dots indicate half exceedances. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

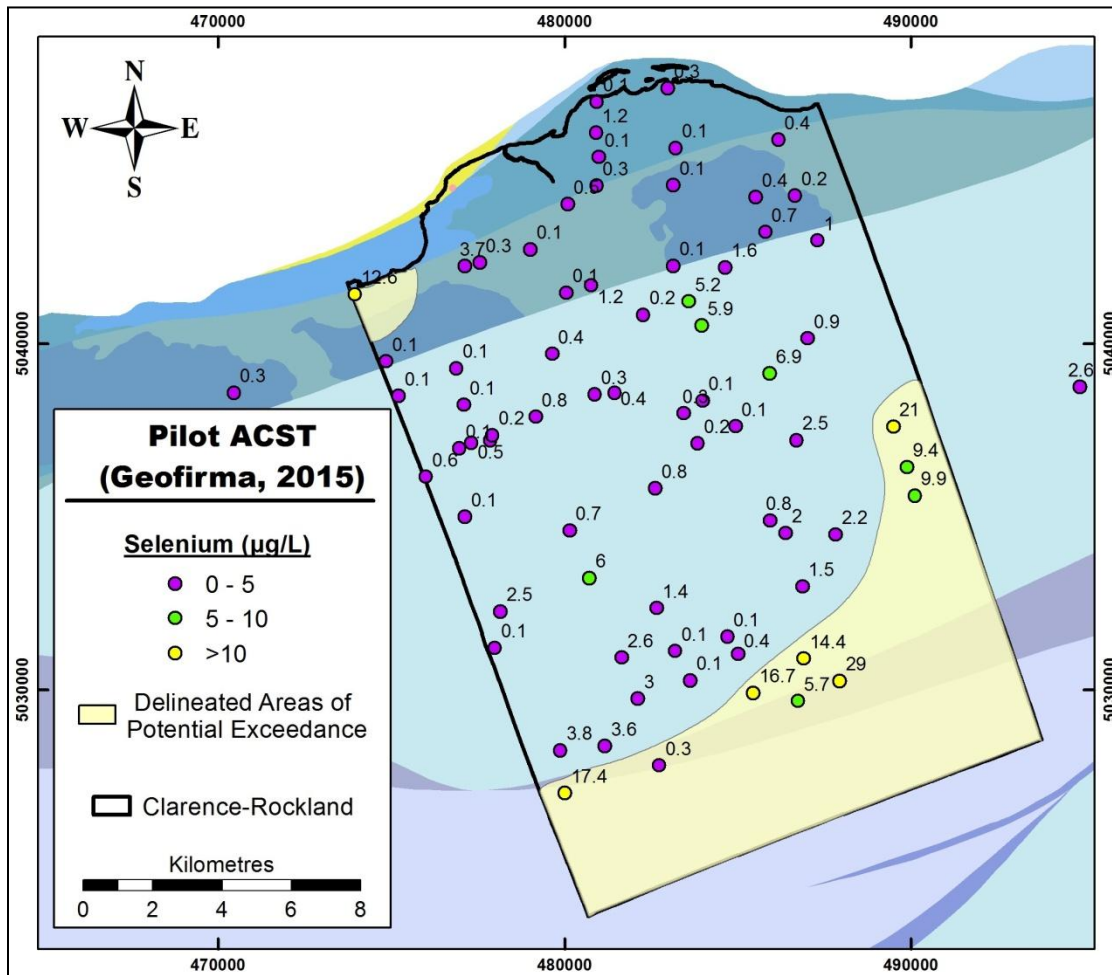


Figure 5-2. ACST groundwater quality map showing delineated areas of potentially elevated selenium in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Health Standard for selenium. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

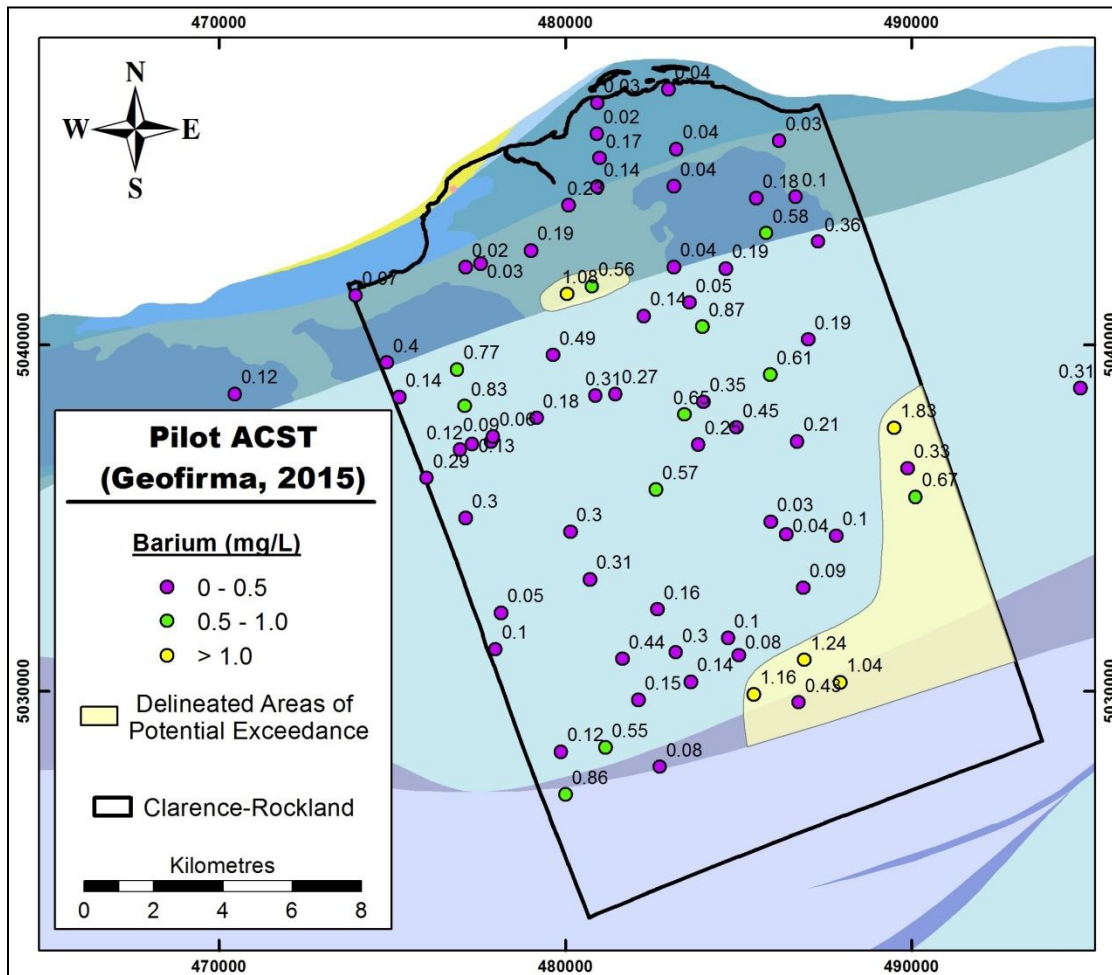


Figure 5-3. ACST groundwater quality map showing delineated areas of potentially elevated barium in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Health Standard for barium. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

For aesthetic parameters, delineations were made only for parameters with exceedances of the Maximum Concentrations Considered Reasonably Treatable (MCCRTs) that were outlined in Procedure D-5-5 (MOE, 1996); these exceedances were also discussed in **Section 4**. The main aesthetic parameters with MCCRT exceedances were chloride, sodium, total dissolved solids (TDS), dissolved organic carbon (DOC), colour and methane. The Pilot ACST maps (Geofirma, 2015) showing delineated areas of potentially elevated chloride, sodium, DOC and methane in drilled wells are presented in **Figure 5-4**, **Figure 5-5**, **Figure 5-6** and **Figure 5-7**, respectively. Delineations were not made for TDS or colour because those exceedances were abundant and scattered throughout the City; TDS and colour are considered to be potential concerns regardless of location.

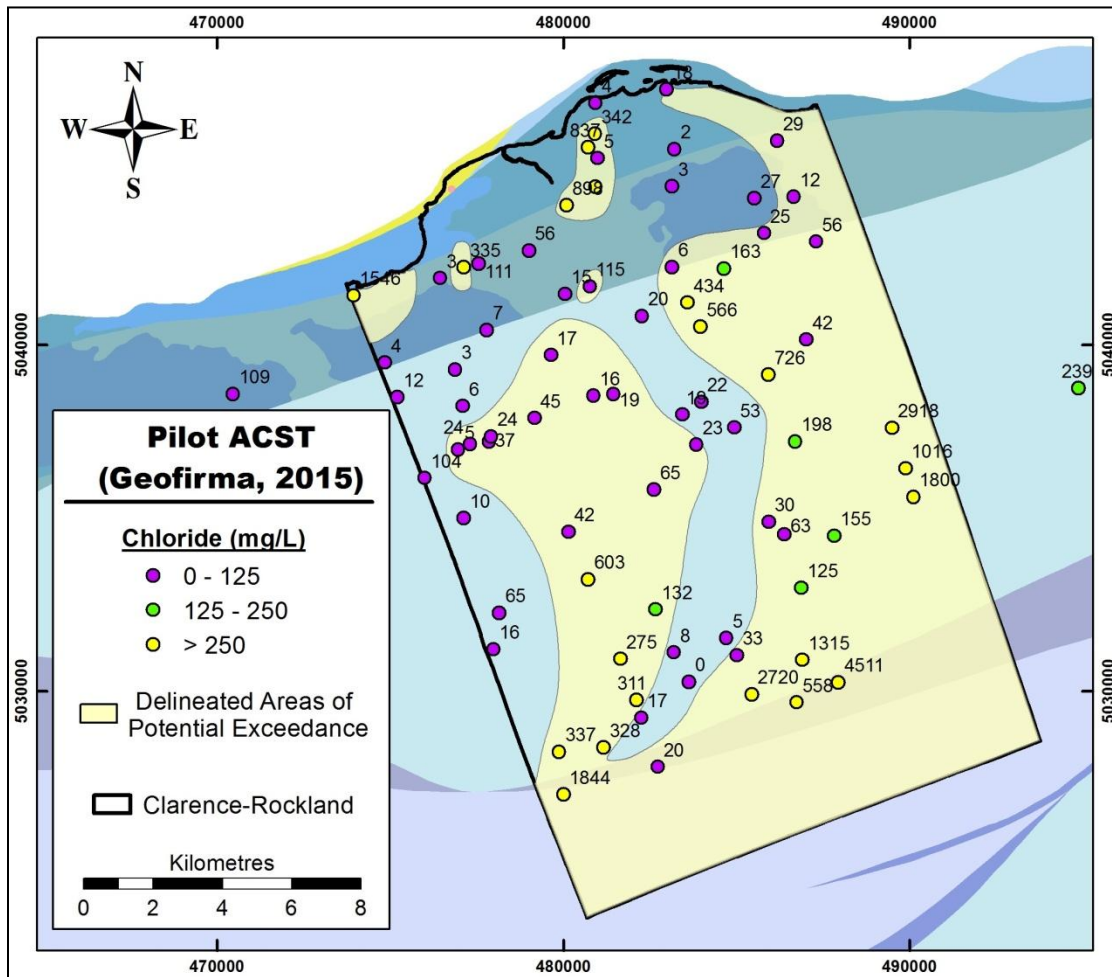


Figure 5-4. ACST groundwater quality map showing delineated areas of potentially elevated chloride in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Aesthetic MCCRT for chloride. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

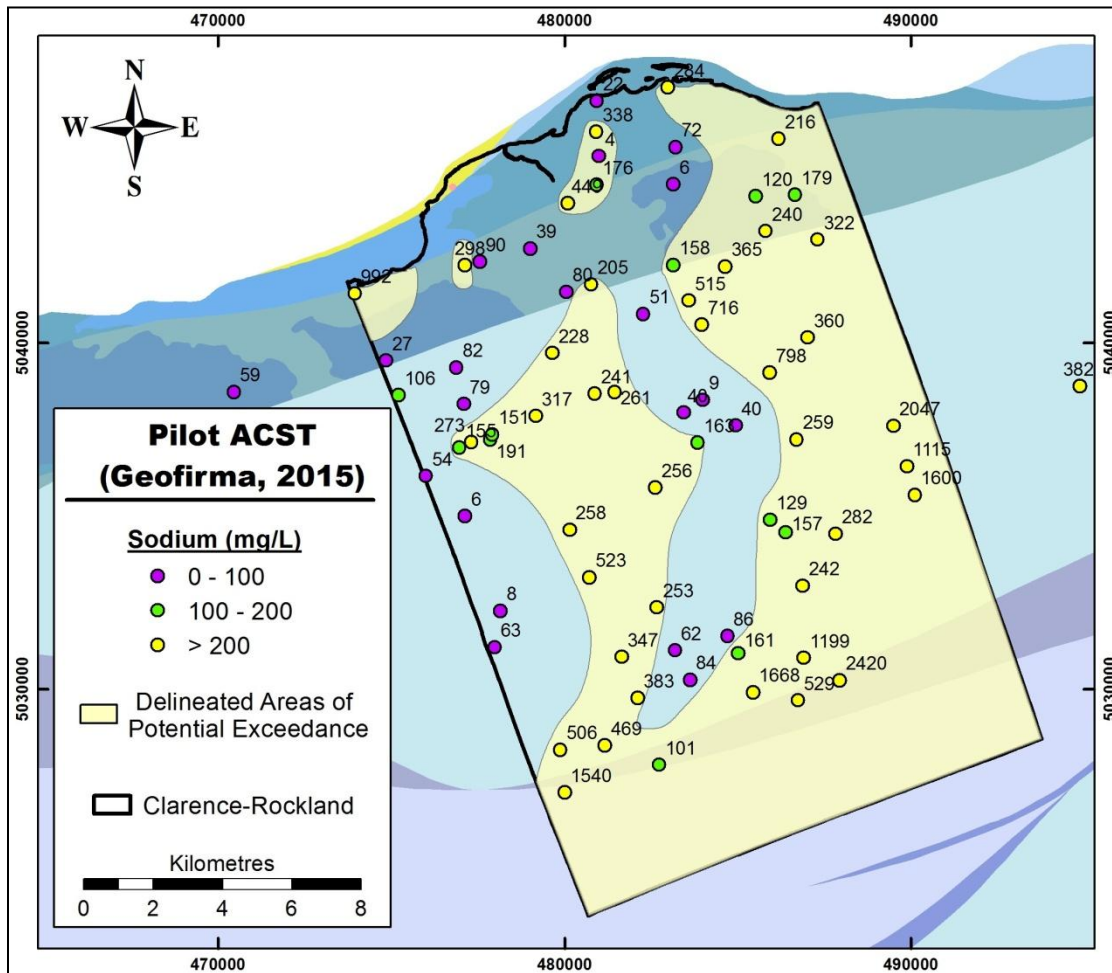


Figure 5-5. ACST groundwater quality map showing delineated areas of potentially elevated sodium in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Aesthetic MCCRT for sodium. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

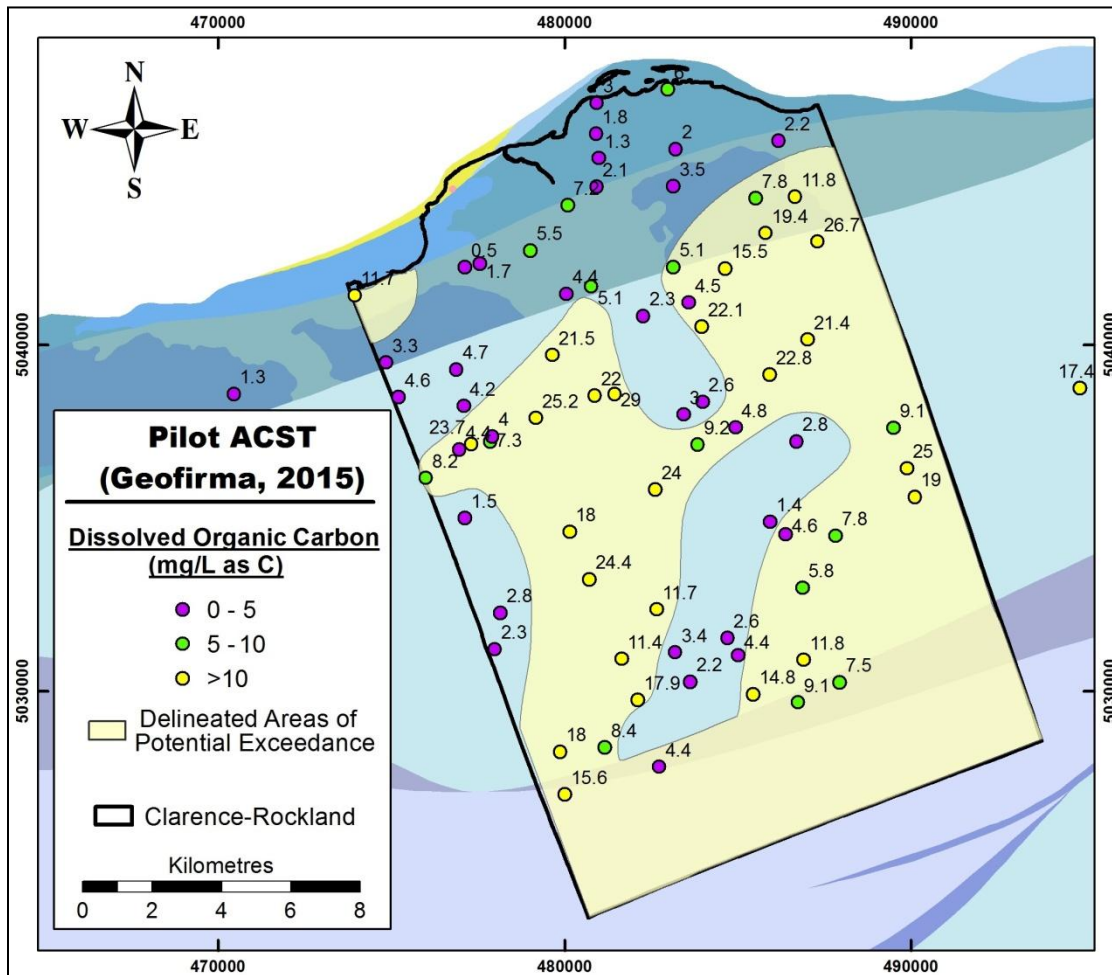


Figure 5-6. ACST groundwater quality map showing delineated areas of potentially elevated dissolved organic carbon in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Aesthetic MCCRT for dissolved organic carbon. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

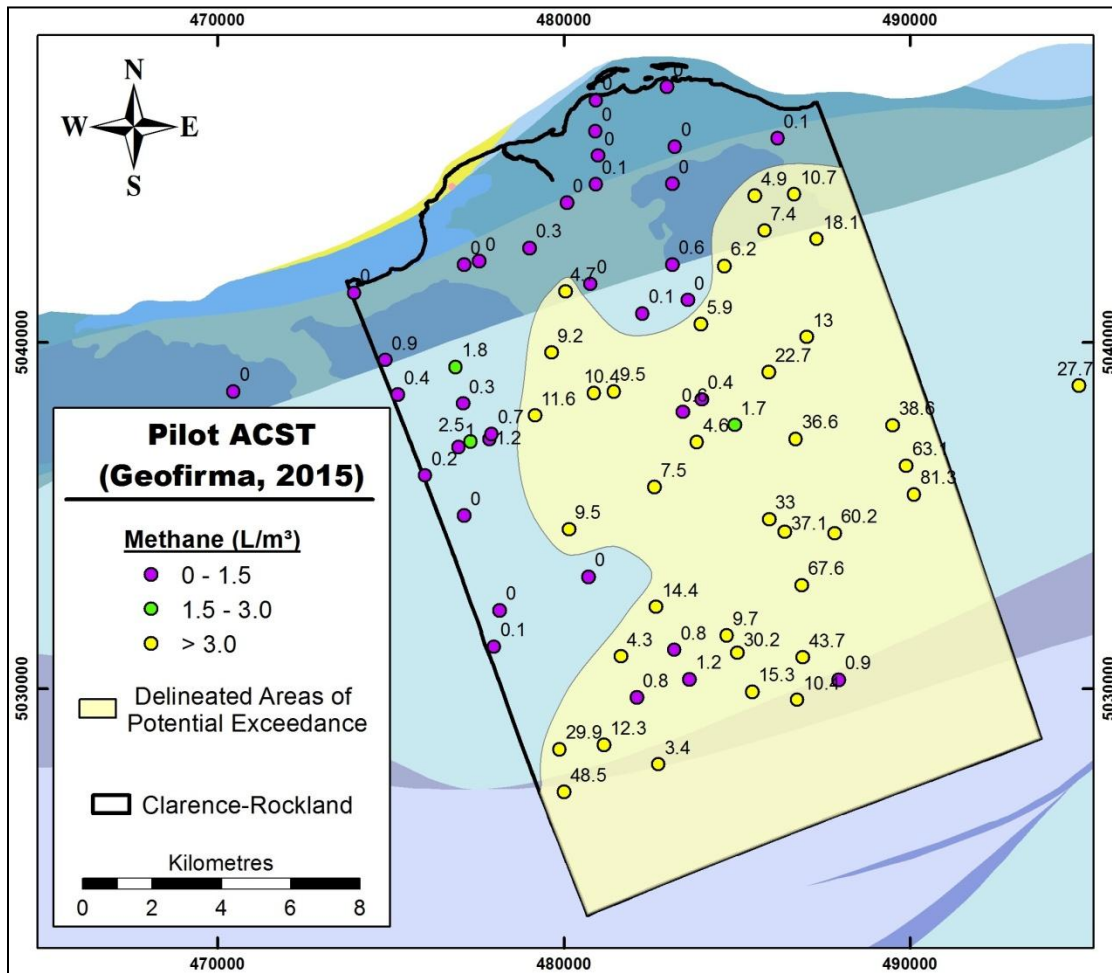


Figure 5-7. ACST groundwater quality map showing delineated areas of potentially elevated methane in drilled wells throughout the City of Clarence-Rockland, Ontario. Yellow and green dots respectively indicate exceedances and half exceedances of the Aesthetic Objective for methane. Map reproduced in ArcMap with permission from Geofirma Engineering Ltd. (2015).

Geofirma made no delineations for the chemistry of dug wells. There were two reasons for this. Firstly, the dug wells sampled revealed no health exceedances (apart from Coliform bacteria which was widespread) and very few aesthetic MCCRT exceedances. Secondly, no spatial patterns were observed; exceedances in dug wells did not appear to correspond to particular deposit types on the surficial geology maps and the chemistry of dug wells can be greatly influenced by land use (septic systems, agricultural, rural, urban, etc.), which varies accordingly with each site. Rather than groundwater quality, the main problems with dug wells in the City are understood to be their limited physical yield which depends on surficial geology (Geofirma, 2015).

For drilled wells, the delineations of each parameter were drawn conservatively to include any well locations where exceedances had occurred. The delineated areas were also extended to include any wells above half of the exceedance criteria that were located nearby wells with exceedances. Including that half exceedance area provided a safety factor of 2 to the

delineation, allowing it to account for potential variability of concentrations over time. Any locations encompassed within the delineated areas are considered to have the potential of producing groundwater that exceeds health standard MACs and aesthetic MCCRTs. In consideration of that, Geofirma's "delineated areas with potentially elevated concentration" are referred to in this thesis as "delineated areas of potential exceedance".

For areas where data gaps existed, the extents of delineations were positioned using professional judgement. When seemingly appropriate, nearby geological boundaries were taken into consideration as possible extents for areas of poor quality. Such was the case for dissolved organic carbon in the southern part of the City, where the shales of the Billings and Carlsbad Formations were considered to be a potential source.

Geological process maps used to create a second set of delineations for chloride and sodium, which are not shown here. These process maps depicted glaciomarine clay thickness, which was modelled across Ontario by Logan et al. (2009). Areas with clay thickness exceeding 25 meters are considered to potentially produce elevated sodium and chloride concentrations, since they are believed to provide longer residence time for the groundwater allowing for more natural water softening to occur via cation exchange. Since the softened waters are positively correlated with sodium and chloride, the extents of delineations based on groundwater chemistry covered many of the same areas as the process map delineation; however both layers are to be used in tandem in the final product.

5.2 Data Source Evaluation: The Outcome of Using Existing Data

Budgets and costs are at the core of municipal decision making. When making an ACST, it would be much easier and more cost effective for the municipality to make use of existing documents that are readily available rather than launching a Groundwater Sampling Program (GSP) as was done in this study. The aim of this Data Source Evaluation was to assess whether ACST maps made from only existing report data would be sufficient in terms of accuracy and spatial coverage compared to the Pilot ACST produced from field sampling data. To do this, an Existing Data Compilation (EDC) was performed by gathering groundwater chemistry data from available existing reports and documents. The methods and results of the EDC are discussed herein.

5.2.1 Existing Data Compilation (EDC)

The objective of the EDC was to gather existing groundwater chemistry data for wells in the City so that comparable ACST maps could be made. The EDC dataset and resulting EDC ACST maps are compared to the GSP dataset and Pilot ACST for the purpose of identifying possible benefits or problems associated with using existing data in the production of future ACSTs.

Approximately 2000 scanned documents had been gathered into an electronic E-Library by the South Nation Conservation Authority. These documents were screened for relevance, identifying 117 documents that were located in or just outside the study area and were related to hydrogeology or groundwater chemistry. The useful documents consisted mainly of consultant reports for municipal subdivisions and land severances. An additional 25 reports were provided in physical form and scanned, giving a total of 142 documents that then closely reviewed to obtain groundwater chemistry data.

Three qualifying rules were used to determine whether data in those 142 documents would be used in the EDC: (1) A sample analysis needed to be present, (2) the well depth needed to be provided either within the document or in an attached MOE Well Record that corresponded to the well sampled, and (3) the location of the well needed to be identified either with latitude and longitude coordinates or on a map from which the coordinates could be inferred. If any of these three conditions were not met, the document was not used in the EDC.

This process resulted in a total of 43 documents that were used in the EDC, which provided groundwater chemistry data for 80 unique wells. There were 9 wells with a second set of chemistry data from a different sampling; in these cases the newer data were used unless the older data had a more thorough chemical analysis. The two sets of data could not be compared due to varying sampling or analytical methods. The resulting EDC dataset has not been included with this Thesis but is contained along with the GSP dataset in the file “**GSP_Database.mdb**”, which can be requested from the South Nation Conservation Authority located in Finch, Ontario.

5.2.2 Spatial Coverage of Existing Data

In the City, the spatial coverage of dug and drilled wells in the EDC dataset was poor compared to the coverage of the GSP dataset discussed in **Section 3.3.2**. The locations of the 80 wells in the EDC dataset, consisting of 5 dug wells and 75 drilled wells, are shown in **Figure 5-8**.

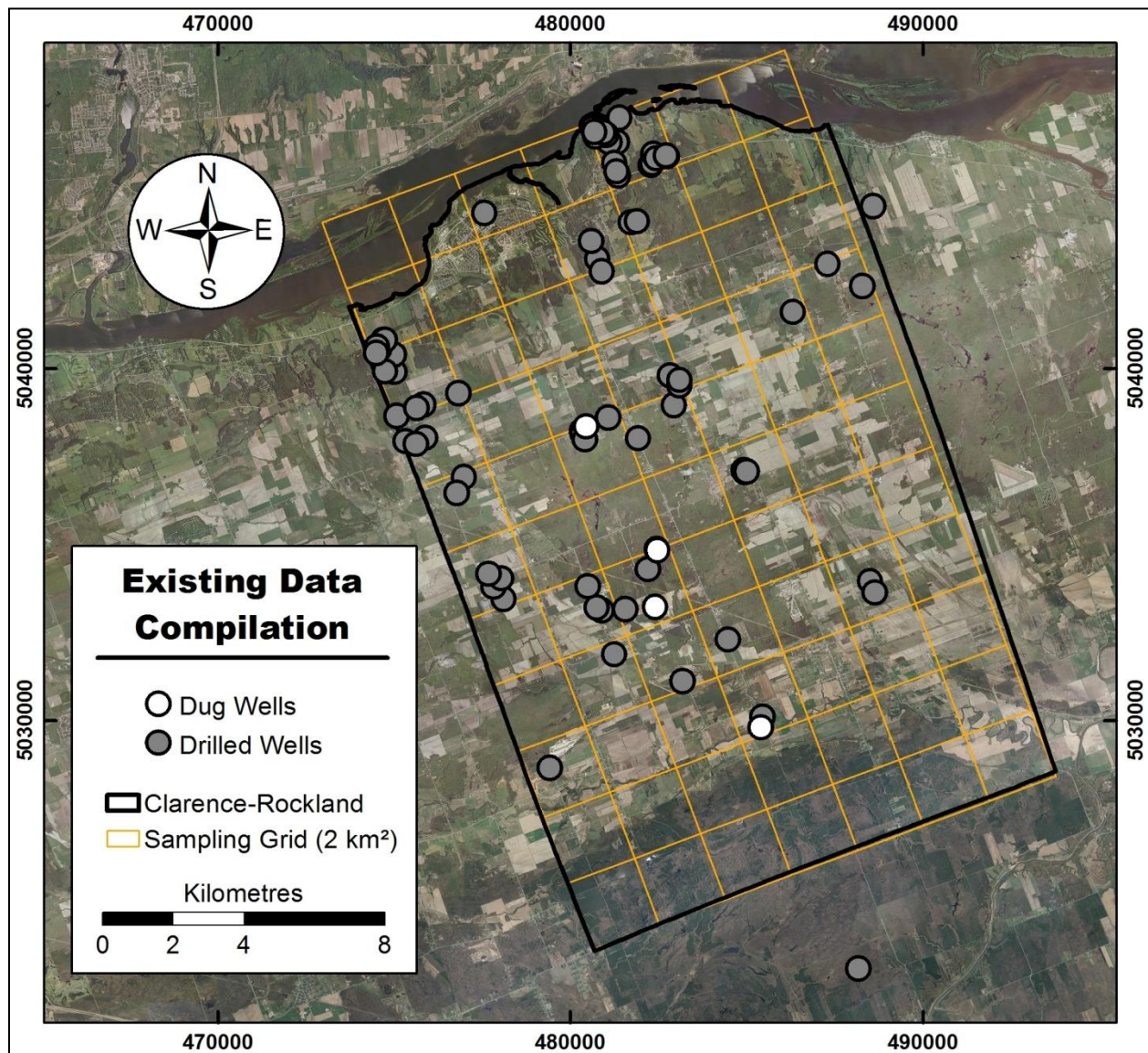


Figure 5-8. Locations of dug and drilled wells with usable groundwater chemistry data that were gathered in the Existing Data Compilation.

Of the 5 dug wells, only 4 dug wells appear in **Figure 5-8** because two were very close to each other. With only the 5 dug wells with existing groundwater chemistry data, it would not have been possible to map shallow overburden groundwater quality or to identify differences in groundwater chemistry compared to drilled wells. Although the Pilot ACST (Geofirma, 2015) did not delineate potential exceedance areas for dug wells, it was important to sample dug wells and identify whether health and aesthetic exceedances were common and/or spatially predictable.

The number of drilled wells found in the EDC (n=75) was similar to the number sampled in the GSP (n=74), but the spatial distribution of the datasets were completely different. The GSP had been planned according to a 2x2 km² sampling grid whereas most of the drilled wells in the EDC were clustered into small areas, leaving large portions of the City unaccounted for.

This was because the available existing reports were mostly limited to areas which had been proposed for land severances or subdivisions.

When gathering existing data, there were many reports and documents that presented groundwater chemistry results for wells whose physical information were unknown. An example of this was in Report #655 from the SNC E-Library, which collected and analyzed a groundwater sample but stated: “[Client’s Name] could not find the well record of his/her well and our search with the MOE’s database was unsuccessful”. There were also reports which presented chemistry data from a sampled well while providing physical information from a different well that may or may not have been nearby. Since the physical information of the sampled wells could not be identified, these chemistry data could not be included in the EDC dataset. If it had been possible to identify the well locations and depths in these reports, the EDC dataset could have included more locations throughout the City and the spatial coverage could have been improved.

5.2.3 Quality of Existing Data

The availability of chemistry parameters from the 80 wells in the EDC dataset are shown in **Table 5-1**. None of the wells had been analyzed for all parameters, and the analyses had varying levels of completeness. Similar to what was done for the GSP dataset in **Section 3.4**, the quality of analysis at each well was inspected by calculating the Cation-Anion Charge Balance Error (CBE) for each well. The resulting CBEs are shown in **Figure 5-9**.

Table 5-1. Availability for all chemistry parameters found in the sampling data for the 80 wells of the Existing Data Compilation dataset.

Parameter	Availability	Parameter	Availability
Total Coliform Bacteria	69 /80 (86%)	Fluoride	79 /80 (99%)
Fecal Coliform Bacteria	64 /80 (80%)	Chloride	76 /80 (95%)
Heterotrophic Plate Count	40 /80 (50%)	Sulphate	76 /80 (95%)
Escherichia coli	45 /80 (56%)	Sodium	77 /80 (96%)
Fecal streptococcus	27 /80 (34%)	Potassium	62 /80 (78%)
pH	76 /80 (95%)	Magnesium	68 /80 (85%)
Alkalinity	75 /80 (94%)	Calcium	70 /80 (88%)
Hardness	75 /80 (94%)	Iron	77 /80 (96%)
Total Dissolved Solids	51 /80 (64%)	Manganese	68 /80 (85%)
Specific Conductance	75 /80 (94%)	Arsenic	3 /80 (4%)
Turbidity	69 /80 (86%)	Barium	3 /80 (4%)
Colour	75 /80 (94%)	Boron	3 /80 (4%)
Tannin + Lignin	59 /80 (74%)	Cadmium	3 /80 (4%)
Phenols	66 /80 (83%)	Chromium	3 /80 (4%)
Dissolved Organic Carbon	46 /80 (58%)	Copper	3 /80 (4%)
Nitrate	75 /80 (94%)	Lead	3 /80 (4%)
Nitrite	65 /80 (81%)	Mercury	2 /80 (3%)
Nitrate + Nitrite	69 /80 (86%)	Selenium	3 /80 (4%)
Total Kjeldahl Nitrogen	51 /80 (64%)	Silver	2 /80 (3%)
Ammonia + Ammonium	69 /80 (86%)	Uranium	3 /80 (4%)
Organic Nitrogen	40 /80 (50%)	Zinc	3 /80 (4%)
Hydrogen Sulphide	58 /80 (73%)		

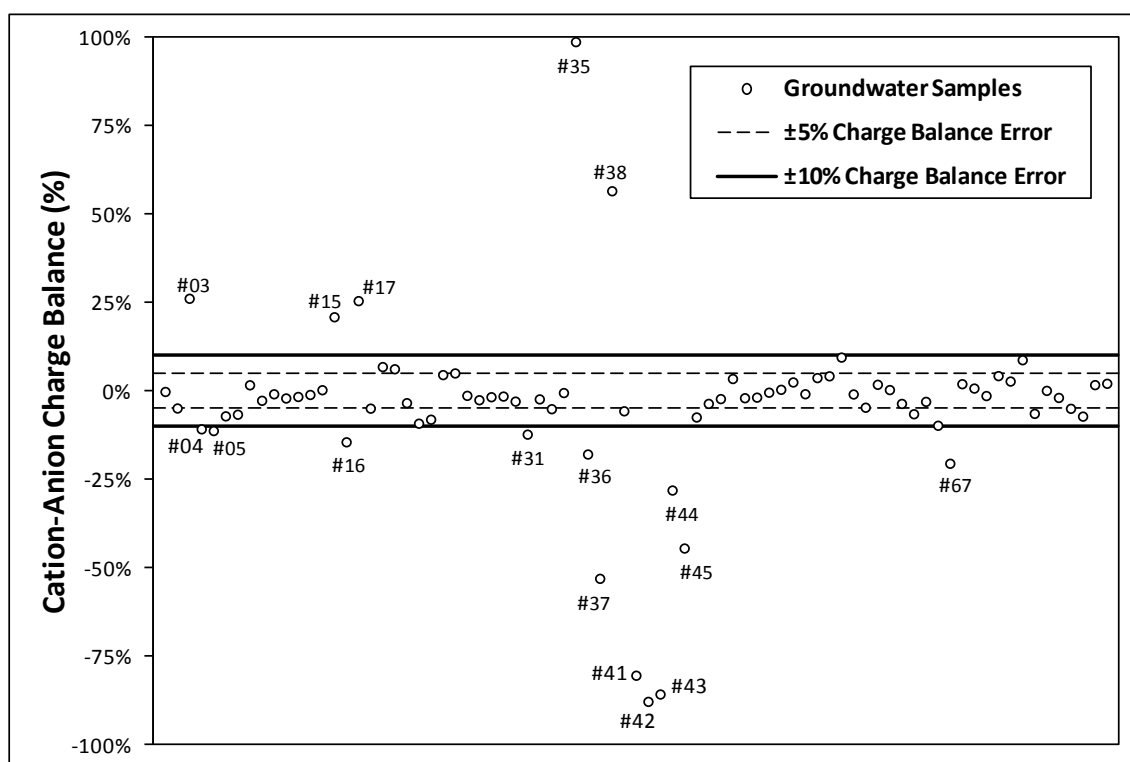


Figure 5-9. Charge balance error (CBE) calculated for all well samples (n=80) gathered in the Existing Data Compilation.

Of the 80 wells in the EDC dataset, there were 17 with more than 10% CBE, 15 between 5% and 10% CBE, and 48 with less than 5% CBE. This is quite poor compared to the GSP dataset which had 2 wells with more than 10% CBE, 10 wells between 5% and 10% CBE, and 124 with less than 5% CBE. Due to the large number of wells in the EDC with high CBE, it is apparent that the data contained in the EDC dataset is of low quality. Most of the wells in **Figure 5-9** that have high CBE ($> \pm 10\%$) can be explained by the sample analyses being limited or incomplete. For example, the samples collected from EDC Well #35 to #38 and #41 to #45 were not analyzed for calcium, magnesium and potassium; these are critical parameters in analysis as they represent high percentages of ions in natural waters. The 8 other wells with more than 10% CBE were not missing any major chemistry parameters, which can suggest that their analyses were inaccurate and unreliable.

While reviewing the existing documents for groundwater sampling data, it became clear that the wells had been sampled and analyzed using a wide range of methods and protocols which were often not comparable. This made it difficult to evaluate how representative the samples in the EDC dataset were of raw groundwater quality. Most datasets had a limited number of analytes, and while none of them had the correct analytes to fully compare to the ODWSOG, some did not even meet the guidelines of Procedure D-5-5. The age of the available data was another concern as sampling dates ranged from 1974 to the present. It was also unclear whether the samples had been filtered in the field or even in the laboratory prior to analysis; not filtering samples in the field allows turbidity to affect the concentrations of dissolved ions, which may result in falsely high counts of iron for example.

For many samples in the EDC dataset it is also unlikely that the wells were properly purged prior to sampling. Some reports indicated that taps were run for several minutes before sampling to ensure a representative sample was taken from the well, but most reports had no mention of any well purge prior to sampling. Furthermore, purging for several minutes is often not enough to get past the stagnant water in the pressure tank; during the GSP, purging times varied greatly and it sometimes took more than 20 minutes to obtain stable temperature readings indicative of fresh groundwater. Depending on the volume of the pressure tank and the pumping rate in the well, considerably longer purge times may be required to obtain a representative sample, and these factors should be considered rather than simply the purge duration.

5.2.4 ACST Delineations Made Using Existing Data

The delineation process described in **Section 5.1** was repeated for various chemistry parameters using the EDC dataset. The water quality parameters included in the ACST were Coliform bacteria, fluoride, selenium, barium, chloride, sodium, total dissolved solids (TDS), dissolved organic carbon (DOC), colour and methane. Of the 75 drilled wells in the EDC dataset, the availability of these parameters and numbers of drinking water standard exceedances are shown in **Table 5-2**.

Table 5-2. Availability of ACST groundwater quality parameters and their exceedance counts for drilled well sampling data gathered from existing documents.

Water Quality Parameter	Type of Exceedance	Exceedance Criteria	Availability among Drilled Wells (n=75)	Number of Exceedances
Total Coliform Bacteria	Health MAC	>5 counts/100 mL	64 (85%)	9 (14%)
Fecal Coliform Bacteria	Health MAC	>0 counts/100 mL	59 (79%)	2 (3%)
Fluoride	Health MAC	>1.5 mg/L	74 (99%)	10 (14%)
Selenium	Health MAC	>10 µg/L	3 (4%)	0 (0%)
Barium	Health MAC	>1.0 mg/L	3 (4%)	0 (0%)
Chloride	Aesthetic MCCRT	>250 mg/L	71 (95%)	15 (21%)
Sodium	Aesthetic MCCRT	>200 mg/L	72 (96%)	33 (46%)
Total Dissolved Solids	Aesthetic MCCRT	>500 mg/L	46 (61%)	26 (57%)
Dissolved Organic Carbon	Aesthetic MCCRT	>10 mg/L as C	41 (55%)	9 (22%)
Colour	Aesthetic MCCRT	>7 TCU	70 (93%)	44 (63%)
Methane gas	Aesthetic MCCRT	>3 L/m ³	0 (0%)	---

The intent had been to produce maps for all parameters in the Pilot ACST, but this was not possible for selenium, barium or methane due to limited data availability. Delineations were also not made for bacteria, TDS or colour, since they were not delineated in the Pilot ASCT. Similarly to the Pilot ACST, delineations were not made for dug wells; this was due to a lack of available groundwater chemistry data for dug wells (n=5).

Delineations of potential exceedance areas were made for the following parameters: fluoride, chloride, sodium and DOC. The point data and delineated areas for each parameter are shown in **Figure 5-10**, **Figure 5-11**, **Figure 5-12** and **Figure 5-13**, respectively. Again, these delineations were made for the purposes of comparing a potential outcome of using existing data instead of collecting new data, and should not be mistaken for the Pilot ACST delineations of these parameters that were shown in **Section 5.1**.

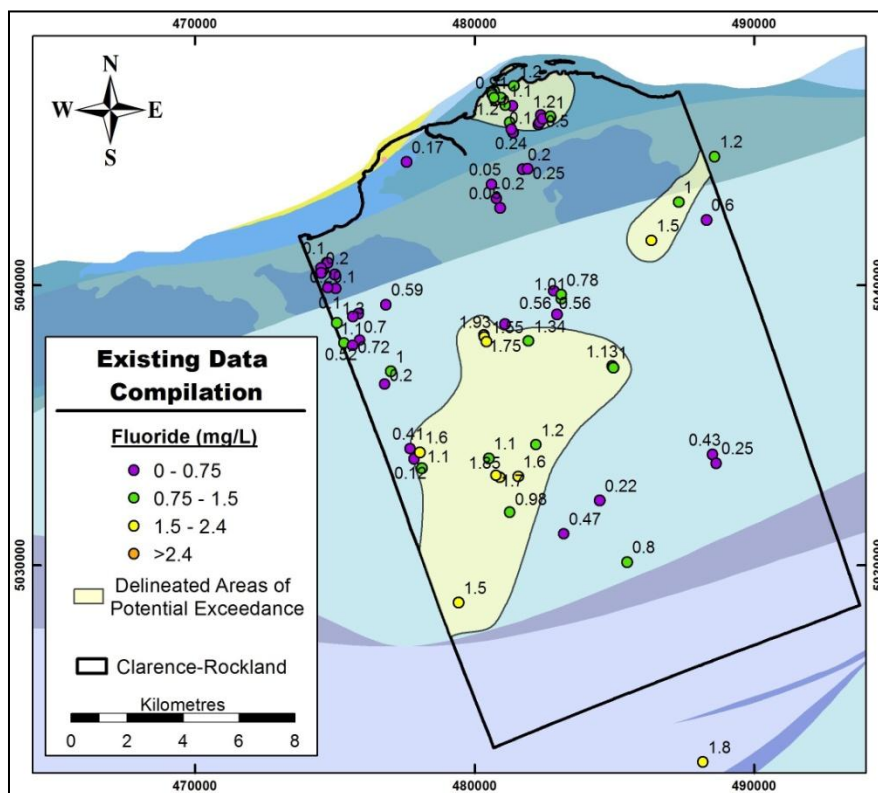


Figure 5-10. Delineated areas of potential exceedance for fluoride in drilled wells based on existing groundwater chemistry data gathered at 74 locations.

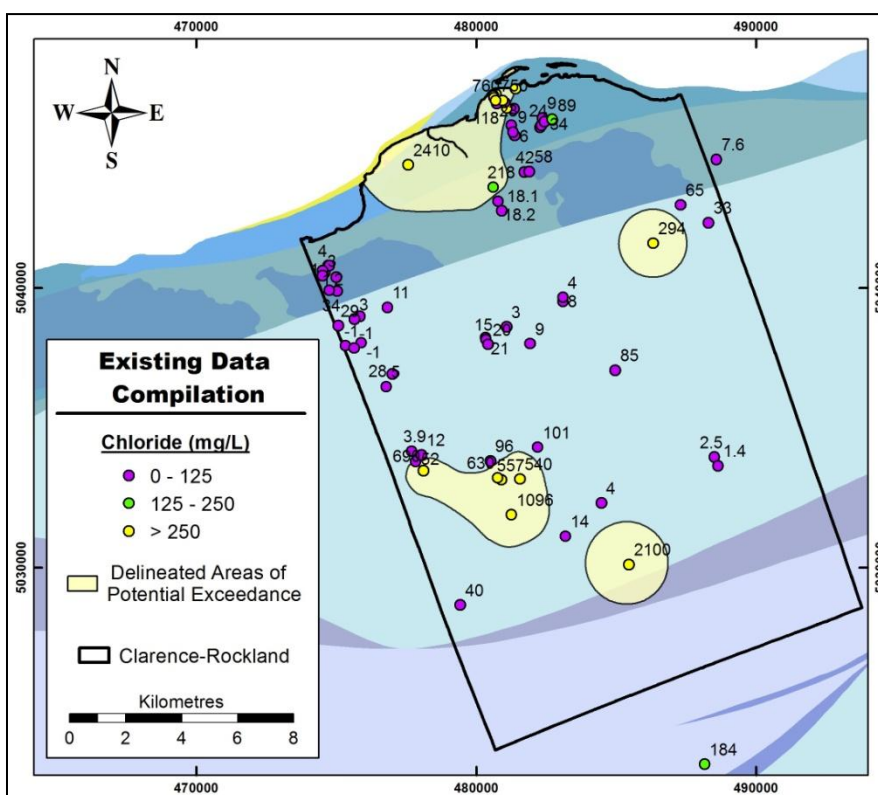


Figure 5-11. Delineated areas of potential exceedance for chloride in drilled wells based on existing groundwater chemistry data at 71 locations.

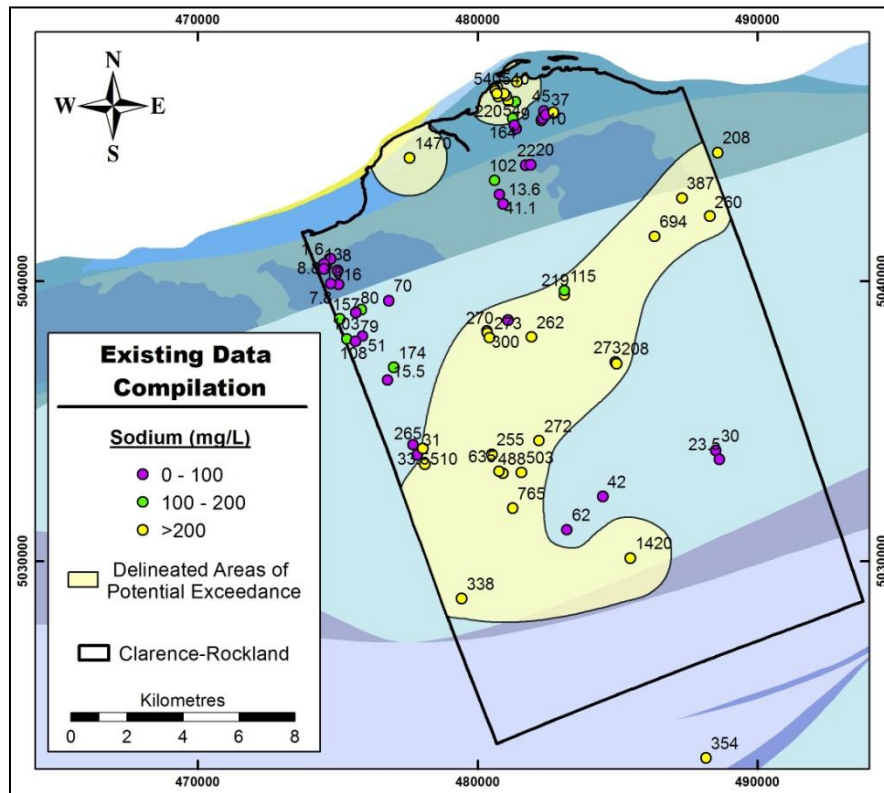


Figure 5-12. Delineated areas of potential exceedance for sodium in drilled wells based on existing groundwater chemistry data gathered at 72 locations.

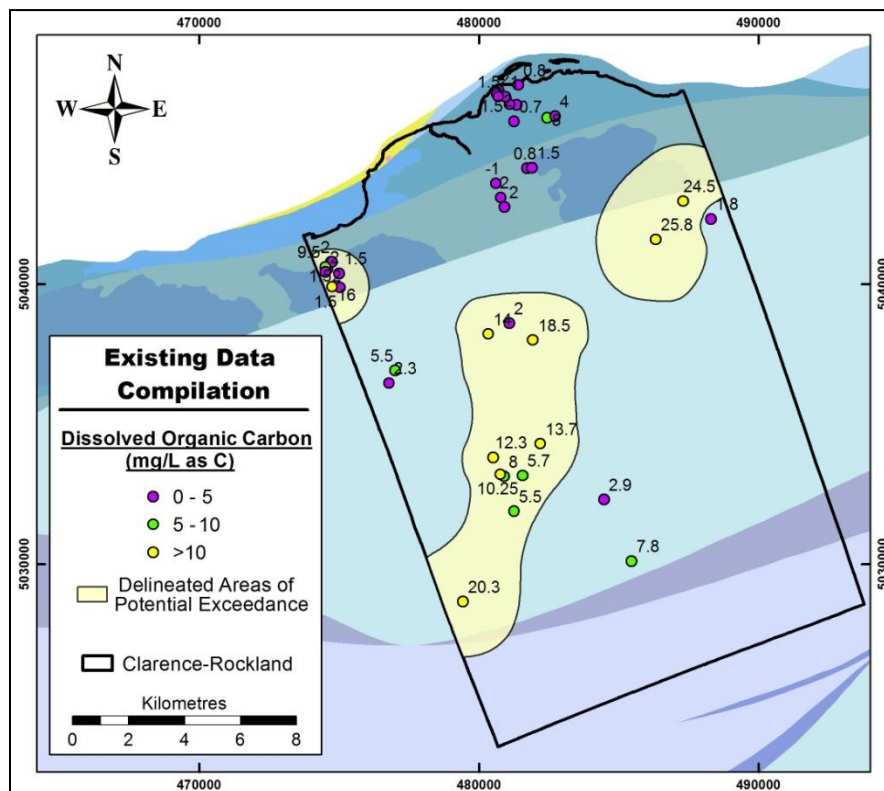


Figure 5-13. Delineated areas of potential exceedance for dissolved organic carbon in drilled wells based on existing groundwater chemistry data gathered at 41 locations.

Comparing these maps to those of the Pilot ACST, we see completely different spatial coverage of the delineated areas of potential exceedance. Most areas where exceedances were identified in the EDC dataset had also been found in the GSP. In addition to this, there were many areas where exceedances had been identified in the GSP dataset that were not found in the EDC dataset. This was ultimately due to the lack of spatial coverage in the EDC dataset, and resulted in the EDC delineations encompassing much less of the City compared to the Pilot ACST.

The limited spatial coverage and clusters of points also imparted great uncertainty to the delineated maps of the EDC dataset. Decisions of how far to delineate the areas away from exceedance points were more difficult to make since the clustered data often showed high variability. Though data gaps were still a concern for the Pilot ACST made from the GSP dataset, the data gaps were considerably smaller since the data were better distributed with more regularly spacing between points. Furthermore, there was not enough information in the EDC dataset to make connections between groundwater chemistry and geological boundary and process maps as was done with the GSP dataset, which further limited the EDC's ability to accurately portray groundwater quality throughout the City.

Although Coliform bacteria exceedances were not delineated, it was interesting to observe that exceedances in existing documents were quite rare compared to what was found in the sampling program. Only 14% of the EDC drilled wells which reported Total Coliform bacteria exceeded 5 counts/100 mL, compared to 57% in the GSP. The higher frequency of wells with bacterial exceedance found in the GSP may have been due to wells being sampled regardless of their age or appearance, while many hydrogeological assessments in existing reports would have sampled new wells or wells that were up to code and properly maintained. Temporal variation may also be a factor, as bacterial presence can change over time for a variety of reasons.

5.2.5 Summary of Findings

Overall, it is clear that the existing report data gathered in this study was less suitable for ACST development than the data obtained from field sampling. The EDC dataset lacked analytical completeness and was considered unreliable due to varying protocols for sampling and analysis, and there were not spatial coverage of each chemistry parameter to accurately portray areas of potentially poor groundwater quality throughout the City. With access to more documents and more existing data the EDC dataset may have obtained better coverage, but the quality limitations of the existing data would still be difficult to overcome.

An ACST produced solely from existing data would have also failed to show areas where exceedances of selenium, barium and methane may be encountered. As we saw from the EDC, these parameters are not commonly analyzed; however the thorough chemical analysis of the GSP showed that these parameters are of concern in the City and hence should be sampled for.

Now that these exceedances have been found, hopefully new studies will also analyze their samples for selenium, barium and methane.

5.3 Data Scale Evaluation: Finding the Necessary Data Scale

The aim of this Data Scale Evaluation was to identify scale requirements or sampling grid spacing necessary for groundwater sampling data to be used to delineate potential exceedance areas and produce ACST maps. To evaluate the necessary data scale, two approaches were taken. The first approach involved resampling the wells of the GSP dataset according to coarser sampling grids and delineate areas of potential exceedance at each scale, in order to simulate the effects of collecting fewer samples. The second approach involved determining the correlation scales for each of delineated parameters in order to determine which scale of sampling would be necessary to statistically explain the spatial variations observed in the data.

5.3.1 Resampling Exercise and Data Scale Comparison

A data scale comparison was performed in order to demonstrate the effects of what might have occurred if the groundwater sampling had of been performed using larger grid scales to accommodate a smaller sampling budget. Data were selected from the GSP dataset which corresponded to differently sized grids with $4 \times 4 \text{ km}^2$, $3 \times 3 \text{ km}^2$, $2.5 \times 2.5 \text{ km}^2$ and $2 \times 2 \text{ km}^2$ grid spacing. For each scale of sampling grid, the drilled well that was most central to the grid block what selected to be included in the dataset. The data at each location were then used to delineate areas of potentially elevated concentrations using the methods of the official ACST by Geofirma (2015).

This scale comparison focussed on delineating areas of potential exceedance for the health standard parameter fluoride. Fluoride, discussed in **Section 4.2.2**, has a maximum allowable concentration of 1.5 mg/L, and concentrations above 2.4 mg/L are a health concern. Delineations for potential fluoride exceedance were made for the $4 \times 4 \text{ km}^2$, $3 \times 3 \text{ km}^2$, $2.5 \times 2.5 \text{ km}^2$ and $2 \times 2 \text{ km}^2$ scale datasets, and are shown in **Figure 5-14**.

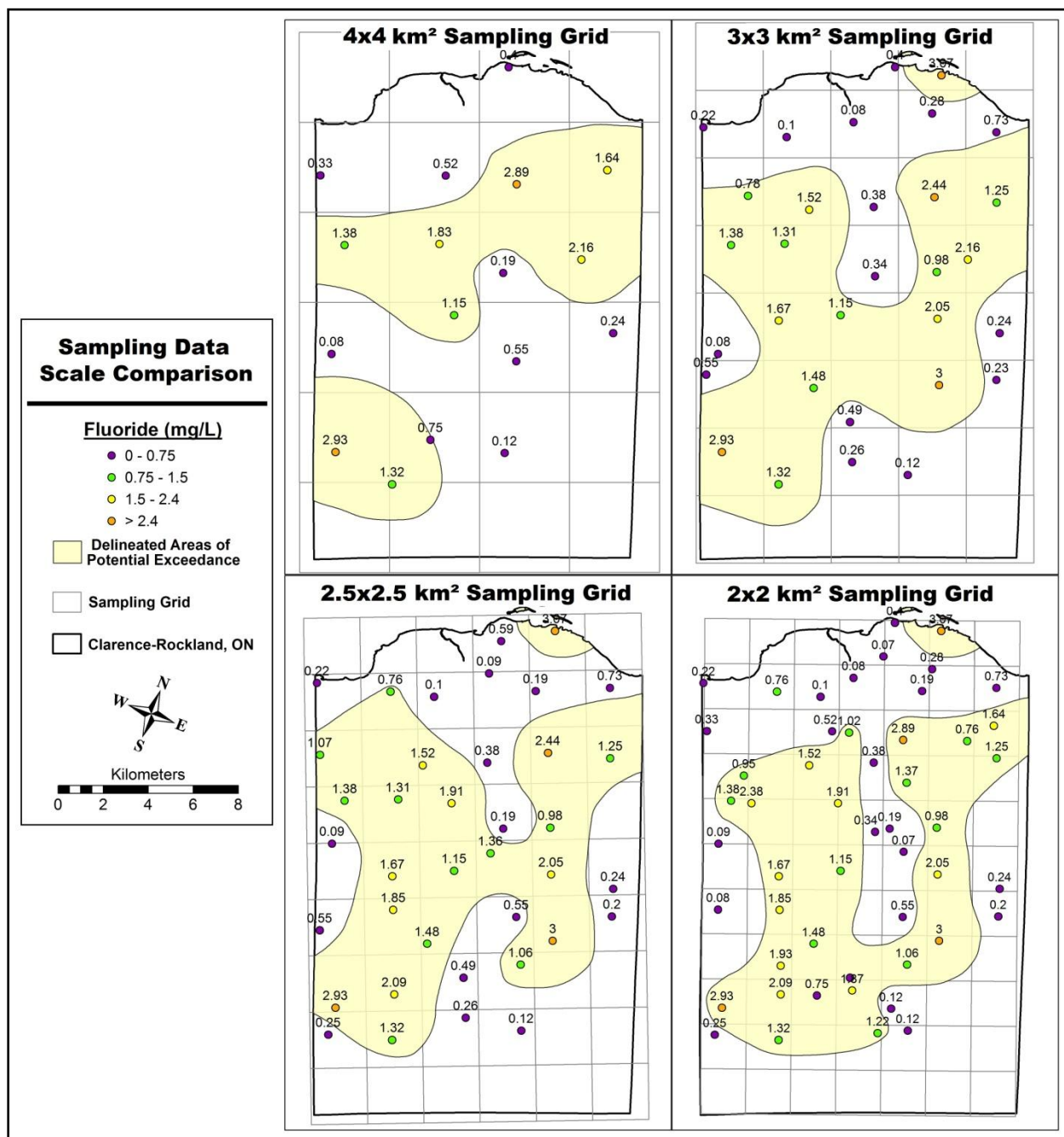


Figure 5-14. Delineated areas of potential fluoride exceedance in drilled wells at different scales. Each scaled dataset was produced by selecting points from the 74 drilled well locations of the Groundwater Sampling Program.

From the scale comparison in **Figure 5-14**, we see that even the 4x4 km² scale shows that fluoride exceedances can occur in the City. However, the 4x4 km² scale data could not predict exceedance areas with any accuracy compared to the finer resolutions and would not be appropriate for city planning. The 3x3 km² scale dataset produced potential exceedance areas of fluoride with the same general shape as the ACST map and finer scale resolutions; however, due to the large distances separating each point, the delineated areas at the 3x3 km² scale were larger and much more expansive. At the 2.5x2.5 km² and 2x2 km² scales, there was less separation

between points, allowing for more accurate delineations of areas with elevated fluoride concentrations.

It should be noted that the GSP dataset had several grid blocks containing more than one well. This gave the GSP dataset an even finer spatial resolution in some areas compared with the 2x2 km² dataset shown here. Hence, these scaled dataset maps are for demonstration only, and should not be mistaken for the potential exceedance areas in the Pilot ACST prepared for the City by Geofirma (2015).

The end result of delineating areas of potentially elevated concentrations ultimately depends on the locations where high concentrations are encountered. The grid scale comparison, which selected points based on different sampling grid resolutions, sometimes did not find exceedances in areas where exceedances were known to exist, simply because there were non-exceedance wells located nearby that could also be sampled. Since the groundwater chemistry sampled throughout the City can vary even in close proximity, it really is crucial to collect as many samples as possible, even in areas where samples have already been collected. If even one exceedance is found in a cluster of nearby wells, that presents a possibility for developed wells in that area to exceed Provincial drinking water standards.

Overall, having greater resolutions of sampling data for groundwater chemistry will result in ACST delineations which better predict the actual groundwater quality that can be obtained. The final ACST maps produced from groundwater chemistry data at different well locations will more accurately represent the obtainable groundwater chemistry with higher resolution sampling data. If additional sampling were to be done at new locations, then without a doubt, the spatial coverage of delineated areas of potential exceedance would change, improving the accuracy of the ACST that is produced.

5.3.2 Determination of Correlation Scale

When producing contour maps of chemistry parameters—whether hand drawn or by interpolation methods such as kriging—it is important to consider the correlation scale; that is, the distance over which parameters are correlated (Gelhar & Axness, 1983; Russo & Jury, 1987). Having the large dataset gathered in the Groundwater Sampling Program allowed examination of the spatial trends that exist between those parameters in order to determine the correlation scale.

One means of estimating the correlation scale is through the semivariogram, which is plotted to explore the spatial relationship of spatially correlated data. Semivariograms serve to quantify the assumption that nearby features are more similar than distant features. A semivariogram, exemplified in **Figure 5-15**, gives a measure of the variability between pairs of measurements as a function of the distance (or lag) separating them. It has three main components (depending on the model): range, sill, and nugget. The range is the lag (or separation distance) at which the curve of a semivariogram levels off into a flat line; it is one possible measure of the correlation scale for what is called the spherical variogram model. The sill is the value of the semivariance at lag values past the range, which is numerically equal to $\frac{1}{2}$

of the variance. The nugget is unexplained variability when measurements are closely spaced. Beyond the range, a correlation cannot be observed and there is only noise.

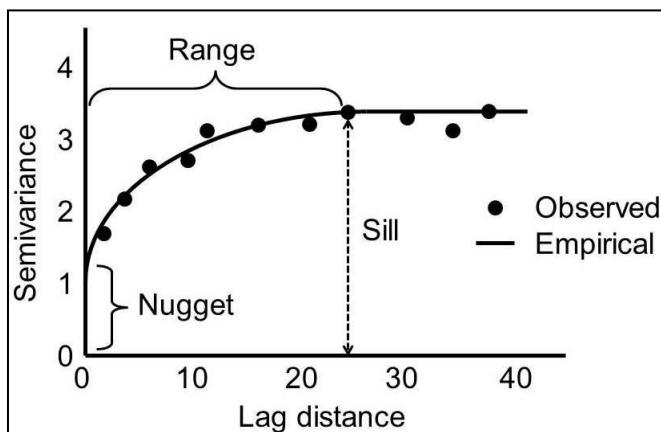


Figure 5-15. A typical example of a semivariogram showing derivable components. *Taken from Biswas & Si (2013).*

Knowing the correlation scales allows us to infer the appropriate sampling scale. Gathering sampling data at a spatial scale that is equal or smaller than the correlation scale will be enough to show spatial correlations in the data, which is necessary for producing accurate maps. Gathering data at a spatial scale larger or coarser than the correlation scale will produce results that are spatially random.

The purpose of this exercise was to explore the spatial relationship among the chemistry parameters that were mapped in the Pilot ACST in order to determine the correlation scale for the data of each parameter. Spatial relationships were examined for fluoride, barium, selenium, sodium, chloride, dissolved organic carbon, methane and total dissolved solids. Semivariograms were produced for each parameter in ArcMap through the dialogue for Ordinary Kriging. The resulting semivariograms are shown from **Figure 5-16** to **Figure 5-23**. In each figure caption the lag size, range, nugget and sill of the semivariogram are reported; these data are summarized in **Table 5-3**.

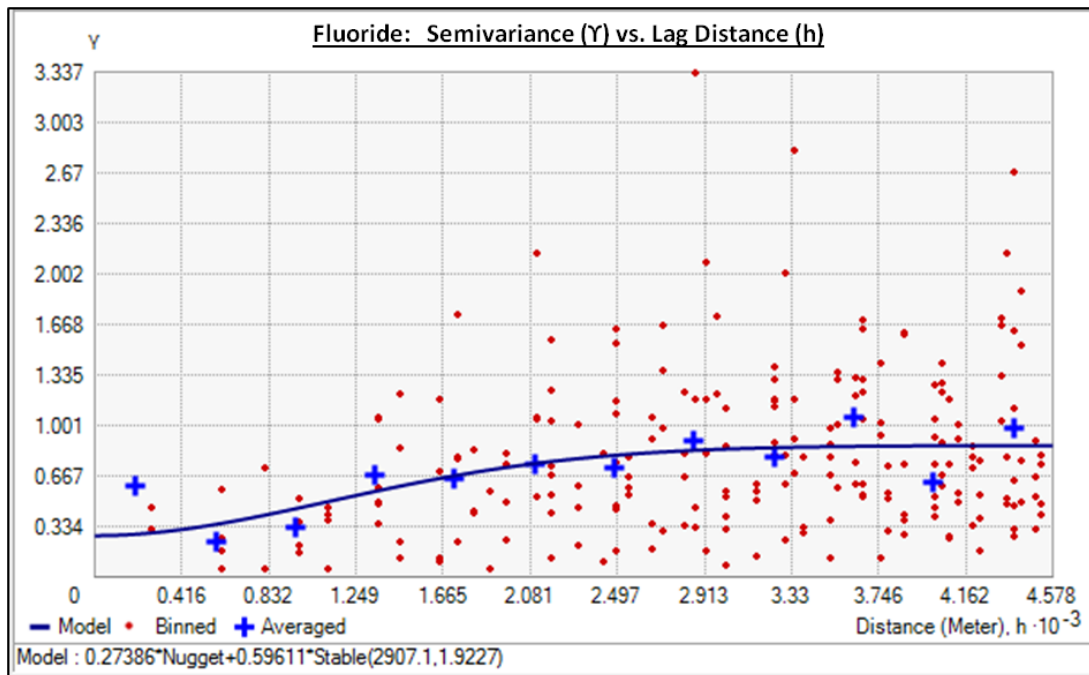


Figure 5-16. Semivariogram for the fluoride concentration in drilled wells (mg/L, $n=74$). Lag size: 0.382 km, Range: 2.907 km, Nugget: 0.274, Sill: 0.870. Produced using Ordinary Kriging in ArcMap.

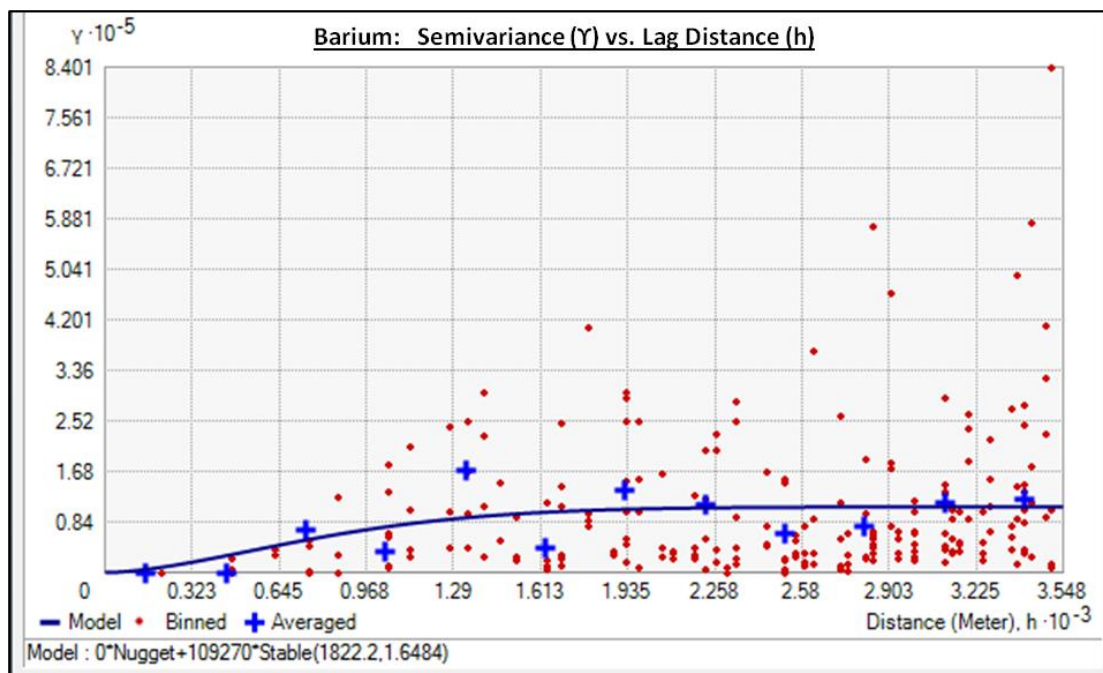


Figure 5-17. Semivariogram for the barium concentration in drilled wells ($\mu\text{g/L}$, $n=74$). Lag size: 0.296 km, Range: 1.822 km, Nugget: 0, Sill: 109275. Produced using Ordinary Kriging in ArcMap.

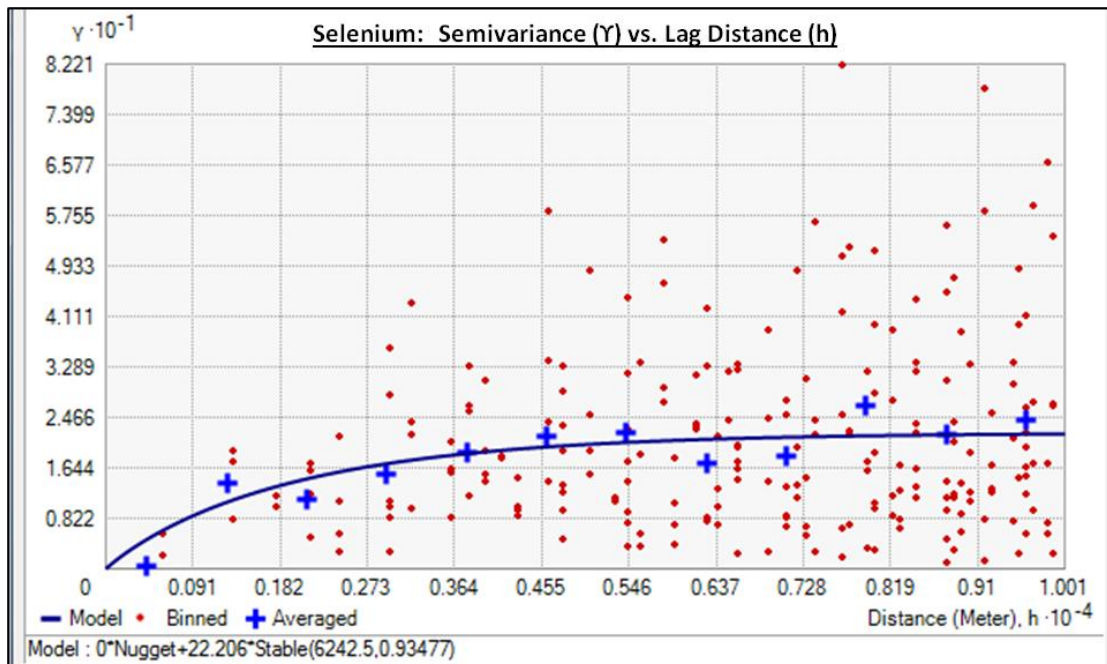


Figure 5-18. Semivariogram for the selenium concentration in drilled wells ($\mu\text{g/L}$, $n=74$). Lag size: 0.834 km, Range: 6.243 km, Nugget: 0, Sill: 22.206. *Produced using Ordinary Kriging in ArcMap.*

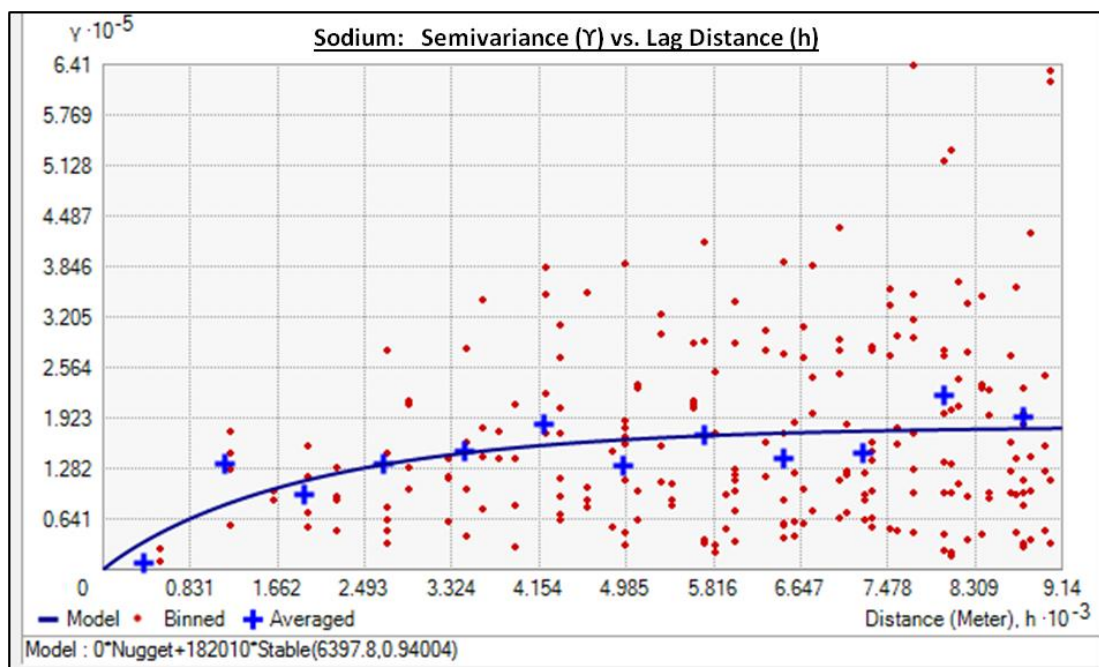


Figure 5-19. Semivariogram for the sodium concentration in drilled wells (mg/L , $n=74$). Lag size: 0.762 km, Range: 6.398 km, Nugget: 0, Sill: 182006. *Produced using Ordinary Kriging in ArcMap.*

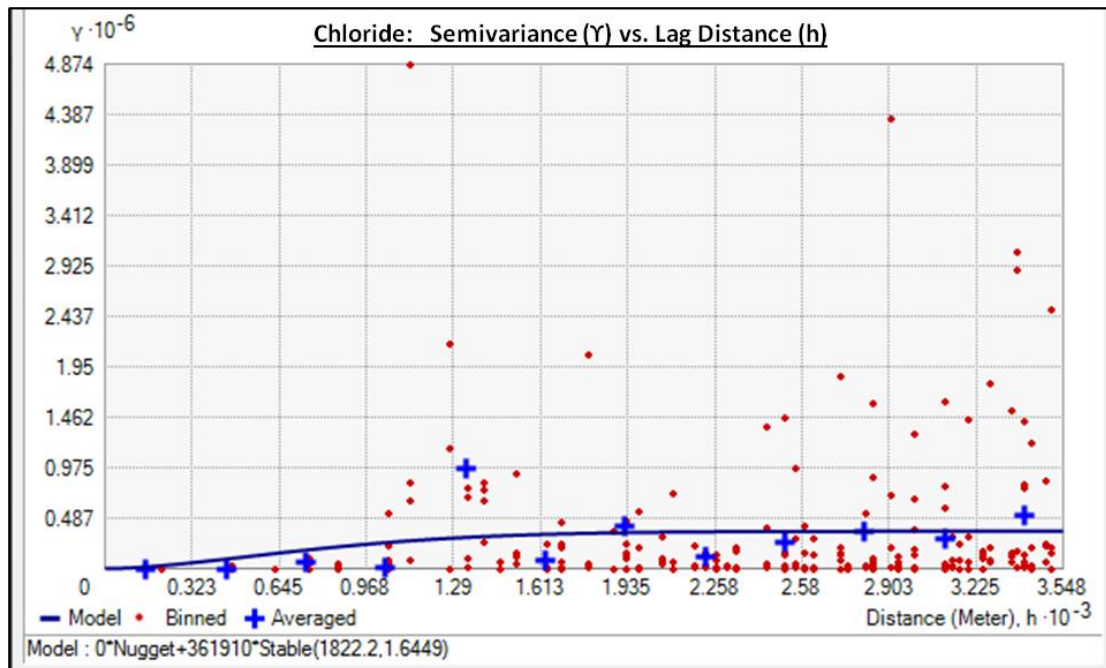


Figure 5-20. Semivariogram for the chloride concentration in drilled wells (mg/L, $n=74$). Lag size: 0.296 km, Range: 1.822 km, Nugget: 0, Sill: 361906. *Produced using Ordinary Kriging in ArcMap.*

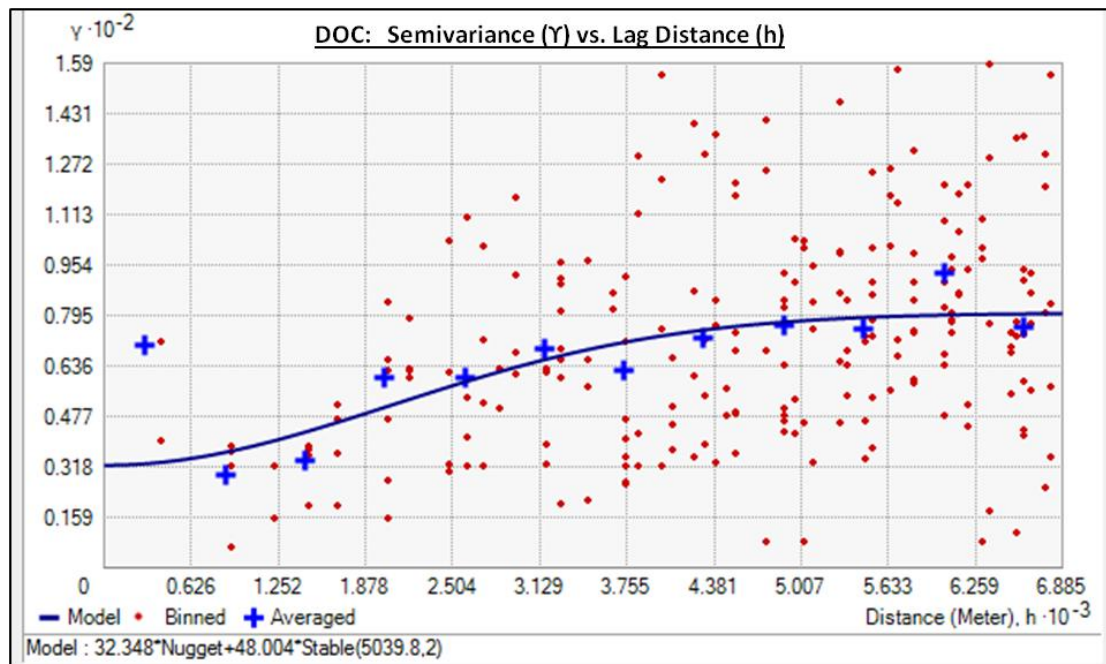


Figure 5-21. Semivariogram for the dissolved organic carbon concentration in drilled wells (mg/L, $n=74$). Lag size: 0.574 km, Range: 5.040 km, Nugget: 32.348, Sill: 80.252. *Produced using Ordinary Kriging in ArcMap.*

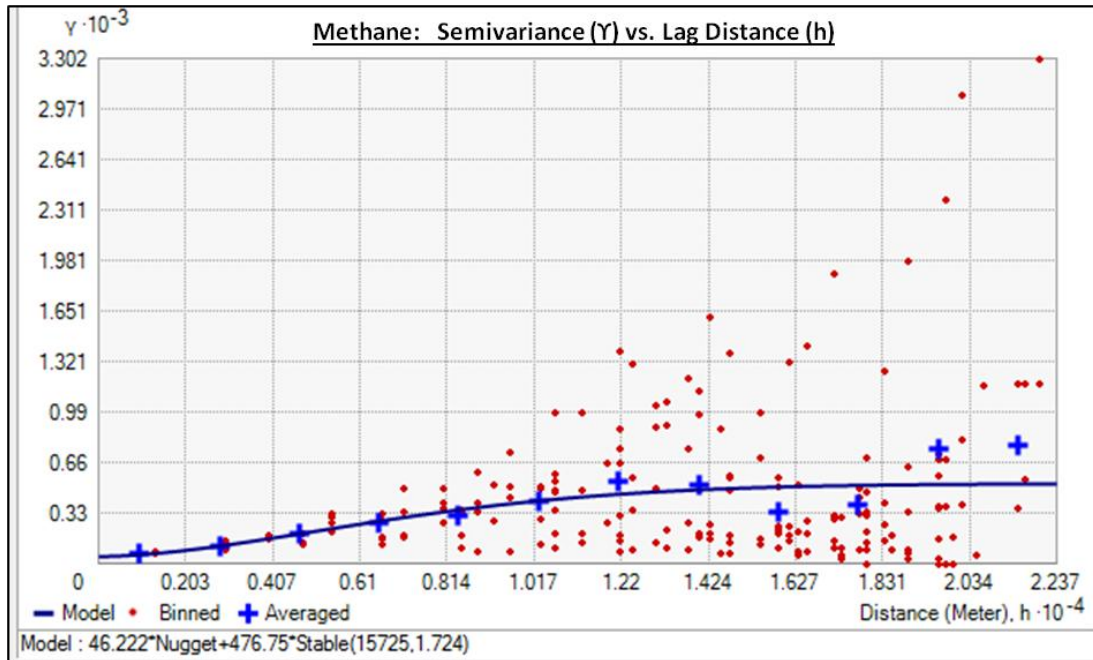


Figure 5-22. Semivariogram for the concentration of dissolved methane gas in drilled wells (L/m^3 , $n=74$). Lag size: 1.865 km, Range: 15.725 km, Nugget: 46.222, Sill: 522.977. *Produced using Ordinary Kriging in ArcMap.*

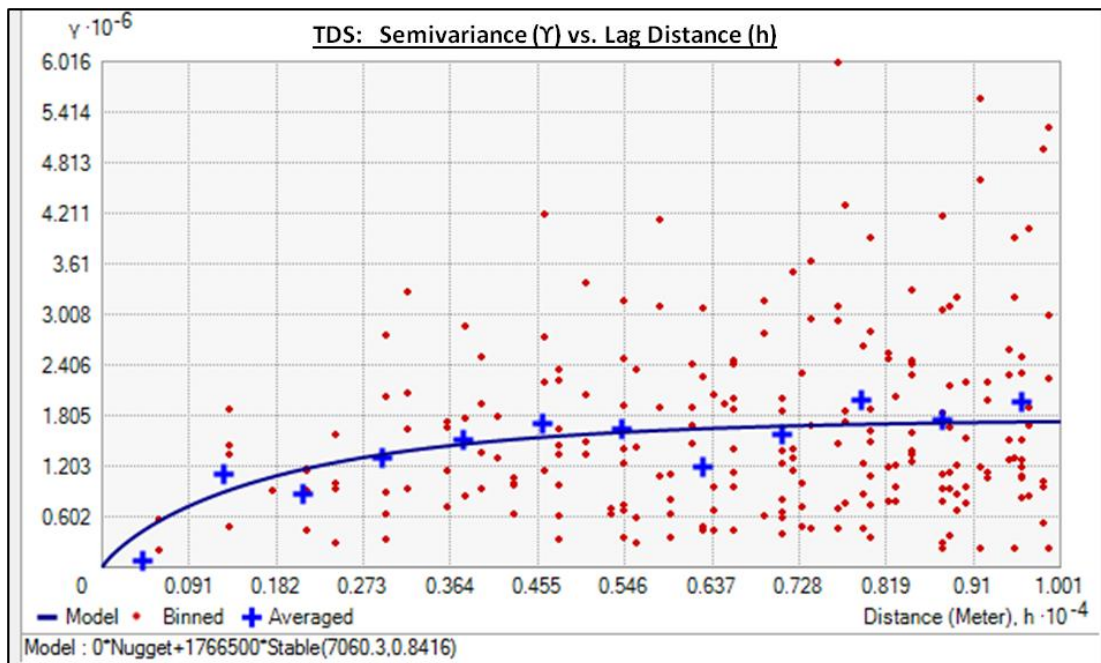


Figure 5-23. Semivariogram for the total dissolved solids concentration in drilled wells (mg/L , $n=74$). Lag size: 0.834 km, Range: 7.060 km, Nugget: 0, Sill: 1766546. *Produced using Ordinary Kriging in ArcMap.*

Table 5-3. Summary of components for each of the semivariograms, showing the lag size, range, nugget and sill. Semivariograms used the spherical model and included data from 74 drilled well locations from the Groundwater Sampling Program.

<u>Chemistry Parameter</u>	<u>Lag Size (km)</u>	<u>Range (km)</u>	<u>Nugget</u>	<u>Sill</u>
Fluoride	0.382	2.91	0.274	0.870
Barium	0.296	1.82	0	1.09 x 10 ⁵
Selenium	0.834	6.24	0	22.2
Sodium	0.762	6.40	0	1.82 x 10 ⁵
Chloride	0.296	1.82	0	3.62 x 10 ⁵
Dissolved Organic Carbon	0.574	5.04	32.2	80.3
Methane	1.865	15.73	46.2	523.0
Total Dissolved Solids	0.834	7.06	0	1.77 x 10 ⁶

Each parameter had been examined for closeness to a normal distribution using Quantile-Quantile plots. Without adjustments or transformations, each parameter showed negative skewness (left-skew) compared to a normal distribution. Logarithmic transformations rendered the data approximately normally distributed for barium, sodium and chloride, but there was still some skewness. For the other parameters, logarithmic transformations resulted in similar or different skewness. For these reasons, no transformations were applied to the datasets before producing the semivariograms.

It is important to note that the error on the semi-variance increases with lag distance, as there are fewer and fewer points in the estimation of the semi-variance at large lags. The semivariograms were presented in their entirety here, but it should be pointed out that it is common practice to truncate them past a certain lag distance (based on the range). Another point is that the resolution of the semivariogram (at small lags) is largely dictated by the sampling grid size, and consequently correlation scales less than approximately 2 km would be difficult to identify in this study.

According to the ranges in **Table 5-3**, coarse sampling scales with less than 5 km between points would be sufficient for producing kriged maps for selenium, sodium, DOC, methane and TDS, but finer sampling scales would be needed to accurately map fluoride, barium and chloride. Among these parameters, fluoride is of very high importance due to the abundance of exceedances and the associated health implications with exceedances. With the correlation scale for fluoride being 2.9 km, in order to have enough data to accurately krige fluoride an even smaller sampling grid spacing would be required. The 2x2 km² grid spacing used in this study may have been enough for this, however following this points can be up to 4 km apart and there were data gaps as well. For barium and chloride the correlation scales were less than 2 km, indicating that the sampling spacing obtained in our dataset was too coarse for kriging to be accurate for those parameters.

These findings are not without their associated error. The datasets were not normally or log-normally distributed, which can imply that either: (1) the data obtained did not represent one population, and (2) that the distribution models and semivariograms could show different results if more data points were available. Realistically, the data very likely did not come from one population, since the depths of nearby wells often varied by tens of meters resulting in water being drawn from potentially different aquifers with different chemistry. This could be corrected by separating out the wells based on their geological setting or depth, however such was not done in the Pilot ACST. The data availability, on the other hand, could not be helped; there were only 127 samples allotted for analysis in the budget of this project and even getting those was difficult in some areas, resulting in data gaps as was discussed in **Section 3.3.2**.

Because of this error, the correlation scales reported above are best considered only as suggestions, and it is still recommended that budgets for future projects be optimized to support the collection of as many samples as possible. A 2x2 km² grid spacing for sample collection seemed appropriate for many parameters, however having more data gathered could still refine the data and produce maps with better accuracy for ACST development.

5.3.3 Summary of Findings

The correlation scales of the mapped parameters have indicated that more accurate ACST maps could be produced from collecting groundwater samples at a finer scale than was used in this study. The comparison of different grid scales in the resampling exercise showed marginally similar results among the 2x2 km² and 2.5x2.5 km² grid scales, whereas the 3x3 km² and 4x4 km² scales produced delineations that differed greatly compared to the finer scales and the official product in both shape and spatial coverage. The differences between the 3x3 km², 2.5x2.5 km² and 2x2 km² effectively demonstrated that using smaller sampling grids can result in more accurate ACST maps being drawn. Moving forward in future studies, it is recommended to optimize the sampling strategy according to the available budget so that as small a grid scale can be used as is feasibly possible.

6 Conclusions and Recommendations

The objectives of this thesis were to collect and analyze groundwater samples, investigate exceedances of Provincial drinking water standards and provide an evaluation of the sampling data requirements necessary to develop groundwater quality maps of an Aquifer Capability Screening Tool (ACST). The Pilot ACST developed in this project is the first of its kind and is intended to help municipalities pre-screen areas for development applications. The tool itself was prepared by Geofirma (2015) for the City of Clarence-Rockland, Ontario, using information gathered in this project.

This study completed a highly successful groundwater sampling program in which drilled wells and dug wells throughout the City were sampled, and the chemistry results obtained were compared to the Ontario Drinking Water Standards, Objectives and Guidelines (ODWSOG) (MOE, 2006) in order to identify exceedances. The comparisons revealed that the main health concerns in the groundwater were bacteria, fluoride, barium and selenium, and the main aesthetic concerns were colour, total dissolved solids, dissolved organic carbon, chloride, sodium, methane, iron and manganese. Using the exceedance locations of health and aesthetic parameters identified in this study, Geofirma (2015) delineated areas where concentrations may potentially exceed drinking water standards. These delineated areas make up the groundwater quality maps of the Pilot ACST.

Evaluations were made to determine whether the use of existing data would be appropriate and to identify the data scale requirements needed for accurate maps to be made showing areas of predictably poor groundwater quality. Comparing the delineated potential exceedance areas for sampling data collected at different scales in **Section 5.3.1** demonstrated that the outcome of an ACST can change and improve considerably with finer scales of groundwater sampling. The correlation scales for each of the delineated ACST in **Section 5.3.2** provided further insight to which scale is needed for each parameter. The results suggest that the 2x2 km² sampling grid used in this study will be sufficient for most parameters. However, better results can always be observed with more data, regardless of the data scale that was originally intended.

With this in consideration, it is recommended that future ACST development projects should plan a sampling program and optimize its budget so that as many locations can be sampled as possible. It may also be possible to use a varying scale, in which problematic areas are sampled on a smaller grid size; this could be a multi-step process with one round of sampling at coarse scale followed by a scale refinement based on exceedances or development pressure. Future ACST development projects should not sacrifice the quality of the sampling procedure and analysis, but many of the analyzed parameters that were analyzed in this study can safely be excluded to bring down project costs. Sampling operations should continue using OGS protocols for field sampling, making the same field measurements, and sample analysis should include all major cations and anions (including bromide) as well as any chemistry parameter for which there is an Ontario Drinking Water Standard, Objective or Guideline.

It may be possible to improve the accuracy of the delineated areas by including some exceedances locations from existing reports. However, if existing data is to be used then appropriate measures will need to be taken to ensure that the data is reliable and accurate. Due to the additional time (and resources) required to gather and screen existing data, paired with the uncertainty of sampling methodology and often poor analytical quality of existing data, it is recommended that caution should be exercised when including existing data in the development of future ACSTs.

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APPENDIX

Appendix 1 Groundwater Sampling Forms



Groundwater Sampling Program

The United Counties of Prescott and Russell and the City of Clarence-Rockland have partnered with South Nation Conservation, the University of Ottawa and the Ontario Geological Survey to carry out a groundwater sampling program across the City of Clarence-Rockland. The purpose is to determine the levels of natural substances in groundwater. We are asking well owners to allow us to sample their untreated well water to help create maps of groundwater. In return, homeowners will receive a detailed copy of the analysis of their untreated well water if they request it. The results will be published by the Ontario Geological Survey in both map and database format and will be used to produce groundwater maps for the City of Clarence-Rockland.

By signing below, I agree to allow the University of Ottawa to collect and analyze water samples. I am aware that the results of the analysis will be used in a published database for the purpose of this study. ***No homeowner names, personal information or addresses will be published or released to a third party.*** Wells will be referenced by their original well numbers or by their geographic coordinates only.

Signed

Date

Analytical results requested ☐ Yes ☐ No

Homeowner Name : _____

 Address : _____

 Phone : _____

 Email : _____

Figure A1-1. Homeowner consent form presented to private well owners upon arrival at each site to authorize groundwater sampling. This form was prepared in English and French by the South Nation Conservation Authority.

13 – AG – _____

Date: _____ Time: _____ Easting: _____ Northing: _____ Grid ref.# 17, __, __, __ MOE Well ID: _____ MOE Tag#: _____ Samplers Names: _____ MEASUREMENTS Purging volume: _____ Litres (one pale = ~75 L) Instrument: ☐ YSI ☐ Other _____ Subscript values show the typical range Temp (°C) ₆₋₁₂ _____ Cond. (µS) _{>50} _____ ORP (mV) _{-350 to +250} _____ pH ₆₋₉ _____ DO (%) _{drilled=0} _____ → ☐ Winkler: _____ Alkalinity (100 mL, 1.6 N H₂SO₄, digit multiplier: 1) pH > 8.3: Phenylthaleine (mg/L CaCO₃ P_{Alk}) ☐ colourless (P_{Alk} = 0) ☐ pink _____ pH > 5.0: Bromocresol (mg/L CaCO₃ T_{Alk}) Endpoint colour: g/b-gray violet-gray pink Reading: _____ Gas Phase ☐ none ☐ exsolution (in water or standing) ☐ free bubbles comments: _____ ☐ vapour phase sample Water Colour ☐ colourless ☐ yellow → ☐ pale ☐ dark ☐ orange ☐ grey ☐ other: _____ Water Clarity ☐ clear ☐ turbid → ☐ slight ☐ very H₂S Low (0 – 0.55 mg/L) with lengthwise adaptor; lower scale Reading: _____ mg/L as S²⁻ Medium (0 – 2.25 mg/L) no adaptor; upper scale Reading: _____ mg/L as S²⁻ High (0 – 11.25 mg/L) no adaptor; w/ tubes inserted; upper scale Reading: _____ mg/L as S²⁻ Smell ☐ none ☐ H₂S ☐ petrol. ☐ Fe ☐ other: _____ Missing Bottles: ☐ none anions cations mercury iodide isotopes tritium TKN/nitrites ammonia bacteria methane	Aquifer Type: ☐ Bedrock ☐ Overburden ☐ Atypical Terrain: ☐ agricultural ☐ rural (non-ag.) ☐ urban ☐ other: _____ Water use: ☐ domestic including drinking ☐ domestic (no drinking) ☐ outdoor/barn only ☐ other: _____ Historic water quantity problems? ☐ no ☐ yes: _____ Historic water quality problems? ☐ no ☐ yes: _____ Water treatment ☐ no ☐ yes ☐ softener ☐ UV filter ☐ perox. ☐ Fe filter ☐ aerator ☐ R.O. ☐ chlorine ☐ sediment filter ☐ charcoal ↙ From nearby records <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th></th> <th>MOE (ft)</th> <th>✓</th> <th>Measured (m)</th> <th>Owner (ft)</th> </tr> </thead> <tbody> <tr> <td>Well age</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>Well depth</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>Depth to rock</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>Static WL</td> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table> Pressure tank location ☐ basement ☐ well pit ☐ insulated hut ☐ barn ☐ other: _____ Well type ☐ drilled_(small dia.) ☐ bored_(big dia.) ☐ dug ☐ sand point ☐ spring ☐ monitoring ☐ other: _____ Well cap ☐ standard steel ☐ vermin-proof ☐ concrete ☐ fibreglass ☐ sanitary seal /comments: _____ Casing diameter ☐ 5.5" ☐ 6.5" ☐ 36" ☐ other: _____ Stickup (cm): _____ ☐ N/A – well pit ☐ N/A – buried Pump type ☐ electric submersible_(wires) ☐ jet pump_(2 pipes) ☐ suction pump_(1 pipe) ☐ Waterra foot valve_(manual) ☐ jack pump → ☐ electric ☐ windmill ☐ hand ☐ Grundfoss: OGS / CA ☐ shaft impeller ☐ other: _____ Sampling point: after pressure tank or before pressure tank ☐ outside tap ☐ hydrant at well ☐ basement tap ☐ in front of tank (T) ☐ kitchen tap ☐ pumped from well/spring ☐ (flow-through tank) ☐ no tank ☐ other: _____ Comments: ☐ Standard Protocol not followed ☐ Extra samples ☐ Photo not taken _____ _____ _____ Oddities: high DO: (1) in B/R, (2) in drilled OB well, (3) with –ORP, (4) with +H₂S high ORP: (1) >+250, (2) with +H₂S pH<6, pH>9, Temp>12, Temp< 7		MOE (ft)	✓	Measured (m)	Owner (ft)	Well age					Well depth					Depth to rock					Static WL				
	MOE (ft)	✓	Measured (m)	Owner (ft)																						
Well age																										
Well depth																										
Depth to rock																										
Static WL																										

Figure A1-2. Groundwater sampling form used to record information at each site. This form was modified from the one used by the Ontario Geological Survey in the Ontario Ambient Groundwater Geochemistry Project.

Appendix 2 Maps of Groundwater Chemistry Results

This appendix contains maps which both visually express the results of the Groundwater Sampling Program (discussed in **Section 3**) and identify locations where chemistry exceeded the Ontario Drinking Water Standards (discussed in **Section 4**). The 136 sampled wells are divided into two categories: drilled wells (n=74) and dug wells (n=62). Drilled well locations are shown overlaying the Paleozoic bedrock geology map data from MRD219 (Armstrong & Dodge, 2007), shown in **Figure 2-4** of **Section 2.2**. Dug well locations are shown overlaying the surficial geology map data from MRD128 (OGS, 2010), shown in **Figure 2-7** of **Section 2.3**.

The chemistry parameters mapped in this appendix, in order, include: Temperature, Specific Conductance, pH, Oxidation Reduction Potential (ORP), Alkalinity, Hardness, Total Dissolved Solids (TDS), Apparent Colour, Total Coliform Bacteria, Fecal Coliform Bacteria, Methane Gas, Dissolved Organic Carbon (DOC), Hydrogen Sulphide, Nitrate, Ammonia/Ammonium, Organic Nitrogen, Sulphate, Phosphate, Fluoride, Chloride, Iodide, Sodium, Potassium, Magnesium, Calcium, Barium, Selenium, Iron, Manganese and Tritium.

Graduated symbol sizes were used to display the data ranges in different intervals. Interval endpoints were carefully chosen to reflect both the statistical distributions of the data and the related exceedance criteria. Values equal to half and double the exceedance criteria were also often used as interval endpoints.

A uniform colour scheme for symbols was used to indicate exceedances of the Ontario Drinking Water Standards, Objectives and Guidelines. For exceedances of bacterial Health Standards, chemical Health Standards, Aesthetic Objectives, Operational Guidelines and Maximum Concentrations Considered Reasonably Treatable, circles have been coloured in brown, pink, yellow, grey and orange, respectively. Exceptions to this colour scheme include the maps for pH, Apparent Colour, DO and ORP.

A2.1 Temperature in Drilled Wells

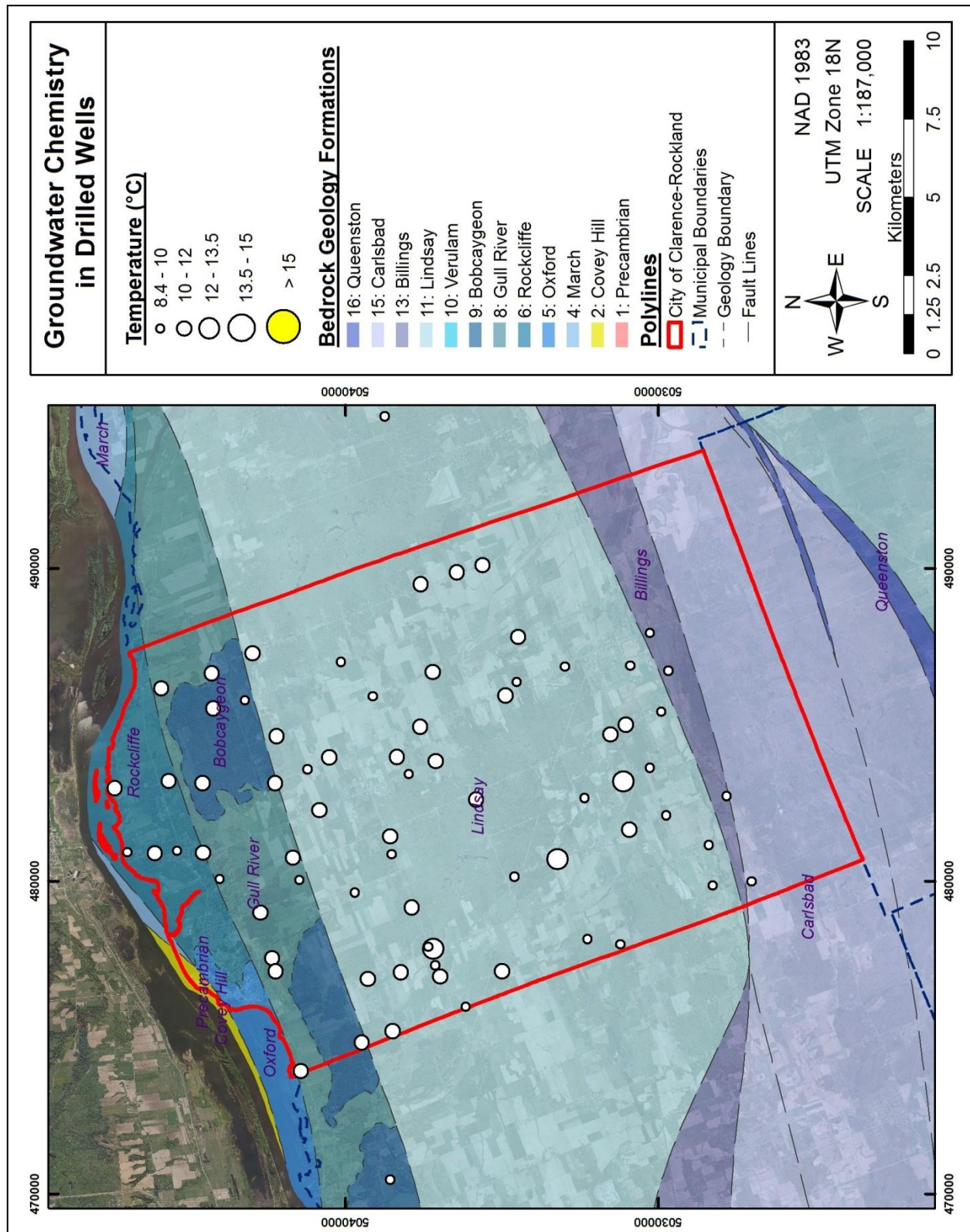


Figure A2-1. Groundwater temperature sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (15°C).

A2.2 Temperature in Dug Wells

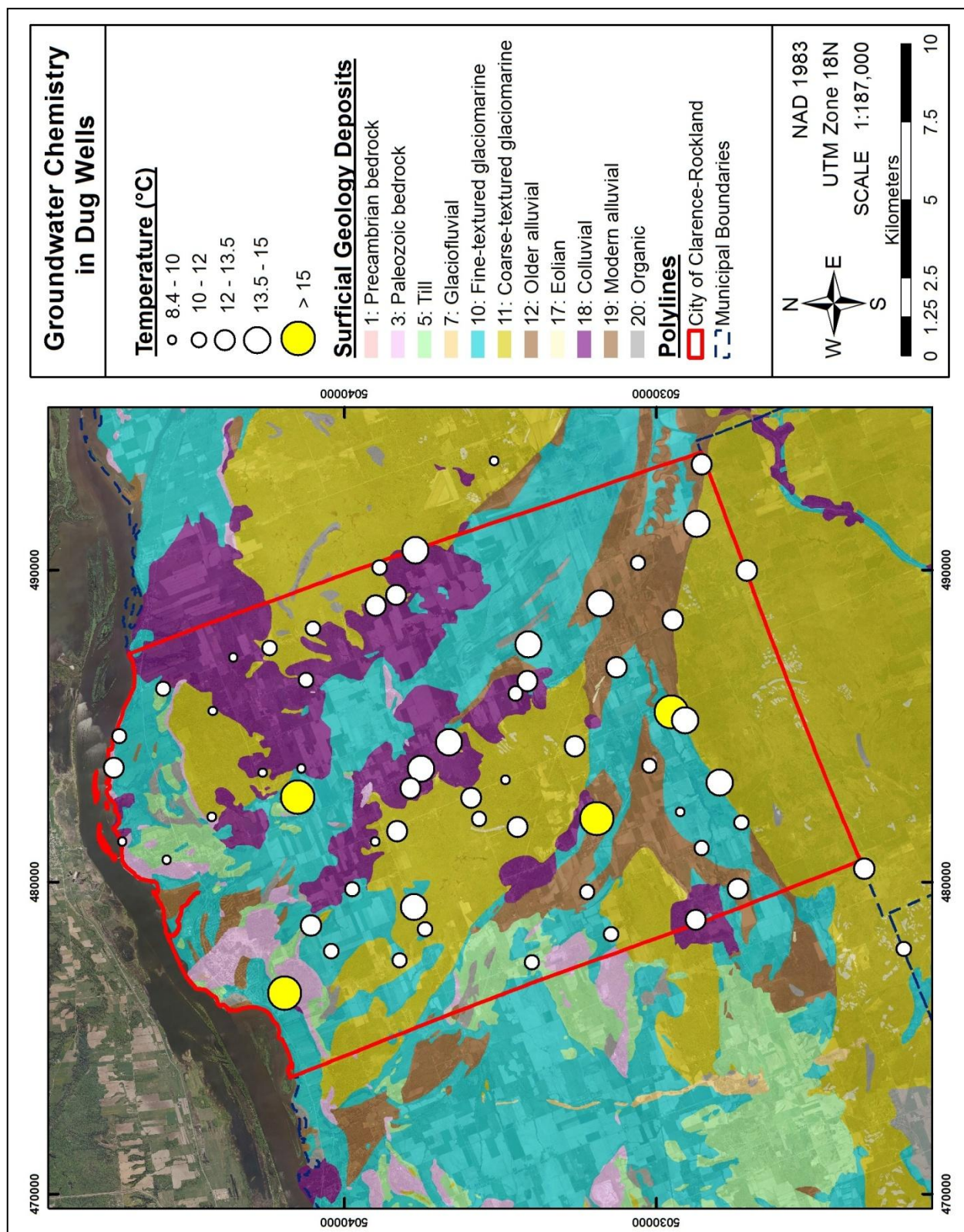


Figure A2-2. Groundwater temperature sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (15°C).

A2.3 Specific Conductance in Drilled Wells

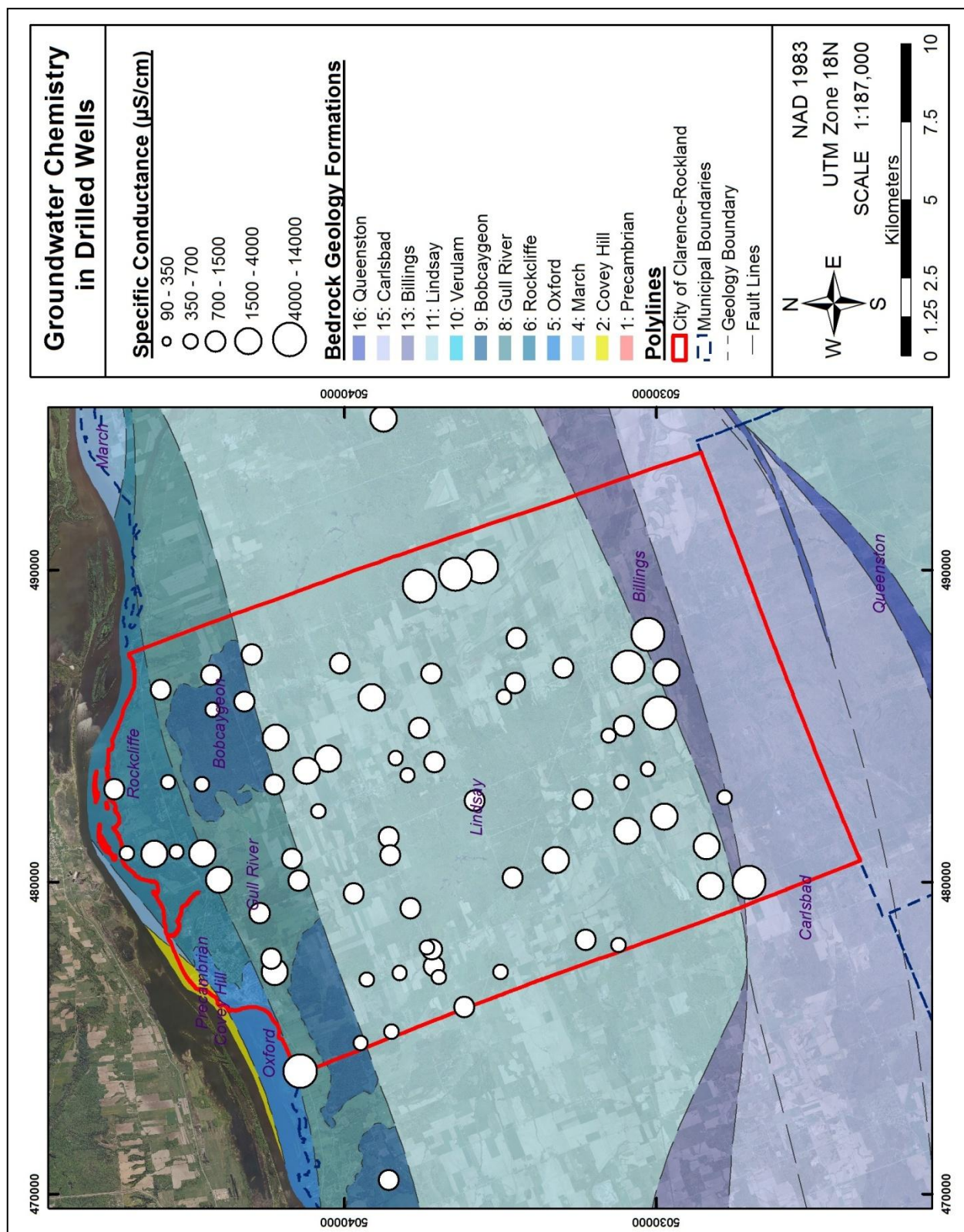


Figure A2-3. Specific conductance of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.4 Specific Conductance in Dug Wells

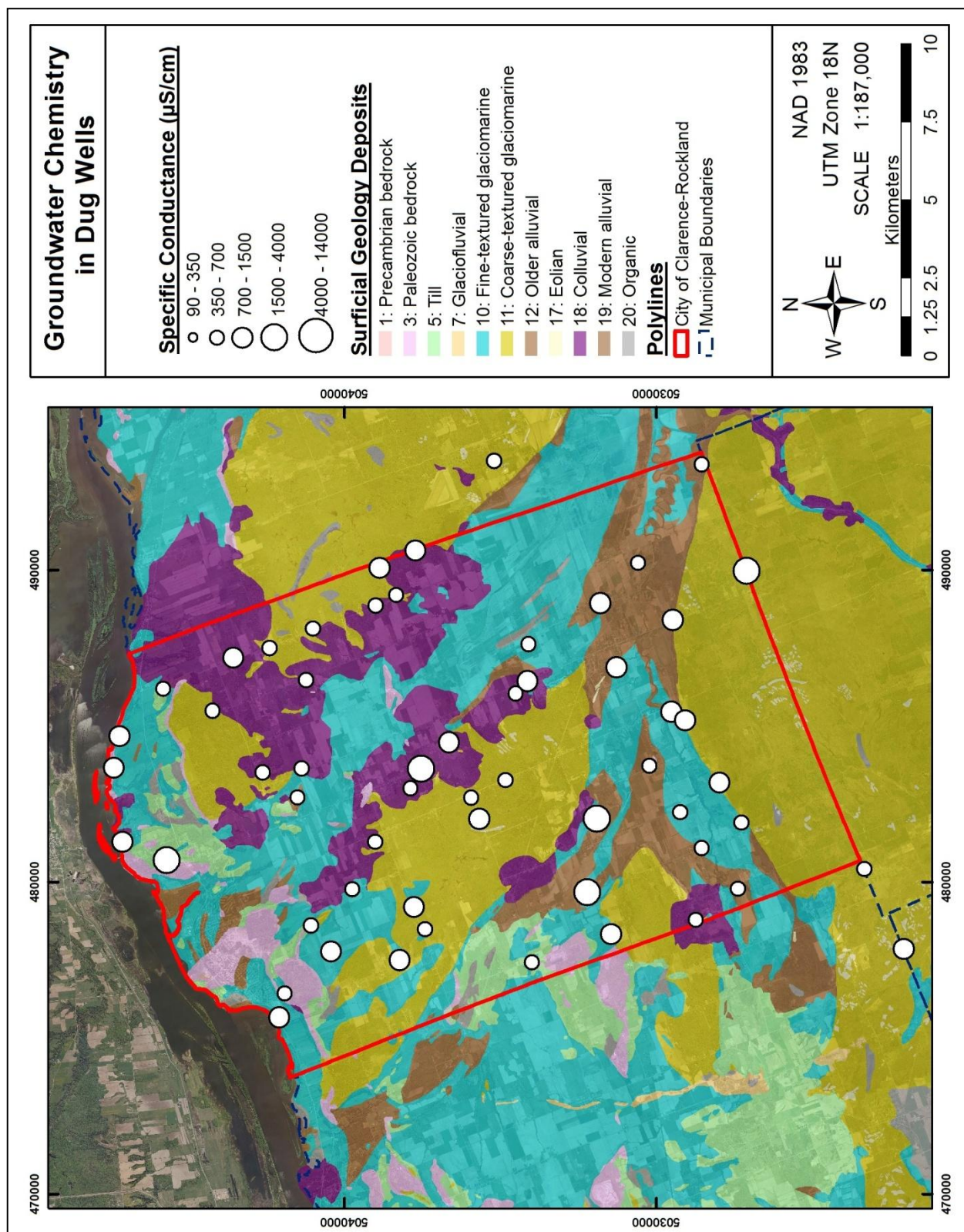


Figure A2-4. Specific conductance of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.5 pH in Drilled Wells

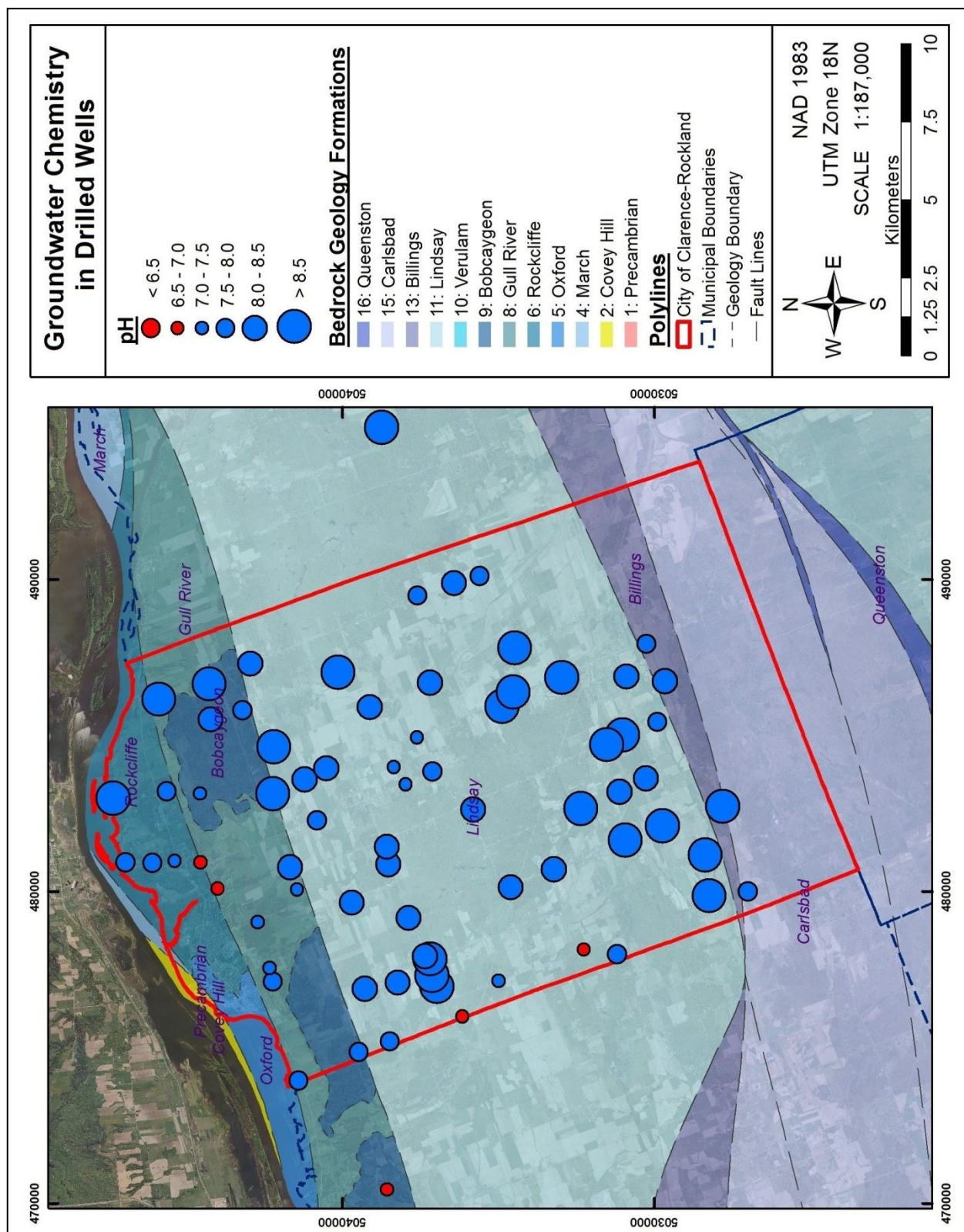


Figure A2-5. pH of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Red circles indicate acidic conditions and blue circles indicate basic conditions.

A2.6 pH in Dug Wells

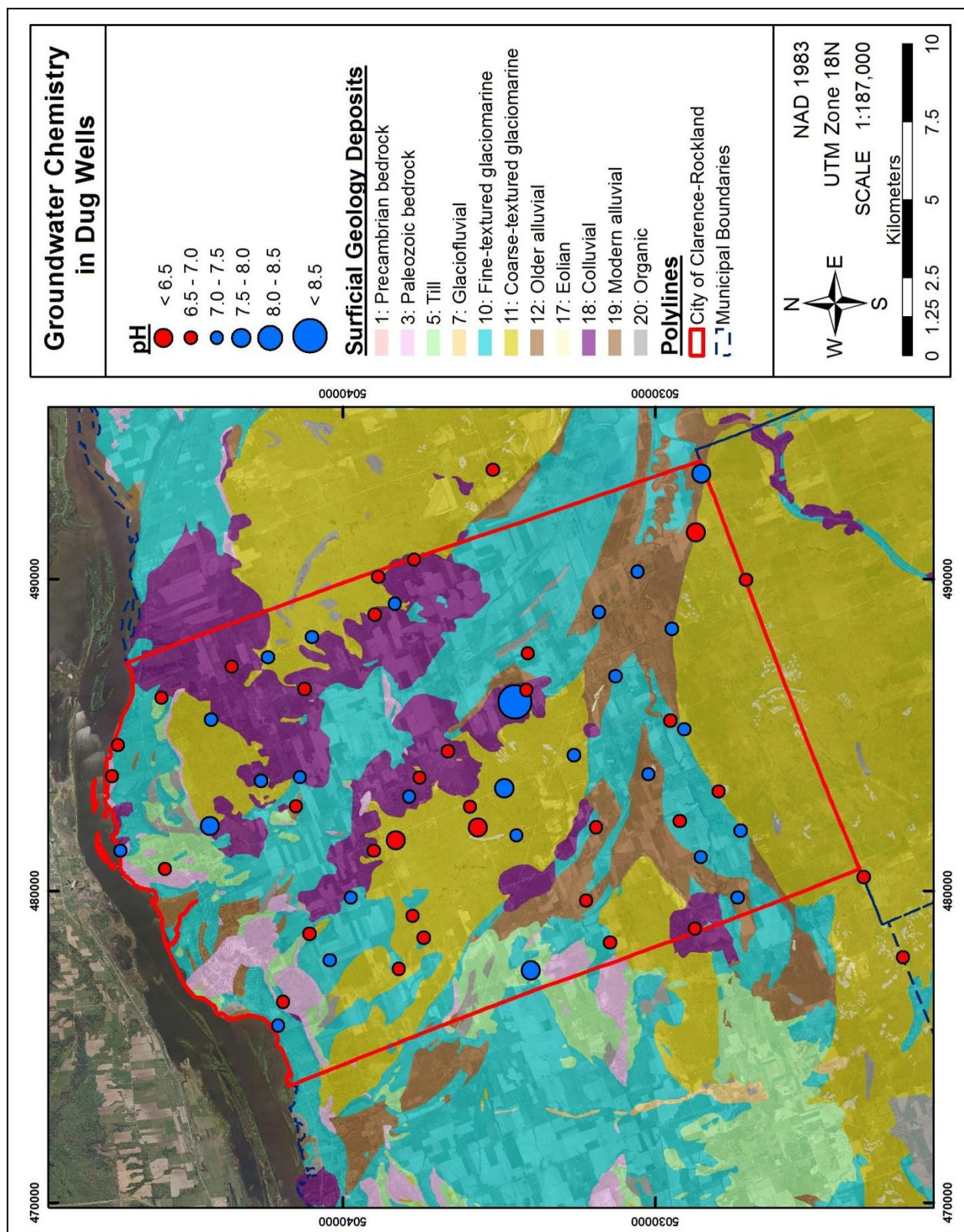


Figure A2-6. pH of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Red circles indicate acidic conditions and blue circles indicate basic conditions.

A2.7 Oxidation Reduction Potential in Drilled Wells

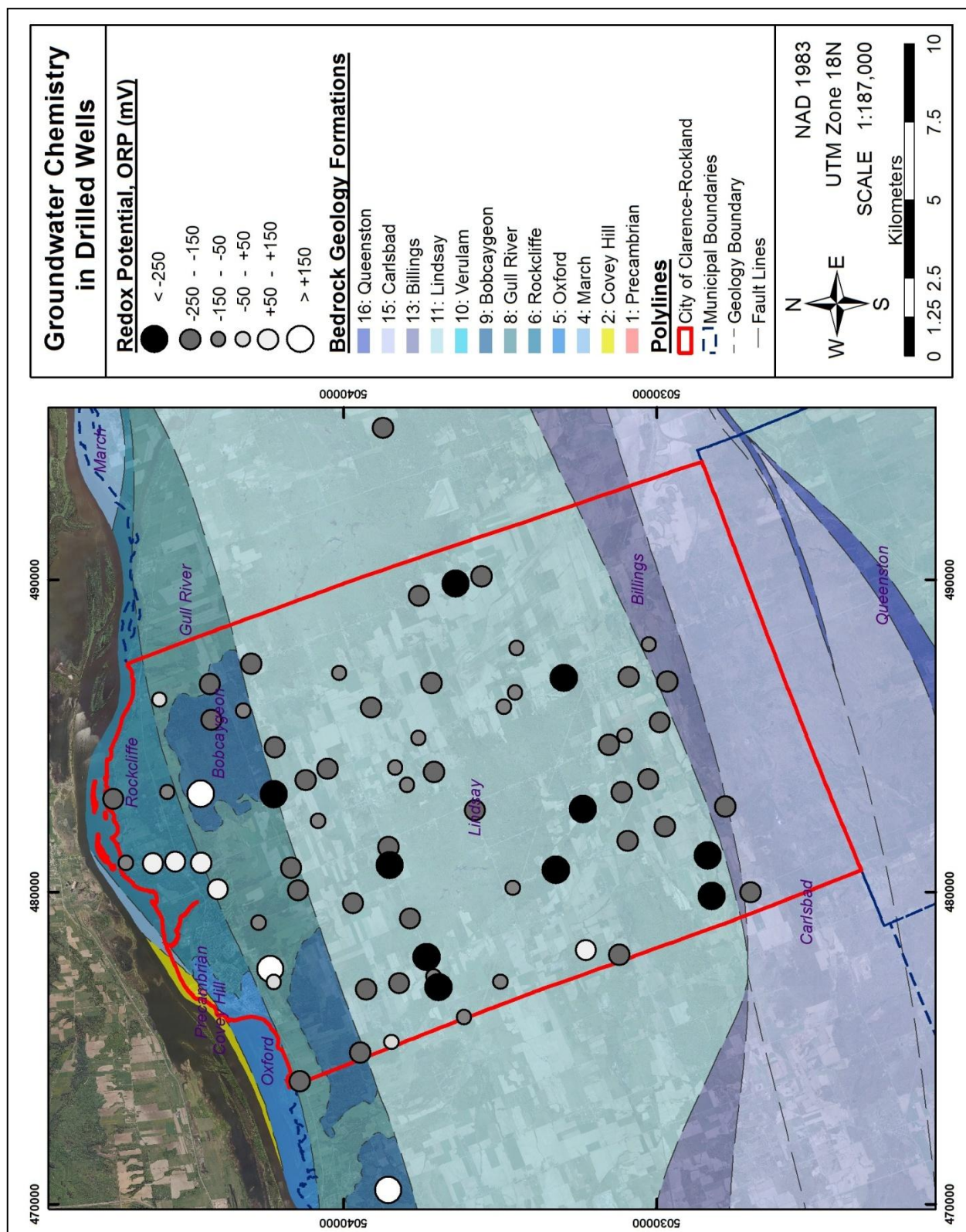


Figure A2-7. Oxidation Reduction Potential (ORP) of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Black and grey circles indicate reducing conditions and white circles indicate oxidizing conditions.

A2.8 Oxidation Reduction Potential in Drilled Wells

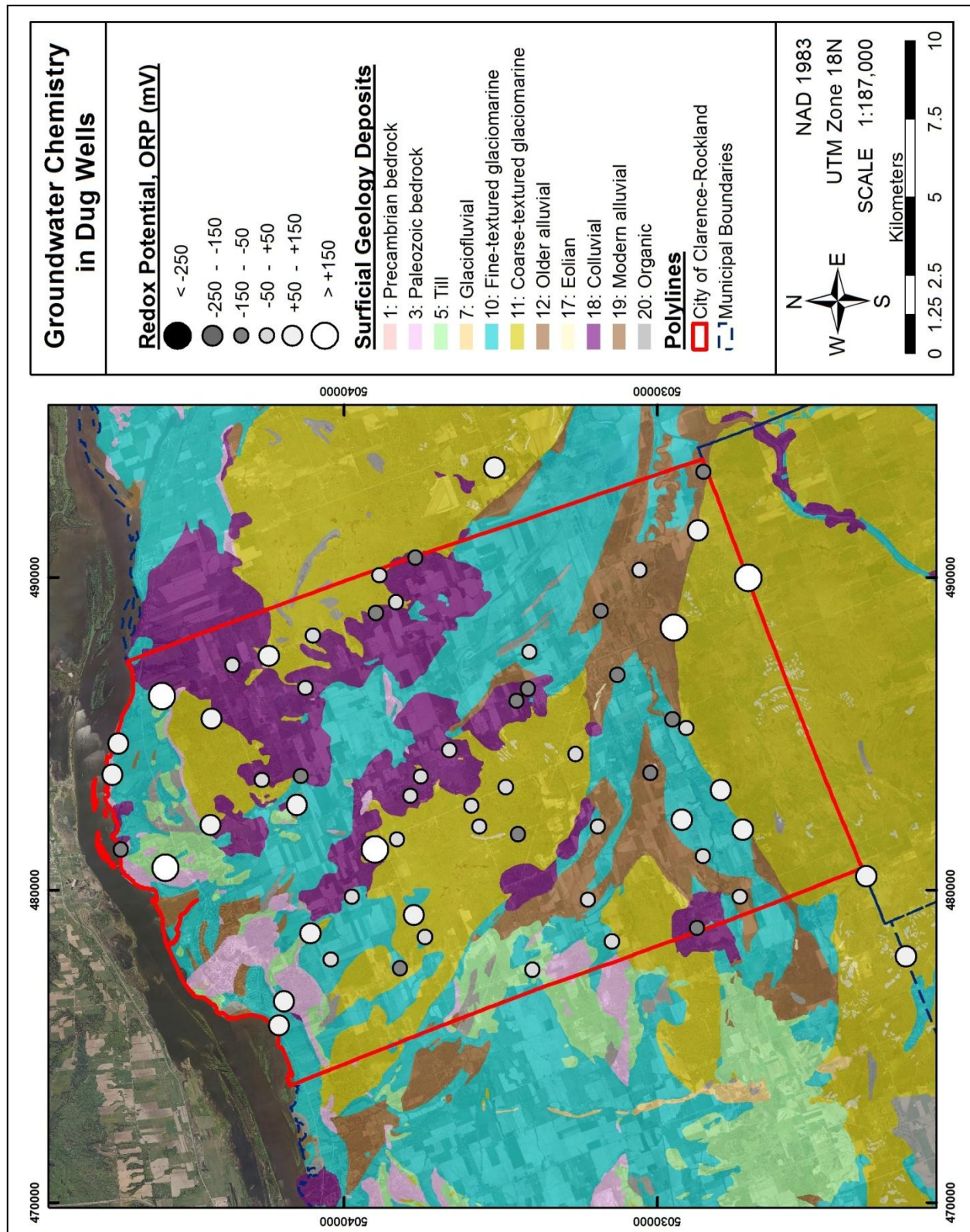


Figure A2-8. Oxidation Reduction Potential (ORP) of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Black and grey circles indicate reducing conditions and white circles indicate oxidizing conditions.

A2.9 Alkalinity in Drilled Wells

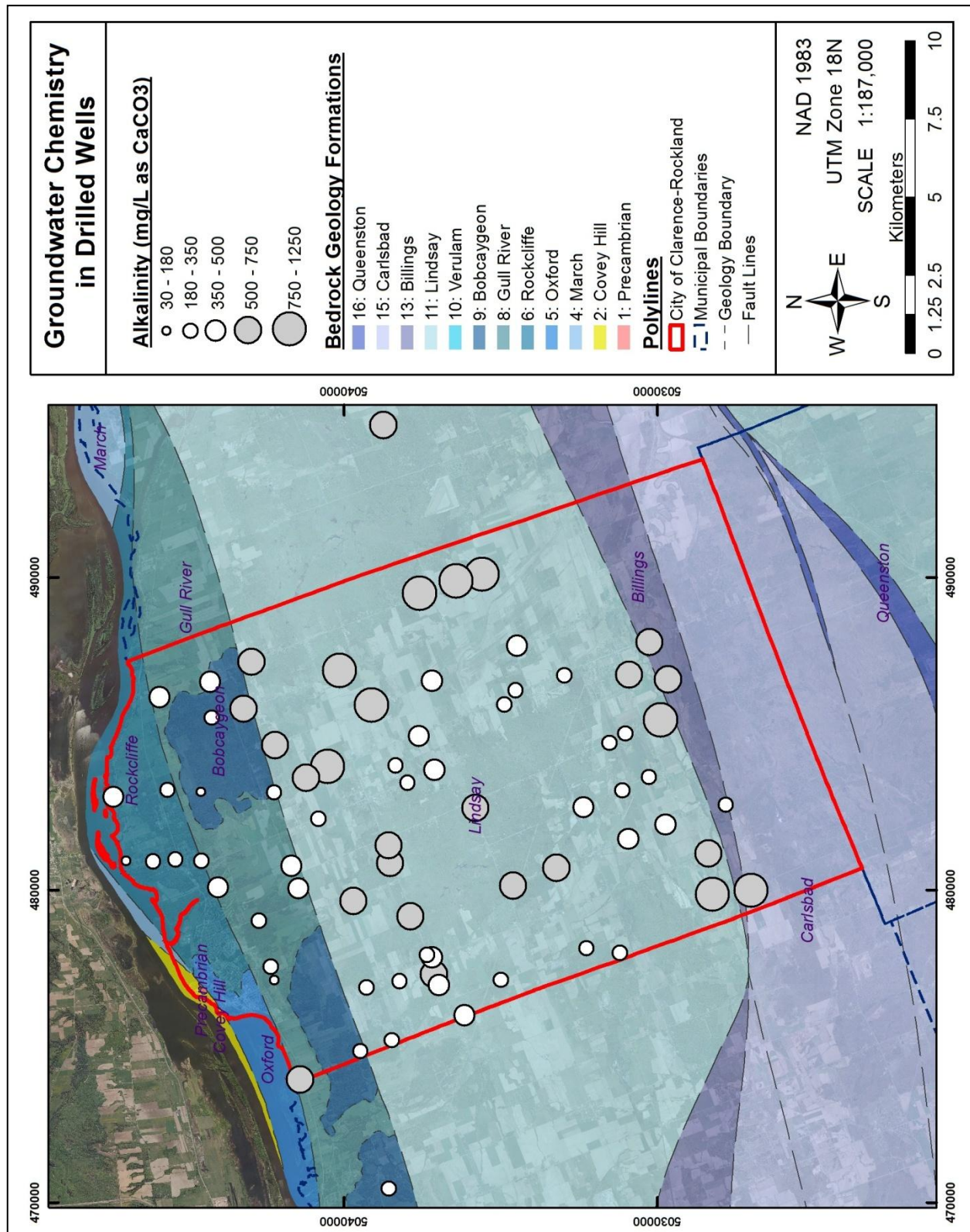


Figure A2-9. Alkalinity of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the operational guideline (30-500 mg/L as CaCO₃).

A2.10 Alkalinity in Dug Wells

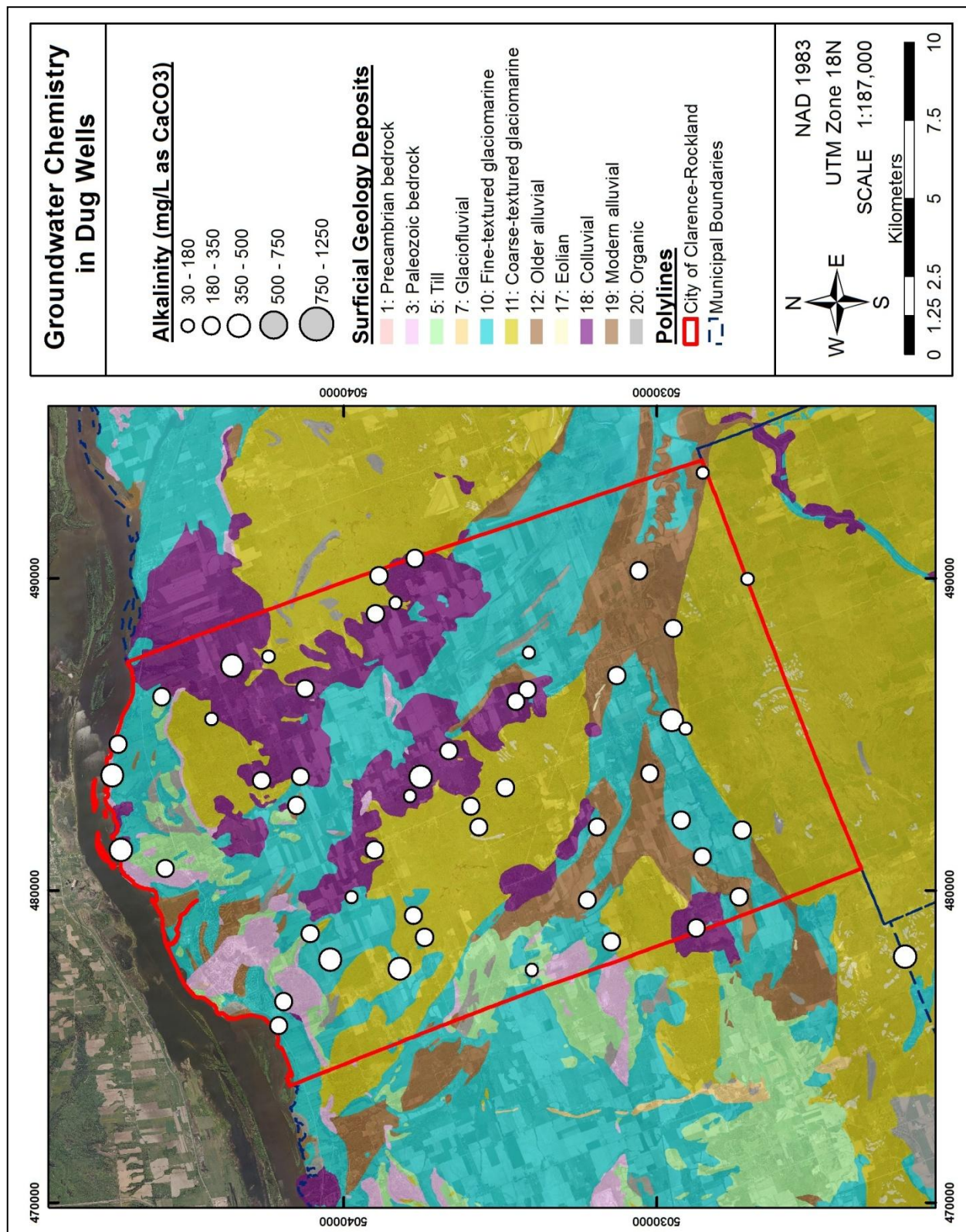


Figure A2-10. Alkalinity of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the operational guideline (30-500 mg/L as CaCO₃).

A2.11 Hardness in Drilled Wells

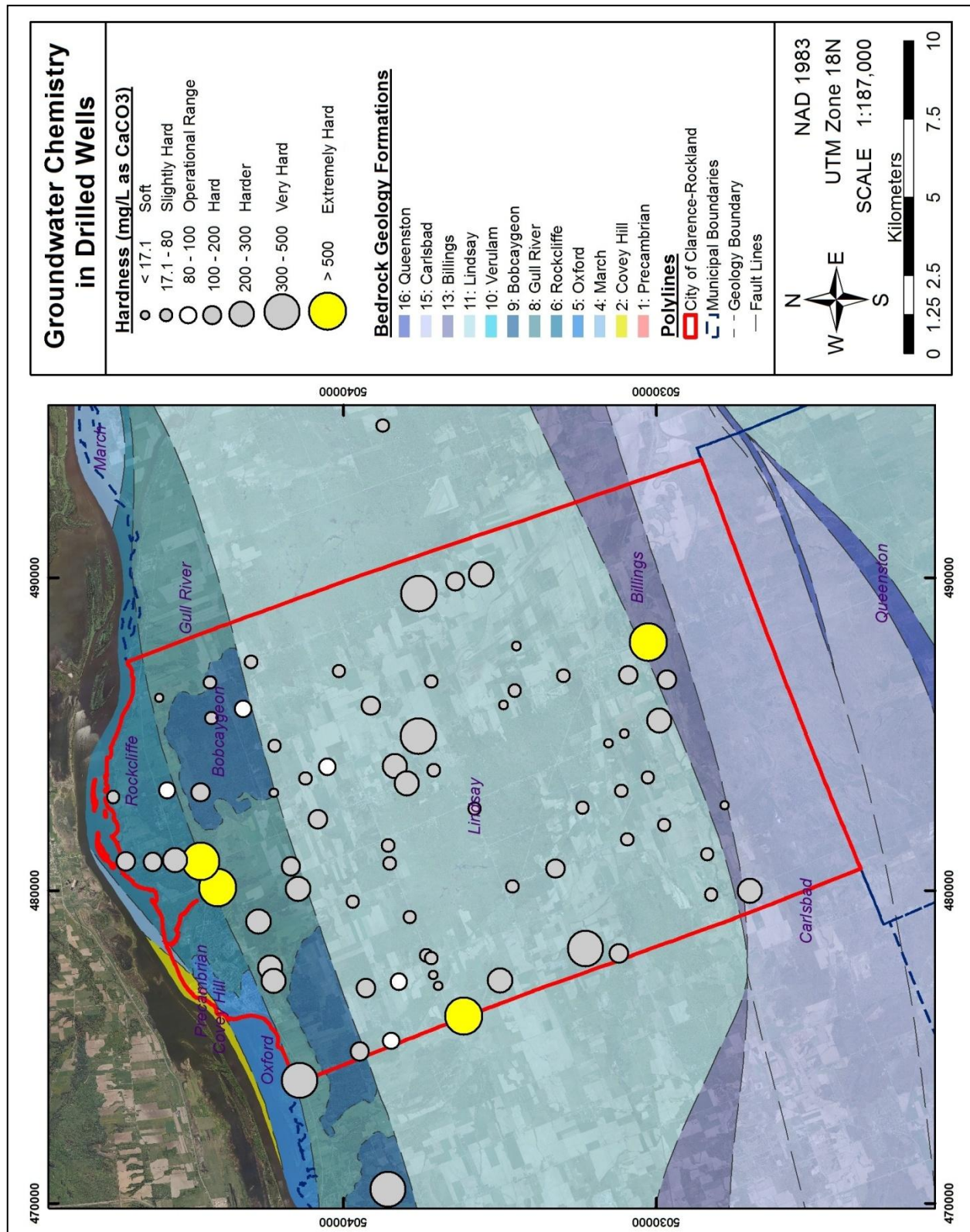


Figure A2-11. Hardness of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the operational guideline (80-100 mg/L as CaCO₃). Yellow circles indicate levels of hardness that will cause sodium exceedances when softened.

A2.12 Hardness in Dug Wells

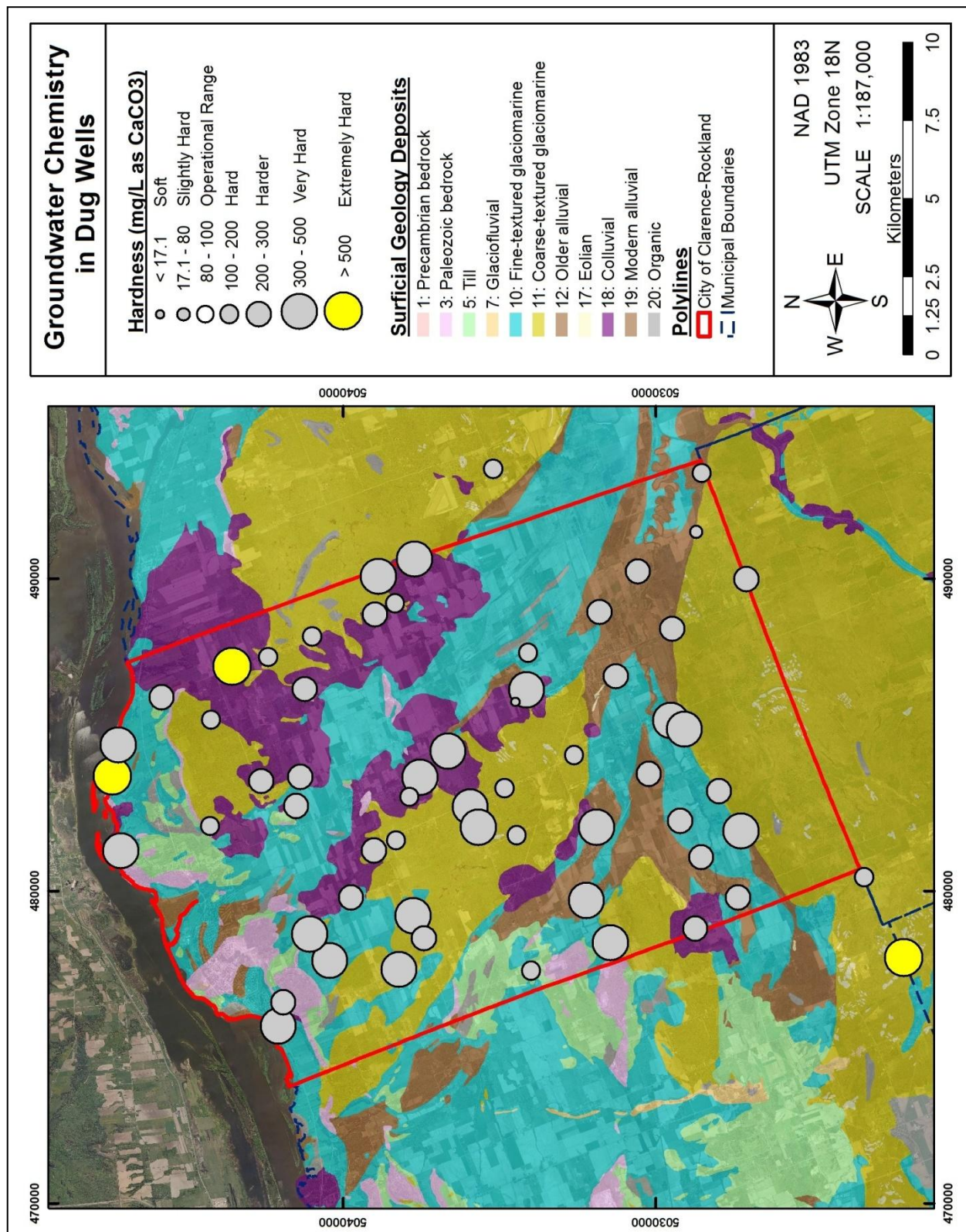


Figure A2-12. Hardness of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the operational guideline (80-100 mg/L as CaCO₃). Yellow circles indicate levels of hardness that will cause sodium exceedances when softened.

A2.13 Total Dissolved Solids in Drilled Wells

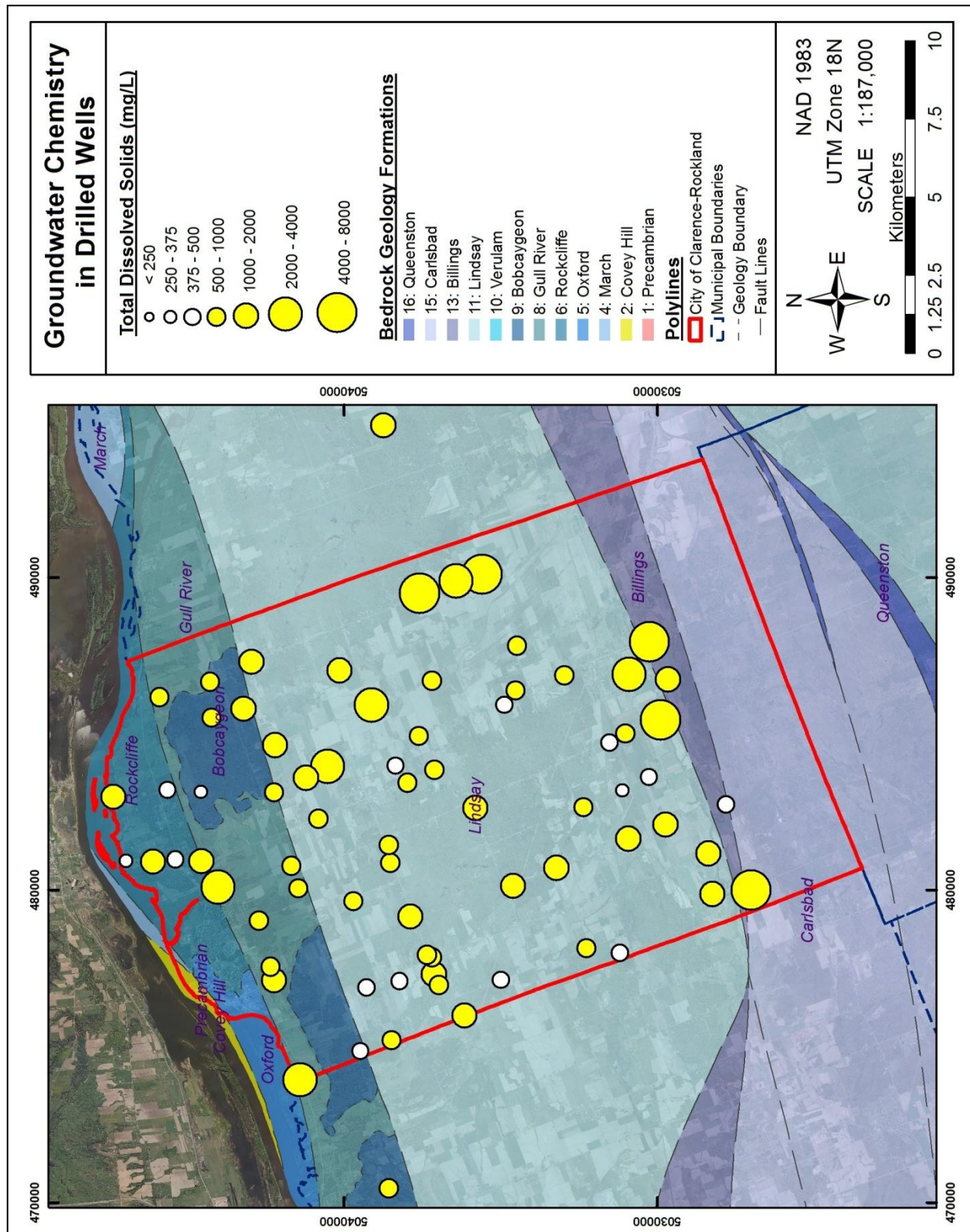


Figure A2-13. Total dissolved solids concentrations of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (500 mg/L).

A2.14 Total Dissolved Solids in Dug Wells

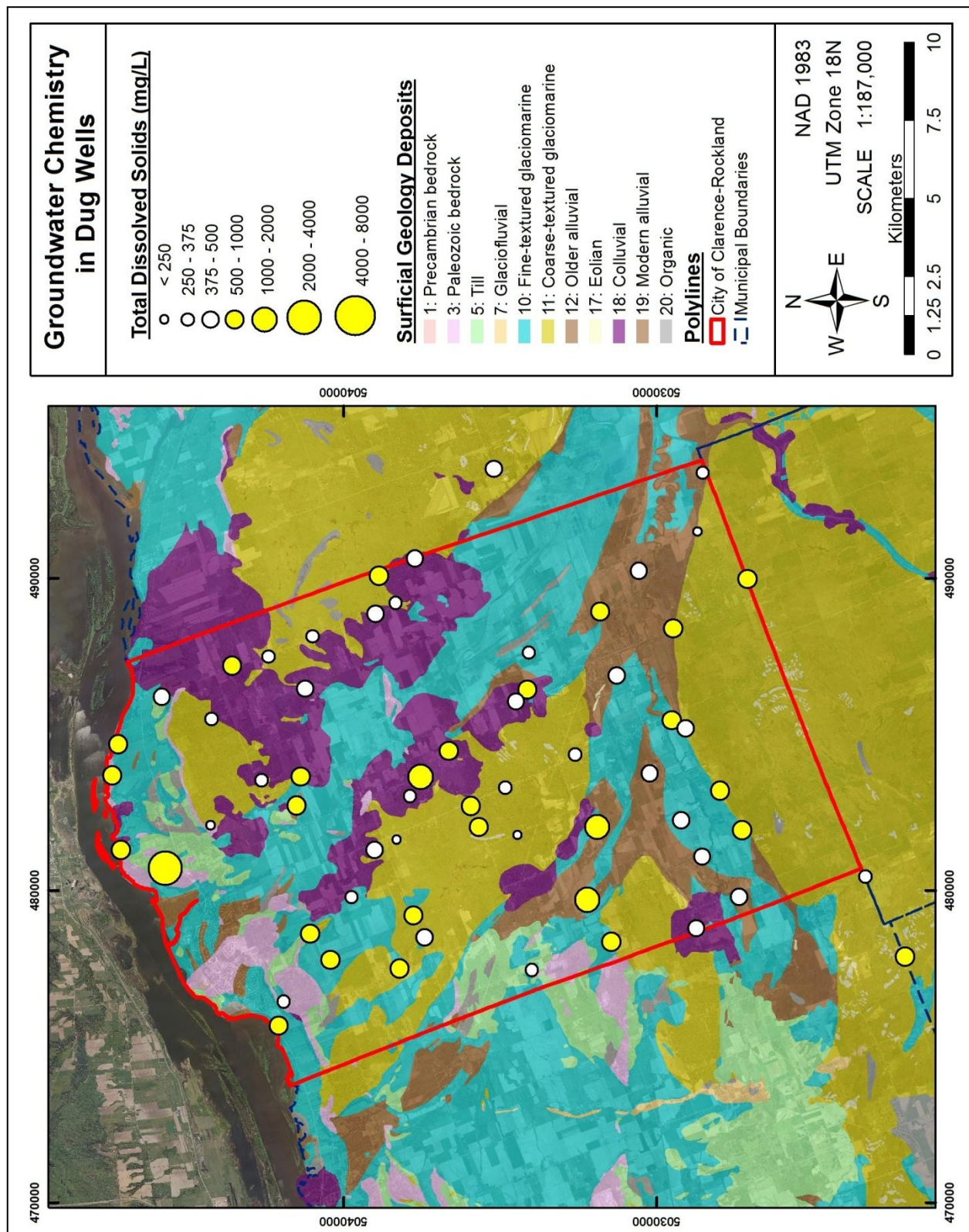


Figure A2-14. Total dissolved solids concentrations of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (500 mg/L).

A2.15 Colour in Drilled Wells

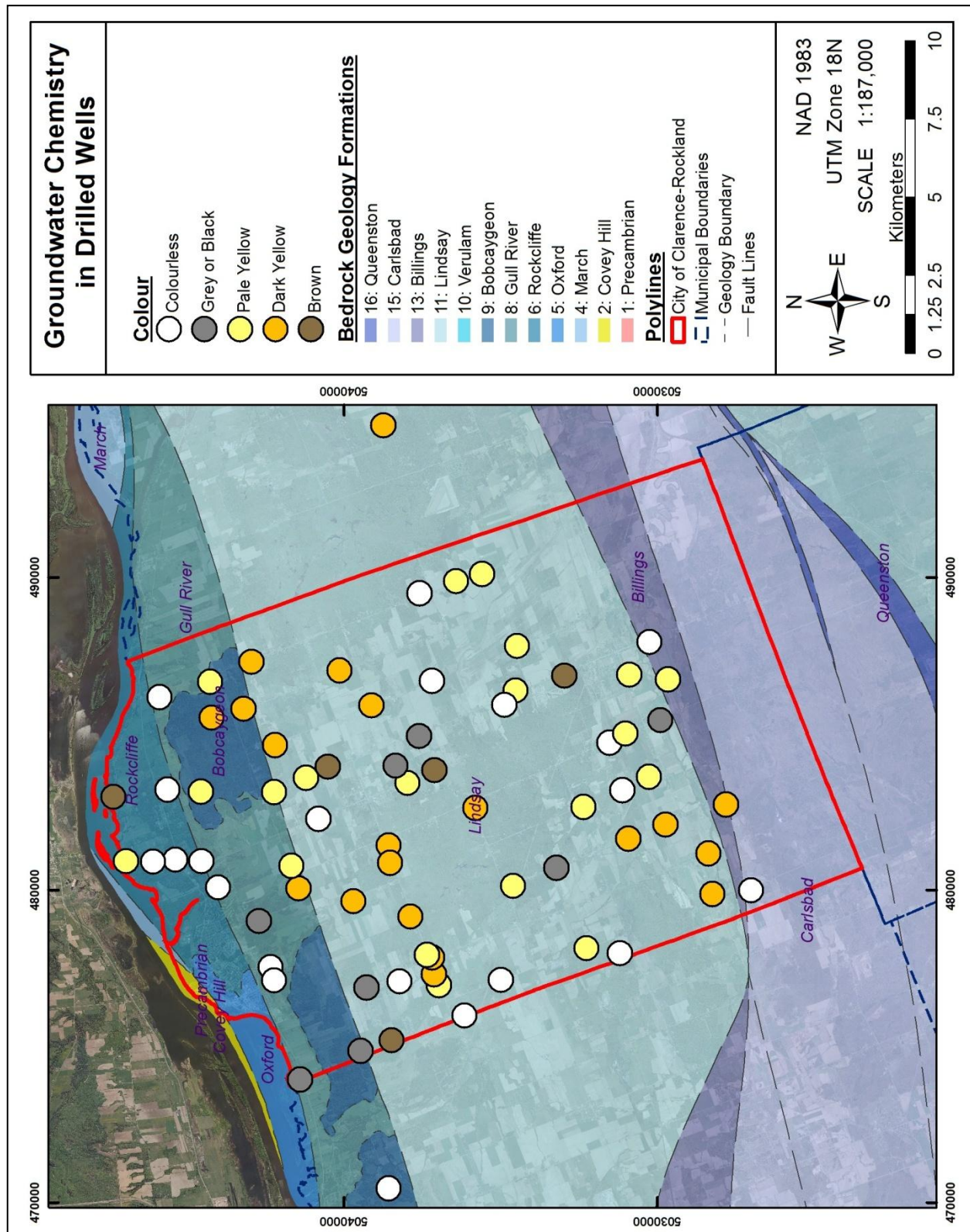


Figure A2-15. Apparent colour of groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.16 Colour in Dug Wells

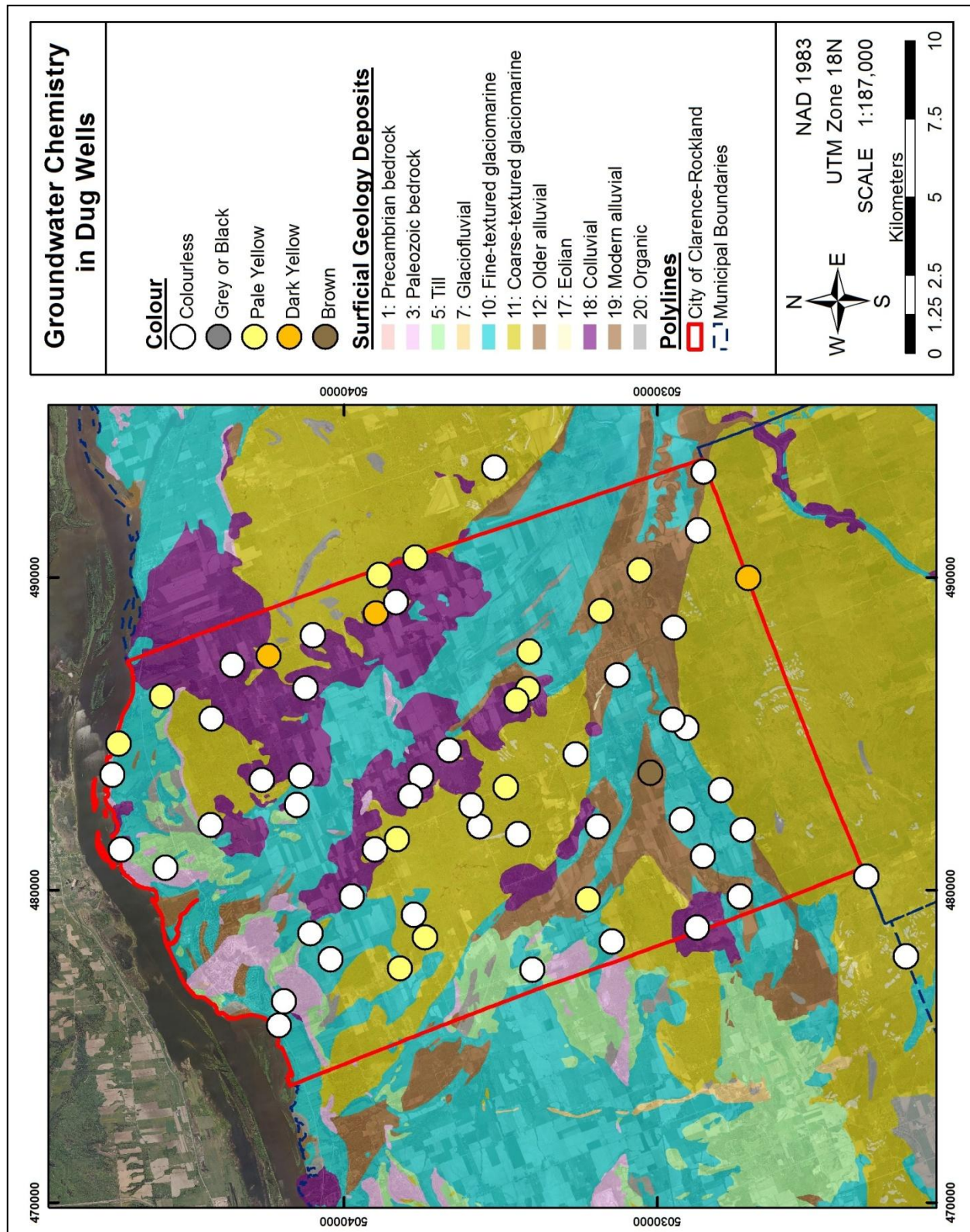


Figure A2-16. Apparent colour of groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.17 Total Coliform Bacteria in Drilled Wells

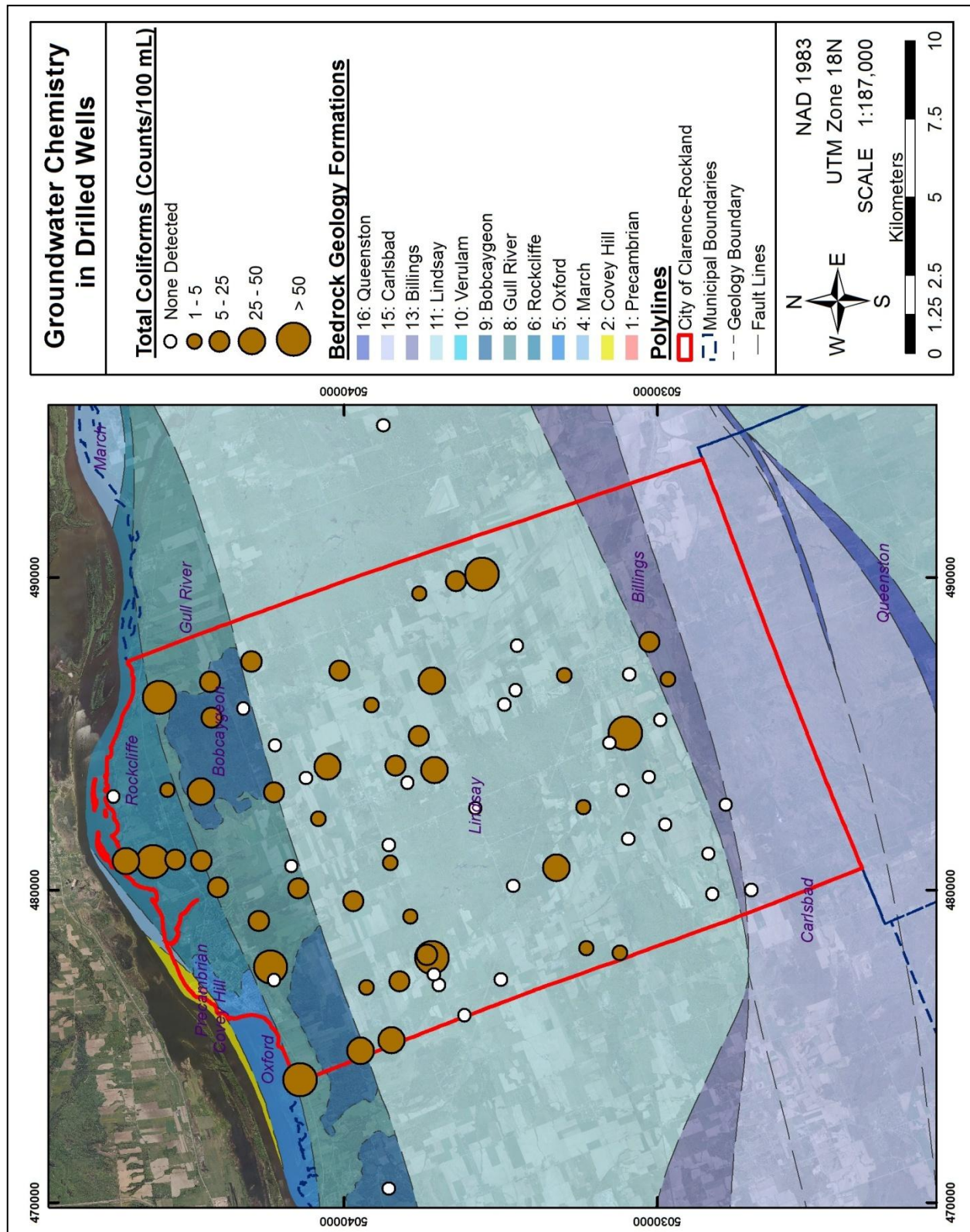


Figure A2-17. Total Coliform bacteria counts in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Brown circles indicate the presence of Coliform bacteria.

A2.18 Total Coliform Bacteria in Dug Wells

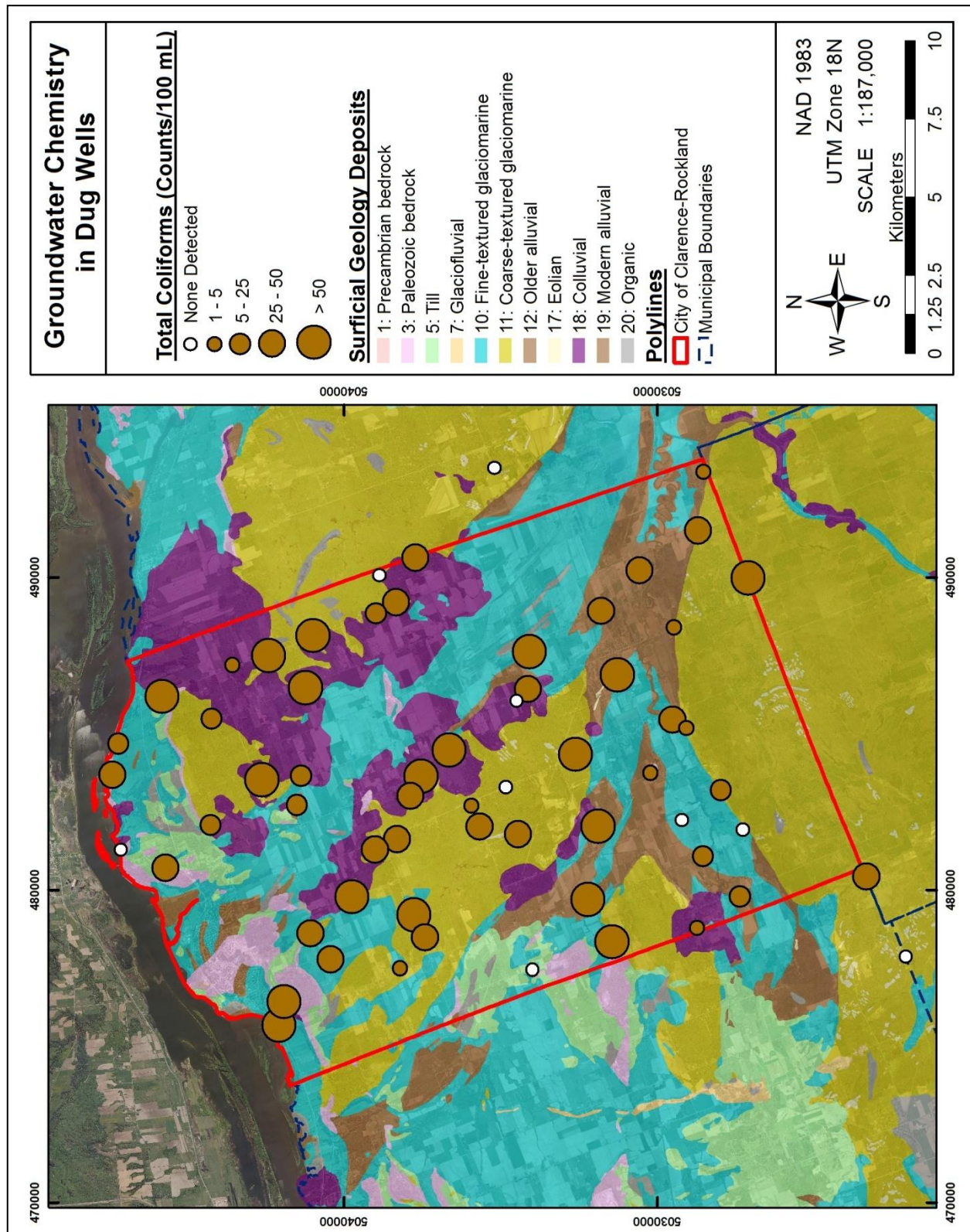


Figure A2-18. Total Coliform bacteria counts in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Brown circles indicate the presence of Coliform bacteria.

A2.19 Fecal Coliform Bacteria in Drilled Wells

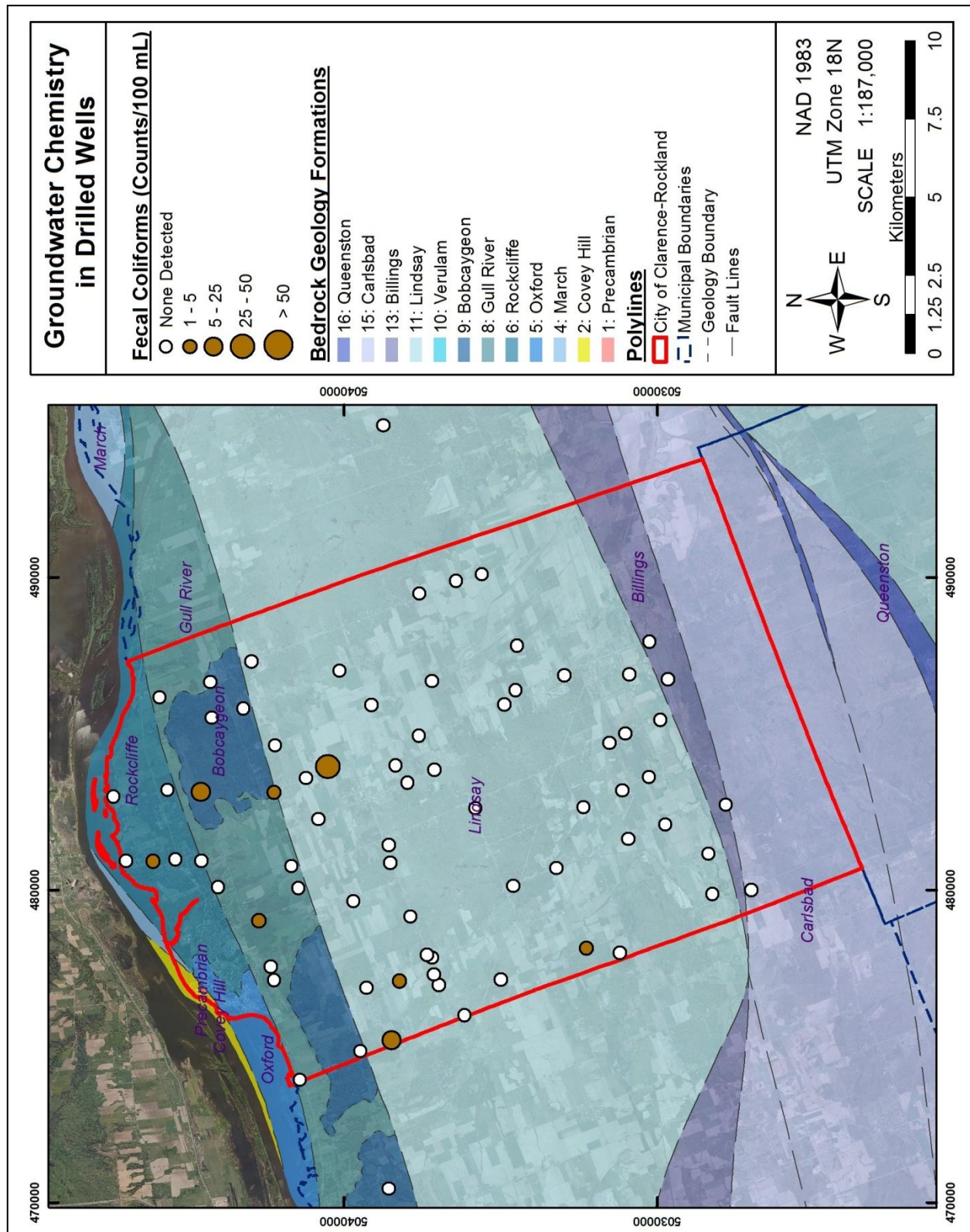


Figure A2-19. Fecal Coliform bacteria counts in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Brown circles indicate the presence of fecal Coliform bacteria.

A2.20 Fecal Coliform Bacteria in Dug Wells

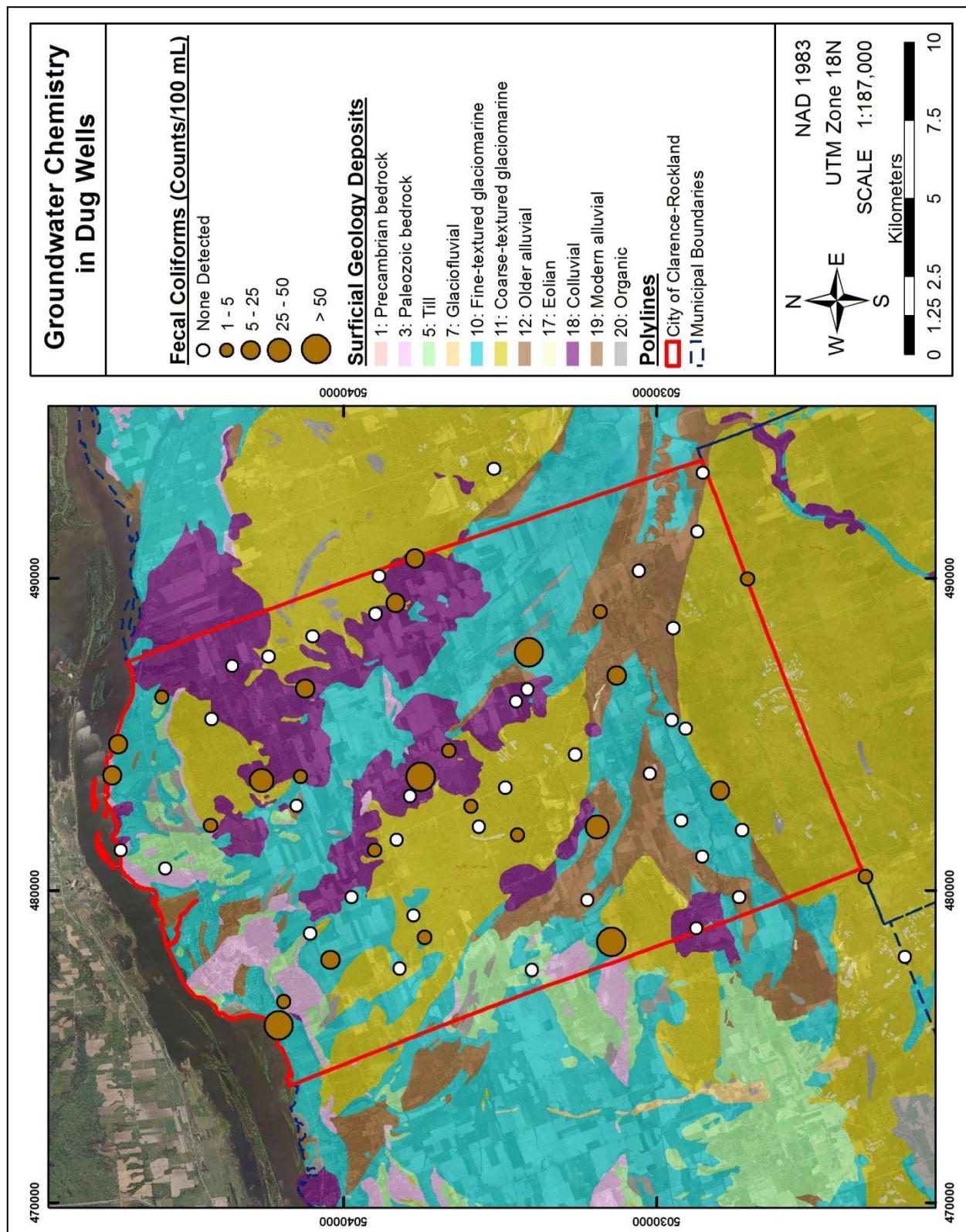


Figure A2-20. Fecal Coliform bacteria counts in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Brown circles indicate the presence of fecal Coliform bacteria.

A2.21 Methane Gas (Dissolved) in Drilled Wells

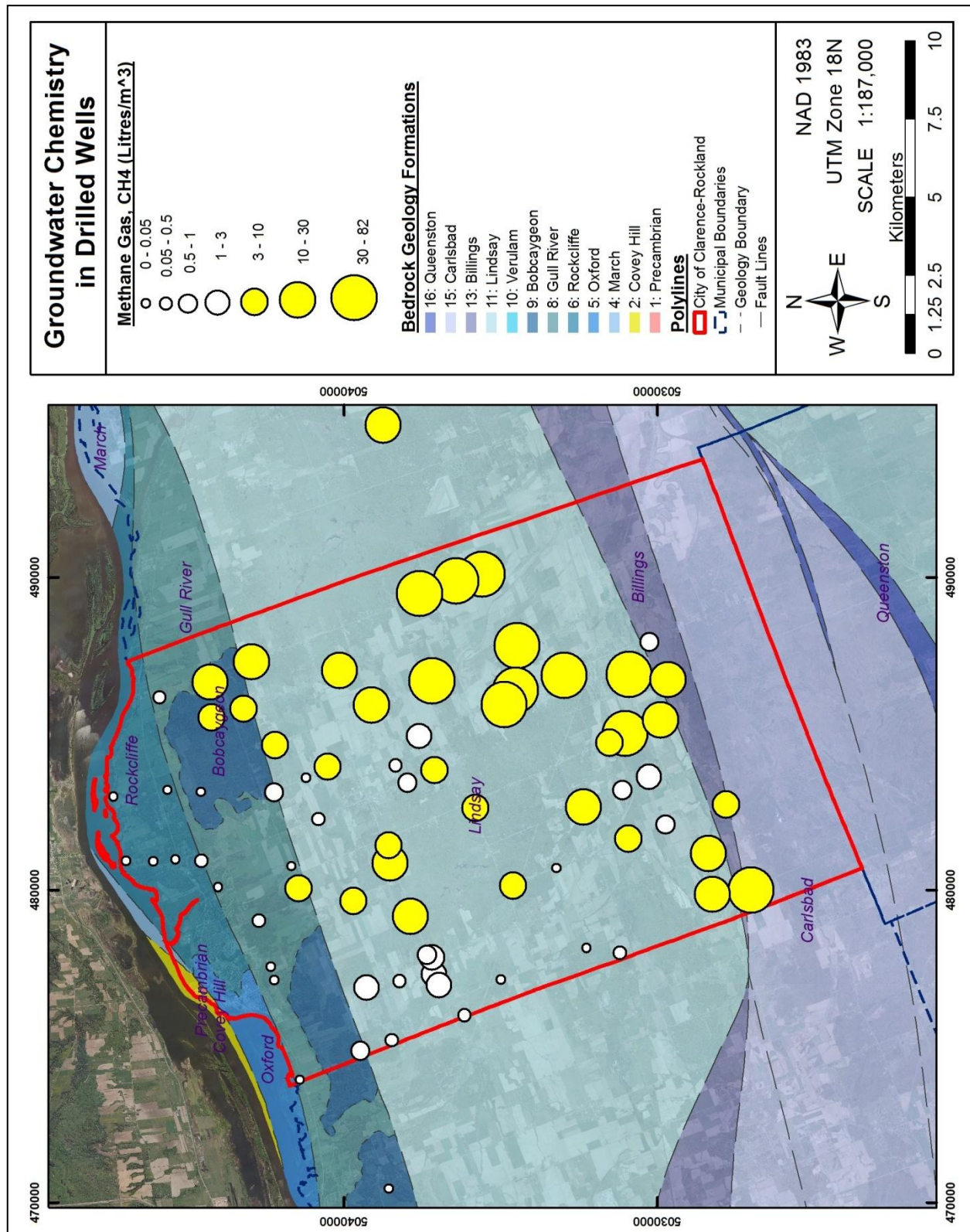


Figure A2-21. Methane gas concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (3 L/m³).

A2.22 Methane Gas (Dissolved) in Dug Wells

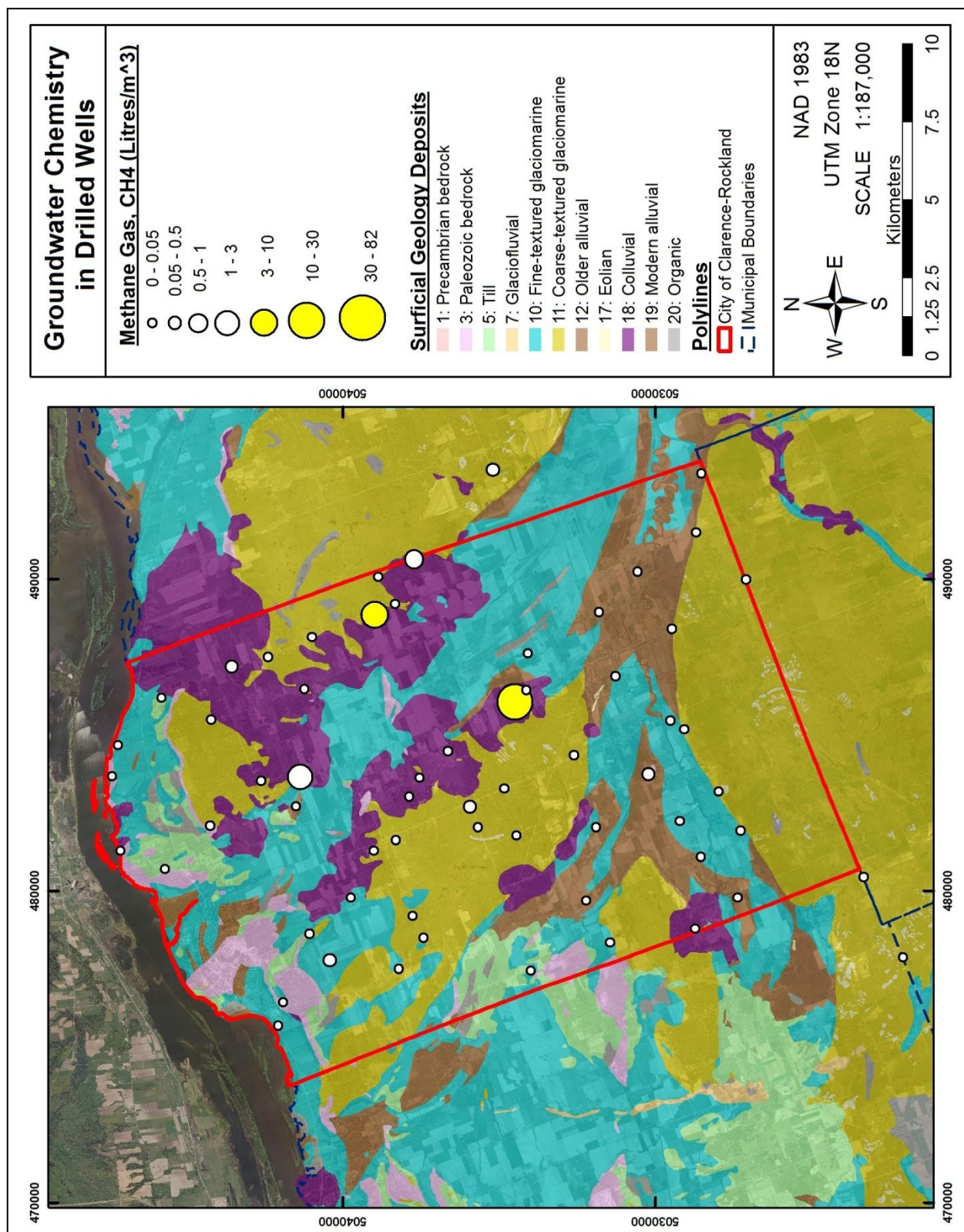


Figure A2-22. Methane gas concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (3 L/m³).

A2.23 Dissolved Organic Carbon in Drilled Wells

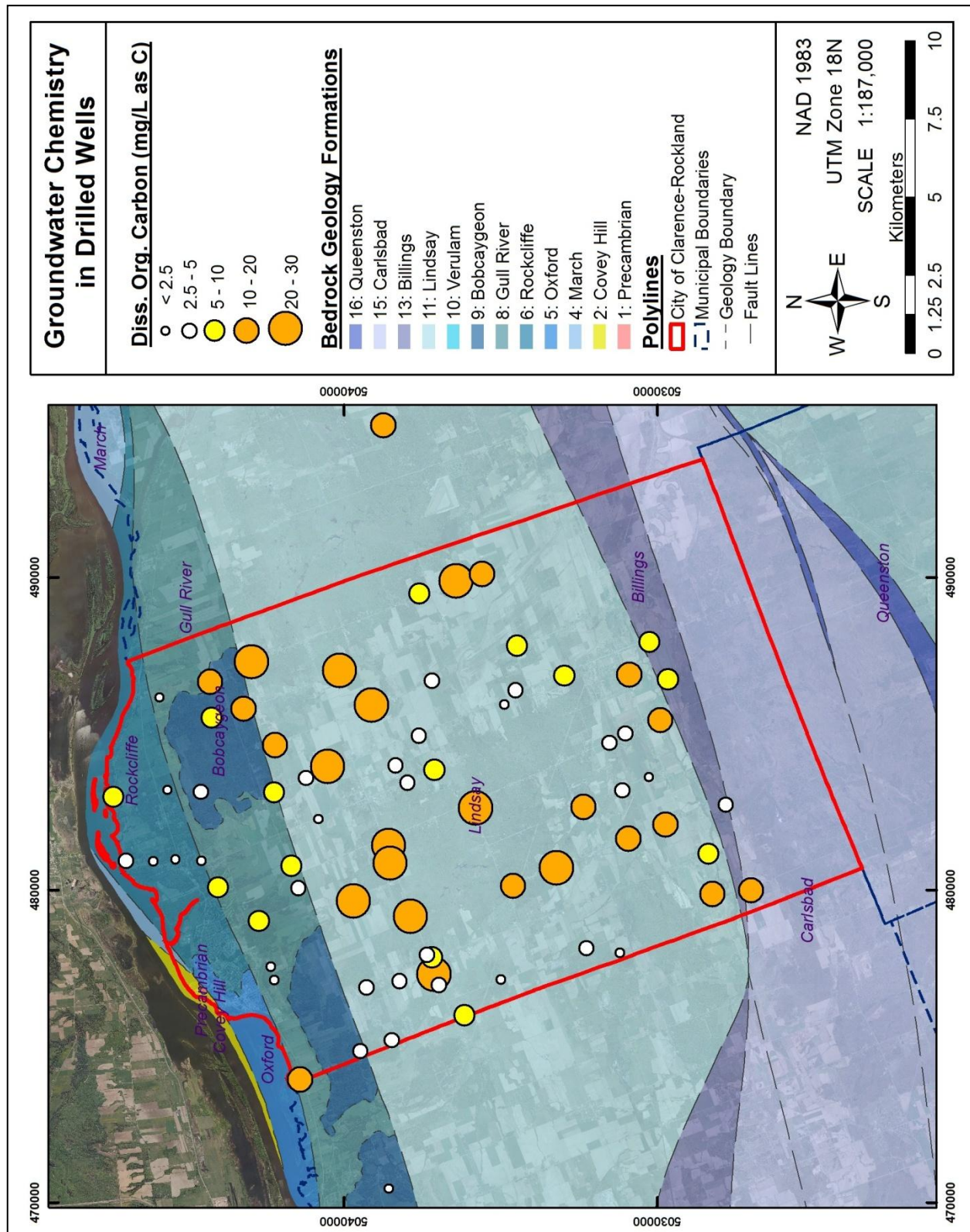


Figure A2-23. Dissolved Organic Carbon in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (5 mg/L as C) and Maximum Concentration Considered Reasonably Treatable (10 mg/L as C).

A2.24 Dissolved Organic Carbon in Dug Wells

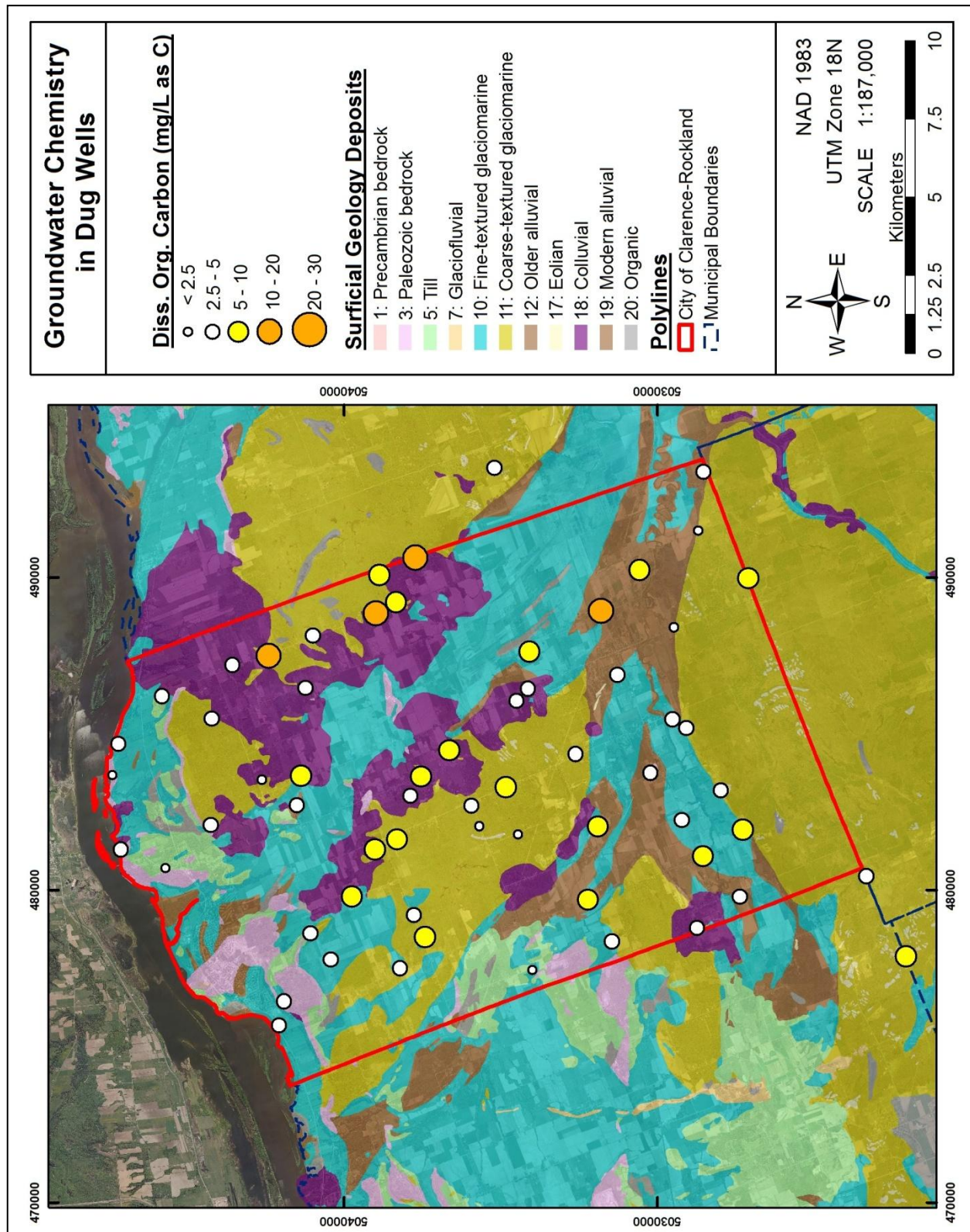


Figure A2-24. Dissolved Organic Carbon in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (5 mg/L as C) and Maximum Concentration Considered Reasonably Treatable (10 mg/L as C).

A2.25 Hydrogen Sulphide in Drilled Wells

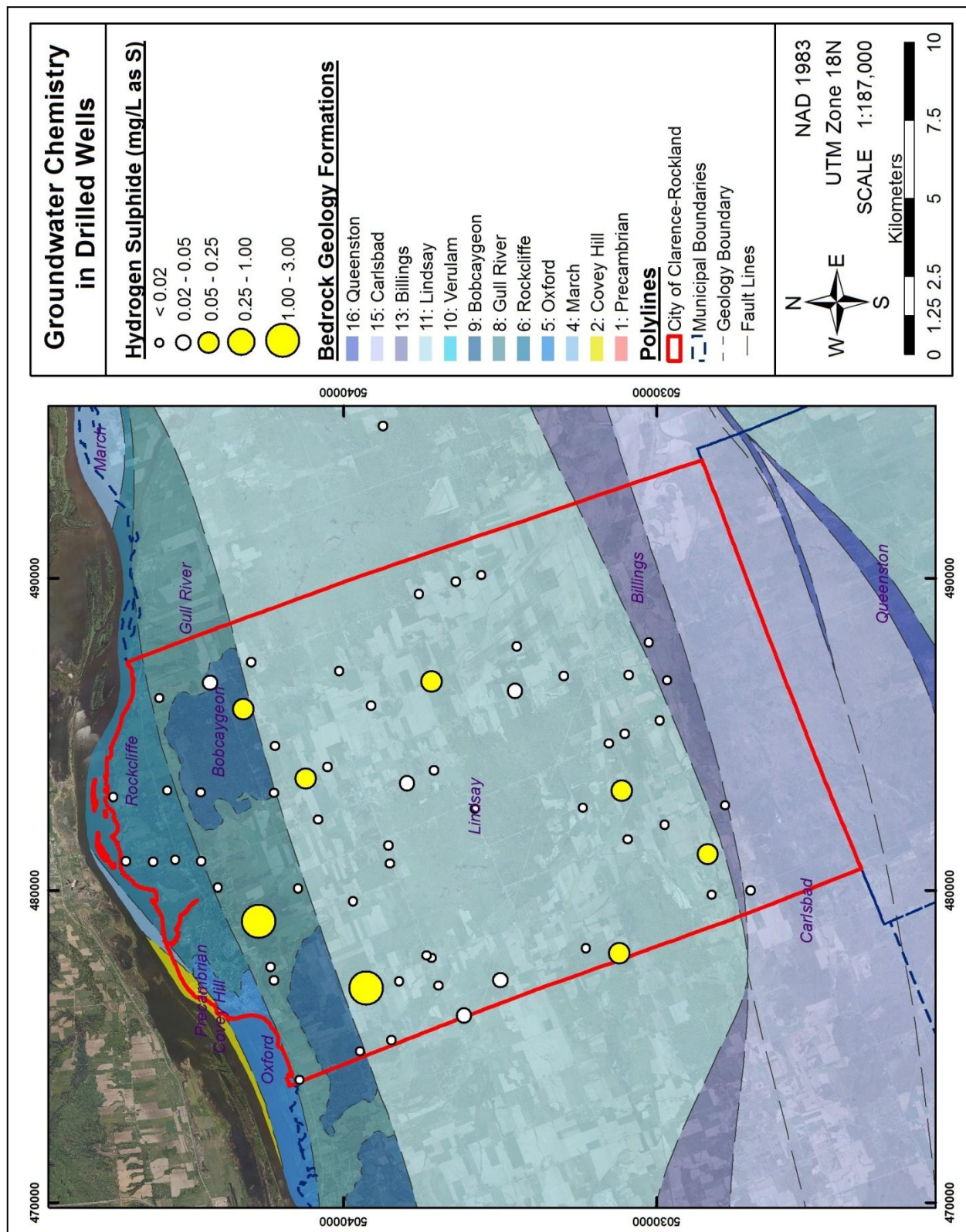


Figure A2-25. Hydrogen sulphide concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (0.05 mg/L as S).

A2.26 Hydrogen Sulphide in Dug Wells

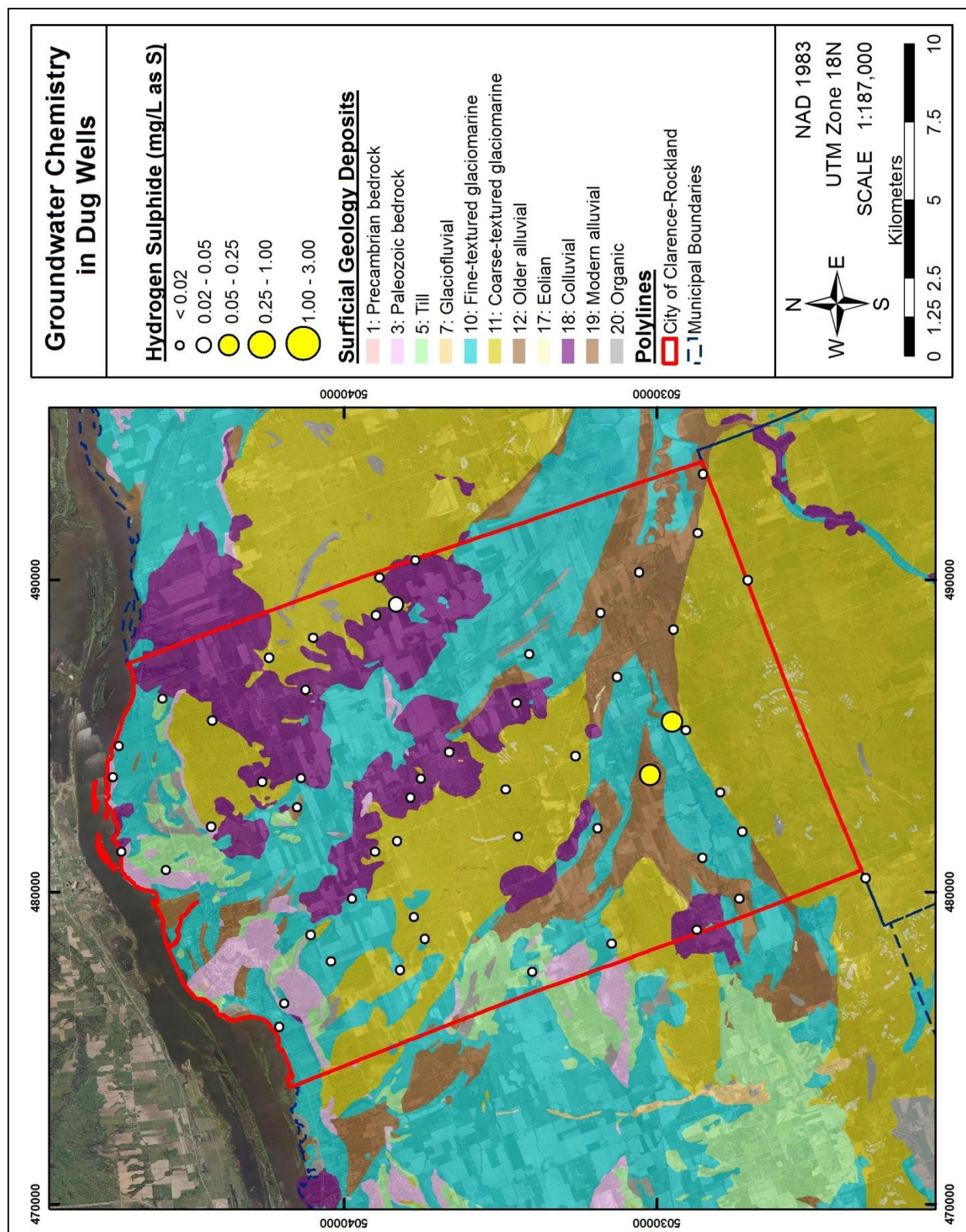


Figure A2-26. Hydrogen sulphide concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow circles indicate exceedances of the Aesthetic Objective (0.05 mg/L as S).

A2.27 Nitrate in Drilled Wells

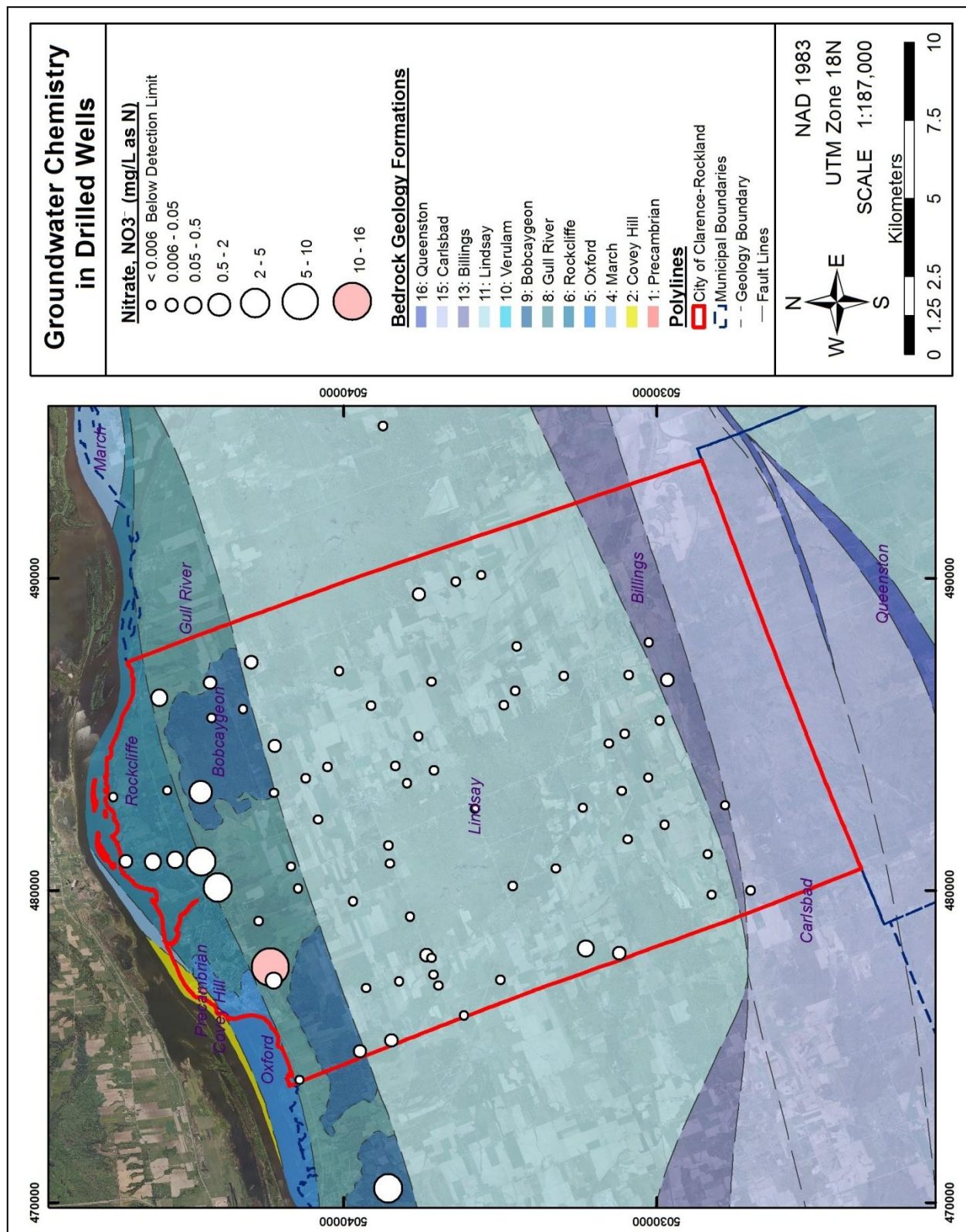


Figure A2-27. Nitrate concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (10 mg/L as N).

A2.28 Nitrate in Dug Wells

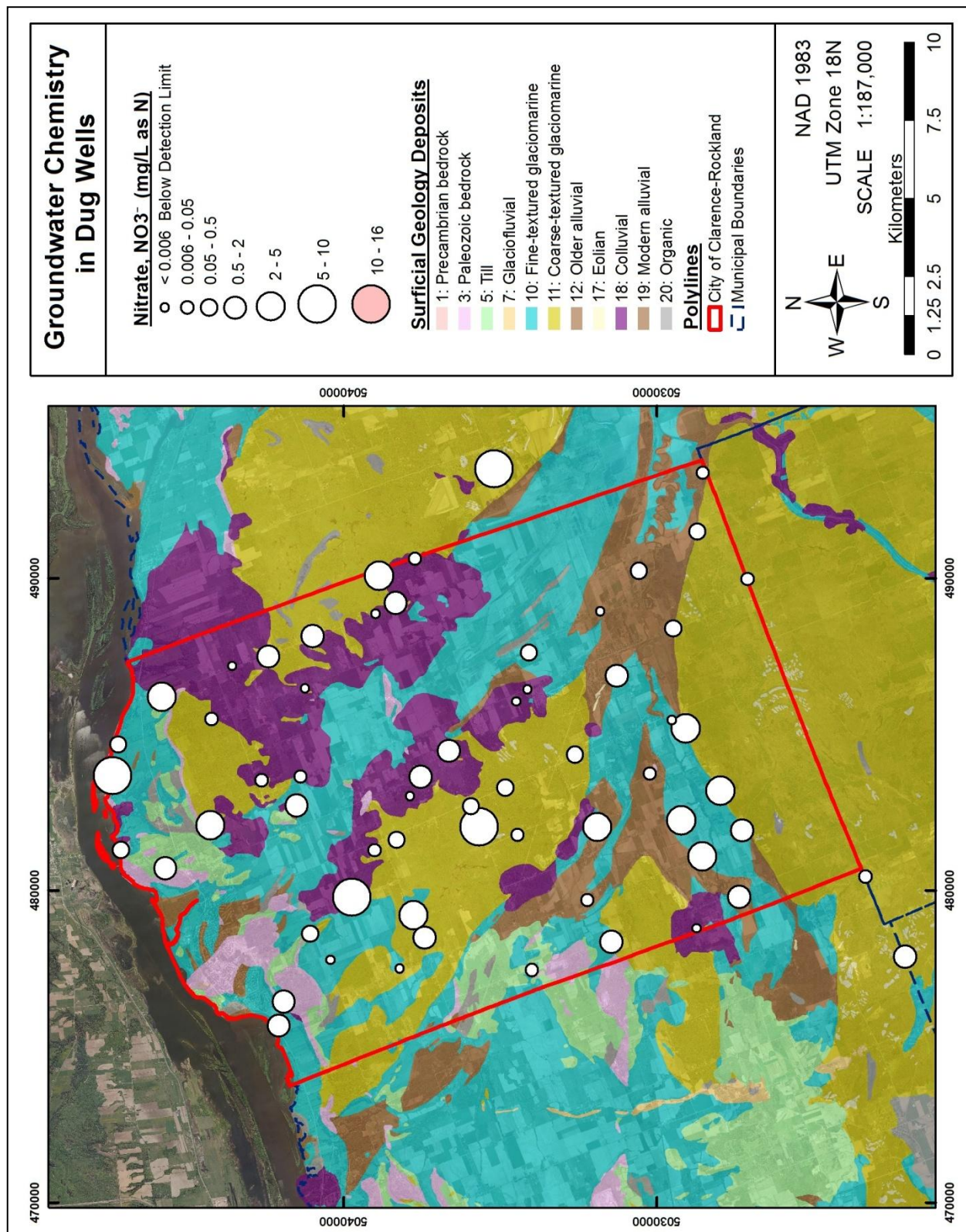


Figure A2-28. Nitrate concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (10 mg/L as N).

A2.29 Ammonia/Ammonium in Drilled Wells

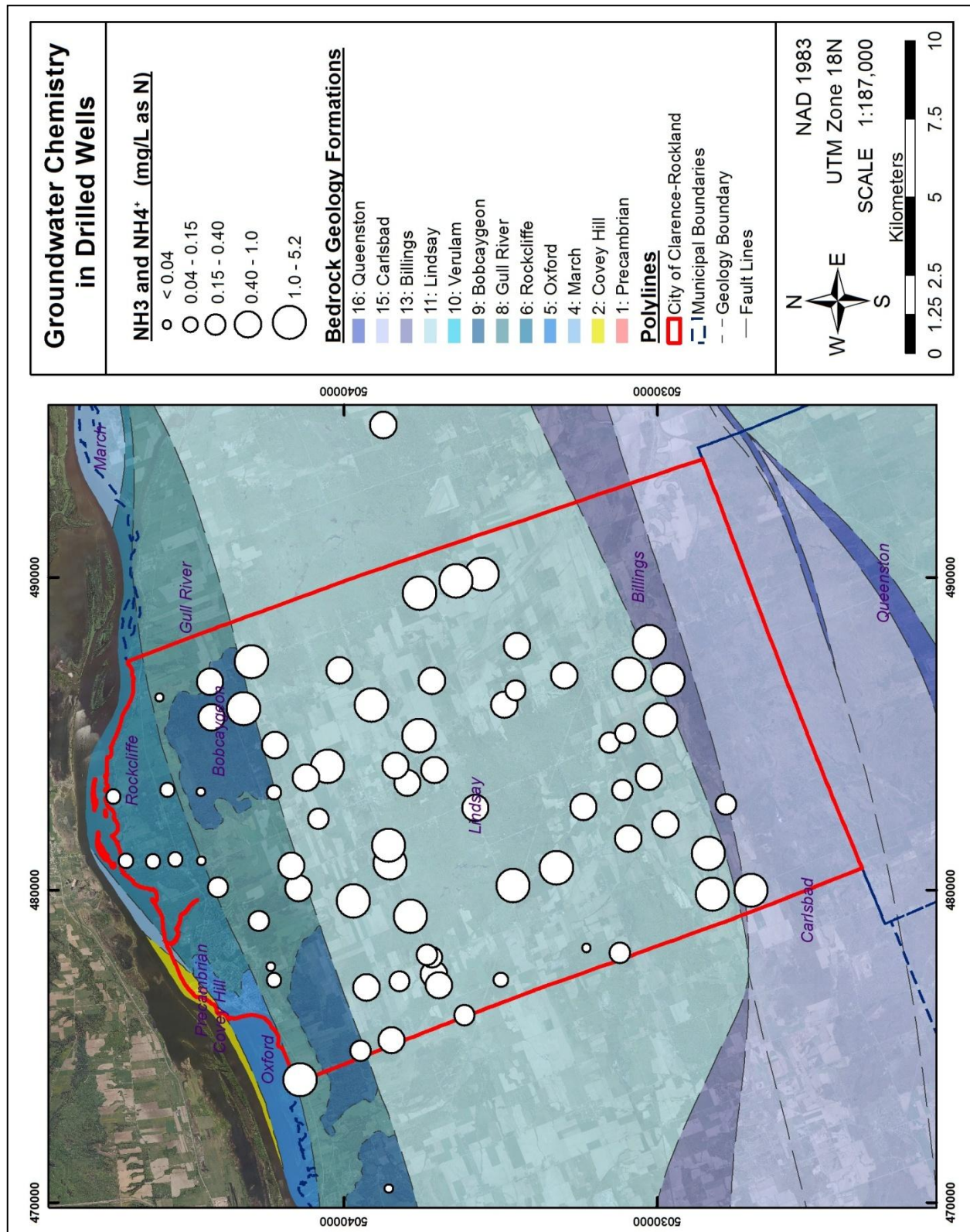


Figure A2-29. Ammonia/ammonium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.30 Ammonia/Ammonium in Dug Wells

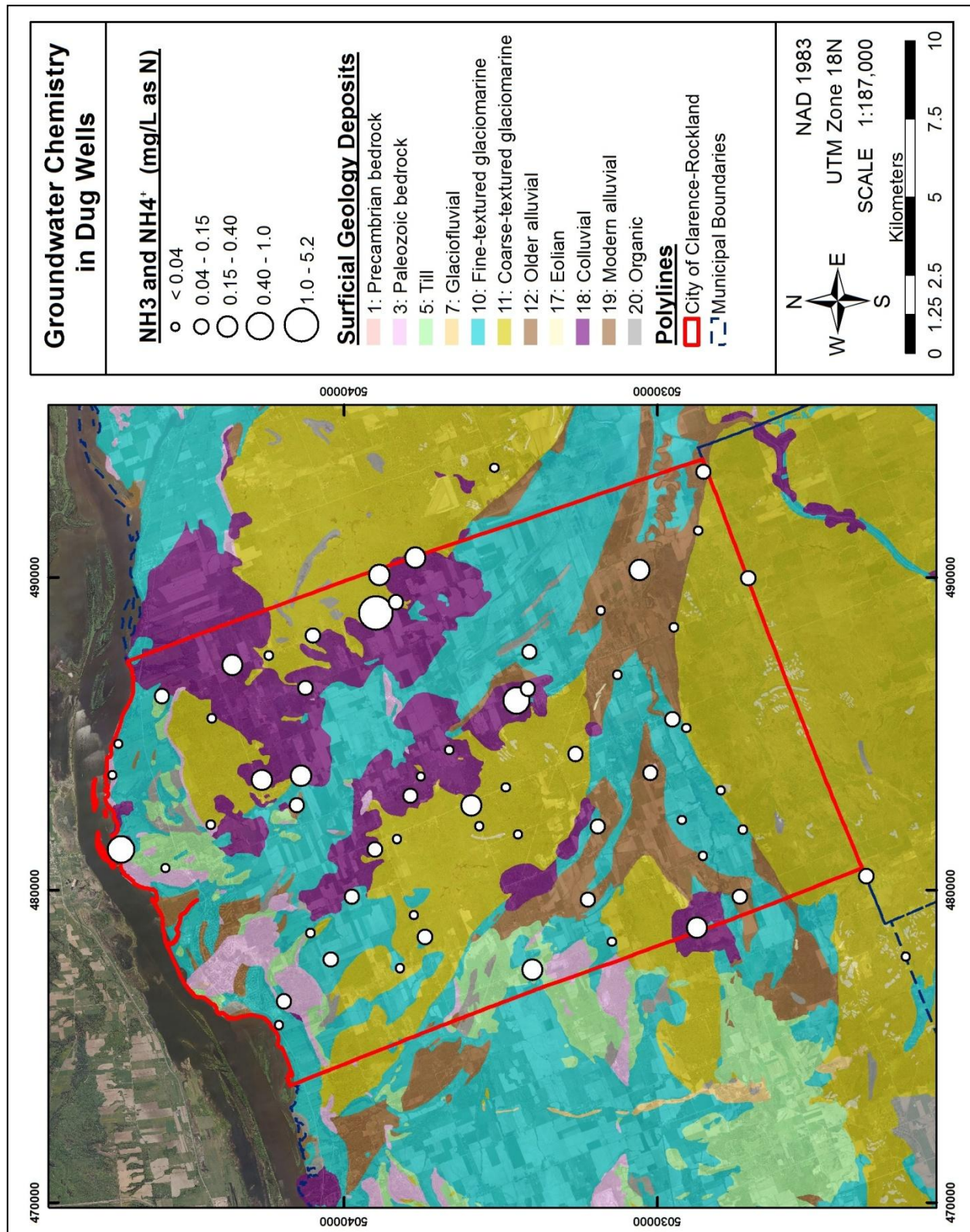


Figure A2-30. Ammonia/ammonium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.31 Organic Nitrogen in Drilled Wells

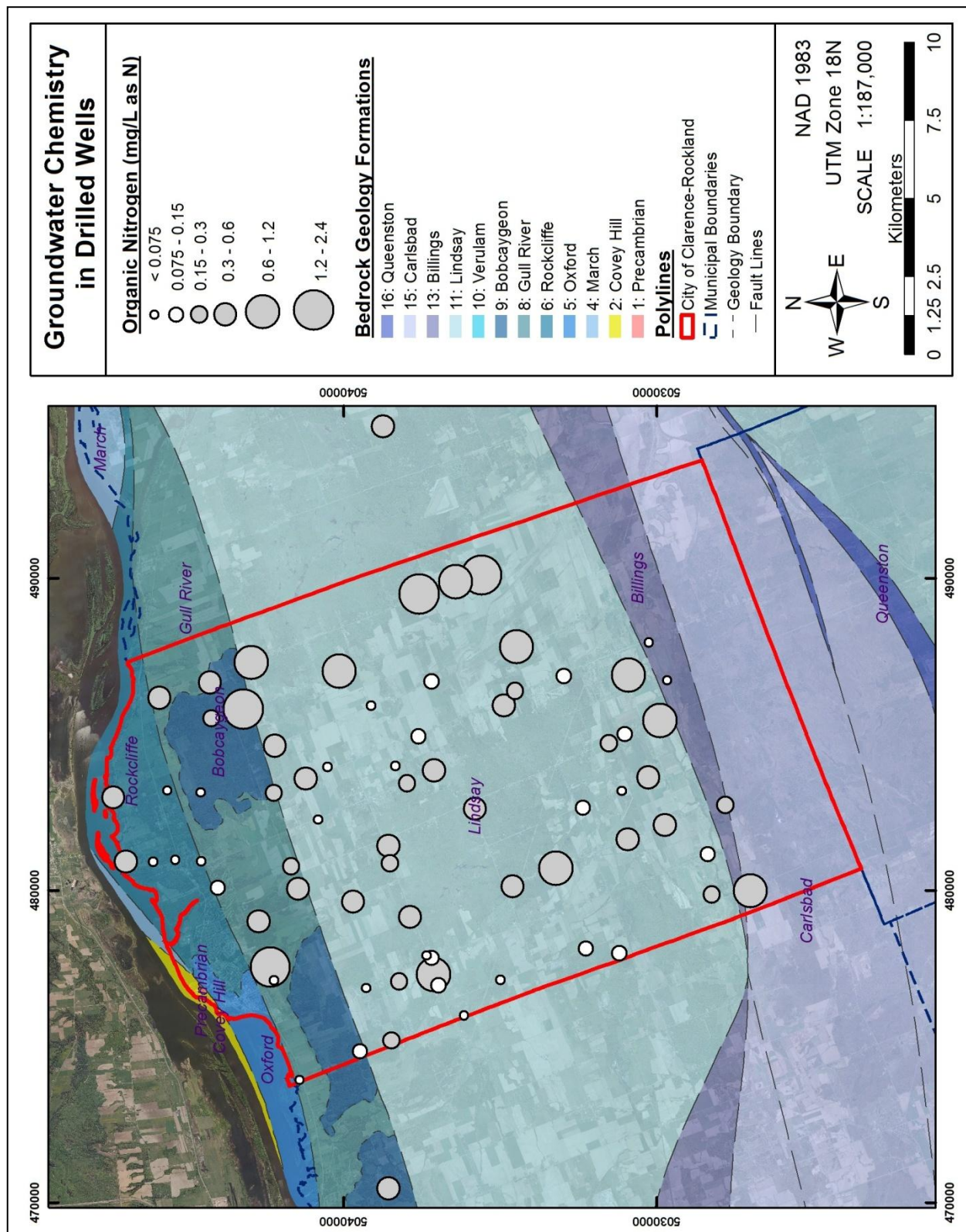


Figure A2-31. Organic Nitrogen concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the Operational Guideline (0.15 mg/L as N).

A2.32 Organic Nitrogen in Dug Wells

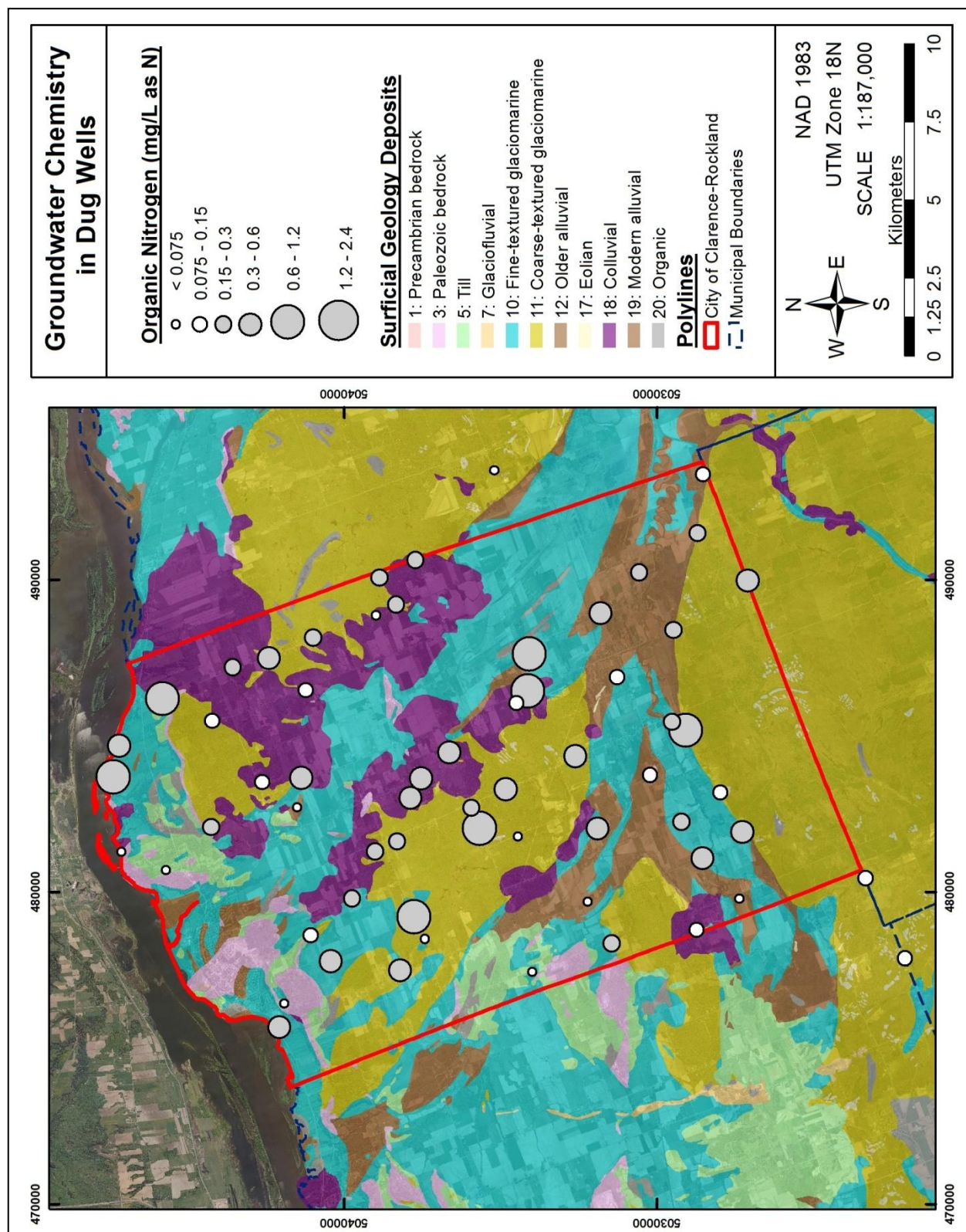


Figure A2-32. Organic Nitrogen concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Grey circles indicate exceedances of the Operational Guideline (0.15 mg/L as N).

A2.33 Sulphate in Drilled Wells

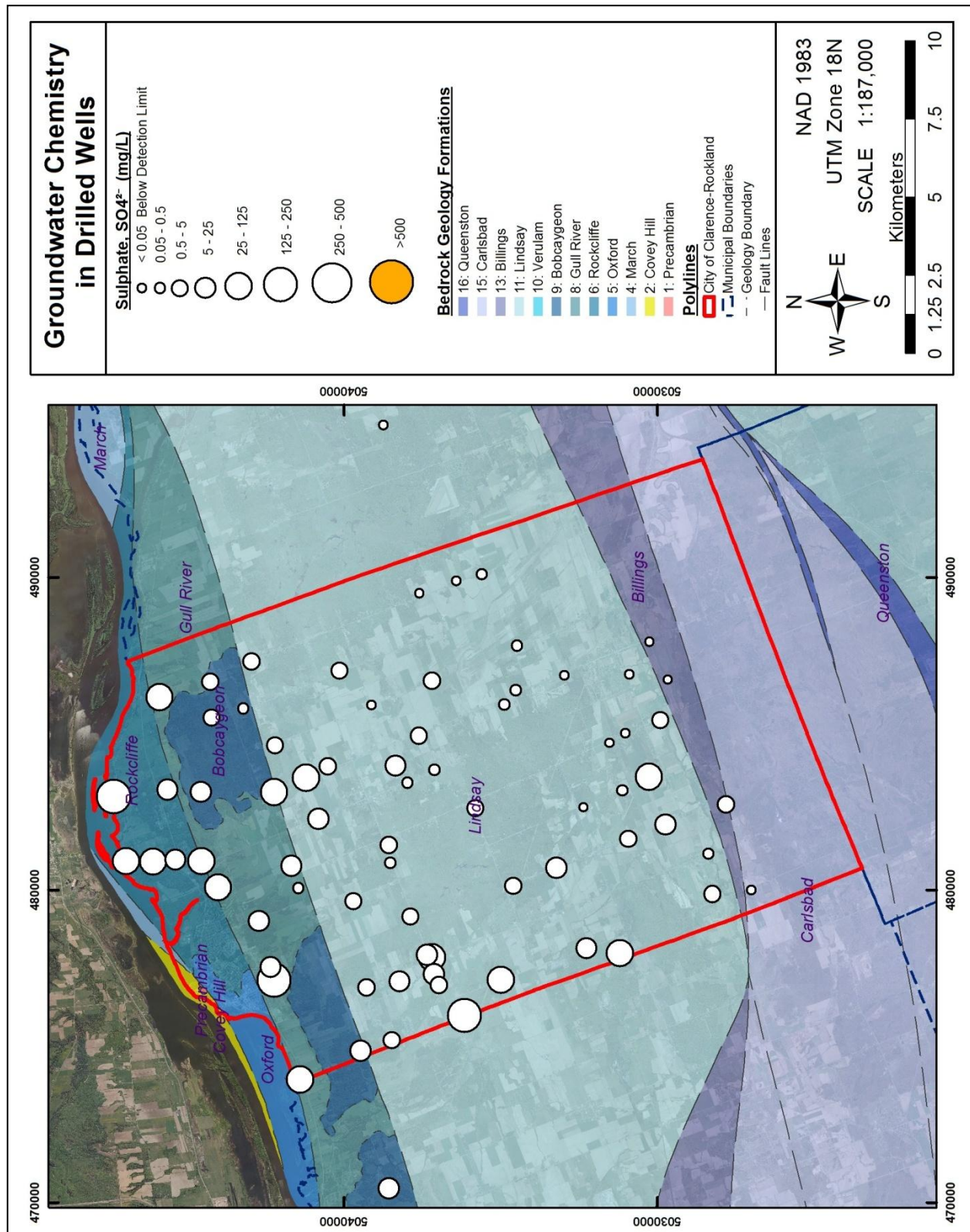


Figure A2-33. Sulphate concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (500 mg/L).

A2.34 Sulphate in Dug Wells

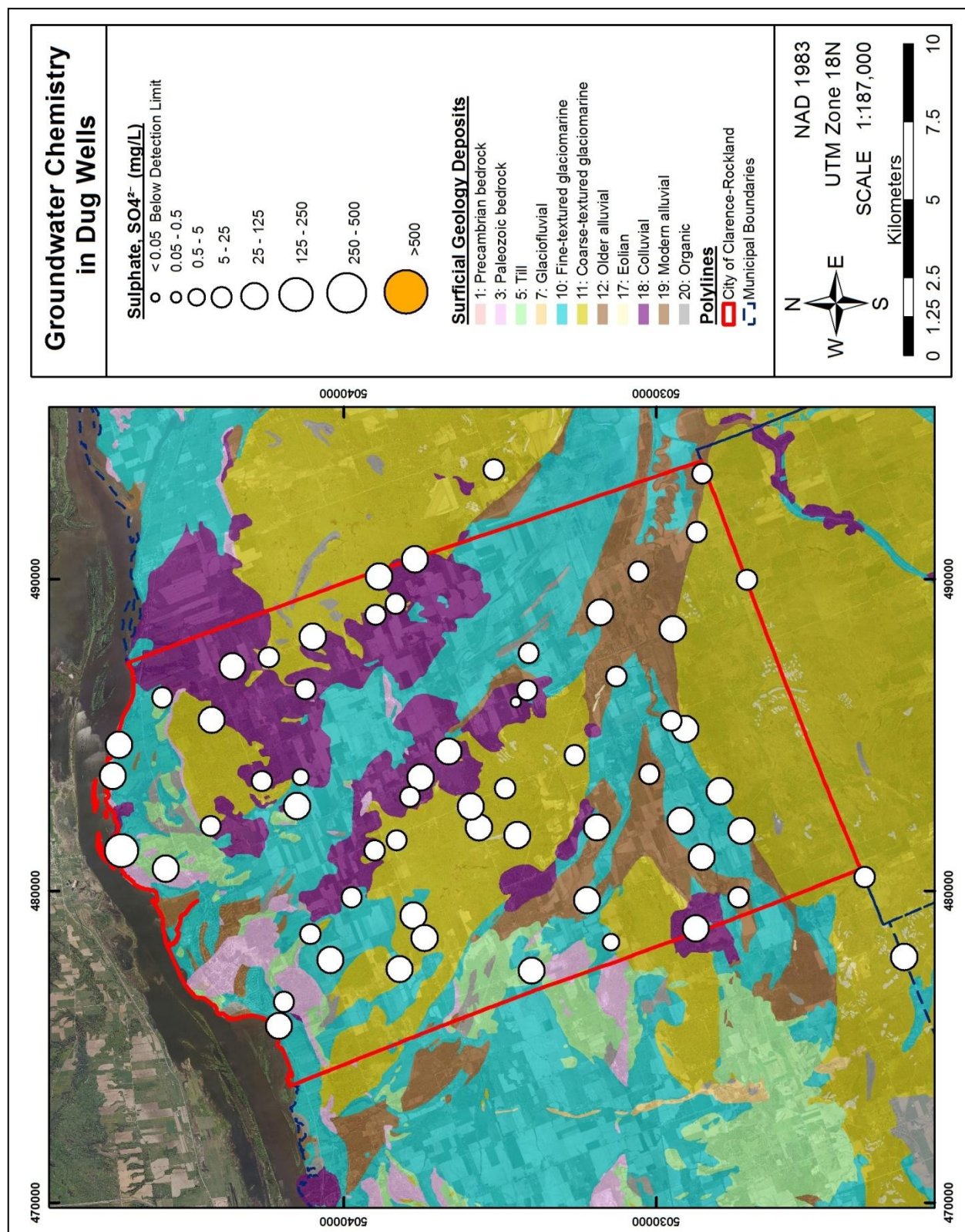


Figure A2-34. Sulphate concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (500 mg/L).

A2.35 Phosphate in Drilled Wells

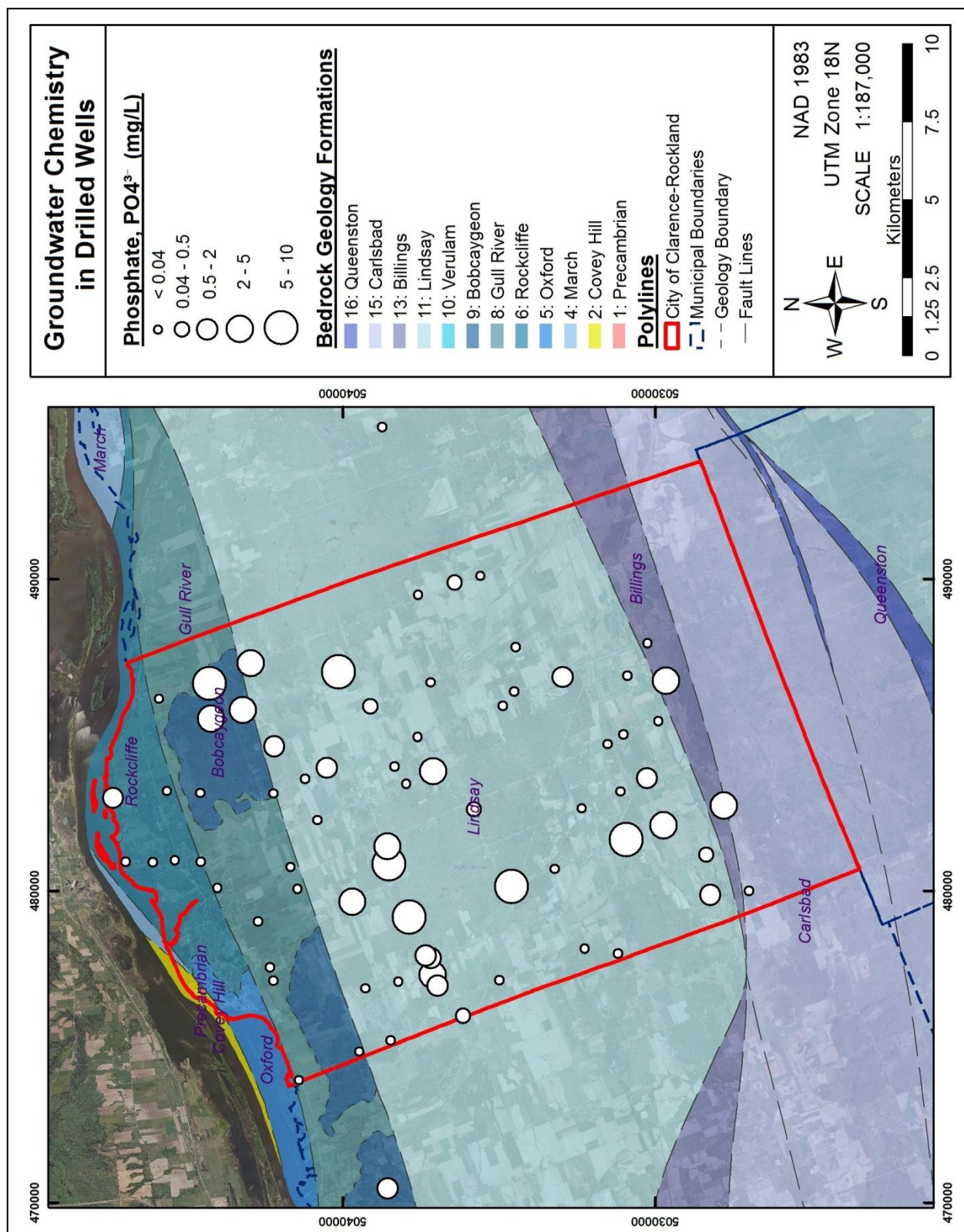


Figure A2-35. Phosphate concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.36 Phosphate in Dug Wells

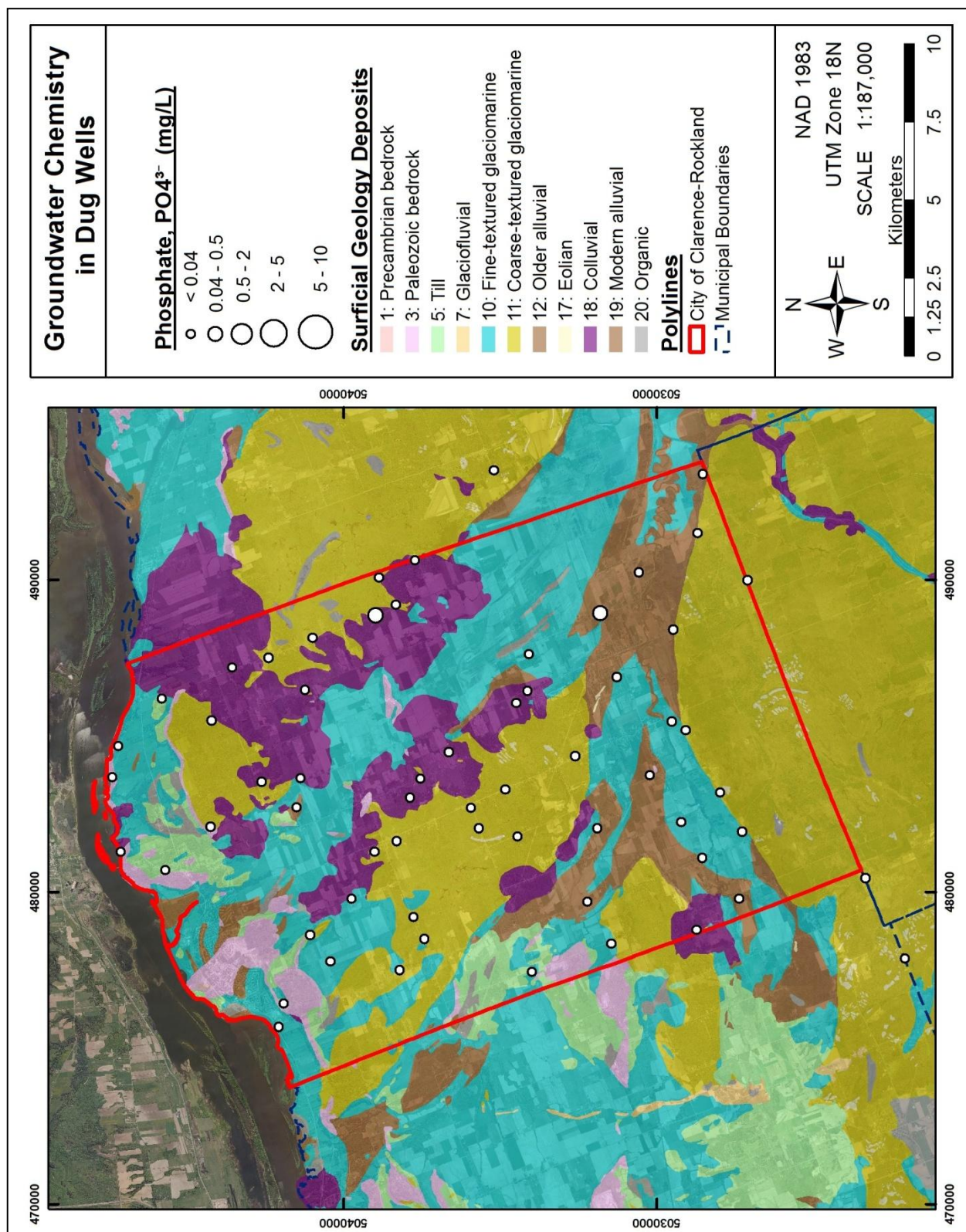


Figure A2-36. Phosphate concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.37 Fluoride in Drilled Wells

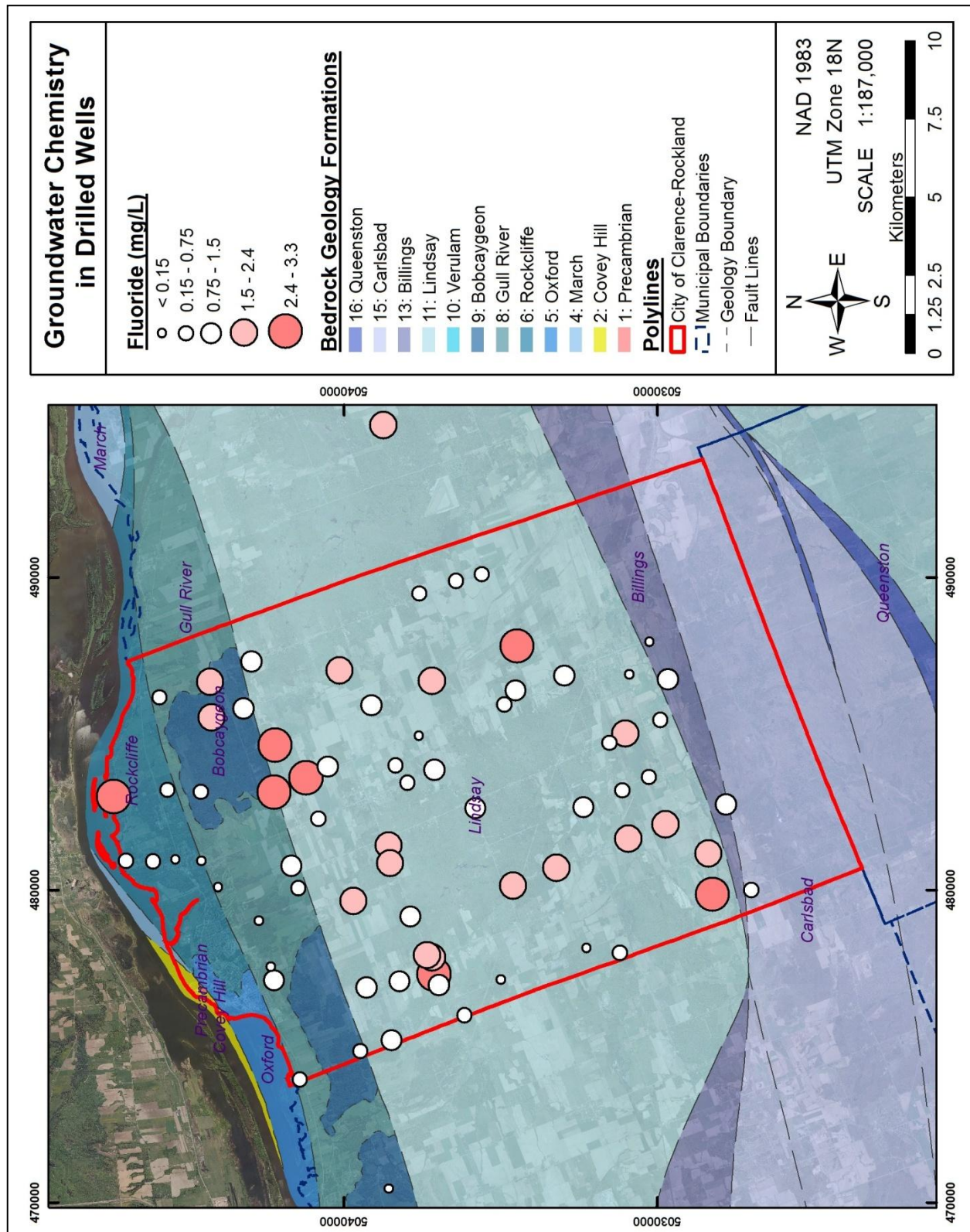


Figure A2-37. Fluoride concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (1.5 mg/L). Reddish circles indicate concentrations that may pose a health risk and are unacceptable for drinking purposes.

A2.38 Fluoride in Dug Wells

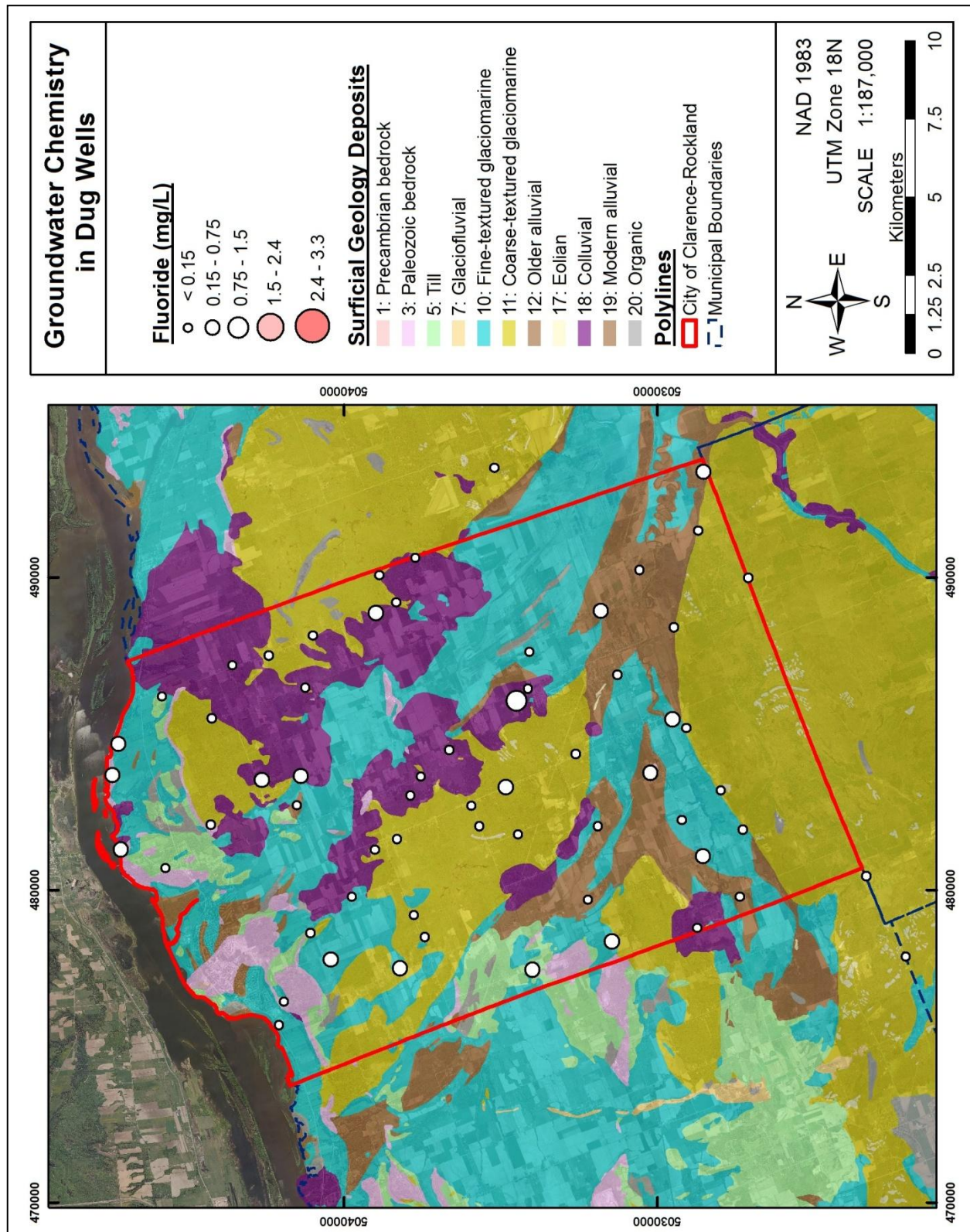


Figure A2-38. Fluoride concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (1.5 mg/L). Reddish circles indicate concentrations that may pose a health risk and are unacceptable for drinking purposes.

A2.39 Chloride in Drilled Wells

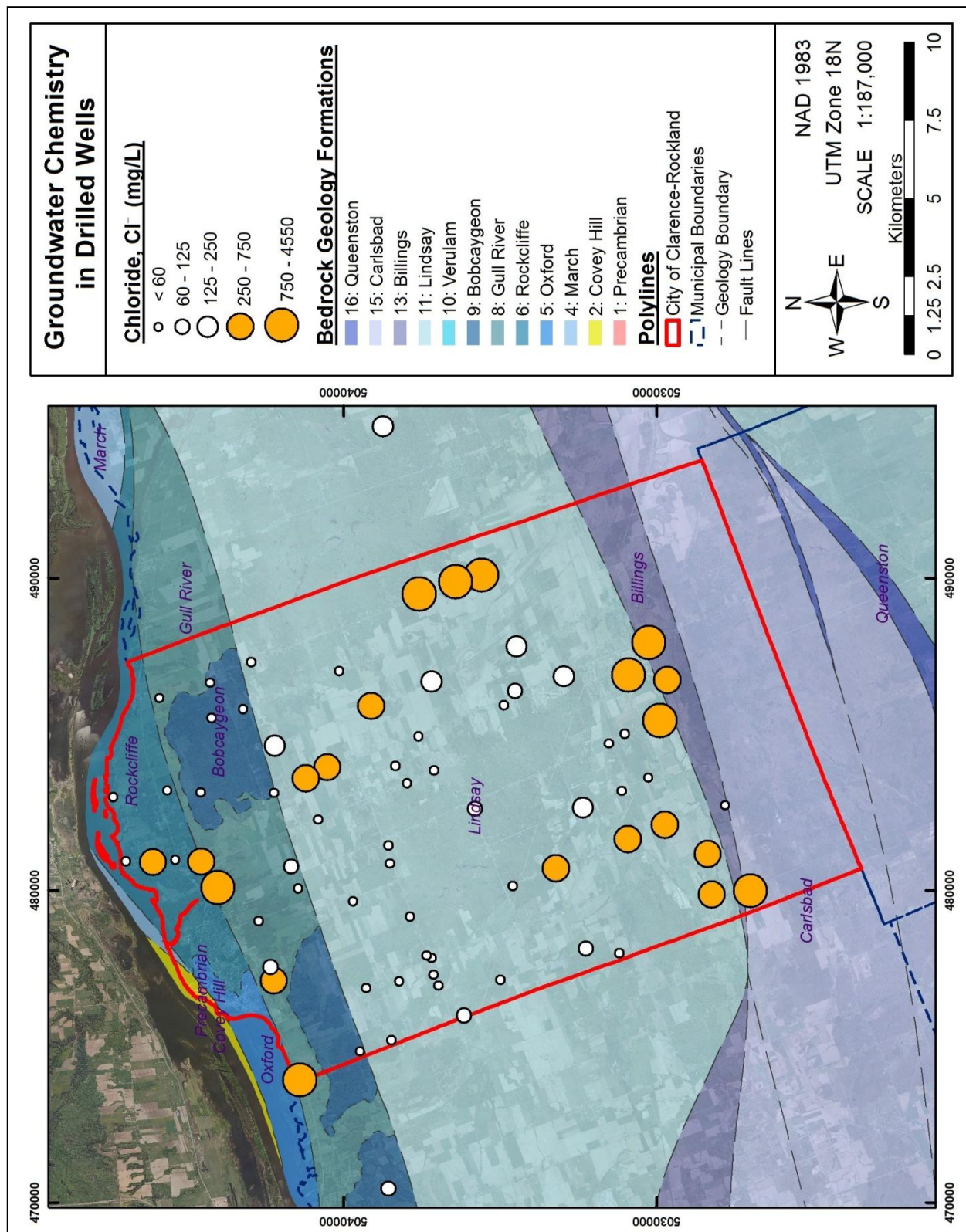


Figure A2-39. Chloride concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (250 mg/L).

A2.40 Chloride in Dug Wells

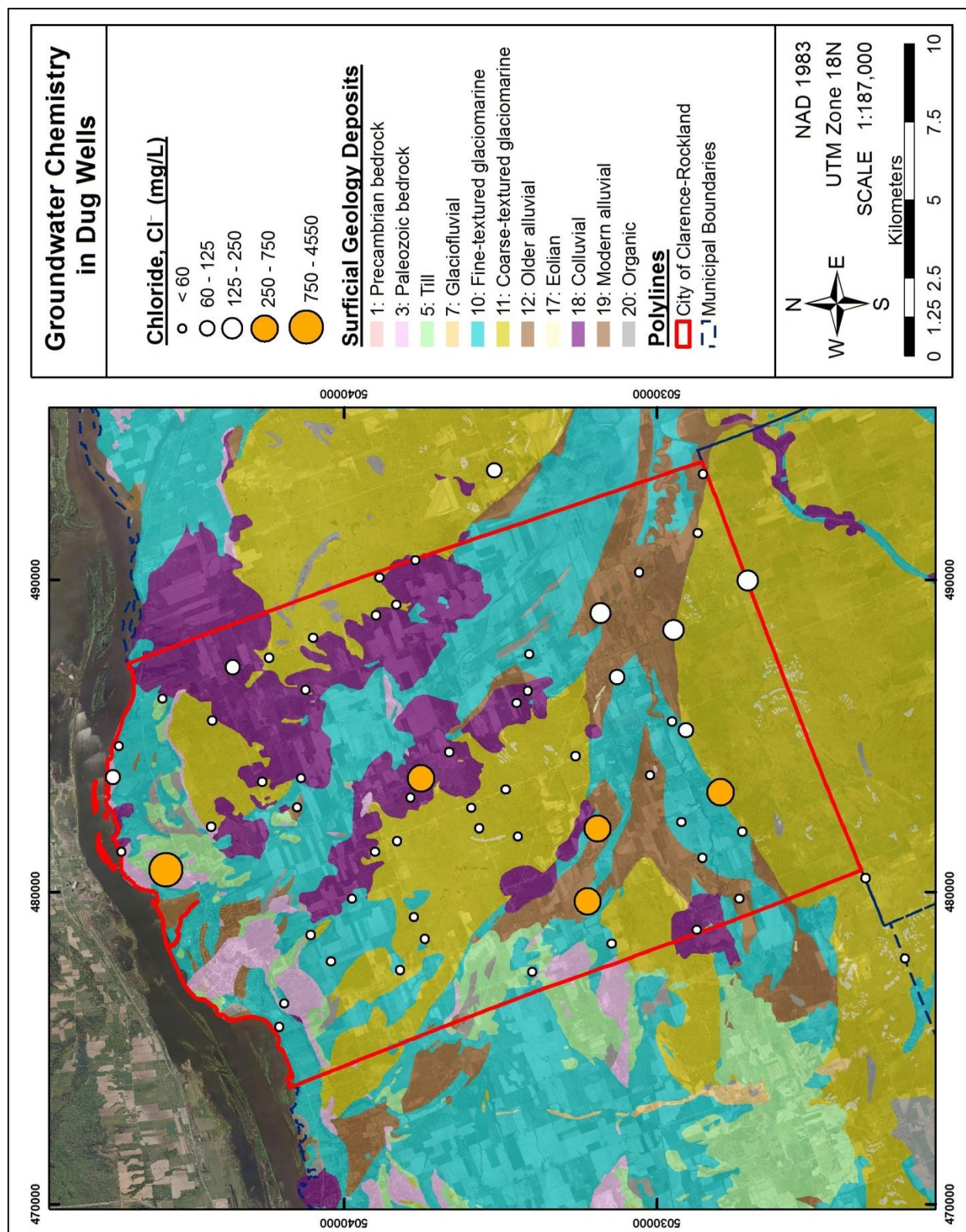


Figure A2-40. Chloride concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (250 mg/L).

A2.41 Iodide in Drilled Wells

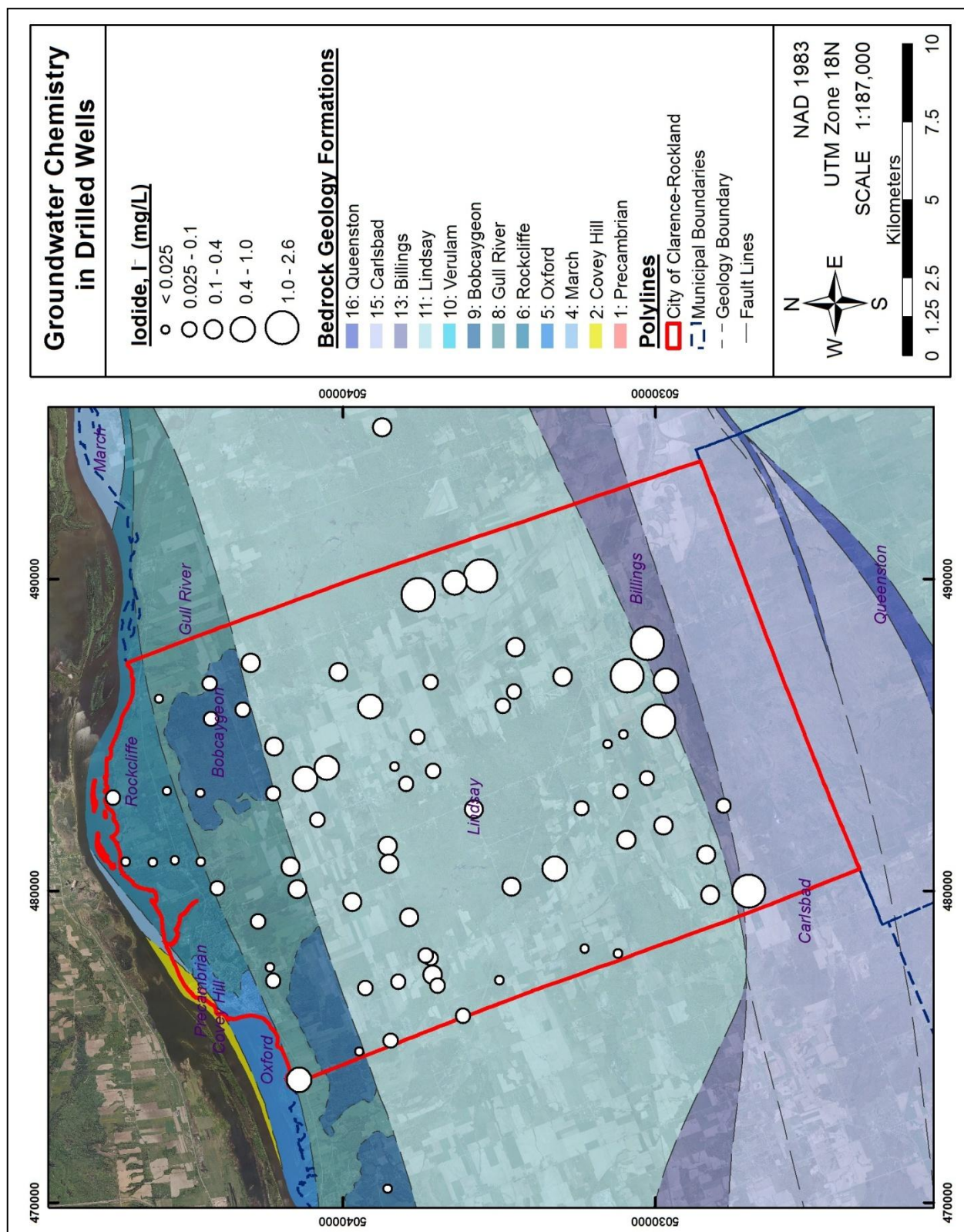


Figure A2-41. Iodide concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.42 Iodide in Dug Wells

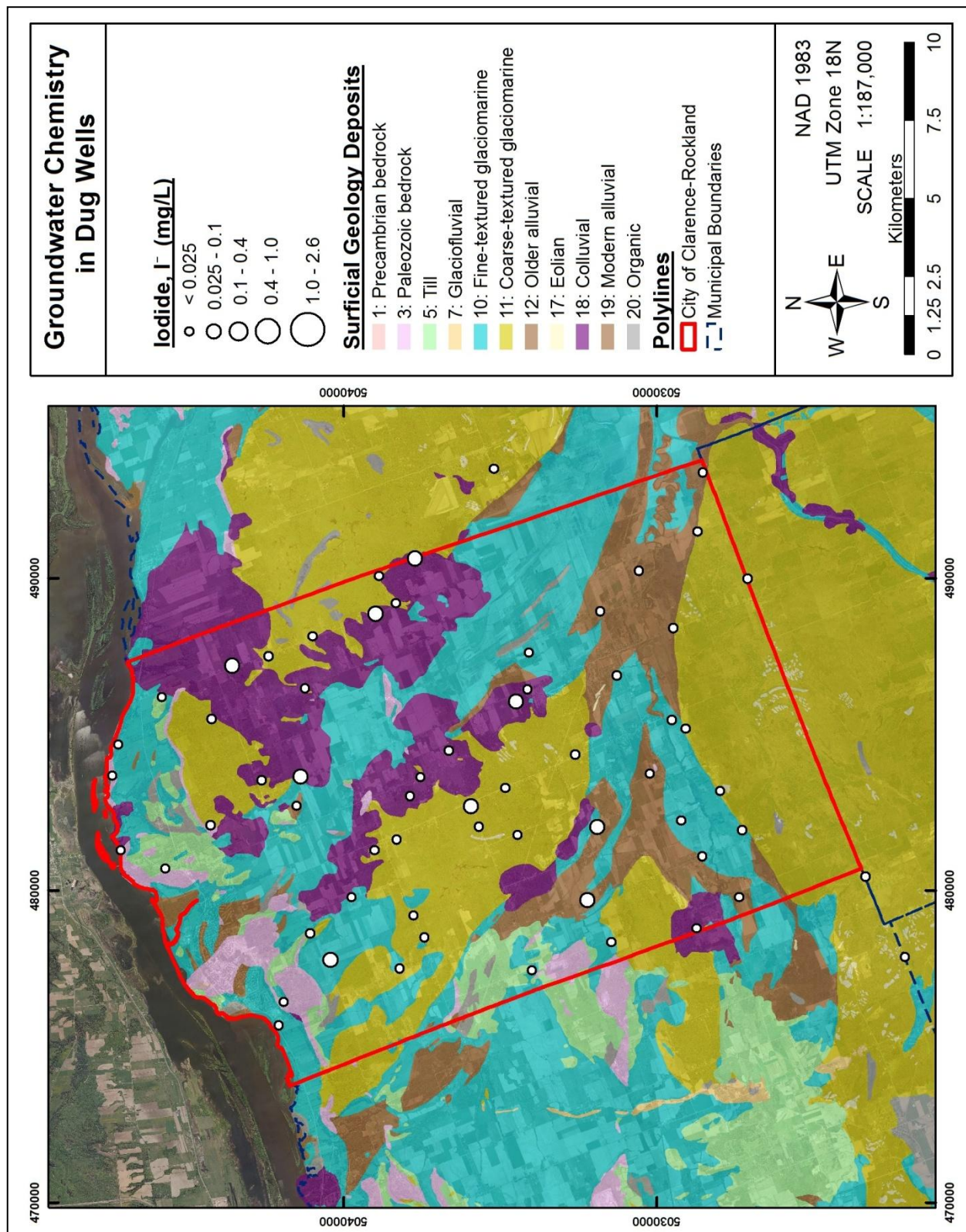


Figure A2-42. Iodide concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.43 Sodium in Drilled Wells

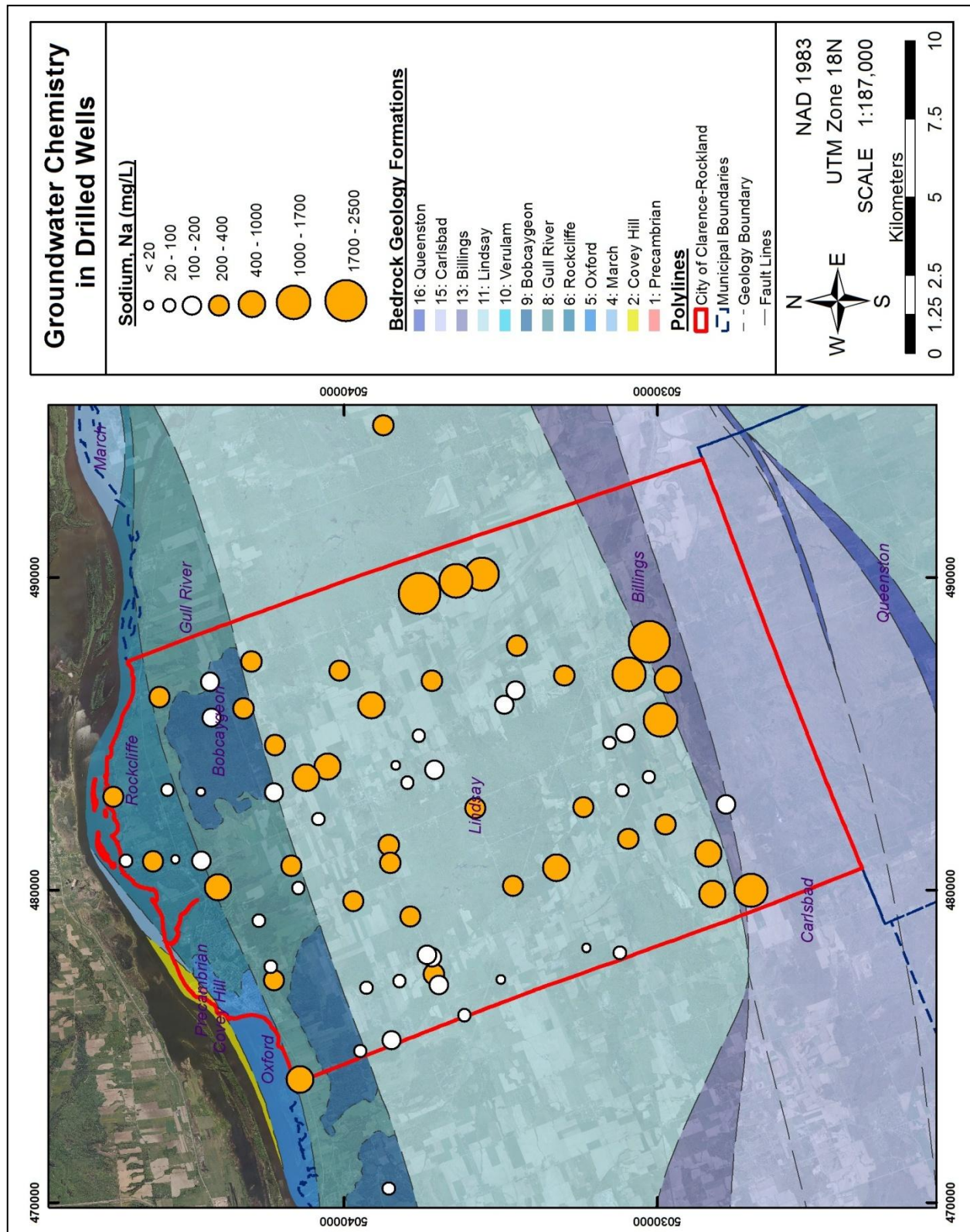


Figure A2-43. Sodium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (200 mg/L).

A2.44 Sodium in Dug Wells

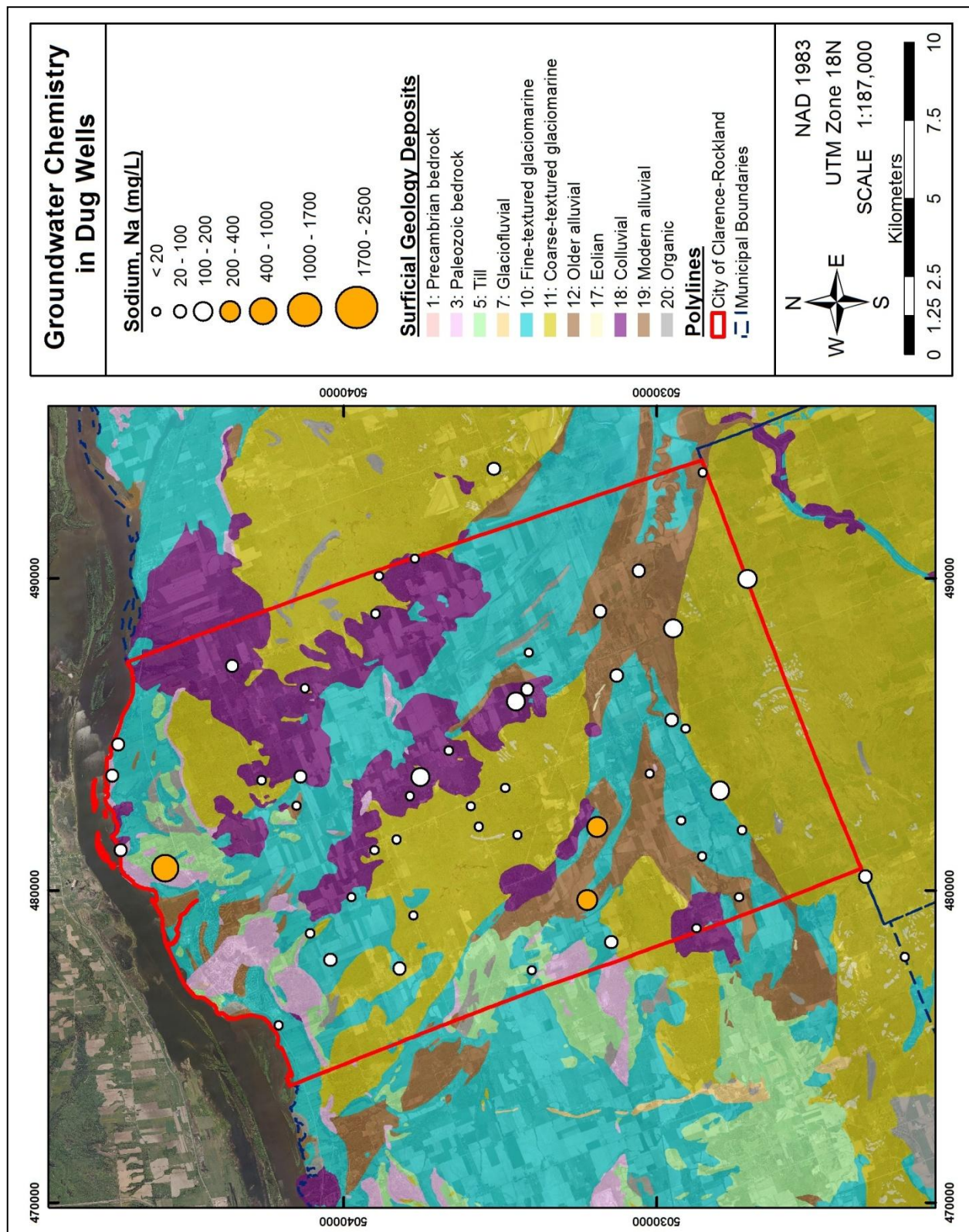


Figure A2-44. Sodium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Orange circles indicate exceedances of the Aesthetic Objective and Maximum Concentration Considered Reasonably Treatable (200 mg/L).

A2.45 Potassium in Drilled Wells

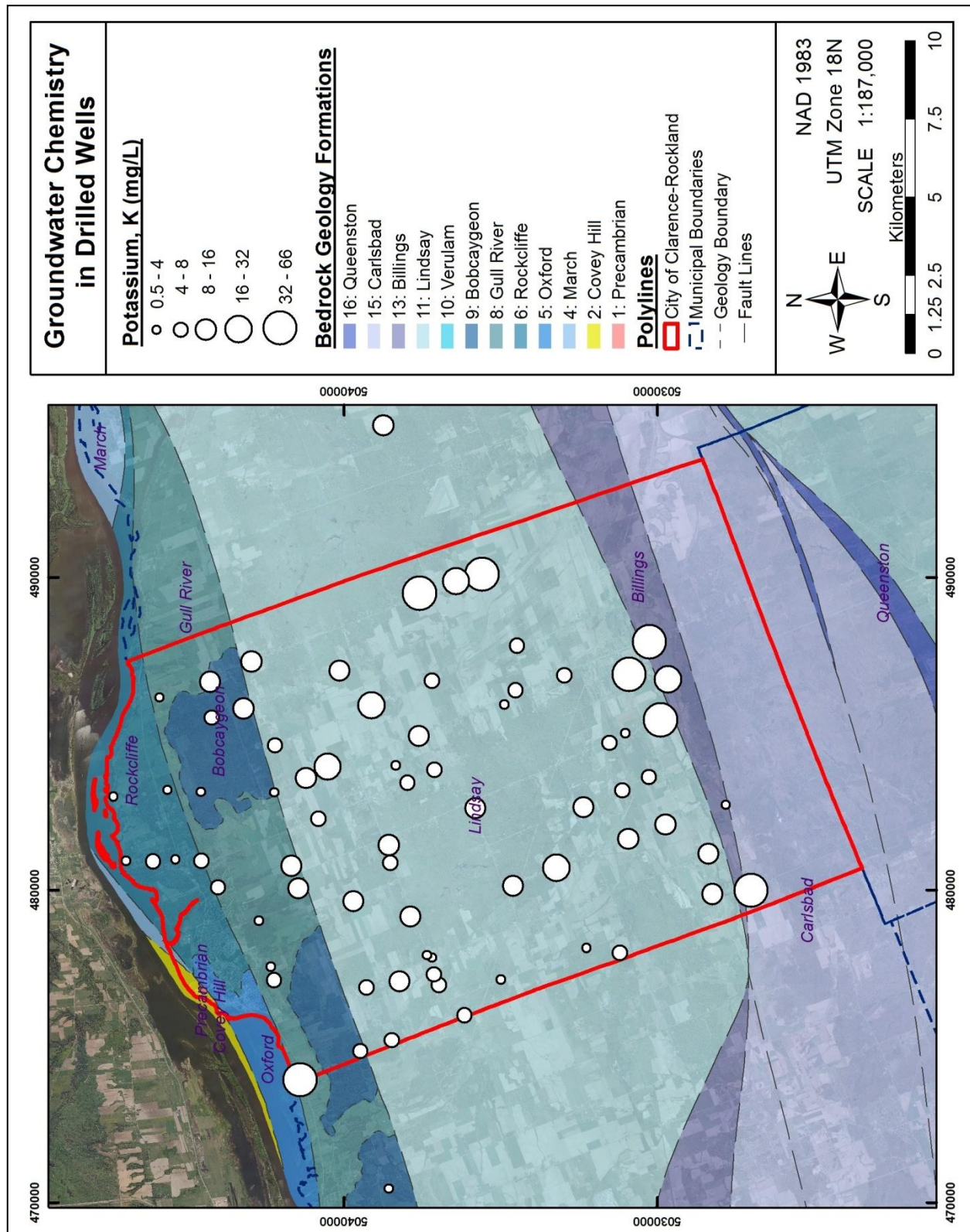


Figure A2-45. Potassium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.46 Potassium in Dug Wells

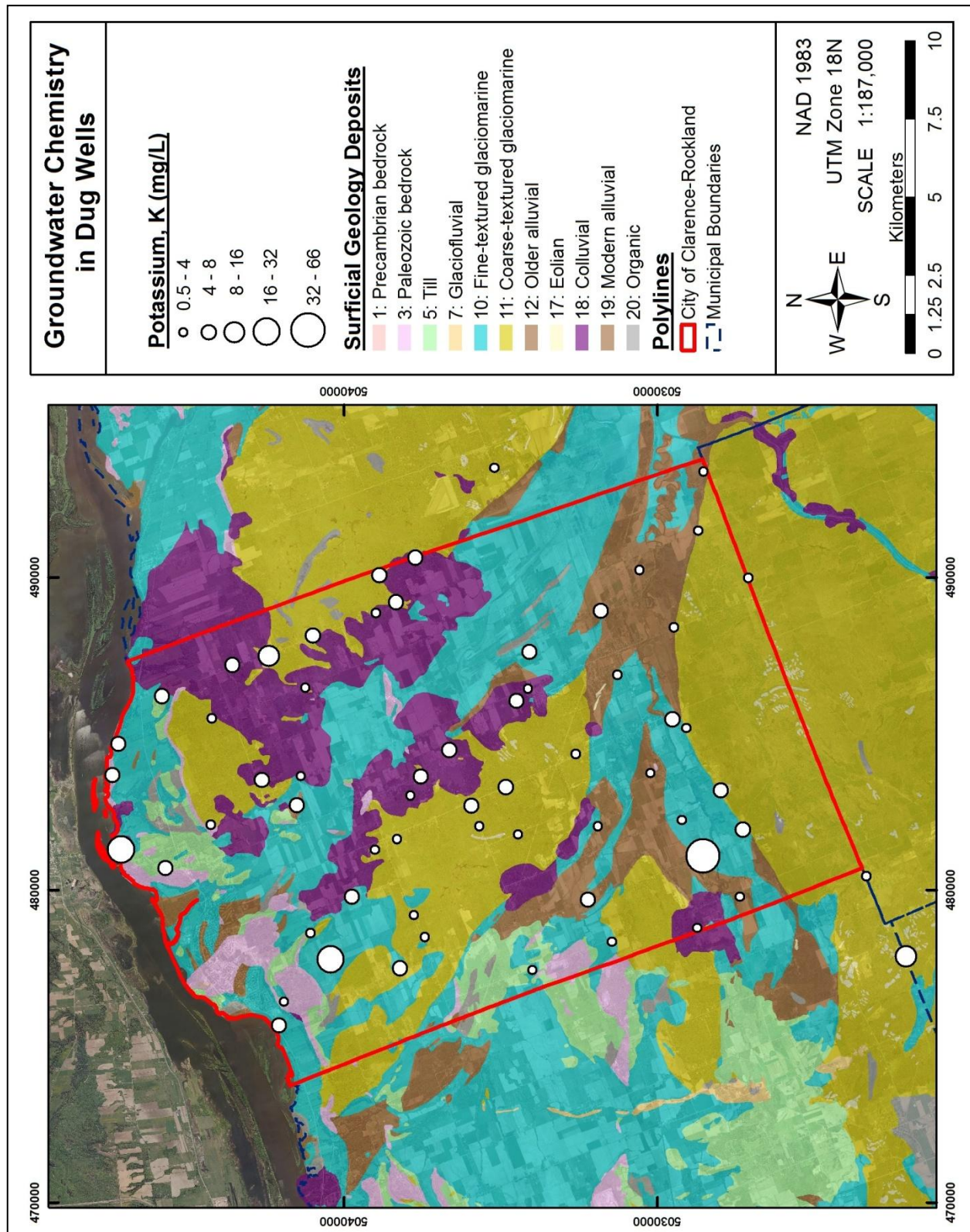


Figure A2-46. Potassium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.47 Magnesium in Drilled Wells

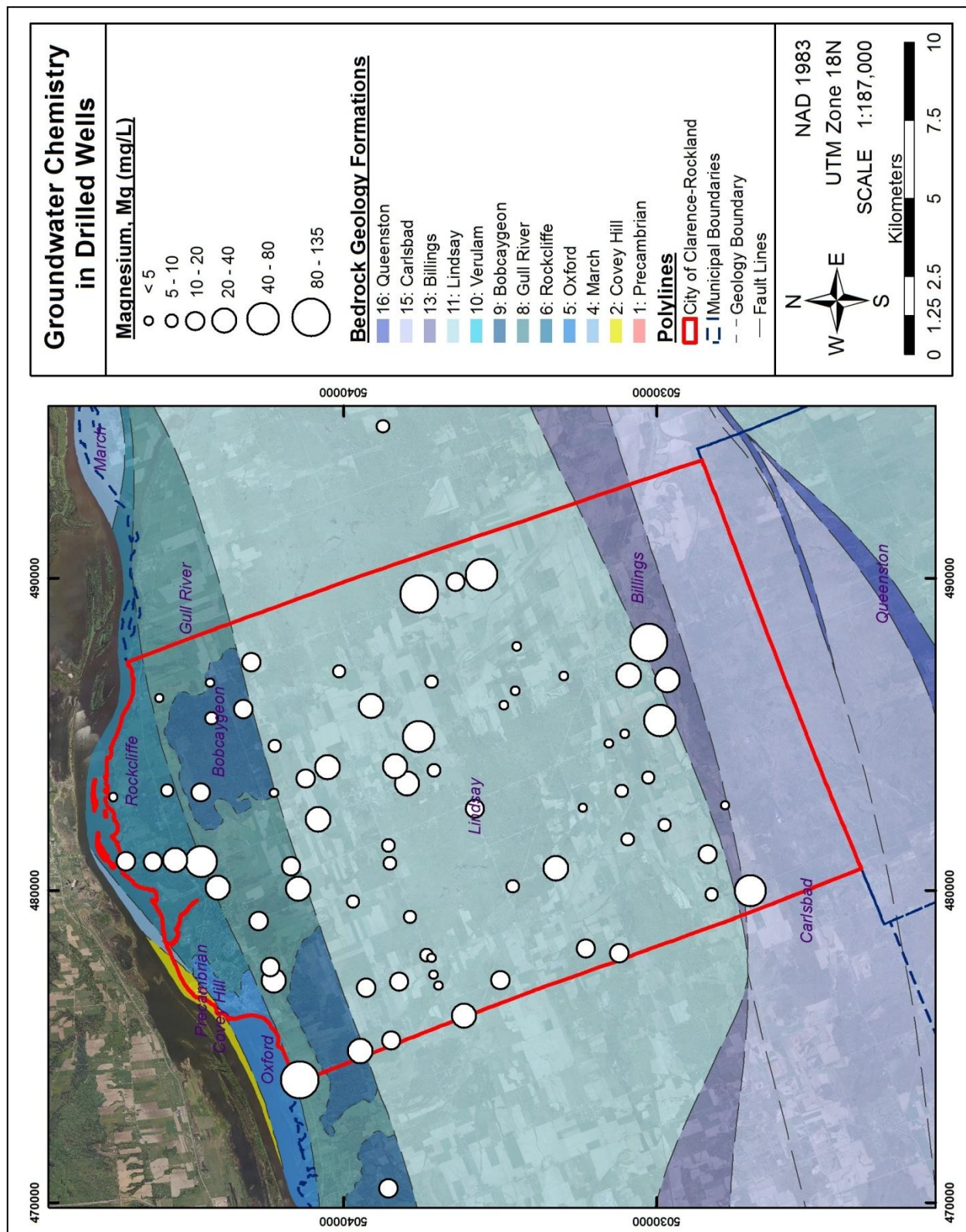


Figure A2-47. Magnesium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.48 Magnesium in Dug Wells

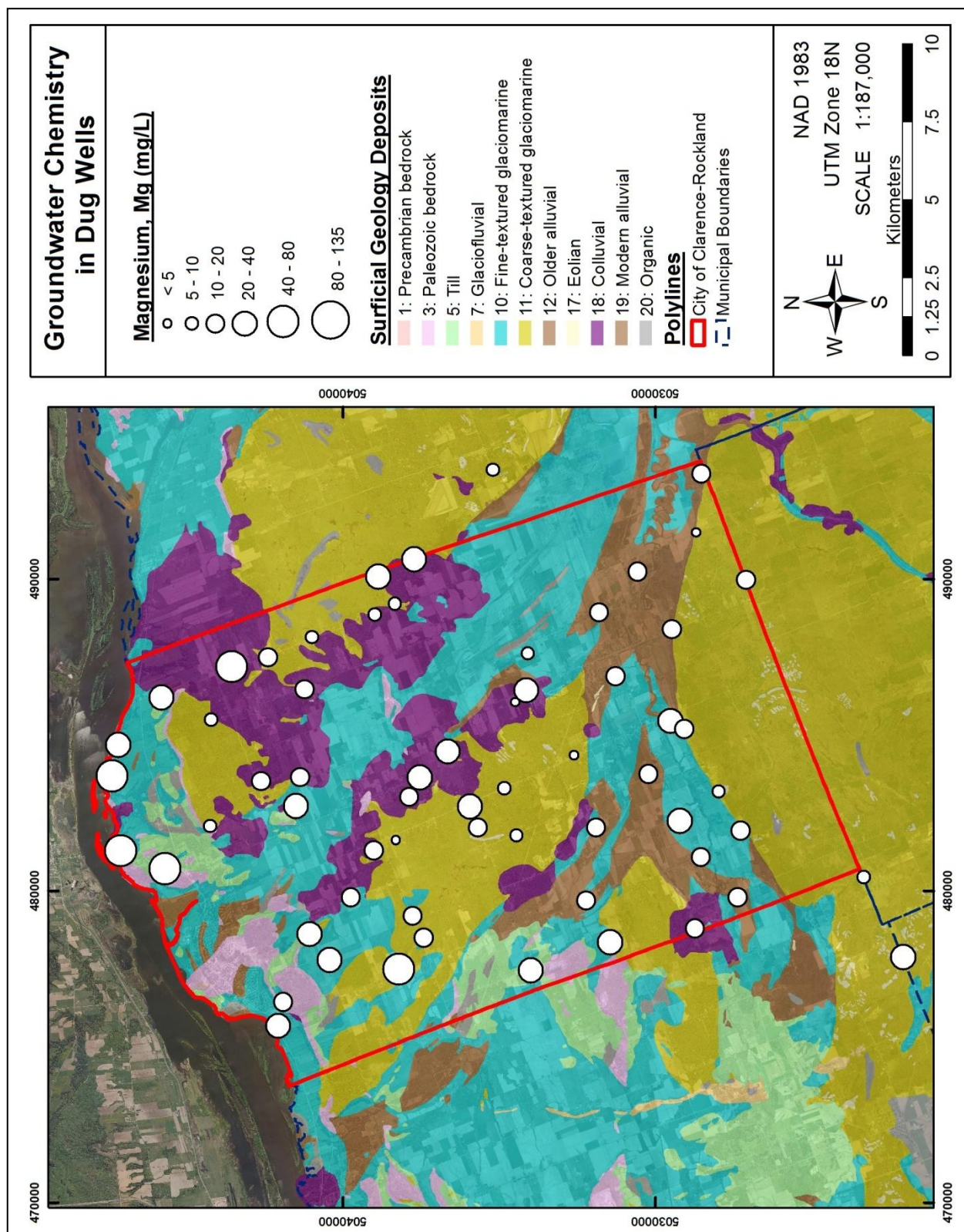


Figure A2-48. Magnesium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.49 Calcium in Drilled Wells

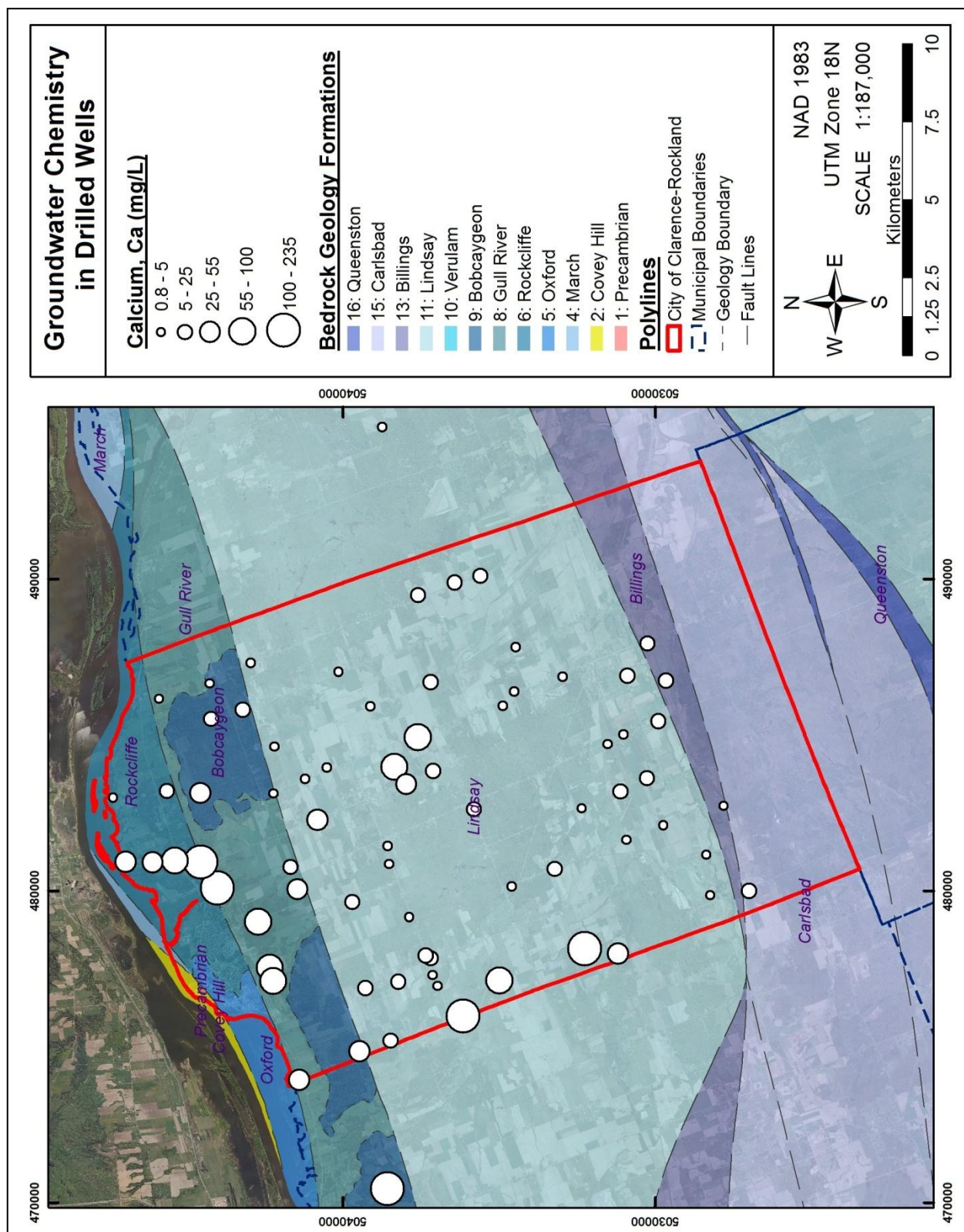


Figure A2-49. Calcium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.

A2.50 Calcium in Dug Wells

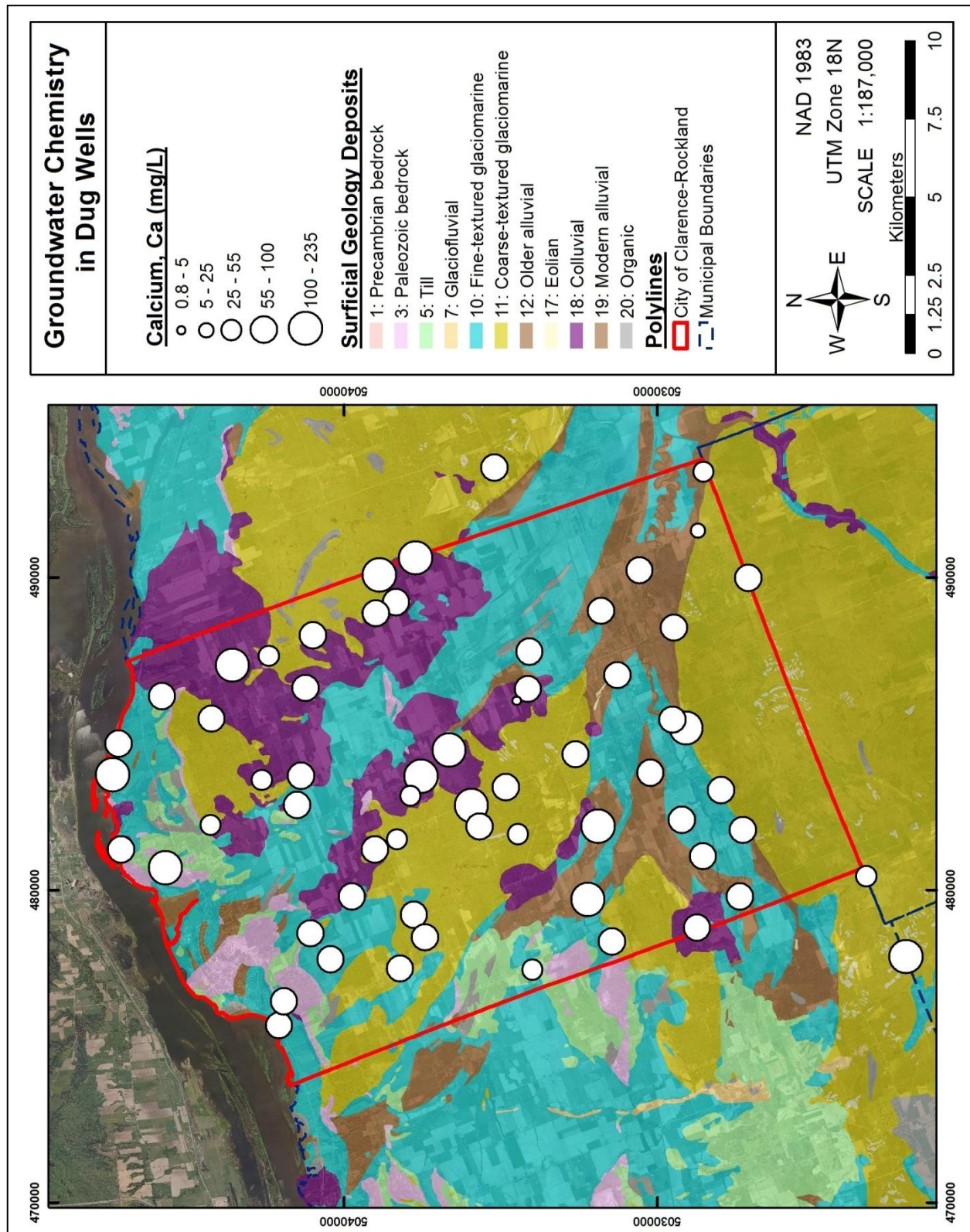


Figure A2-50. Calcium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON.

A2.51 Barium in Drilled Wells

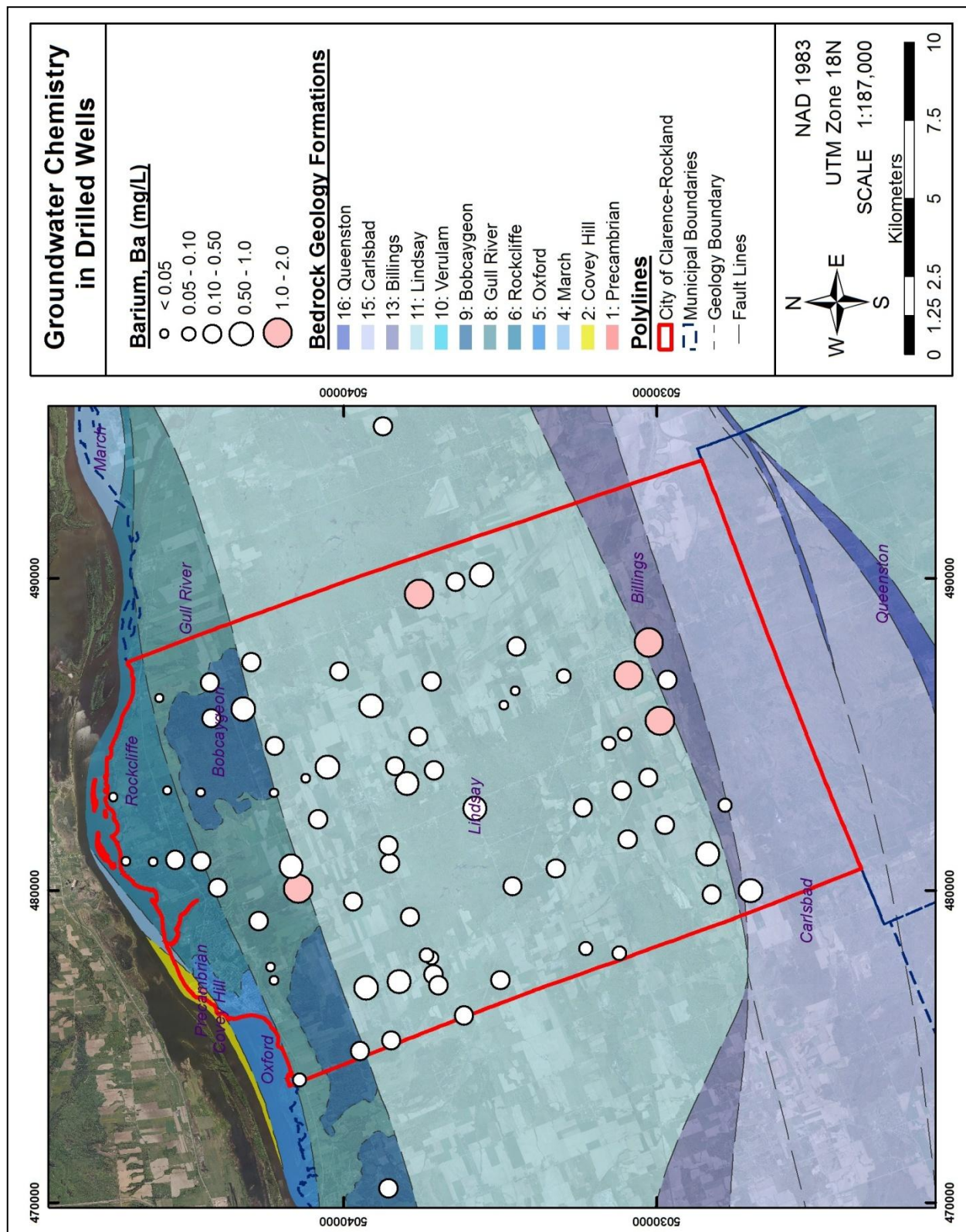


Figure A2-51. Barium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (1.0 mg/L).

A2.52 Barium in Dug Wells

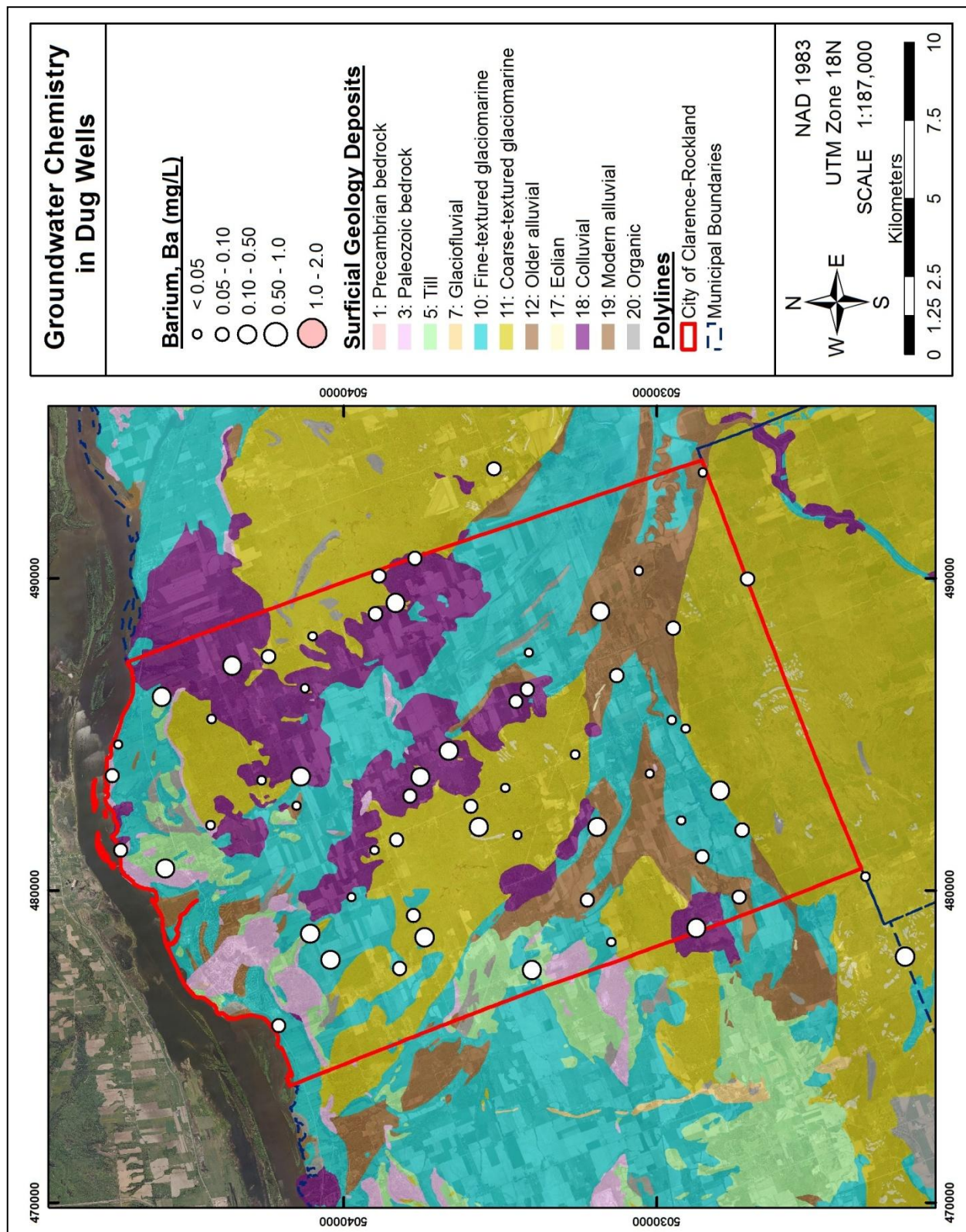


Figure A2-52. Barium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (1.0 mg/L).

A2.53 Selenium in Drilled Wells

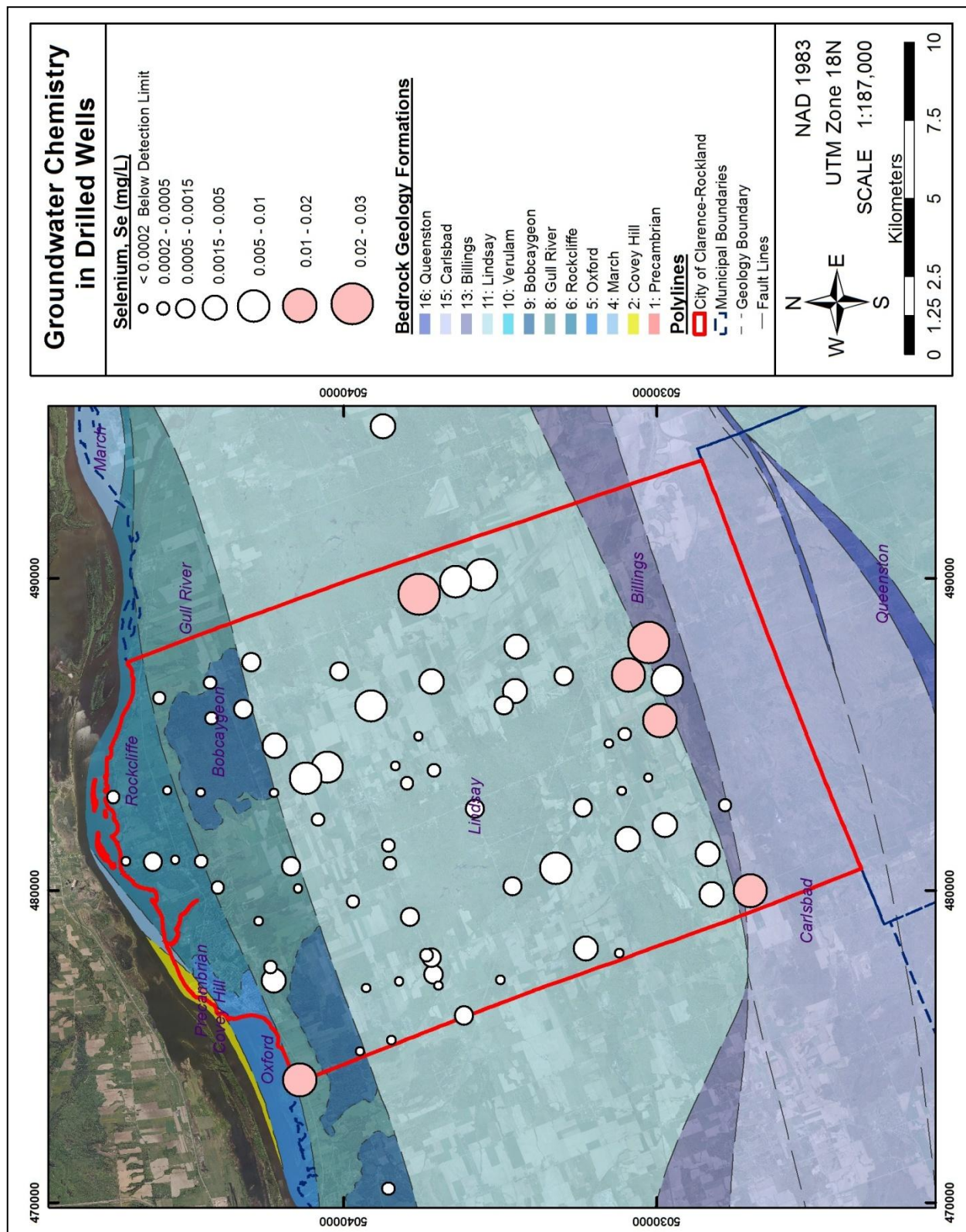


Figure A2-53. Selenium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (0.01 mg/L).

A2.54 Selenium in Dug Wells

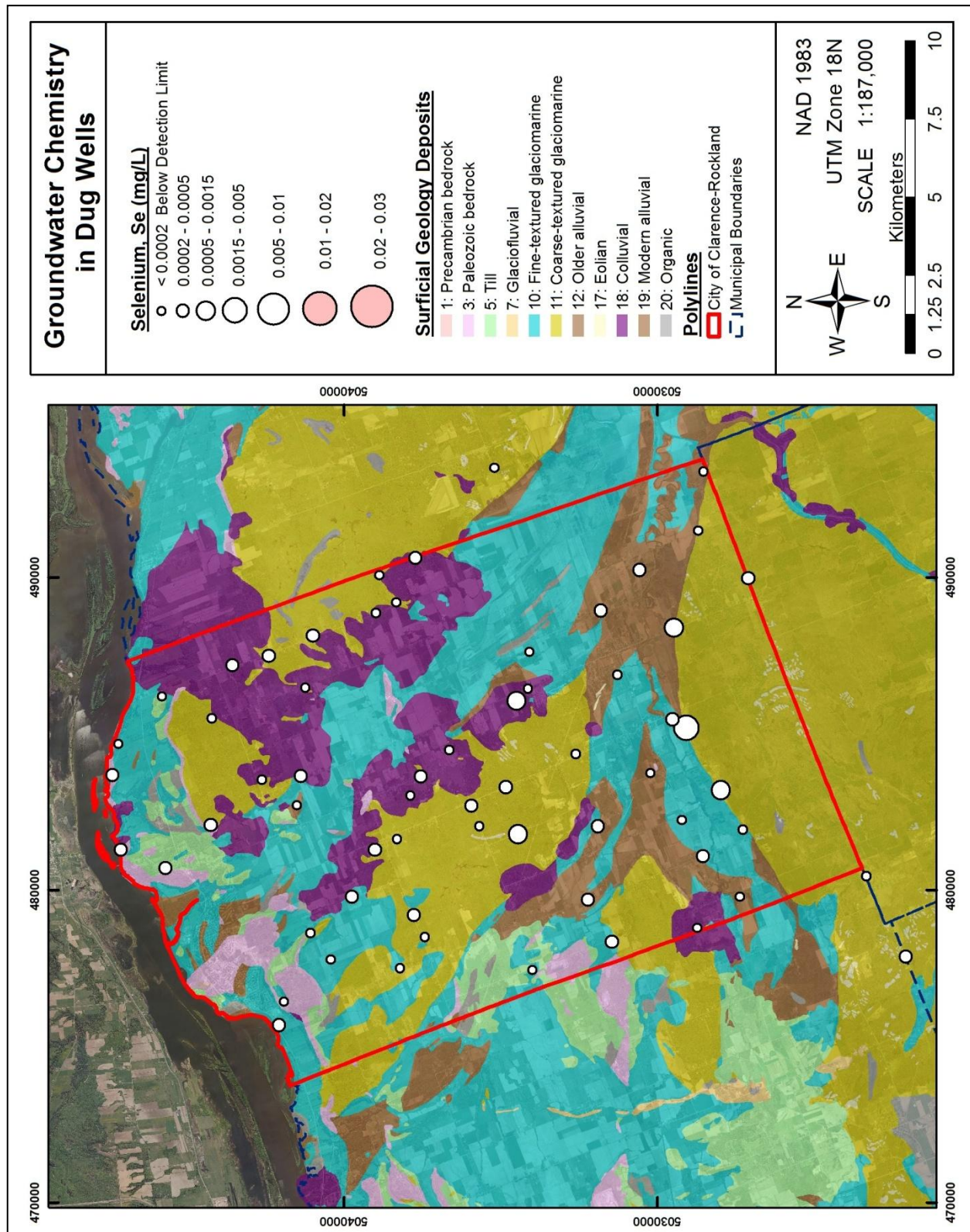


Figure A2-54. Selenium concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Pink circles indicate exceedances of the Health Standard (0.01 mg/L).

A2.55 Iron in Drilled Wells

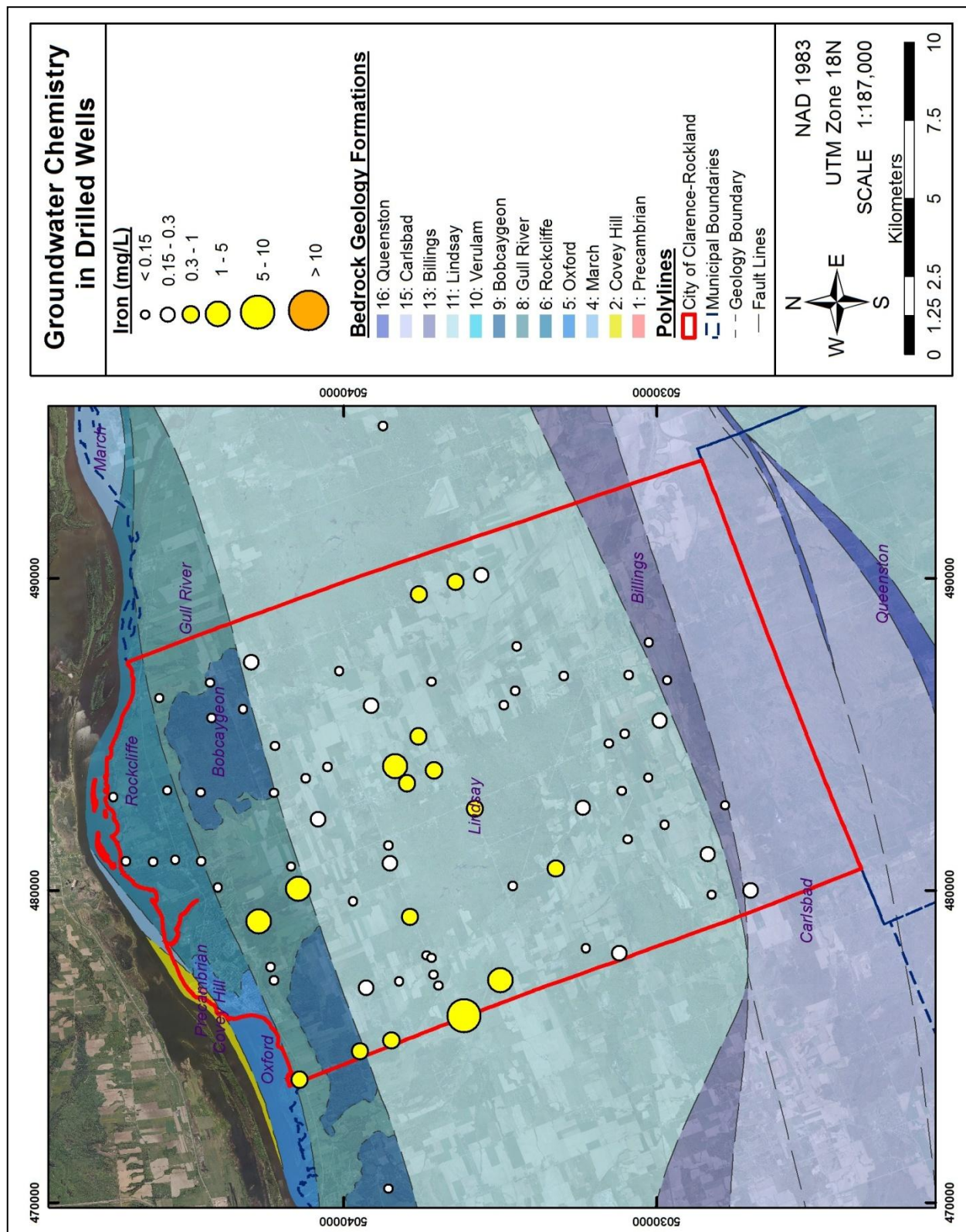


Figure A2-55. Iron concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (0.3 mg/L) and Maximum Concentration Considered Reasonably Treatable (10 mg/L).

A2.56 Iron in Dug Wells

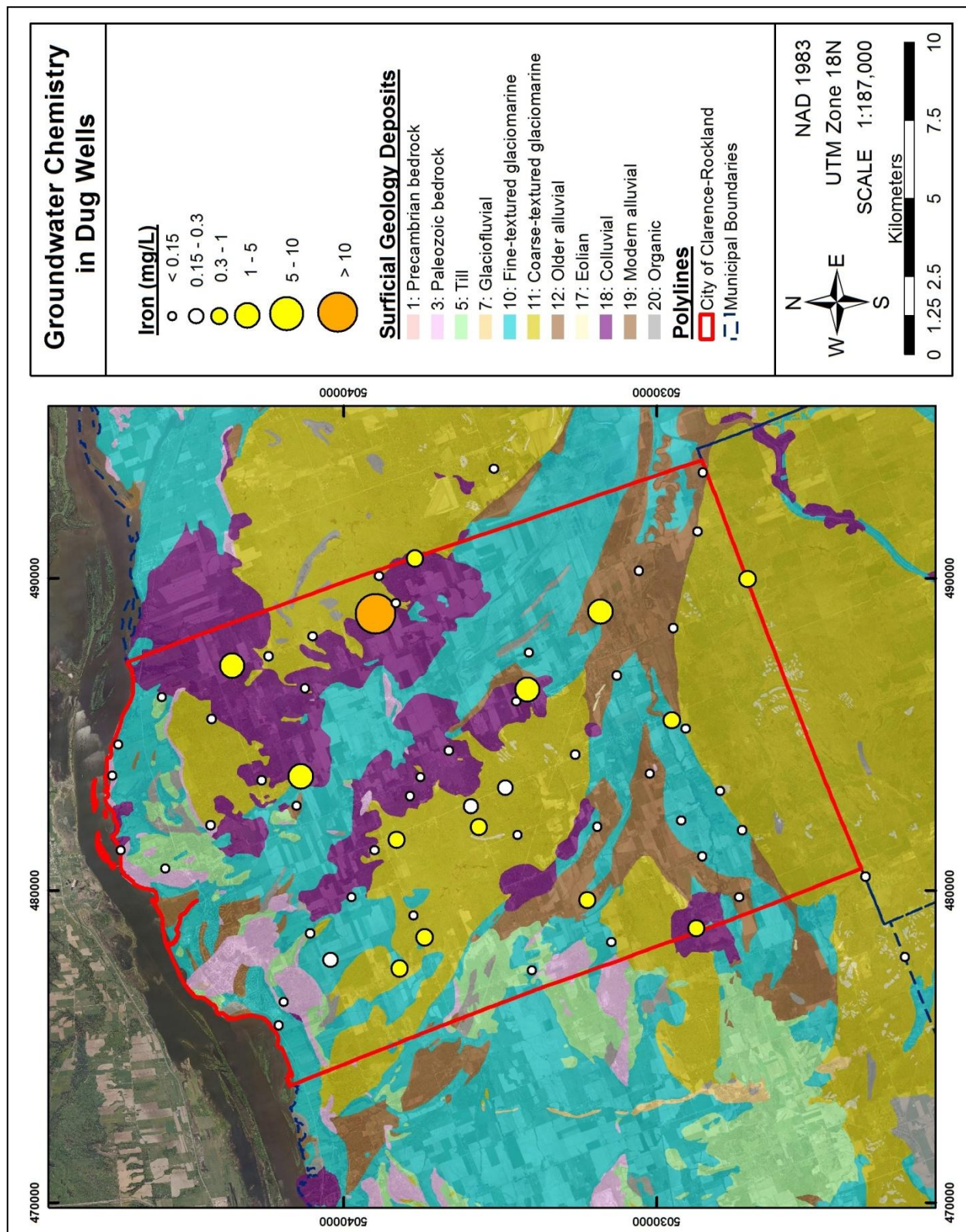


Figure A2-56. Iron concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (0.3 mg/L) and Maximum Concentration Considered Reasonably Treatable (10 mg/L).

A2.57 Manganese in Drilled Wells

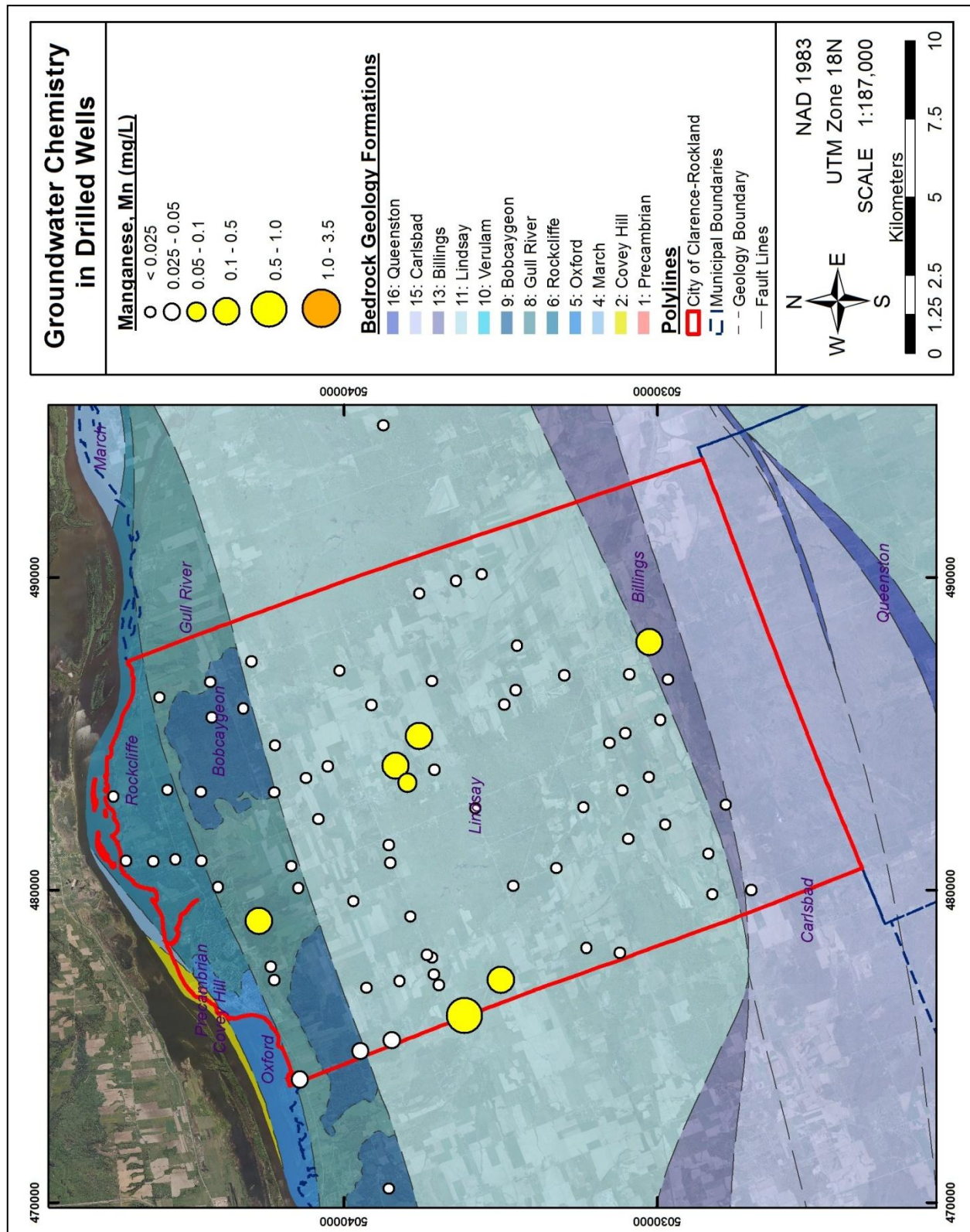


Figure A2-57. Manganese concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (0.05 mg/L) and Maximum Concentration Considered Reasonably Treatable (1.0 mg/L).

A2.58 Manganese in Dug Wells

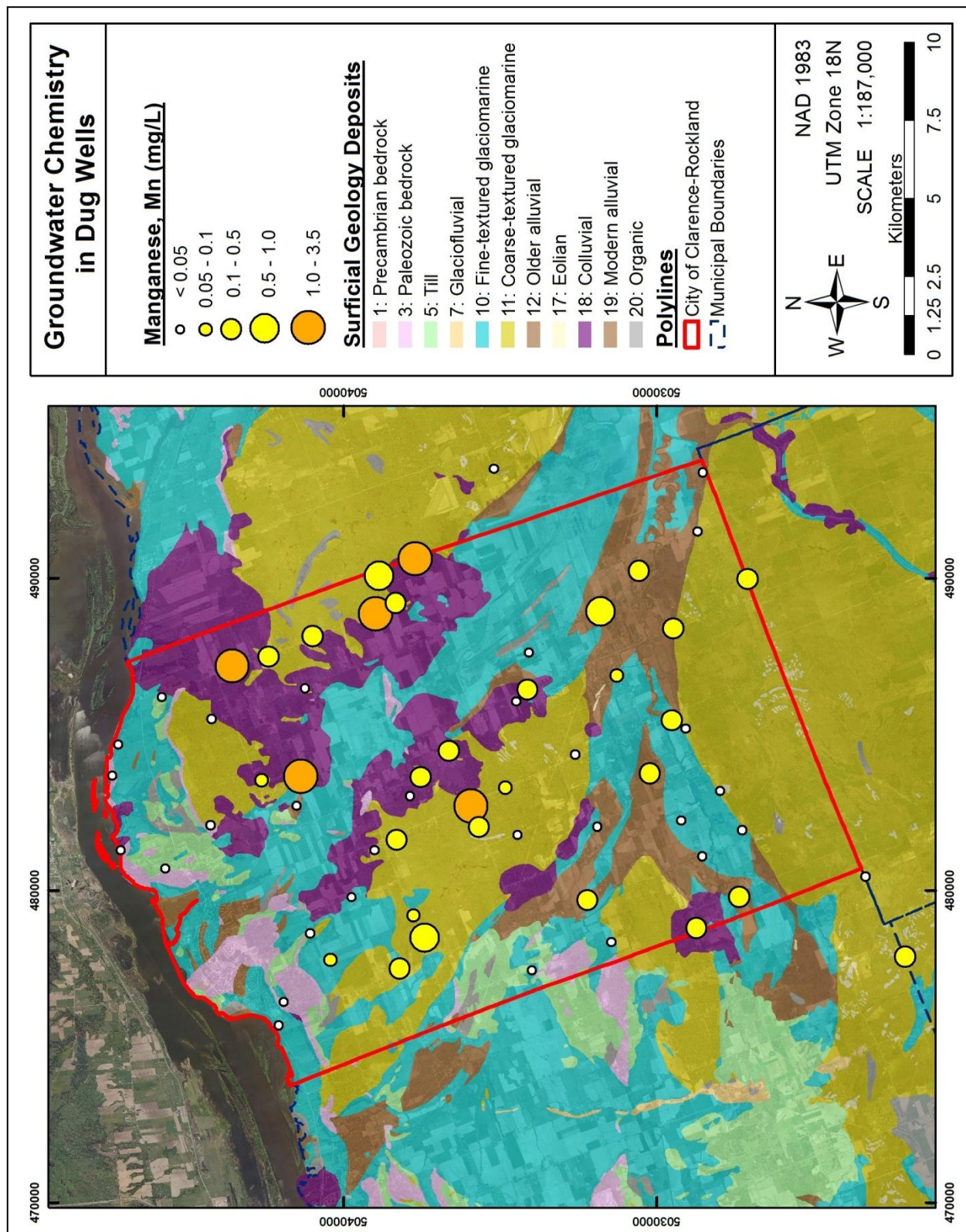


Figure A2-58. Manganese concentrations in groundwater sampled from dug wells throughout the City of Clarence-Rockland, ON. Yellow and orange circles respectively indicate exceedances of the Aesthetic Objective (0.05 mg/L) and Maximum Concentration Considered Reasonably Treatable (1.0 mg/L).

A2.59 Tritium in Drilled Wells

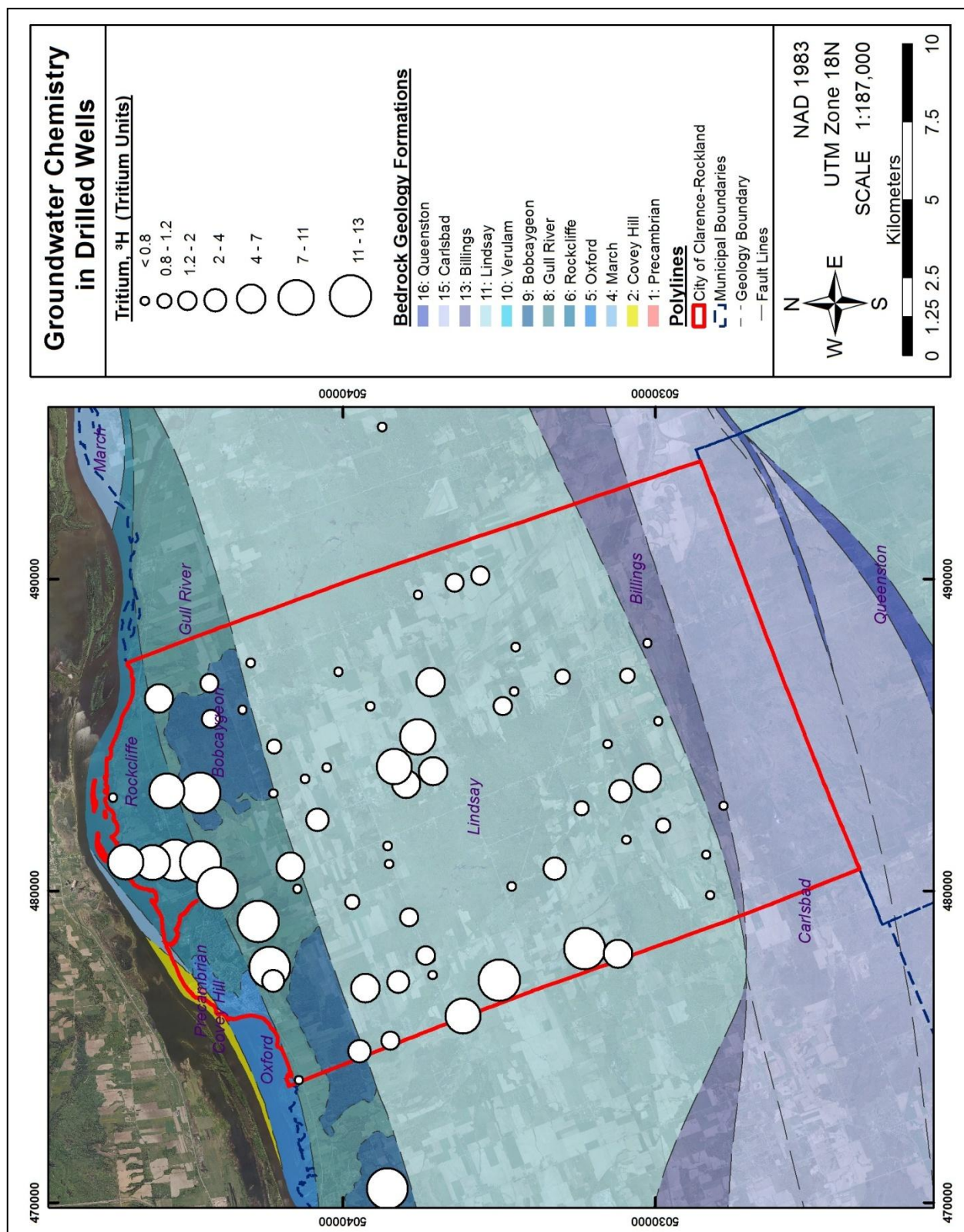


Figure A2-59. Tritium concentrations in groundwater sampled from drilled wells throughout the City of Clarence-Rockland, ON.