CATARAQUI REGION
CONSERVATION AUTHORITY

# Groundwater Vulnerability Analysis Report

***for the Cataraqui Source Protection Area***

*Prepared by:*

***Dillon Consulting Limited***

*In association with*

***Malroz Engineering Inc.***

***August, 2008***

Groundwater Vulnerability Analysis Report
Cataraqui Source Protection Area
August, 2008

August 31, 2008

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Attention: Mr. McRae, MCIP, RPP

**Cataraqui Source Protection Area**
**Groundwater Vulnerability Assessment Report**

Dear Mr. McRae:

Dillon Consulting Limited (Dillon), in association with Malroz Engineering Inc. (Malroz), is pleased to present the Groundwater Vulnerability Assessment Report for the Cataraqui Source Protection Area (CSPA). The report provides information on the hydrogeology of the CSPA as it pertains to the regional groundwater flow patterns, significant groundwater recharge areas and high vulnerability aquifers. Knowledge gained during this study can be used in the CSPA Assessment Report and the future Source Protection Plan.

We have enjoyed working with the CRCA staff on this assignment. If you have any questions about the report, please call the undersigned.

Yours sincerely,

**DILLON CONSULTING LIMITED**

Darin Burr, M.Sc., P.Geo.
Project Manager

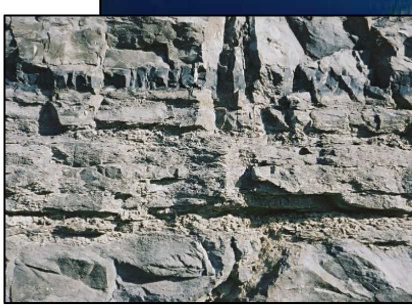
DTB:lpt
Encl.

**Our File: 07-7590**

CATARAQUI REGION
CONSERVATION AUTHORITY

# Groundwater Vulnerability Analysis Report

***for the Cataraqui Source Protection Area***

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***August, 2008***

## EXECUTIVE SUMMARY

Dillon Consulting Limited (Dillon), in association with Malroz Engineering Inc. (Malroz), was retained by the Cataraqui Region Conservation Authority (CRCA) to undertake the Groundwater Vulnerability Assessment Report (GVAR) study for the Cataraqui Source Protection Area (CSPA). Information from the GVAR will be incorporated into the CSPA Assessment Report that is currently being compiled by CRCA as part of the *Clean Water Act*, 2006 requirements for the watershed.

The GVAR project was comprised of the following four tasks:

- Review of literature that is applicable to the CSPA;
- Development of Geological Cross-Sections;
- Mapping of Significant Groundwater Recharge Areas; and,
- Mapping of High Vulnerability Areas.

A summary of the scope and main findings of each of these tasks is presented below:

Literature Review

A review was undertaken of select regional groundwater studies and technical papers whose topics included the characterization of regional groundwater flow through fractured rock. The purpose of this review was to obtain information from previous studies and academic research that could be used to facilitate the subsequent technical analyses. In total, six regional groundwater studies and 25 technical papers were reviewed.

Previous studies have shown that the geology and hydrogeology of the study area is complex. The geology consists of Paleozoic aged sedimentary rocks (primarily limestone and sandstone) situated along the east and west portions of the CSPA, flanking an exposed central core of Precambrian igneous and metamorphic rocks. The bedrock is exposed over most of the study area, with the exception of local deposits of clay, sand and glacial tills, which have been deposited in depressions in the bedrock surface, or as glacial drumlins, moraines and river deposits. Groundwater is extracted mainly from bedrock aquifers; however, some localized overburden aquifers are utilized. Groundwater flow in the bedrock is predominantly via fracture flow, while groundwater movement in the overburden is within the pore spaces.

Geological Cross-Sections

Geological cross-sections were prepared to assist in the conceptual understanding of the geology and hydrogeology of the CSPA. Cross-sections were produced at both a regional scale (30-150 km length) and municipal scale (6-20 km length). Sections were constructed primarily using information from the Ontario Ministry of the Environment (MOE) Water Well Records. Select high quality borehole records from environmental investigations and government studies (Ontario Geological Survey, Ministry of Northern Development and Mines) were used to augment the MOE data.

Key findings from the geological assessment included:

- At the regional scale, most of the CSPA is considered highly vulnerable to groundwater contamination because of the predominant use of the fractured bedrock as the potable water aquifer and the lack of overlying protective layers. Vertical fractures pass through the bedrock and provide a direct, downwards pathway for contaminant migration. Contaminants introduced into the bedrock can move quickly through fractures compared with transport in porous media. In some areas, moderate vulnerability conditions will exist where there are deposits of glaciolacustrine clay and glacial till overburden; however, these areas are generally isolated. Overburden potable water supplies are limited to near surface sand and gravel deposits, and will generally have a high vulnerability.

- The most permeable bedrock material in the CSPA is the sandstone of the Nepean Formation. The March Formation is also relatively permeable because of sandstone interbeds. Nevertheless, most groundwater flow is along fractures rather than pore spaces in the rock (porosity). It is postulated that these formations are recharged where they are exposed at surface. Where these deposits are buried beneath carbonate rocks, it is speculated that they may act as preferential groundwater flow pathways between the underlying lower permeability Precambrian shield and overlying Paleozoic carbonate rocks. Therefore, it is possible that the regional groundwater flow is affected by the regional or fracture geometry of these higher permeability formations, and that the groundwater flow, especially at depth, may not coincide with surface drainage patterns. For example, deep groundwater flow in the neighboring Rideau watershed may be partially recharged in the CRCA watershed where the Nepean and March Formations are exposed.

- Cross-boundary flow may also occur at depth, where groundwater flow patterns will reflect larger scale topography trends, rather than the smaller scale watershed drainage patterns. For example, the boundary between the Napanee and CRCA watersheds may reflect a groundwater flow divide for shallow groundwater flow, but at depth, groundwater may flow beneath the Napanee River and discharge to Lake Ontario.

- Based on the relative elevations of the inferred water table relative to surface water features, the following water bodies were identified as potentially having a significant groundwater base flow component: Napanee River, Cataraqui River, Wiltse Lake, Millhaven Creek, Wilton Creek, Little Cranberry Lake, Upper Beverley Lake, Fosters Creek, Charleston Lake, Jones Creek, Colonel By Lake and Spring Creek.

Significant Groundwater Recharge Areas

Significant Groundwater Recharge Areas are vulnerable areas that will be subject to source protection. The draft Technical Rules indicate that SGRAs are synonymous with areas of high volume recharge (HVRA). Previous technical guidance modules had defined SGRAs as HVRAs that support either a sensitive ecological environment or a water supply. For the purpose of this study, we have identified both HVRAs (referred to in this study as SGRAs) and sensitive features that are supported by SGRAs. Two methods were used to assess SGRAs. Method #1 mapped areas that potentially experience a vertical groundwater flux, while Method #2 identified areas of relatively high infiltration using a conceptual water budget analysis.

Some of the key findings of the study include:

- Groundwater recharge is expected to occur over most of the study area; however, the rate and volume of recharge will differ with location. Areas that have the greatest potential for being SGRAs are topographically elevated locations where coarse-grained geological materials are present at surface.

- The role of recharge in the large areas of shallow to exposed bedrock is uncertain. In many cases, these lands are characterized by small and poorly connected lakes, rivers, swamps and local surface depressions. While high rates of recharge may not occur in any particular location, significant volumes of recharge likely occur at the watershed scale. Where these surface depressions are connected to fracture networks in the bedrock, surface water recharge to groundwater would be enhanced.

- Areas where the regionally significant Nepean Formation Aquifer (and to a similar extent, permeable horizons of the March Formation) crop out or are covered by permeable materials, are speculated to be SGRAs. These permeable formations crop out along the northeastern extent of the watershed.

- SGRAs that support ecological features were identified in two locations (streams near South Lake and Wilton Creek). Cold-water lakes are present in several locations, but their sensitivity to groundwater input is unclear. Four wetlands were identified (Butternut Creek, Eel Bay/Sydenham Lake, Kingston Mills and Loon Lake wetland) as being both reliant on groundwater inputs and being ecologically significant.

Aquifer Vulnerability

High vulnerability aquifers were identified using two methods: a) MOE Intrinsic Susceptibility Index (ISI) protocol; and b) surficial geology information to qualitatively rank aquifer vulnerability based on the relative permeability of overburden materials. Key conclusions are as follows:

- Vulnerability rankings change over short distances, reflecting the complex geology of the CSPA. Areas of low vulnerability will be juxtaposed with areas of high vulnerability.

- Both analysis methods indicate that the majority of the CSPA is highly vulnerable. Approximately 84% of the known wells were identified as being highly vulnerable using the MOE ISI methodology. Using the surficial geology methododology, approximately 61% of the area was deemed as highly vulnerable, however, this method will underestimate the amount of highly vulnerable areas as it does not explicitly take into account the overburden thickness.

- Vulnerability rankings change over short distances, reflecting the complex geology of the CSPA. Areas of low vulnerability will be juxtaposed with areas of high vulnerability.

- Areas of low to moderate vulnerability are mostly concentrated in parts of Loyalist Township, City of Kingston, and select areas within The Township of Leeds and the Thousand Islands. These low to moderate vulnerability areas are associated with thick deposits of silt and clay.

Considering that the vast majority of wells were ranked as high vulnerability across the CSPA and that low to moderate vulnerability areas only appeared as small and noncontiguous areas, the study proposed that the entire study area be considered highly vulnerable for the purposes of the Assessment Report and Source Protection planning. While isolated low vulnerability areas exist, they are few and limited in extent, and are not mappable with a high degree of confidence at the property parcel scale at which source protection will be applied. This recommendation is further supported by the fact that the uncertainty associated with mapping low to moderate vulnerable areas based on the surficial geology maps is high, and therefore these areas should also be mapped as highly vulnerable unless future site specific data indicates otherwise.

While there are limitations in the application of the vulnerability map, the following uses of the map are identified:

- The map can be used to underscore the fact that unlike many other Source Protection Areas in Ontario, the CSPA is intrinsically vulnerable and complex. Land development will require additional study at the local and property parcel scale in order to assess actual vulnerability.

- The map can be used as a guidance tool for future Source Protection activities such as identifying general areas for voluntary-based protection initiatives and for guiding future technical studies.

- The map can be used to identify areas that have the greatest probability of being highly vulnerable (areas of shallow rock and surficial sands and gravels). Future source protection activities such as education programs, spills prevention programs, incentive programs etc. that target high vulnerability conditions could focus on these areas. Conversely, areas of low vulnerability could be targeted under source protection for the management of transport pathways such as improperly abandoned wells.

- The map can be used to identify areas where the vulnerability is less predictable, such as in areas of clay, silt, or till deposits. In these areas, future studies involving well surveys and test drilling could be conducted to verify vulnerability conditions. Identification and confirmation of low vulnerable areas could be used as input into future land use planning decisions.

- While the map is regional in nature, it can be used to help assess aquifer vulnerability at more local scales, as long as certain precautions are followed, namely interpretation via qualified personnel.

Recommendations

The report concluded by making several general recommendations that build upon the findings of this study. These recommendations were:

1) There is a need to improve the understanding of regional groundwater flow patterns, considering the hydrogeological complexity of the CSPA, and the general lack of good quality groundwater data. Future studies should also focus on understanding groundwater flow within the Nepean Formation aquifer, and in determining the presence and significance of interwatershed groundwater flow.

2) The relationship between surface water features (lakes, rivers and wetlands) and aquifer recharge should be assessed. The work should include determining the significance that these features have on maintaining seasonal water levels in the aquifer and their contribution to aquifer storage.

3) Significant Groundwater Recharge Areas (SGRA) that were identified in the GVAR study should be confirmed through field investigations. SGRA delineation can also be improved by mapping important groundwater discharge areas, and relating these discharge areas to the recharge areas that support them.

4) Identify SGRAs that provide groundwater recharge to the aquifers that are used by rural settlements serviced by private wells. Protection of these SGRAs will be important to ensure an adequate water quality and quantity to these communities.

5) Identify ecosystems that are sensitive to groundwater contributions, such as cold water streams, or sensitive wetlands. These features may be vulnerable to nearby changes in land use or groundwater pumping.

6) Update the vulnerability maps as additional site specific information becomes available. The study has shown that the majority of aquifers in the CSPA can be considered highly vulnerable; however, aquifer vulnerability at a property parcel level may differ from regional conditions.

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# INTRODUCTION

Dillon Consulting Limited (Dillon), in association with Malroz Engineering Inc. (Malroz), was retained by the Cataraqui Region Conservation Authority (CRCA) to undertake the Groundwater Vulnerability Assessment Report (GVAR) study for the Cataraqui Source Protection Area (CSPA). Information from the GVAR will be incorporated into the CSPA Assessment Report that is currently being compiled by CRCA.

The GVAR was conducted following our proposal dated January 19, 2007, as amended by work scope changes detailed in our letter dated June 1, 2007. The Terms of Reference for the project, developed by CRCA, was dated December 21, 2006.

## Background

The Ontario Government has passed the *Clean Water Act*, 2006 for the purpose of protecting drinking water at its source. The *Act* requires Source Protection Areas to develop protection plans for municipal potable water sources. These plans will address water quality and quantity threats that have been identified in vulnerable areas within the Source Protection Area. The *Act* identifies four types of vulnerable areas: i) groundwater source well head capture zones; ii) surface water source intake protection zones; iii) significant groundwater recharge areas; and iv) high vulnerability aquifers. The purpose of this report is to identify the vulnerable areas in the latter two conditions (significant recharge areas and vulnerable aquifers). Identification of the other two vulnerable areas (well head capture zones and intake protection zones) is being undertaken separately. The results of the current assessment will be used as input into future threat inventories and hazard assessments, and for the development of the source protection plan for the CSPA.

Methodologies used in the study were largely based on the Ontario Ministry of the Environment (MOE) Draft Assessment Report technical guidance modules that were released in October 2006. These guidance modules were updated in June 2008, by the release of the draft MOE Technical Rules. In some cases, differences exist between methodologies outlined in the guidance modules and the Technical Rules. In addition, the Study team used slightly modified approaches for some of the technical studies to account for the unique characteristics of the study area. Where modifications have been made that differ from the current Technical Rules, a description of those changes is presented.

**Scope**

The GVAR project involved completion of the following four tasks:

- Literature Review
- Development of Geological Cross-Sections
- Mapping of Significant Groundwater Recharge Areas
- Mapping of High Vulnerability Areas.

Each of the tasks formed a part of the larger effort to map vulnerable areas within the CSPA. The literature review involved perusal of select technical documents and academic articles on groundwater flow in fractured rock terrains. Information gleaned from this review was used as input into the selection of assessment methods used for mapping of recharge areas. Geological cross-sections were constructed through the CSPA to gain an increased understanding of the hydrogeological conditions at depth, including identifying the location of aquifers and protective aquitards. The last two tasks focused on developing the two key deliverables of the GVAR study, which included mapping significant groundwater recharge areas and high vulnerability areas.

**Report Organization**

The report is presented in five parts: Part 1 (Literature Review); Part 2 (Geological Sections); Part 3 (Significant Recharge Areas); Part 4 (Aquifer Vulnerability); and Part 5 (Recommendations). Parts 1 through 4 are presented as stand-alone sections, and describe the objective, methodology and results of the particular topic discussed. Part 5 presents recommendations from all study elements.

**Limitations**

This report was prepared by Dillon for the sole benefit of our Client. The material in it reflects Dillon's best judgment in light of the information available to it at the time of preparation. Any use which a third party makes of this report, or any reliance on or decisions made based on it, are the responsibilities of such third parties. Dillon accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

# PART 1 LITERATURE REVIEW

## 1.1 Introduction

A review was undertaken of select regional groundwater studies and technical papers whose topics included the characterization of regional groundwater flow through fractured rock. The purpose of this review was to obtain information from previous studies and academic research that could be used to facilitate the subsequent technical analyses of identifying significant groundwater recharge areas. In total, six regional groundwater studies and 25 technical papers were reviewed, and are listed in **Appendix A**. Most of the technical papers were provided to Dillon by CRCA staff. The literature review was not exhaustive, and was limited to a cross-section of studies and papers that the team thought would provide additional insight into the mapping of significant groundwater recharge areas within the study region.

A summary of the reports and papers that were deemed most relevant to the GVAR project is summarized in **Section 1.2** (regional studies) and **Section 1.3** (papers) below. **Section 1.4** capsulates the intent of the remaining studies that were reviewed, but were considered more site-specific in nature and not as applicable to the regional objective of the GVAR study.

## 1.2 Previous Regional Groundwater Studies

A number of regional groundwater studies have recently been conducted in either the Cataraqui Region watershed or adjoining watershed areas. A summary of the findings of these studies, as they pertain to groundwater recharge, is presented below by study.

<u>Renfrew County – Mississippi – Rideau Groundwater Study (Golder and Dillon, 2003)</u>

This groundwater study was performed in the neighboring Mississippi Valley and Rideau watersheds and the County of Renfrew. The study is relevant to the GVAR study in that the hydrogeological terrain is similar, with both Precambrian rock and Paleozoic rock aquifers being present. Pertinent observations made in the study are as follows:

- Bedrock aquifers can be locally confined in areas where the overlying rock is not significantly fractured or in areas where the aquifer is confined by clay overburden or relatively thick deposits of fine-grained till.

- In Precambrian aquifers, flow is through secondary porosity that has developed as a result of tectonic process (Ostry and Singer, 1981). Primary porosity in Precambrian rocks is generally 2% (Freeze and Cherry, 1979). Distribution and density of fractures commonly decreases with depth. Near surface, the development of horizontal fractures via "sheeting" can result in increased aquifer permeability. Estimates of bulk hydraulic conductivity of Precambrian rocks range from $10^{-6}$ to $10^{-2}$ cm/s (Freeze and Cherry, 1979).

- The most productive aquifer are the sandstone formations such as the Nepean Formation and the lower portions of the March Formation that contains a high percentage of sandstone interbeds. The sandstone aquifers are an important source of groundwater in southeastern Ontario, where it is tapped for large municipal wells or commercial/industrial purposes. In the sandstone aquifer, groundwater flow is within primary porosity as well as secondary porosity produced by fractures. Hydraulic conductivity estimates range from $10^{-6}$ to $10^{-4}$ cm/s (Raven Beck Environmental, 1994).

- Regional mapping of groundwater recharge areas was undertaken using two methods: a) mapping of vertical hydraulic gradients by subtracting the derived water table surface from the potentiometric surface map. Potential recharge areas were mapped where the water table was >5m above the potentiometric surface, while potential discharge areas were mapped where the water table was >5m below the potentiometric surface; and b) identifying areas where the water table is expected to be near surface, and discharge conditions may prevail. Overall, both maps were limited in their ability to identify recharge areas, mainly because of the problematic input data (sparse well data and open-hole well construction). Nevertheless, the mapping suggested that, in general, recharge conditions exist in upland areas corresponding with watershed boundaries, and that discharge conditions are manifested near the centre of watersheds.

- Overburden aquifers may recharge bedrock aquifers where they are hydraulically connected.

- The study looked at groundwater chemistry to assess groundwater age and relative groundwater recharge patterns. In general, the chemical composition of groundwater changes with residency time and travel from being fresh with little dissolved solids to being saline (Chebotarev, 1955). In the study area, the bicarbonate anion was dominant in all regional aquifers, suggesting possible relatively short groundwater residence time. A slightly lower abundance of bicarbonate was present in highly mineralized water from the sandstone aquifers (Nepean and March formations), suggesting longer residency times. These formations, however, are more siliciclastic, and therefore the decrease in bicarbonate may be intrinsic to the aquifer. Based on a limited amount of tritium testing, there appeared to be no correlation between well depth and age of groundwater, implying that groundwater in the top portions (<30m) of the bedrock aquifer is relatively recent.

<u>United Counties of Leeds and Grenville Groundwater Management Study (Dillon, 2000)</u>

This study included the upper and eastern portion of the Cataraqui watershed, as well as the geographic area of the United Counties of Leeds and Grenville. Main findings that pertain to groundwater recharge are as follows:

- Ostry and Singer (1981) estimated that the active groundwater flow in the Precambrian rock is mainly within the top 30m. Analysis conducted during the Leeds and Grenville study using well records indicated that 80% of the potable water found was within 35m of the bedrock surface.

- It was postulated that local topographic highs produced from sand and gravel deposits act as locally significant recharge areas for the bedrock, especially where these areas are flanked by low permeability clay.

- Mapping of recharge areas was performed by two methods: a) mapping areas where permeable coarse-grained deposits are present as indicated on overburden geology maps; and b) mapping static water levels. Areas identified as potential recharge areas included: elevated coarse-grained esker and moraine deposits; sand plains as a local recharge source to tributaries and wetlands; and exposed drumlins that protrude through lower permeability deposits.

- Infiltration is considered to be lower in bedrock than in overburden; however, because of the large areal extent of exposed bedrock, recharge is deemed to be significant.

Quinte Regional Groundwater Study (Dillon, 2004)

The Quinte Regional Groundwater Study was part of the third round of regional groundwater studies conducted in the area. Some new methods of predicting groundwater recharge areas were used that were not applied in either the Mississippi-Rideau or United Counties of Leeds and Grenville studies. A summary of the findings as they pertain to recharge are as follows:

- In addition to the standard vertical gradient and soil infiltration mapping approach to identify recharge areas, the direction of vertical groundwater movement was mapped by estimating the depth to the water table surface. Areas where the water table was near ground surface were anticipated to be prone to discharge conditions, while areas where the water table was deep were considered prone to recharge conditions. Essentially, the recharge map identified topographical areas that are significantly above the average local water table surface. These locations were considered as potential recharge areas. The analysis method was deemed more useful than mapping vertical gradients from water well records because it avoided the problems associated estimating with the potentiometric surface from wells with open hole construction.

- Hydrograph analysis showed that water levels in the aquifers are highest in the spring and fall, when precipitation is greatest and water demand by plants is low. Conversely, water level elevations are lowest in the winter when frozen ground conditions prevail and in summer when precipitation is low and water demand by plants is highest. At the observed monitoring stations, the spring thaw period appeared to be one of the more significant periods of aquifer recharge during the year. Fluctuations in the water table appeared greater for wells that were installed in fractured rock compared with those in overburden, possibly reflecting the effects of reduced storage capacity in a fractured bedrock environment.

Preliminary Hydrogeological Investigation, Prince Edward County, WESA, 1984

This study was conducted for the Prince Edward County area. Groundwater flow in the County is dominated by flow through fractured Ordovician limestone, with some flow through minor overburden sand aquifers associated with glaciofluvial deposits. Mapping of recharge and discharge areas was based on mapping static water level elevations as reported in the water well records. Local and regional recharge areas were identified where gradients were diverging and the water table surface was elevated. Local and regional discharge areas were identified where gradients were convergent and in low-lying areas.

<u>Western Cataraqui Regional Groundwater Study, Trow, 2007</u>

Mapping of recharge areas was based on the spatial distribution of the overburden and bedrock geology as depicted on surficial geology maps. Areas overlain by either fine-grained glaciolacustrine, glaciomarine or organic deposits were identified as having a low recharge potential. A low recharge potential was also assigned to areas where Precambrian rock was near the surface or exposed. Portions of the study area that were mapped as either coarse to medium textured glaciofluvial, glaciolacustrine or till overburden deposits were mapped as having a moderate recharge. A high recharge potential was given to areas where the Paleozoic bedrock was near surface or exposed.

<u>Source Water Protection Water Budget Conceptual Report, CRCA, 2007</u>

CRCA recently completed the conceptual water budget report for the Cataraqui Source Protection Area. As part of this report, an assessment of the spatial variability in infiltration was determined. The method used was primarily based on an adaption of the MOE methodology outlined in their document *Hydrogeological Technical Information Requirements for Land Development Applications*, MOEE, 1995. This document referenced an earlier document titled *Guidelines for the Preparation of a Rural Servicing Report for Development to be Serviced by On-Site Sewage System*, MOEE, 1989. Estimation of the infiltration rates across the watershed was based on determining the key components of the waterbudget (precipitation, evapotranspiration, run-off) at the watershed scale, which takes into consideration long-term average annual conditions. Infiltration rates were estimated from the calculated surplus water using a portioning relationship that linked infiltration to topographic slope, land cover and soil type. Essentially, higher infiltration rates are assigned to areas with coarse soil, flat land and forested land use. Areas that were deemed to have the highest infiltration were open sandy loam deposits associated with ice-contact stratified deposits and coarse-grained glaciolacustrine material. Many of these areas fell within the Precambrian shield. Till deposits, as well as, other coarse-grained glacial deposits that fell in the Paleozoic areas also received a high infiltration rate. Special consideration was also given to areas of shallow soil over bedrock where infiltration is expected to be low.

The water budget study also assessed recharge rates by analysis of static groundwater level fluctuations in response to precipitation events following the Healy and Cook, 2002 methodology.

## 1.3 General Technical Papers on Recharge

This section provides a summary of the technical papers that were considered most applicable to the objectives of the literature review.

<u>Estimating ground water recharge from topography, hydrogeology and land cover, Cherkauer and Ansari, 2005</u>

One of the main purposes of this paper was to provide a relatively simple and accurate measurement of groundwater recharge in humid areas using readily available information. Cherkauer and Ansari say that, to date, much of the effort to quantify recharge has focused on semi-arid areas. However, in many humid areas showing rapid population growth dependent on groundwater, demand exceeds recharge, and the availability of recharge cannot be factored into the planning process unless it has been quantified. The scale of the assessment methodologies used to quantify recharge are important because some methods work at small, single wellhead scales (well hydrograph analysis), and other methods are more appropriate at larger watershed scales (budget analysis).

Cherkauer and Ansari propose a method that provides a quick way to obtain a reasonably accurate estimate of recharge from commonly available information using baseflow separation from total stream discharge. Based on this information, they established a relationship between recharge rate and the controlling physical properties of watersheds.

Hydrograph separation inherently assumes that direct surface runoff and groundwater discharge are the only components of streamflow. Watersheds with significant surface storage locations (lakes and wetlands) should be avoided. Although this constraint would exclude the shield area of the GVAR study area, it may be suitable in the flat Paleozoic areas in the east and west of sections in the study area. An advantage of this method is that it uses data from stream gauge stations as its main source of information. This data can be used in a possible follow-up phase as a means to calibrate the categories of relative significant recharge areas mapped in the current phase of the GVAR project.

Factors affecting recharge to crystalline rock in the Mirror Lake Area, Grafton County, New Hampshire, Harte and Winter, 1996

This is a general paper that investigates factors that affect local and regional recharge to crystalline bedrock from overlying glacial drift. In their introduction, Harte and Winter state that "The spatial distribution of bedrock recharge from overlying unconsolidated deposits is an important factor in delineating areas susceptible to the advective transport of contaminants."

They use two steady-state numerical cross-sectional models to evaluate recharge processes. The hypothetical setting used in the models is based on the physiographic and hydrogeological characteristics of the Mirror Lake area in northeast United States, an area of crystalline rock overlain by glacial drift. This setting is similar to the Canadian Shield terrain of the Frontenac Axis in the GVAR study area. Harte and Winter compare vertical hydraulic gradients between the glacial drift and underlying bedrock with modeled chemistry along the groundwater flowpath.

One of the paper's main conclusions is that the distribution of bedrock recharge in the Mirror Lake area is controlled primarily by relief of the land and bedrock surface above groundwater discharge areas (e.g., lakes and streams) and lateral trends in horizontal hydraulic conductivity (K). Their results confirm that there are four factors that affect bedrock recharge patterns.

Regional distribution of bedrock recharge is controlled by:

- Relief of land and bedrock surface above groundwater discharge areas
- Lateral trends in bulk rock horizontal K.

Local distribution of bedrock recharge is controlled by:

- Local topographic features
- Drift stratigraphy.

<u>Choosing appropriate techniques for quantifying groundwater recharge, Scanlon, Healy and Cook, 2002</u>

This paper provides an overview of techniques for quantifying recharge. It is applicable to the GVAR project only in the sense that it summarizes the important factors in choosing techniques most appropriate for a study with specific goals in a particular area. The authors distinguish between methods appropriate for humid areas versus semi-arid/arid areas, and stress the uncertainties that are inherent in each quantification technique.

Some of the most relevant points in the paper are as follows:

- Whereas the evaluation of water resources requires techniques to obtain regional estimates of recharge, aquifer vulnerability studies need determination of the spatial variability of recharge and preferential flow.

- Climatic regions (e.g., arid versus humid) have fundamental differences in recharge that require different approaches.

- In humid areas, surface water and saturated zone techniques are more widely used than unsaturated zone techniques.

- Watershed modeling techniques may be more accurate in humid regions where perennial surface water flow can be used for model calibration.

- Water-budget techniques are generally more accurate in humid areas than in semi-arid/arid regions.

- Saturated zone techniques generally provide recharge estimates that are more reliable because they estimate actual recharge, whereas surface water and unsaturated zone techniques estimate potential recharge.

- Techniques that require K data, such as Darcian methods and models, are inherently inaccurate because K can vary over several orders of magnitude.

<u>Groundwater recharge: an overview of processes and challenges, DeVries and Simmer, 2002</u>

Although this paper provides a useful overview of the processes and techniques used to quantify recharge, its relevance to the GVAR project is limited. DeVries and Simmer focus on semi-arid/arid regions where the need for information is greatest.

<u>Karst Compilation for Southern Ontario (Brunton, Dodge and Shirota, 2005, 2006)</u>

These Open File Reports present updates on the Ontario Geological Survey (OGS) reconnaissance-level mapping survey of karst features within Phanerozoic strata in southern Ontario. Karst is produced by chemical leaching of sedimentary rocks and may result in the development of enhanced rock permeabilities and conduit groundwater flow. Mapping in the 2005 field season was conducted in the Ordovician limestone plains of southeastern Ontario. The paper reported that all Ordovician limestone displayed good joint-set fractures with major joints extending “tens of metres” and through more than one formation. Cave features are restricted mainly to the Gull River Formation with the greatest likelihood of karstic features being along: a) the Paleozoic-Precambrian unconformity; b) along major rivers and adjoining wetlands; and c) margins of small escarpments between major rivers. Brunton et al., stated that karst is best developed in areas where the Bobcaygeon Formation is present as a thin caprock on top of the Gull River Formation. The geometry of the karst generally follows the regional joint patterns. Some caves in the Belleville area were reported to have in excess of 5 km of interconnected pathways.

Personal communication with F. Brunton stated that the Verulam Formation (which crops out at the southern extremities of the CSPA) is not as prone to karst as the Gull River or Bobcaygeon Formations. The OGS plans to publish a map of the karst survey later in 2008.

### 1.4 Site-Specific Technical Papers

Other papers that were reviewed as part of the literature review are listed in **Appendix A** (Sections A-3 to A-4). These papers deal with aspects of groundwater flow in fractured rock and/or site-specific studies that use various field methods to quantify recharge, rather than investigate regional scale conditions. Many of the investigated sites are in arid or semi-arid areas where the hydrologic conditions are much different from those in the GVAR. As a result, detailed summaries are not provided.

## 1.5 Discussion

In general, the characterization of groundwater recharge patterns in a fractured rock environment is difficult considering that flow patterns are dependent upon the scale of the investigation and the definition of the aquifer being recharged. At a regional level, recharge is expected to occur over most areas; however, it is expected that some areas are more conducive to recharge than others. Conditions that would be required to create areas of higher recharge would be a permeable material exposed at surface and a downward vertical hydraulic gradient. Overall, based on a review of past regional groundwater studies and a review of select technical literature, several different methods may be required to understand recharge potential in the CSPA. Further details on the mapping methods chosen to assess recharge conditions are presented in **Part 3** of this report.

# PART 2 GEOLOGICAL SECTIONS

## 2.1 Introduction

This section presents a series of geological cross-sections that have been constructed through the Cataraqui Source Protection Area (CSPA). Cross-sections were produced at both a regional scale (30-150km length) and municipal scale (6-20km length).

## 2.2 Scope and Objectives

Geological cross-sections were prepared to assist in the conceptual understanding of the geology and hydrogeology of the CSPA. The spatial relationships between the Precambrian rock and the Paleozoic formations were interpreted, and the influence that these geometries have on the regional hydrogeology were examined.

The scope was limited to the review and analysis of available data that was provided to Dillon in database, well log and mapped GIS form. Key input data included topography mapping, surficial and bedrock geology mapping, and Ontario Ministry of the Environment water well records. Where available, high quality borehole records produced from environmental investigations and government studies (Ontario Geological Survey, Ministry of Northern Development and Mines) were incorporated to improve the accuracy of the interpretation.

## 2.3 Methodology

Geological cross-sections were developed following a step-wise process: Step 1 – database development; Step 2 – borehole plotting; and Step 3 – cross-section preparation. Details on each of these steps are presented below.

### 2.3.1 Step 1 - Database Development

Borehole and Water Well Data Sources

The Ontario Ministry of the Environment (MOE) water well information system (WWIS) database (MOE, 2006) was the main source of geological and hydrogeological information used to develop the cross-sections. The data was provided by the MOE in Microsoft Access™ format via the CRCA. Prior to its use, the database was processed by Earthfx Limited to remove known database errors and convert the database structure to facilitate its analysis. This water well record database included detailed information about all existing water well records in the CSPA. The following key fields were included in the database:

- Well record number
- Geographical (UTM) coordinates
- Ground surface elevation
- Total borehole depth
- Geological material descriptions and associated depths
- Static water level.

The database included a UTM Coordinates Confidence Code field. This code assigns a number (between 1 and 9) to each well record based on the margin of error associated with the coordinates. The following codes are applied:

| | |
|---|---|
| 1 | margin of error: <3m |
| 2 | margin of error: 3 - 10m |
| 3 | margin of error: 10 - 3m |
| 4 | margin of error: 30 – 100m |
| 5 | margin of error: 100 – 300m |
| 6 | margin of error: 300 m – 1km |
| 7 | margin of error: 1 – 3km |
| 8 | margin of error: 3 – 10km |
| 9 | unknown UTM. |

In general, only well records that had an accuracy code of five or smaller were used in the creation of the cross-sections.

The use of MOE Water Well Records to delineate geology is limited by the inherent uncertainties associated with the data. Water Well records are completed by the driller at the time of well construction, and provide an approximation of material encountered during drilling. Their original purpose was to provide general information on the lithology of the area, well construction details and water supply potential, rather than to collect information for future scientific study. Often the driller is not trained in lithological characterization, and material descriptions are based on their local experience. Furthermore, common methods of water well drilling (rotary, cable-tool) do not allow precision material sampling, and therefore description of the encountered lithology and position of lithological contacts is generalized Nevertheless, in the absence of highly quality data in the study area, water well records are the major source of lithological information. As a result, the stratigraphic correlations shown on the sections are general approximations only and show regional trends in stratigraphy. Actual lithological conditions at the well and between the wells will likely differ.

Select high quality borehole records, often referred to as “Golden Spikes”, were used to develop the cross-sections. These high quality borehole records were created by either government organizations or private consulting firms. The high quality boreholes that were incorporated into the sections and entered into the database are tabulated below:

**Table 2.1: Golden Spike Boreholes**

| Well/Borehole | Section |
|---|---|
| PGWMN Well #248868 | G-G’ |
| PGWMN Well #260637<br>OGS 90-16D<br>BH3 - Malroz<br>BH5 – Malroz | D-D’ (Lansdowne) |
| OGS 90-16D<br>PGWMN #260555 | W-W’ |
| PGWMN # 248868 | H-H’ |
| PGWMN #248868 | J-J’ |
| OGS 90-16D | 9-9’ |
| BH3 – Malroz<br>BH5 – Malroz | CC-CC’ |
| BH5 – Malroz | DD-DD’ |

In addition to these boreholes, select environmental reports provided by CRCA staff were reviewed to gain additional geological knowledge of the area.

### 2.3.2 Step 2 - Borehole Plotting

Following the development of the database, a base map of the CSPA was developed using ViewLog™ software. Layers within the mapping included the study area boundaries, watercourses and waterbodies, topography, bedrock geology, surficial geology, and towns and cities. These GIS files were provided by CRCA.

Boreholes included in the geological cross-sections were extracted from the database by queries. A "Master Well Location" query was developed that included tabulating the well record number, geographical coordinates, the ground surface elevation, the borehole bottom elevation and the coordinate confidence code (<6). Criteria within the query included eastings coordinates (317000 to 470000), northings coordinates (4873000 to 4960000), ground surface and borehole bottom elevations, and a coordinates confidence code of less than 6. A "Lithology" query was developed that included the well record number and the top and bottom elevation of each geological material at that location.

The georeferenced borehole locations were plotted on the base map by linking the map to the "Master Well Location" query discussed above. The result was a GIS application that included the various base map layers as well as all boreholes (displayed as points) that fit the defined criteria (i.e., within the study area, confidence code <6). Geological information was included in ViewLog™ through a link to the "Lithology" query, which enabled a geological borehole log to be displayed by selecting the borehole on the map.

#### 2.3.3 Step 3 - Cross-Section Preparation

The final step in the process was building the sections using the geological cross-section software (ViewLog™). Section line locations were selected based on input from CRCA. In general, the location of the line depended upon the objective of the analysis. To understand the general geology, several section lines were positioned perpendicular and parallel to the Frontenac arch and regional strike of the Paleozoic geology. Section lines were also placed perpendicular to the main drainage patterns in order to investigate the relationship between surface water drainage and hydrogeology. In addition, several smaller local sections were prepared through communities that either currently have a municipal system (Lansdowne, Cana Subdivision), or may build a municipal system in the future.

Following the development of the initial sections, the locations of the section lines were adjusted to maximize the intersection of high quality boreholes. Final boreholes used in the analysis were selected based on the following criteria:

- Plausible geological descriptions based on conventional geological theory. For example, borehole logs that displayed granite-overlying fill were rejected based on this implausible scenario. Section lines were shifted to avoid such wells.

- Plausible geological descriptions based on existing geological mapping. For example, borehole logs that displayed granite in the upper stratigraphic layer within an area generally known to consist of Paleozoic limestone were rejected. Section lines were shifted to avoid such wells.

- Ground surface elevations within ±5 m of the DEM surface.

The final stage in cross-section development was importing the sections into AutoCAD™ DXF™ format and providing correlative interpretation of the geological contacts between well logs based on input from regional bedrock and surficial geology maps. Major surface features, including towns, lakes and rivers were identified on the cross-sections. The formation thicknesses/dips and approximately elevation of the top of the Precambrain bedrock were estimated based on Ministry of Natural Resource Oil and Gas structural mapping (MNR, 1983).

A list of sections that were generated is presented in the following table. Section lines are presented in **Figure 2.1** located at the back of the text.

**Table 2.2: Geological Cross-Section Locations**

| | |
|---|---|
| **REGIONAL SECTIONS** | |
| **Section #** | **General Location** |
| | |
| A-A’ | West to East: Hay Bay to Brockville |
| B-B’ | Southwest to Northeast: Simcoe Island – Seeley’s Bay – Toledo |
| C-C’ | Southwest to Northeast: Bath – Sydenham – Westport |
| D-D’ | North to South: Newburgh – Morven - Amherst Island |
| E-E’ | North to South: Hartington – Sydenham - Wolfe Island |
| F-F’ | North to South: Desert Lake – Battersea - Howe Island |
| G-G’ | Westport – Seeley’s Bay - Gananoque |
| H-H’ | North to South: Crosby – Lyndhurst - Rockport |
| I-I’ | North to South: Elmgrove – Charleston - Mallorytown |
| J-J’ | North to South: Elmgrove – Athens – Mallorytown |
| | |
| **MUNICIPAL SECTIONS** | |
| K-K’ | West to East: west of Harrowsmith to east of Sydenham |
| L-L’ | West to East: west of Elginburg to east of Sydenham |
| M-M’ | West to East: Seeley’s Bay |
| N-N’ | West to East: Mallorytown |
| O-O’ | West to East: Cana |
| P-P’ | North to South: Cana |
| Q-Q’ | West to East: Napanee area to west of Morven |
| R’-R’ | North to South: Marysville (Wolfe Island) |
| S-S’ | North to South: Stella (Amherst Island) |
| T-T’ | West to East: Wolfe Island – Howe Island |
| U-U’ | West to East: Lansdowne |
| V-V’ | North to South: Lansdowne |
| W-W’ | West to East: Athens |
| X-X’ | North to South: Athens |
| Y-Y’ | North to South: Harrowsmith |

In the production of the cross-sections, different scales were chosen (50x and 100x vertical exaggeration) depending upon the length of the cross-section to allow the most detail to be shown on the printed figures.

## 2.4 Results

This section presents the results of the assessment. **Section 2.4.1** provides background information on the regional geology and hydrogeology. Regional scale cross-sections are described in **Section 2.4.2** and municipal scale cross-sections are discussed in **Section 2.4.3**.

### 2.4.1 Regional Geology and Hydrogeology

Precambrian Bedrock

Precambrian aged rocks of igneous and metamorphic origin underlie the entire CSPA, and form a region commonly known as the Precambrian shield. The shield forms the core of the North American continent, and is composed of a series of accreted crustal material that, over time, merged into the North American continent. Because of the complexity of the rock types, geologists have subdivided the region into “belts” and “terranes” based on common lithology and age of development. The Precambrian rock in the CSPA is part of the Frontenac terrane, which is a subunit of the Central metasedimentary belt. The Precambrian rock is comprised of a combination of felsic, mafic to ultramafic plutonic rocks and carbonate to clastic metasedimentary rocks. The Precambrian rock is exposed along a northwest – southeast trending basement high, referred to as the Frontenac arch. Along the east and west flanks of this ridge, younger clastic, and then carbonate Paleozoic age sediments were deposited. These sediments lithified, and are expressed today as limestone, dolostone and sandstone.

Groundwater flow within the Precambrian rock is mainly through secondary porosity produced from fractures that have developed as a result of tectonic processes (Ostry and Singer, 1981). In general, primary porosity within igneous rocks is commonly less than two percent (Freeze and Cherry, 1979). The distribution and density of fractures commonly decreases with depth. Near surface, stress releases cause bedrock “sheeting” that produces horizontal fractures parallel to the ground surface. A significant cause of sheeting was the release of stress following glaciation during glacial retreat. These shallow fractures, when filled with water, can be of sufficient density to provide an adequate potable water source. Vertical fractures that have formed as a result of jointing processes are also present. These fractures connect the horizontal fractures, and can allow vertical migration of water. Estimates of bulk hydraulic conductivity of fractured igneous and metamorphic rocks typically range from $10^{-6}$ to $10^{-2}$ cm/s (Freeze and Cherry, 1979). The depth of active groundwater flow will vary spatially; however, previous studies (Ostry and

Singer, 1981) have suggested that in the thousand-island area, most flow is within the top 30m. This value is supported by the fact that most wells drilled in the CSPA take water from within the same depth. Nevertheless, many wells in the CSPA have been drilled up to 50m, suggesting that flow does occur at greater depths.

Regional groundwater flow patterns in Precambrian rock are mainly controlled by both topography and the density/connectivity of horizontal and vertical fractures. Because of the complexity of groundwater flow patterns in Precambrian rock, local scale groundwater movement is difficult to describe and predict. At the regional scale, patterns will be similar to that observed for porous media, in that groundwater flow generally moves from areas of high elevation to low elevation. As with all areas dominated by exposed or shallow buried fractured bedrock, recharge at the regional level is expected to occur over most of the area. However, at the local scale, there will be a tremendous variability in local recharge. Local recharge conditions may exist where surface water features are located in local topographical depressions.

Paleozoic Bedrock

Overlying the igneous and metamorphic rocks of the Precambrian shield are sedimentary rocks of Paleozoic (Cambrian to Ordovician) age. Deposition of these sediments began approximately 500 million years ago when a shallow ocean inundated the eastern portion of the ancestral North American continent known as “Laurentia”. During the development of marine conditions, erosion of the Precambrian land mass resulted in the deposition of sands and gravels along its continental shores. East of the Frontenac Axis, these Cambrian aged sediments are referred to as the Covey Hill and Nepean Formations, which together are often referred to as the Potsdam Group (Williams, 1991) or Nepean Formation (Wilson, 1946). For purposes of this study, the Wilson (1946) description will be used. As sea levels increased, and quieter, deeper water environments prevailed, carbonate rich sediments were deposited on top of the clastic deposits. East of the Frontenac axis, these deposits formed the Oxford and March Formations. While these carbonate sediments were being deposited, the landmass west of the arch was exposed. It was later inundated by an ocean, resulting in the deposition of carbonate deposits (Gull River, Bobcaygeon and Verulam Formations) as seas became deeper. The Shadow Lake Formation is presently generally west of the arch, and underlines the Gull River Foundation. It consists of arkosic siltstones, sandstone and shale and represents the last stages of clastic sedimentary inputs. A schematic geological cross-section showing how these formations are positioned across the Frontenac arch is shown as **Figure 2.2**. The stratigraphic correlation of the deposits is presented as **Figure 2.3**. An overburden geology map showing areas where bedrock is covered is presented as **Figure 2.4**. Descriptions of the formations, and their geology and hydrogeology properties, are summarized in the table below.

**Table 2.3: Paleozoic Formations West of Frontenac Arch**

| Formation | Description | Hydrogeological Properties |
|---|---|---|
| Verulam | Fossiliferous limestone beds with shale interbeds. It is exposed mainly in the southwestern extremity of the watershed, as well as on Amherst Island and the southern portion of Wolfe Island. | Well yields are often poor, indicating relatively low bulk permeability as compared to other Paleozoic rocks in the study area. |
| Bobcaygeon | Limestone with shale content increasing at higher stratigraphic intervals. Formation is exposed on Wolfe Island and east of Loyalist Township. | Wells yield adequate to acceptable for domestic consumption (10 to 13 L/min). |
| Gull River | Dolomitic limestones, shaley limestone becoming massive at higher intervals. Exposed over much of the areas west of Gananoque. | Wells yield adequate to acceptable for domestic consumption (10 to 13 L/min). Formation can be karstic, especially where overlain by a thin cap rock of Bobcaygeon Formation. |
| Shadow Lake | Arkosic sandstones, siltstone and shale. The formation was deposited on top of Precambrian Rock, and represents the last stages of clastic sedimentary inputs, and the beginning of generally continuous carbonate deposition. It is rarely exposed in CRCA area, and is not present east of the arch. Thickness ranges from 0 to 5 m. | No data available, however, where encountered, permeabilities are expected to be higher than underlying Precambrian Rock and overlying limestones. Where exposed, may provide higher recharge. |

Note: Formations are listed from youngest to oldest.

**Table 2.4: Paleozoic Formations East of Frontenac Arch**

| Formation | Description | Hydrogeological Properties |
|---|---|---|
| Oxford | Dolostone and shale interbeds. Exposure is limited to the far eastern extremity of the watershed, east and north of the City of Brockville. | Reported to be moderately permeable, with hydraulic conductivity enhanced by solution weathering of joint fractures. Estimated hydraulic conducted are $10^{-8}$ to $10^{-2}$ cm/s (RVCA, 1996). Generally, less permeable than March and Nepean aquifers. |
| March | Interbedded sandstone and dolostone, with thicknesses ranging from 0 to 20 m in study area. It is exposed along the eastern extremities of the watershed. | Reported to be fairly permeable, especially where sandstone interbeds are present. Hydraulic conductivity estimated to be $10^{-4}$ to $10^{-2}$ cm/s (J.D. Paterson, 1991). |
| Nepean/Covey Hill (also referred to as Potsdam Group or Nepean Formation) | Well-sorted quartz sandstone, overlying conglomerate at its base. Unit was deposited on top of Precambrian rock. Thickness ranges from 0 to >50 m. Is disconformable with the younger Shadow Lake Formation in the west. In general, the Potsdam Group is present mainly east of the arch. | Flow through both primary and secondary porosity produced from fractures. Known to be a high yielding aquifer. Hydraulic conductivity estimated to range from $10^{-6}$ to $10^{-4}$ cm/s (Raven Beck Environmental, 1994). |

Note: Formations are listed from youngest to oldest.

Based on the lithology and hydrogeological properties of the various formations, it is postulated that the bulk permeability of the Precambrian bedrock is lower than that of the overlying sedimentary rock. In addition, the most permeable sedimentary rocks are expected to be the Nepean Formation and the Shadow Lake Formation due to their higher primary porosity. The Nepean Formation is much thicker than the Shadow Lake Formation and will therefore have the highest transmissivity. Overall, the sedimentary rocks east of the Frontenac Arch will have higher transmissivities than the corresponding formations west of the arch due to higher content and thickness of sandstone interbeds. The Oxford, March and Gull River Formations are often affected by solution weathering (Golder and Dillon, 2003), which will increase their permeability at the local scale. Conversely, the Verulam Formation to the west is reported as a “tight” aquifer because of its poor well yield characteristics, likely a reflection of low primary and secondary porosity.

### 2.4.2 Regional Cross-Sections

Regional cross sections are presented in **Appendix B**. In total, ten sections were constructed, with four perpendicular to the Frontenac arch and the general strike of the overlying sedimentary bedrock, and six-positioned parallel to those features. The locations of these sections are presented in **Figure 2.1**.

General Bedrock Configuration

The general configuration of the bedrock geology is best shown in **Section A - A'**, which was constructed along the southern portion of the watershed, perpendicular to the Frontenac arch. The section shows the exposed Precambrian rock of the Frontenac arch in the centre, flanked to the east and west by the Paleozoic aged eastern and western St. Lawrence carbonate platforms, respectively. For simplicity, the limestone formations west of the arch (Gull River, Bobcaygeon and Verulam Formations) and east of the arch (Oxford and March Formations) are grouped together because of the difficulty in differentiating these formations within the water well records. Where data is available, the approximate boundaries between these formations are shown as dashed lines. Significant observations from the sections are as follows:

- Limestone is more areally extensive and thickest west of the arch attaining thicknesses of >100m, while sandstone is thickest (> 50m) and more extensive east of the arch.

- The irregular topography (which is exaggerated by 100X in cross-section) reflects the effects of glaciation as well as erosion from both preglacial and postglacial drainage systems. The drainage system is generally oriented southwest to northeast and corresponds with regional fault and fracture patterns. According to Chapman and Putnam (1984), some of the major rivers (eg., Napanee and Salmon) predate glaciation and were likely once expressed as relatively deep V-shaped valleys. The valley walls were subsequently plained off during glaciation, leaving the relief more subdued.

- The elevation of the exposed Precambrian bedrock in **Section A - A'** is generally lower than the Paleozoic bedrock along its flanks, indicating that erosion has removed the Paleozoic rock from the top of the arch in this location. The presence of Paleozoic outliers within the Frontenac arch supports this conclusion. This condition is observed for the community of Lansdowne and is further described in the Well Head Protection report for the Lansdowne municipal groundwater system (Malroz, 2007).

- The surface of the Precambrian rock is irregular, even where buried under sedimentary deposits. In some of these Precambrian rock surface depressions, sandstones were deposited. These depressions are likely attributed to faulting or perhaps pre-Paleozoic age erosion.

- From a groundwater vulnerability perspective, there is a lack of thick deposits of low permeability material such as clays, silts and tills at surface. As a result, the underlying fractured bedrock aquifers will be sensitive to contamination. Some exceptions are visible in **Section A - A'**. For instance, West of Odessa near Morven, up to 20 m of overburden deposits are present (shown in green on section) and correspond with glaciolacustrine deposits overlying drumlinized tills. These deposits will provide some protection to the bedrock aquifer. Other areas of localized thick deposits of overburden material exist near the Gananoque River and Mallorytown.

Observations from Other Sections

Observations made from the other regional sections are highlighted below. In most sections, the depth of the static water level in the water wells is shown. Considering that most of the wells are open hole construction, care must be taken when interpreting flow gradients using this information, as the static water levels used in the calculation may not be representative of piezometric conditions. Open hole wells intercept many fractures and possibly different pressure intervals. In general, interpretation of flow gradients is best performed using spatial data shown on the water table maps (**Figure 3.1**). Note that the vertical exaggeration differs between some of the sections, and is shown at either 100x or 50x, depending upon the section size.

- At a broad level, water table elevations generally correspond with topography, with the water table elevation being lower and shallower in depressions, and higher and deeper in upland areas. A good example of this trend is shown in **Section J - J'** in the area between Athens and Wiltse Lake. Based on this section, it is speculated that groundwater flow converges towards this Lake, and therefore may provide base flow to this water body.

- The sections can also be used to identify surface water features that may be subject to groundwater base flow. Surface water bodies that are elevated below the adjacent water table are candidates for being influenced by groundwater, whereas those that have elevations higher than the surrounding water table may be perched. Examples of where surface water levels are lower than surrounding well water levels include the Napanee River (**Section D - D'**) and the Cataraqui River (**Section E - E'**). In contrast, the elevation of Loughborough Lake (**Section E - E'**) appears to be above local water well levels, thereby suggesting that groundwater base flow may be low. However, as reported by CRCA, the western end of Loughborough Lake is a cold-water basin, which is home to lake trout. Since the lake is not much deeper than many of the warm water lakes in the area, there is a possibility that this portion of Loughborough Lake is influenced by groundwater discharge.

- **Sections B - B', D - D', E – E', F - F',** and **T - T'**, pass through Amherst, Simcoe and Wolfe Islands. Some of the water levels in the section wells are lower than the elevation of the surrounding St. Lawrence River. The cause of this phenomenon is not known, as upward gradients would be expected considering that the islands are located in the centre of a major primary watershed. Possible explanations include that the recorded water levels are not representative of static conditions or that the inaccuracies of the water levels taken from predominantly open hole wells will mask the presence of an upward gradient. Anecdotal information also suggests that the hydraulic conductivity of the geology is so low that minimal water is present in the inland areas of the islands (CRCA, personnal communication).

- **Sections A - A'** and **B - B'** bisect the eastern boundary of the watershed and show that the permeable Nepean Formation crops out just west of the Cataraqui/Rideau watershed boundary. Depending upon the permeability contrast between the Nepean Formation and the underlying Precambrian rock, it is speculated that a portion of the infiltrating water may migrate east towards the Rideau valley; however, horizontal gradients based on water well records suggest that the bulk of the flow will be towards the southwest, which is consistent with surface water drainage patterns.

- In **Section C - C'**, which bisects the northeastern boundary of CRCA and RVCA, there is a pronounced topographic high north of Big Rideau Lake in the area of Foley Mountain. Depending upon permeability, depth of active groundwater flow and hydraulic gradients, this elevated area could potentially cause deep groundwater to flow south from RVCA, underneath Big Rideau Lake.

- **Section D - D'**, bisects the Napanee River, that is located near the boundary between CRCA and the Napanee watersheds. The Napanee River is located in a relatively deep incised valley, with depths of up to 50m. Its location is believed to be controlled by faulting that bisects both the Paleozoic and Precambrian rock. It is possible that this river acts as a discharge point for groundwater that comes from both the Quinte watershed and the northern portion of the CRCA watershed. Depending upon the depth of active groundwater flow, it is possible that a component of flow from the north may pass underneath the river and migrate south across the CRCA/Napanee watershed boundary.

- Many of the sections (e.g., **Sections D - D**', **E - E'**) that run parallel with the Frontenac Axis, show undulatory topography. This is caused by the sections running generally perpendicular to the major drainage patterns of the area. The static water level surface, as measured from the water levels recorded by the well drillers, is more subdued. Considering there are considerable inaccuracies associated with the well water levels, interpretation of this phenomenon is difficult. The more subdued water table elevation may suggest that horizontal groundwater flow gradients are more controlled by regional topographic relief rather than the more abrupt local scale relief formed by the many rivers and valleys. If this is true, then many of the surface water features may not be significant discharge areas as they could be "perched" above the regional water table. These perched features may recharge lower aquifers through leakage. An exception could be in areas near major drainage features such as the Napanee River and Cataraqui River in which the elevation of the river base approaches or is lower than the elevation of the regional water table.

- Depressions in the surface of the Precambrian rock that have been filled with sandstone of the Nepean Formation are potential areas of significant groundwater flow (see **Sections F - F', H - H'**, and **J - J'**).

### 2.4.3 Municipal Scale Cross-Sections

Municipal scale cross-sections were made to assess geological conditions near areas that either have a municipal groundwater source water supply (e.g., Lansdowne, Cana Subdivision) or for communities that have been identified by CRCA as being potentially serviced in the future. The results of the sections are summarized below.

<u>Section K - K': West of Harrowsmith to east of Sydenham</u>

This 13km section bisects the Millhaven Creek and Wilton Creek subwatershed, passing through the communities of Harrowsmith and Sydenham. The section shows a good correlation between topographic elevation and the water levels in the wells. Based on this section, groundwater discharge to Wilton Creek and Millhaven Creek is expected. Shallow water levels in the wells located in the valley area west of Millhaven Creek suggest that upward gradients are possible. It is postulated that discharge to the Millhaven Creek may be enhanced by the presence of the permeable Nepean Formation that underlies this section of the creek. Similarly, the increased depth of the water table in the highland areas that bounds the creeks suggest a downward gradient.

From a groundwater supply perspective, both communities could tap the Nepean Formation aquifer, which is reported to have adequate supply potential. The Gull River Formation and the Precambrian rock aquifer could also be a target. However, aquifer vulnerability would be high since both communities are located in areas of shallow overburden.

<u>Section L – L': West of Elginburg to East of Sydenham</u>

Aquifers below the communities of Elginburg and Glenburnie are limestones of the Gull River Formation and Precambrian rock. Nepean Formation sandstones were not detected in the water wells drilled in the area. Overburden comprised of glacial tills and glaciolacustrine deposits appear to be thickest near Glenburnie, as compared with Elginburg. East of Glenburnie, there are glaciofluvial sand and gravel deposits. Considering the limited thickness of low permeability material overlying the bedrock aquifer, the aquifer is considered highly vulnerable.

<u>Section M – M': Seeley's Bay</u>

This section intercepts thick deposits of metasedimentary rocks of the Precambrian shield. Overburden deposits (glaciolacustrine clay and silts) overlay the bedrock to the east of Seeley's Bay. These silts and clays may provide some aquifer protection depending upon their thickness and spatial extent. The section also reveals 10m of sand and gravel below the clay in some areas, which is likely associated with a glaciofluvial esker/outwash deposit that is exposed to the south of the cross-section. Where exposed, this deposit would be highly vulnerable and may act as a contaminant pathway to the underlying bedrock aquifer.

<u>Sections N - N' and I - I': Mallorytown</u>

These two sections run N-S and W-E through the community of Mallorytown. The town currently relies on individual private wells to supply their potable water, but may consider a groundwater source supply in the future. The sections show that the town is underlain predominantly by Precambrian rock, covered with a relatively thin layer of overburden. Based on water levels shown in the sections, and the water table map (**Figure 3.1**), regional groundwater flow to the community is expected to be from the north.

It is also noted that many of the wells in this area are drilled fairly deep (50 to 100m), yet the static water levels are relatively close to the surface (<10m). This observation may suggest that fractures that could provide sufficient quantity were only found at depth, and that the water was pressurized. Alternatively, it may indicate that shallow fractures are present, but the water quality is poorer, and therefore the well was drilled deeper to intercept better water conditions. A third possibility, which is common to some low producing wells, is that the driller extended the well bore past the production horizon to increase the well reservoir capacity in order to reduce pump cycling.

**Section I - I'** , which is a regional cross-section, shows that the water table surrounding Upper Beverley Lake, Foster's Creek, Charleston Lake and Jones Creek is elevated relative to the surface water features. Therefore, these water bodies may be subject to groundwater discharge. The elevation of the St. Lawrence River is below water levels measured to the north, highlighting that the river acts as a regional groundwater discharge area.

<u>Section O - O' and Section P - P': Cana Subdivision</u>

The Cana subdivision is located just east of Kingston Mills and west of Codes Corners and is serviced by a groundwater source municipal water supply. The area is bisected by two geological cross-sections (**Section O - O'** and **Section P - P'**). Both sections show that the community is located within the Cataraqui River valley, and in particular, near the shores of Colonel By Lake. Based on higher groundwater levels on the highland areas of the valley, there is a potential for the area to be in a groundwater discharge zone. Water from the Precambrian aquifer is used for the municipal supply. The vulnerability of the aquifer is variable depending upon location. Near Code Corners, there is up to 10m of glaciolacustrine clays and silts that provide moderate protection; however, to the north and east, higher vulnerabilities exist since the overburden is largely absent.

Section Q - Q': Napanee area to west of Morven

This section passes near the community of Morven and bisects Spring and Wilton Creeks, as well as, the boundary between the CRCA and Napanee watersheds. In the area of the section, Spring Creek is underlain by clay that in turn overlays coarser grained material. The creek has formed in a depression in the bedrock surface, which is likely controlled by faulting. Based on the size of the bedrock depression, Spring Creek may be positioned over a buried bedrock valley that once encompassed a larger watercourse. Elevation of the top of the bedrock below the Creek is approximately 5 to 10m deeper than the current elevation of the Napanee River. The water levels in the well suggest that the CRCA boundary generally corresponds with the groundwater flow divide between the Napanee River and Spring Creek. Groundwater discharge conditions into Spring Creek are expected based on the gradients; however, the volume of discharge will be limited by the presence of clay underlying the creek.

The main aquifers in the community of Morven and west along County Road #2 are the Gull River and Shadow Lake Formations and the Precambrian rock. Most of the wells take water from Gull River limestone. The aquifer vulnerability in this area is considered to be high, with the exception of the area near Spring Creek. Thicker sequences of clays and silts along Spring Creek may provide local pockets of lower vulnerability.

Section R - R': Marysville, Wolfe Island

This section bisects the north shore of Wolfe Island, near Marysville. The area is underlain by 20m of Bobcaygeon Formation, which in turn is underlain by 50 to 70m of Gull River Formation. The topographic elevation difference between Wolfe Island and the St. Lawrence River in this location is approximately 25m. The water level elevations are higher away from the St. Lawrence, suggesting a horizontal gradient towards the surrounding surface water. Some of the well water levels around Marysville are lower than the elevation of the St. Lawrence. The cause of the low water levels is unknown, but may reflect a local depression of the water table surface around the community as a result of pumping individual private wells. Alternatively, it could be caused by the water in the wells not reaching static conditions when the water levels were measured by the drillers. Overall, the vulnerability of the bedrock aquifers below Marysville is considered high because of the absence of an overlying low permeability unit.

Section S - S': Stella, Amherst Island

This section runs N-S through Amherst Island. Few well records were intercepted and therefore structural geology information from MNR records (MNR, 1983) was used to interpret the location and contacts of the Paleozoic formations. While the Verulam Formation is exposed at surface, the wells are believed to intercept the underlying Bobcaygeon and Gull River Formations. Similar to **Section R - R'**, water levels appear depressed below St. Lawrence River levels. The cause is unknown, but may be from well interference or wells not recovering to static conditions prior to water level measurement. Overall, the vulnerability of the bedrock aquifers is considered high in this area because of the absence of lower permeability overburden.

Section T - T': Wolfe Island – Howe Island

This section passes through both Wolfe Island and Howe Island, running generally west to east. The section shows that Precambrian rock is much shallower under Howe Island than under Wolfe Island. Most of the wells on Wolfe Island take water from Paleozoic bedrock, while Nepean Formation and Precambrian rock are common aquifers at Howe Island. The Nepean aquifer usually is a higher yielding aquifer than the overlying limestone aquifers. Aquifers on both Wolfe Island and Howe Island are considered highly vulnerable because of the shallow nature of the bedrock.

Sections U - U' and V - V': Lansdowne

The community of Lansdowne is serviced by a municipal groundwater supply system that takes water from the Precambrian rock aquifer. Overlying the Precambrian rock is an outlier of Nepean Formation (Potsdam Formation). Wellhead protection area modeling currently underway suggests that the aquifer is highly vulnerable within the wellhead capture area.

Sections W - W' and X - X': Athens

Athens is underlain by the Nepean Formation and Precambrian rock aquifers. The Nepean Formation, which is up to 50m thick, is considered a good supply of potable water from both a quality and quantity perspective. Based on the geological cross-sections and the water table map (**Figure 3.1**), groundwater flow towards Athens is likely from the north. The relatively permeable March and Nepean Formations, which crop out in the vicinity of Athens and in the area up gradient of the community, are likely areas of recharge. The vulnerability of the aquifer is considered high because of the shallow nature of the bedrock.

Section Y - Y': Harrowsmith

Harrowsmith is underlain by limestones of the Gull River Formation. Water wells in the area tap the Gull River Formation as well as the underlying Nepean Formation and Precambrian rock aquifers. The shallow nature of the rock suggests that the aquifers will be highly vulnerable to surface contamination. Based on topographic mapping, groundwater flow to the area is likely from the north to northeast.

## 2.5 Discussion

This section presents a discussion of the major findings of this task. Information gained from assessment of the cross-sections is used as input into the development of the methodologies used to map recharge and vulnerable areas in Parts 3 and Part 4 of the GVAR. Presented below is a discussion of how the findings relate to groundwater vulnerability, groundwater/surface water interaction, flow in the Nepean Aquifer and cross-watershed boundary groundwater flow.

Groundwater Vulnerability

At the regional scale, most of the CSPA is considered highly vulnerable to groundwater contamination because of the predominant use of the fractured bedrock as the potable water aquifer and the lack of overlying protective layers. Vertical fractures pass through the bedrock and provide a pathway for vertical contaminant migration. Flow through these fractures, as evident by field-scale studies, can be rapid (Milloy, 2007; Praamsma, 2006). Contaminants introduced into the bedrock can move quickly through fractures compared with transport in porous media. In some areas, moderate vulnerability conditions will exist where there are deposits of glaciolacustrine clay and glacial till overburden; however, these areas are generally isolated. Overburden potable water supplies, which are limited to near surface sand and gravel deposits, will generally have a high vulnerability.

Groundwater/Surface Water Interaction

The cross-sections created as part of this study can be used to help identify surface water systems that may have a significant groundwater base flow component. In general, surface water bodies that have a water level elevation below the average adjacent water table are candidates for being significantly influenced by groundwater inputs. Considering the general poor quality of the water level data, caution must be used in this analysis. At best, the analysis can be used to flag surface water features for further scrutiny. Water bodies that were identified in the cross-sections as potentially having a significant groundwater base flow component include the Napanee River, Cataraqui River, Wiltse Lake, Millhaven Creek, Wilton Creek, Little Cranberry Lake, Upper Beverley Lake, Fosters Creek, Charleston Lake, Jones Creek, Colonel By Lake and Spring Creek. Portions of Loughborough Lake are also suspected to be areas of groundwater discharge based on fishery characteristics.

Groundwater Flow in Nepean Aquifer

The most permeable bedrock material in the CSPA is the sandstones of the Nepean Formation. The March Formation is also relatively permeable because of the sandstone interbeds. These formations have a higher permeability largely because of the presence of both primary and secondary (fracture) porosity. The significance of these formations from both a recharge and vulnerability perspective is difficult to quantify. It is postulated that these formations are recharged where they are exposed at surface. Where these deposits are buried beneath carbonate rocks, it is speculated that they may act as preferential groundwater flow pathways between the lower permeability underlying Precambrian shield and overlying Paleozoic carbonate rocks. Therefore, it is possible that regional groundwater flow is affected by the regional fracture geometry of these higher permeability formations. Also, the groundwater flow, especially at depth, may not coincide with surface drainage patterns. For example, deep groundwater flow in the neighbouring Rideau watershed may be partially recharged in the CRCA watershed where the Nepean and March Formations are exposed. Unfortunately, insufficient water level data is available to adequately test this assumption. Numerical groundwater modeling could be used to examine regional flow in the Nepean Formation by modeling various scenarios of recharge, gradient and permeability contrasts. Isotopic groundwater analysis could also be used to map groundwater flow pathways.

Cross-boundary Groundwater Flow

As stated in the discussion point above, it is postulated that a component of groundwater flow may be directed northwest across the CRCA/Rideau watershed. The likelihood of this occurrence will depend upon the contrast in permeability of the Nepean aquifer and the surrounding rock (Precambrian below and carbonate rock above). A higher contrast translates into a greater potential for cross-boundary flow. The contrast will largely be a result of the density and connectivity of the fractures within the rock unit. If fracture characteristics are the same for all lithologies, then the entire groundwater flow system may act as one aquifer and the potential for cross-watershed boundary flow is reduced.

Cross-boundary flow may also occur at depth, where groundwater flow patterns will reflect larger scale topography trends rather than the smaller scale watershed drainage patterns. For example, the boundary between the Napanee and CRCA watersheds may reflect a groundwater flow divide for shallow groundwater flow, but at depth, groundwater may flow beneath the Napanee River and discharge to Lake Ontario.

## 2.6 Bibliography

Cataraqui Region Conservation Authority, 2007, Source Water Protection Water Budget Conceptual Report.

Cataraqui Source Protection Area, 2007, Frontenac Islands Groundwater and Aquifer Characterization Study, October, 2007.

Chapman and Putnam, 1984, The Physiography of Southern Ontario, 3rd Edition, Ontario Ministry of Natural Resources.

Freeze and Cherry, 1979. Groundwater. Prentice-Hall Inc. Englewood Cliffs, New Jersey, U.S.A. 604p.

Golder and Dillon, 2003, Refrew County – Mississippi – Rideau Groundwater Study.

John D. Paterson & Associates Ltd., 1991, Hydrogeological Impact Study for a Proposed Ground Source Heat Pump System, South Branch Elementary School, Kemptville, Ontario. A report prepared for Leeds Grenville County Board of Education.

Malroz, 2007. Lansdowne Well Head Protection Report.

Milloy, C. 2007. Measurement of Hydraulic Head in the Evaluation of Groundwater Recharge to Discrete Fracture Zones in a Crystalline Bedrock Aquifer. M.Sc. Thesis, Queen's University, Kingston.

Ontario Ministry of Natural Resources, 1983, Oil and Gas Structural Mapping.

Ostry and Singer, 1981, The Hydrogeology of the IFYGL Moira River, Wilton Creek and Thousands Islands Study Aras, Ministry of the Environment, Water Resources Branch, Water Resources Report 5e.

Praamsma, T. 2006. Complex groundwater-surface water interaction in a gneissic terrain, M.Sc. Thesis, Queen's University, Kingston, Ontario.

Raven Beck Environmental Ltd., 1994. Water Resources Study City of Kanata Rural Area. A report prepared for the Corporation of the City of Kanata.

Rideau Valley Conservation Authority (RVCA), 1996. Interim report on the functions and status of Kemptville Creek. Kemptville Creek Watershed Plan. Vol.2 – Component Reports.

Williams, D.A., 1991, Paleozoic Geology of the Ottawa-St. Lawrence Lowland, Southern Ontario; Ontario Geological Survey, Open File Report 5770, 292p.

Wilson, A.E., 1946, Geology of the Ottawa-St. Lawrence Lowland, Ontario and Quebec; Geological Survey of Canada, Memoir 241, 66p.

# PART 3 SIGNIFICANT GROUNDWATER RECHARGE AREAS

## 3.1 Introduction

This section summarizes efforts to identify potential Significant Groundwater Recharge Areas (SGRAs) within the Cataraqui Source Protection Area (CSPA). SGRAs were originally defined in the October 2006 Guidance modules as groundwater recharge areas that provide an important hydrologic function to a specific groundwater receptor, such as a municipal potable water source or a sensitive ecological feature. This definition was changed in the recently released draft Technical Rules (June, 2008). SGRAs are now defined in more general terms as being areas where the annual average rate of infiltration is either: a) 1.15 times or more greater than the annual average recharge in the surrounding watershed, or b) >55% of the rate determined by subtracting the average annual evaporation from the average annual precipitation for the surrounding watershed. Previous guidance had defined these areas as High Volume Recharge Areas (HVRA). Considering that the bulk of the GVAR study was completed prior to the draft Technical Rules, mapping of SGRAs and HVRAs was performed based on the earlier guidance definition. Nevertheless, the method used to delineate HVRAs (which was a perquisite step to defining SGRAs under the former guidance) also meets the new requirements of the draft Technical Rules for definition of SGRAs. For the purposes of this study, we will identify both SGRAs and HVRAs based on the early October 2006 definitions.

Identification of HVRAs and SGRAs in the study area is challenging. Bedrock comprises the main aquifer in the region, and has a relatively low permeability. Flow within this aquifer is through fractures that have complex spatial distributions. Groundwater recharge is expected to occur at a low rate, but to be areally widespread and diffused. Furthermore, the irregular topography in the Canadian shield appears to produce locally controlled flow systems rather than watershed scale recharge and discharge areas. As a result, methods proposed by the MOE to identify HVRAs and SGRAs are not totally applicable for the watershed. Modifications to these methods have been undertaken in this study to improve their applicability. Because of the complex flow characteristics in the watershed, the mapped HVRAs and SGRAs are only considered to be potentials and will require further investigation and ground-truthing to determine their actual importance.

### 3.2 Scope and Objectives

The original objective of this assessment was to map SGRA's that provide an important hydrogeologic function to either municipal potable water aquifers or sensitive ecological features. Following the release of the draft Technical Rules (June, 2008), the objective was revised to also include mapping of areas where infiltration is equal to or higher than the average recharge in the watershed (formerly known as HVRAs). The scope was limited to review and analysis of available data that was provided to Dillon in either database or mapped GIS form. No fieldwork or collection of new data was conducted; however, such work is recommended to confirm or refute the interpretations provided in this assessment. Key input data into the analysis included topography, geology mapping, and MOE water well records produced by government agencies and new data generated by CRCA for their Conceptual Water Budget Report (CRCA, 2007). In general, mapping followed methodologies recommended within the MOE technical Guidance Modules #7, Water Budget & Water Quantity Risk Assessment (March, 30, 2007) and the draft Technical Rules (June, 2008). Additional methodologies were also used to improve the mapping of recharge areas based on approaches identified in our Literature Review (Part 1 of the GVAR).

### 3.3 Methodology

Mapping of HVRAs and SGRAs was performed in two steps. Potential high volume recharge areas (HVRAs) were first identified. Following the methodologies outlined in the October 2006 guidance modules, those HVRAs that potentially provide an important hydrogeologic function were identified as SGRAs. *(Note that the draft Technical Rules released in June, 2008 now define SGRAs and HVRAs as the same*). In addition to these two steps, the locations of significant wetlands that are deemed to have significant groundwater input were identified.

A summary of the mapping methodologies is presented below.

#### 3.3.1 Mapping of Potential High Volume Recharge Areas (HVRAs)

The October 2006 MOE guidance module recommends several methods that investigators can consider for mapping HVRAs. Where high quality borehole and water level data is available, HVRAs can be produced using groundwater flow modelling. For areas such as the CRCA watershed, where groundwater data is sparse and of lower quality, and where no groundwater flow model exists, the MOE recommends alternative methods. Two such methods explored in this study are:

- Method #1: identify coarse-grained overburden deposits that coincide with topographically elevated areas; and,

- Method #2: use by-products of the regional water budget process to map areas where the calculated recharge is >55% of the annual water surplus.

Both methods are endorsed in the draft Technical Rules (Part V.2 44 - 46) as two of three methods to define SGRAs. The other method (identifying areas where the average annual recharge rate is 1.15 times or more higher than the surrounding watershed) is similar to Method #2, but is considered less precise and has not been investigated.

Overall, Method #1 is considered the most useful as it incorporates groundwater flow principals (gradient and permeability), however, Method #2 (which is based mainly on surficial permeability slope and landcover) has also been undertaken for comparison purposes.

**Method #1: Topography and Geological Based**

Method #1 is based on general hydrogeological principals of groundwater flow and infiltration. The method attributes areas of higher local permeability and downward flow gradients as being HVRAs. Relative permeability is based on lithological descriptions taken from overburden geology maps. Vertical gradients are determined by approximating the depth to the water table. Areas that are mapped as having a deep water table and where coarse-grained overburden deposits exist at surface are identified as potential HVRAs.

To develop this map, several mapping steps are required. A description of these steps and the uncertainties associated with each are presented below.

<u>Step 1: Development of Water Table Map.</u>

A Water Table Map (**Figure 3.1**) is created following the same MOE protocols that were used for the Provincial regional groundwater studies. In particular, the static water level data in all wells < 15m deep that had a geographic accuracy code of 100m or better were contoured. The surface elevation of each well was corrected to the Digital Elevation Model (DEM). The contoured water table elevation was conditioned to surface water elevation data as determined on a 100m x 100m DEM provided by the MNR (MNR, 2006). There are several sources of uncertainty associated with this approach, which are explained below.

***Water Level in Well***: The wells were drilled at various times of the year and during different years, and therefore water levels do not represent a single moment in time. Secondly, the accuracy of the reported static level is unknown, as it is unknown if the water level in the well reached static conditions prior to measurement. Thirdly, the geographic position of the well is an approximation at best, and fourthly, the wells are often open-hole and therefore the water level in the well may not necessarily represent the piezometric surface or water table. Because the open hole will intersect numerous fractures along its depth and water in each of these fractures will have a different pressure (head), the static water level in the well will be a weighted average of the various heads. The influence that one particular fracture (or fracture zone) will have on the water level will depend upon the transmissivity of that zone. A true water table is defined as the surface where the water pressure in the pores/fractures is at atmospheric conditions. The water table is independent of the aquifer transmissivity. These conditions would occur in the top most saturated fracture in the well, but water pressure in deeper fractures may affect the overall level of water in the well.

***Surface Water Levels***: The approach used assumed that all surface water features were an expression of the water table. While this assumption is likely valid in low-lying areas, it may not be valid in the upper reaches of streams. It is expected that some streams, wetlands and creeks may be perched above the regional water table.

***Well Density and Contouring:*** The most significant source of uncertainty is associated with the low data density of wells and the effects that the sparse data set has on the contoured water table surface. In general, there are far more surface water elevation points than there are well points. Therefore, the contoured surface is heavily biased towards the elevation of the surface water features. In the current study, partial compensation was made to reduce the influence that surface water points have when creating the water table surface by removing a portion of the surface water elevation points prior to contouring.

While several sources of uncertainty exist, we propose that the resulting water table surface provides useful information that can be used during later steps, namely predicting the relative depth of the water table.

Step 2: Depth to Water Table Map

A Depth to Water Table Map (**Figure 3.2a**) was created by subtracting the estimated water table surface from the DEM. Uncertainties associated with this map are largely a result of the uncertainty regarding the Water Table Map rather than the DEM surface. There are numerous uncertainties with the horizontal and vertical information used to create the Water Table map (See Step 1 above), while the DEM information is based on aerial photography. The DEM has a resolution of approximately 10 m that is uniform across the area, while the water table map resolution will vary greatly depending upon the conditions identified in Step 1. Nevertheless, the map is considered to be of sufficient accuracy to estimate the relative depth of the water table, and therefore the general direction of the vertical gradient.

Step 3: Identification of Permeable Overburden Deposits

Surficial geology maps, developed by the Ontario Geological Survey (OGS, 2003) were used to identify overburden deposits that were moderate to coarse-grained. In essence, the overburden geology map is used as a surrogate map for permeability. In the watershed area, these deposits were associated with eskers, kame moraines, nearshore glaciolacustrine, nearshore glaciomarine and alluvial deposits. Considering the relatively shallow nature of overburden deposits in the study area, fairly high confidence is given to the mapping of these units. It is realized that at the local scale, lithology (and therefore permeability) will vary spatially. In addition, overburden maps only show the surficial lithology. Low permeability tills, silt, clay deposits or bedrock that are buried under coarser grained material will be identified as being permeable even though vertical groundwater flow will be inhibited by the buried lower permeability deposits.

Step 4: Overlaying of Depth to Water Table and Permeable Overburden Deposits

The final step is to overlay the Permeable Overburden Deposit map (Step 3) with the Depth to Water Table Map (Step 2). Regions where the permeable overburden deposits are present in areas where the water table is locally deep (>6m) are identified as potential HVRAs. The 6m depth was chosen because the accuracy of the static water level elevation and the well top of ground surface is estimated to be ±5m. This depth criterion was used in other regional groundwater studies in Quinte, Mississippi and Rideau watersheds. In essence, the greater the depth of the mapped water table surface, the greater the chance that the area is under recharge conditions.

Step 5: Incorporation of Bedrock Data

Step 5 represents a slight modification to the MOE approach in which we incorporate information on the location of regionally significant bedrock aquifers. The Nepean Formation and March Formations are significant aquifers in the adjacent Rideau watershed and crop out along the eastern flank of the Precambrian Frontenac Axis in the eastern most extent of the Cataraqui watershed. In particular, we identified locations where the Nepean and March Formations either crop out at surface or are buried by coarse-grained materials, and have downwards vertical gradient.

**Method #2: Water Budget Based**

Method #2 is based on the outputs of the conceptual water budget undertaken by CRCA in 2007. The method corresponds with MOE Method #2, as described in the MOE Water Budget & Water Quantity Risk Assessment, Appendix B, March 30, 2007. This method is based on the MOEE 1995 method, which calculates a percentage of the available water as infiltration. The method was recommended by the MOE where detailed groundwater models are not present and where there are only subtle changes in estimated recharge rates. Considering the latter assumption and the complex physiography of the watershed, the appropriateness of this method to the study area is debatable. The MOEE 1995 method was not designed for regional assessments, but rather lot scale use for designing septic systems. The map was created by CRCA GIS staff under the direction of Dillon.

Mapped HVRAs are produced through manipulation of the infiltration and surplus water map and the surplus information that was developed for the watershed water budget analysis. Areas that have an infiltration value >55% of the annual average water surplus over the same area is identified as a potential HVRA. In the GIS environment, this comparison is performed at the 100m x 100m pixel resolution. There are numerous steps, assumptions and levels of uncertainty associated with the creation of the component infiltration and surplus water information, which forms the basis of the HVRA analysis. The reader is referred to the Conceptual Water Budget (CRCA, 2007) report for this information.

### 3.3.2 Mapping of Significant Groundwater Recharge Areas (SGRAs)

In the original October 2006 Guidance Modules, significant groundwater recharge areas (SGRAs) were defined as a subset of HVRAs. Classification of a HVRA as a SGRA was based primarily on the hydrological function that the area provided in maintaining groundwater flow to a feature. Two types of hydrogeological functions were considered when mapping SGRAs, and included:

- linkage of recharge area to a municipal aquifer or well; and,
- linkage of recharge area to a cold water ecosystem that depends on groundwater recharge.

In addition to the above situations, the October, 2006 Guidance Module definition of SGRAs also allowed investigators to identify areas outside of HVRAs that contributed groundwater to sensitive areas. In this study, we have identified SGRAs as also being areas that recharge water in support of groundwater discharge to nearby provincially significant wetlands.

The approach taken in this study to define SGRAs was to first identify HVRAs that exist within the recharge areas for the existing municipal systems, and secondly, to identify cold-water surface water features. An exception to this approach was for sensitive wetlands, where the recharge area was not based on the location of a nearby HVRA, but was based on the area immediately surrounding the surface water feature. A description of each approach is presented below.

**SGRAs associated with Municipal Groundwater Systems**

Municipally owned well systems exist for the Town of Lansdowne and the Cana Subdivision. Mapping of the capture zone and recharge area for the Lansdowne system was performed by Malroz (2007) using a 3-D groundwater flow model. Recharge areas resulting from this model were evaluated to identify if any SGRAs were present. Delineation of capture zones for the Cana Subdivision was performed using the uniform flow field approach, which does not explicitly identify recharge areas. Nevertheless, SGRAs associated with this system can be estimated based on the current study. Confirmation of these SGRAs would require further modeling.

**SGRAs associated with Cold Water Surface Features**

Locations of coldwater and coolwater streams and coldwater lakes were provided to Dillon by CRCA staff. The presence of a coldwater or coolwater stream is a potential indicator of significant groundwater input. These streams are often shallow, and the input of groundwater will keep the temperatures cool during warm months. Cold water lakes are present within the study area, however, these lakes are also deep, and thus cool temperatures may be related more to depth than to groundwater input. Therefore, the presence of a cold lake is not deemed to be directly indicative of significant groundwater input. Nevertheless, these lakes, because of their greater depth, may intercept more fractures in the bedrock and, therefore, be more affected by groundwater discharge.

For purposes of this assignment, we have assumed that HVRAs that fall close to cold/coolwater streams are potential SGRAs. For coldwater lakes, we have identified their location on the SGRA map, but have not assigned potential SGRAs to these features as the limits of the recharge areas are likely large and difficult to define. The draft Technical Rules (June, 2008) redefine SGRAs, and there is no longer a need to define an SGRA based on its significance to an ecological habitat. Nevertheless, for the purpose of this study, collection information on cold water features is still recorded on the map.

**SGRAs associated with Significant Groundwater Fed Wetlands**

Wetlands exist where the water table is close to the ground surface for a large portion of the year. Wetlands can exist under various conditions including poor drainage, input from groundwater, or saturation as a result of an adjacent lake or river. Where groundwater input is significant, the wetland ecosystem will largely become dependant upon the physical and chemical attributes of the water. Groundwater provides a water source of relatively uniform temperature and volume that is important to the survival of aquatic and plant species.

The approach taken in this study was a two-step process that first identified wetlands that rely on groundwater discharge, and secondly, identified the area that supports the discharge. CRCA staff provided Dillon with a list of wetlands in the CSPA that had been evaluated using the Ontario Ministry of Natural Resources (MNR) Ontario Wetland Evaluation System (OWES). The OWES evaluated the groundwater discharge component of each wetland through an empirical process that relies on the use of indicators. Depending upon the degree to which a particular indicator was present for the wetland, a score from 0 to 30 would be given, with a higher score being associated with a greater probability of groundwater discharge being important to the wetland being evaluated. The indicators assessed were wetland type (e.g., bog, swamp, marsh, fen), topography, wetland area, lagg development, seeps, marl, iron precipitates, and location relative to a major aquifer. CRCA reported that this assessment has been conducted on 26 of the 116 evaluated wetlands in the CSPA. Therefore, other wetlands that have a significant groundwater component likely exist. In our study, we assumed that any of the wetlands that scored 20 or greater out of the groundwater discharge score of 30 would have a significant groundwater discharge component. The last step was to identify which of the wetlands that had a score of 20 or greater, were also Provincially Significant. The rationale for this step was that Source Protection would only be applicable if the wetland was both fed by groundwater and ecologically significant. Significant recharge areas where mapped as the area within 200m of the wetland boundary. It is realized that a more complex recharge system may exist, and further resolution of the recharge area would required a more in-depth study.

## 3.4 Results

### 3.4.1 Potential High Volume Recharge Areas

Potential HVRAs derived using Method #1 are presented in **Figures 3.2a, 3.2b** and **3.3** and those derived using Method #2 are presented in **Figure 3.4**. Method #1 is considered more representative of actual conditions, while Method #2 is provided for comparative purposes.

#### Method #1 – Topography and Geology Based

Method #1 maps areas where the potential for groundwater recharge is high, based on depth to water table information and overburden geology. HVRAs are identified as areas where the depth to the estimated water table is >6m and where permeable overburden exists (areas mapped as coarse-grained deposits at surface). Also shown are areas where the regionally significant Nepean and March Formations crop out, and are either exposed or covered by permeability materials.

**Figure 3.2a** and **Figure 3.2b** presents the results of this assessment. **Figure 3.2a** is a map of the entire watershed. **Figure 3.2b** shows a "blow-up" of the larger map for the Kingston area, and is provided for illustrative purposes only. Both **Figures 3.2a** and **3.2b** are quite "busy" in appearance; however, for the purposes of this report, the detail is provided in order to describe the assessment methodology and results.

Several observations can be made from the two maps:

- The depth to the water table is controlled by topography. For example, localized areas of topographic relief, such as the drumlinoid features in the southern portions of the Town of Greater Napanee (see **Figure 3.2a**) and the undulating Precambrian shield area are identified as areas where the water table is relatively deep. Localized elevated areas can be interpreted as having a greater potential for having a downward hydraulic gradient. Similarly, lowlands can be considered to have a water table near surface and, therefore, are more likely to have an upward hydraulic gradient.

- Maps show that there are few coarse-grained deposits that attain sufficient lateral extent to be mappable as overburden geological units. Referring to the surficial geology map (Figure A2-15 in the Conceptual Water Budget report, CRCA, 2007), the coarse-grained units are associated largely with sand and gravel kames, eskers, and nearshore glaciolacustrine and glacio-marine beach and deltaic deposits. In most cases, these areas are laterally discontinuous, with the exception of large bands of glacial deposits found in some subwatersheds and the glaciomarine deposits in the southern portion of the Township of Elizabethtown-Kitley, where the units may extend uninterrupted for a few kilometres.

- **Figure 3.2b**, which is close-up view of the map around the Kingston area, is provided to demonstrate the assessment process. The map clearly shows that areas of predicted lower water table (interpreted to mean a dominant downward vertical gradient) are associated with local topographic highs. Coarser grained overburden deposits are present in both the top, sides and between these local highs.

The final stage in the process is to identify those areas where coarser-grained deposits are present where the water table depth is greatest (> 6m). **Figure 3.3** presents the results of this analysis. Also shown are areas where coarse-grained deposits overlay the regionally significant Nepean and March Formations. The highlighted areas are defined as the HVRAs for this assessment method.

**Method #2 – Water Budget Based**

**Figure 3.4** displays the results of the water budget based analysis. Regions where the infiltration is greater than 55% of the annual average surplus water (precipitation minus evapotranspiration) are highlighted in green. These areas are identified as potential HVRAs. Areas highlighted as potential HVRAs include the sandier soil areas on the Precambrian and Frontenac Axis, and the exposed till drumlinoid features in the limestone plains in the southeastern portion of the watershed. The sand plains in the Township of Elizabethtown-Kitley in the west are also highlighted as potential HVRAs.

### 3.4.2 Potential Significant Groundwater Recharge Areas

In the October, 2006 MOE Guidance Modules, the MOE defines SGRAs based on their significance to either an ecological or municipal aquifer receptor. Based on this definition, and the location of municipal systems and sensitive ecological features in the watershed, the following areas are candidates for future SGRA evaluation:

**Table 3.1: Candidates for Future SGRA Evaluation**

| **Location** | **Feature Type** |
|---|---|
| Lansdowne Well Field | Municipal Aquifer |
| Cana Subdivision Well | Municipal Aquifer |
| Stream below South Lake | Cold Water Stream |
| Stream west of Wilton | Cold Water Stream |
| Butternut Creek* | Wetland (GD Pot = 21/30) |
| Eel Bay/Sydenham Lake* | Wetland (GD Pot = 20/30) |
| Kingston Mills** | Wetland (GD Pot = 23/30) |
| Loon Lake Wetland** | Wetland (GD Pot = 22/3) |

Notes:
GD Pot: Groundwater Discharge Potential Score (out of 30) as calculated using the Ontario Wetland Evaluation System
*: Regionally Significant Wetland
**: Provincially Significant Wetland

In addition to the above features, numerous surface water bodies have been classified as cold-water lakes, including Big Salmon Lake, Garter Lake, Buck Lake North, Buck Lake South, Canoe Lake, Charleston Lake, Desert Lake, Devil Lake, Gould Lake, Birch Lake, Knowlton Lake, Loughborough Lake and Red Horse Lake. Cold-water features can be a surrogate for sensitive ecological features. Based on data provided to Dillon by CRCA, the lakes are generally deeper than those not identified as cold water lakes. Therefore, it is unclear if their cold temperature is attributable to the lake depth, presence of groundwater discharge or both.

Water bodies that were identified in the geological cross-sections (Part 2) as potentially having a significant groundwater base flow component are the Napanee River, Cataraqui River, Wiltse Lake, Millhaven Creek, Wilton Creek, Little Cranberry Lake, Upper Beverley Lake, Fosters Creek, Charleston Lake, Jones Creek, Colonel By Lake and Spring Creek.

A comparison of the sensitive features and the mapped HVRAs does not reveal any readily apparent correlation. Based on discussions with Malroz staff, modeling of the Lansdowne system did not reveal any particular significant spatial variations in recharge. For the Cana Subdivision, an area of deep watertable (>15m) is present within the upgradient portion of the capture zone. This area corresponds with a region of elevated land near a local groundwater flow divide. While there is no large accumulation of permeable overburden in this location, this area is expected to be the recharge area for the well. With respect to sensitive ecological features, a possible correlation may exist between the small creek (Willy's Brook) that feeds South Lake, and a mapped overburden HVRA which abuts against the stream. In this area, both Method #1 and Method #2 predict a HVRA in the vicinity of this stream. To a lesser extent, a relationship may exist between the stream west of Wilton (Thorpe Creek) and several transecting HVRAs identified in Method #2.

Neither the draft Technical Guidance Modules nor the draft Technical Rules address the relationships between HVRAs/SGRAs, the groundwater discharge areas that are fed by those HVRAs/SGRAs, and nearby municipal residential drinking water surface intakes. CRCA identified a potential groundwater discharge area in Sydenham that is adjacent to the municipal intake in Sydenham Lake. It is expected that the discharge volumes from the spring are small relative to the volume of the Lake; therefore, the contribution of the spring to the quality of the water at the intake is not expected to be substantial.

### 3.5 Discussion

Delineation of HVRAs and SGRAs in the study area is challenging considering the lack of high quality groundwater data and the complex hydrogeological flow regime. Considering the uncertainty associated with the methods used in this study, and the fact that SGRAs are subject to future threat assessment and risk evaluation, the results of this investigation should be treated with caution. The identified HVRAs and SGRAs are potentials only and should be confirmed or refuted through more detailed assessment. In addition, other HVRAs and SGRAs may exist that were not identified by the methods used in this study.

Few SGRAs that support sensitive ecological features were mapped, largely because of the lack of known sensitive receptors (sensitive ecosystem such as a coldwater stream or municipal aquifer). Further efforts are recommended to identify ecosystems that are sensitive to groundwater. As a starting point, surface water features that abut HVRAs identified in Method #1 should be investigated. For example, in areas where a coarse-grained overburden deposit is located near a stream, temperature monitoring could be conducted.

The significance of bedrock karst on both the groundwater flow regime and the presence and location of HVRAs has yet to be determined. Work performed by the Ontario Geological Survey suggests that karst may be more prominent in the study area than currently suspected. Both the Gull River and Bobcaygeon Formations, which cover large portions of the eastern portion of the study area, have been identified as being sensitive to karst. It is possible that karstic areas may act as HVRAs.

Considering groundwater flow is predominately controlled by fractures at the local scale rather than more regional scale flow patterns that are characteristics of more overburden-type aquifers, it is unlikely that Method #1 or Method #2 will identify all HVRAs and SGRAs. It is possible that many of these features are not mappable at the study scale, and exist as localized areas of bedrock that have relatively high density of open and interconnected fractures. Conversely, areas identified as HVRAs based on either permeable soil or surficial geology, but are not hydraulically connected to the aquifer, will not be recharge areas. Nevertheless, the identified HVRAs and SGRAs are considered as starting points for future refinement. The identified areas can be targeted for field investigations to confirm if they are localized areas of groundwater recharge. Additional investigations could involve drilling cores in strategic locations in the Cataraqui area and install additional Provincial Groundwater Monitoring Network wells to monitor water levels and predict recharge. Delineation of HVRAs and SGRAs can also be improved with mapping of groundwater springs, karstic features and stream temperature monitoring.

### 3.6 Conclusions

The following conclusions are made based on the results of this study:

1) Significant Groundwater Recharge Areas (SGRA) are vulnerable areas that will be subject to source protection. The draft Technical Rules (June, 2008) indicate that SGRAs are synonymous with areas of high volume recharge (HVRA). Previous technical guidance modules had defined SGRAs as HVRAs that support either a sensitive ecological environment or a water supply. For the purpose of this study, we have identified both HVRAs (referred to in this study as SGRAs) and sensitive features that are supported by SGRAs.

2) Two methods were used to assess HVRAs and SGRAs. Method #1 mapped areas of potentially vertical groundwater flux, while Method #2 identified areas of relatively high infiltration. Both methods produce different results. Method #1, which was based on a qualitative assessment of vertical flow gradients and permable surficial geology, identified isolated areas of potential HVRAs. The water budget method (Method #2) was predominantly influenced by the distribution of permeable soils. Method #2 produced HVRAs that were larger and more numerous than the vertical groundwater flux based approach (Method #1). Method #1 is deemed the more reasonable of the two methods to identify HVRAs, as it takes into account hydraulic gradient and surficial geology, and is generally simpler than the more complex water budget approach.

3) Groundwater recharge is expected to occur over most of the study area; however, the rate and volume of recharge will differ with location. Areas that have the greatest potential for being HVRAs are topographically elevated locations where coarse-grained geological materials are present at surface.

4) The role of recharge in the large areas of shallow to exposed bedrock is uncertain. In many cases, these lands are characterized by small and poorly connected lakes, rivers, swamps and local surface depressions. While high rates of recharge may not occur in any particular location, significant volumes of recharge likely occur at the watershed scale. Where these surface depressions are connected to fracture networks in the bedrock, groundwater contribution from these features would be enhanced.

5) Areas where the regionally significant Nepean Formation (and to a similar extent, permeable horizons of the March Formation) crop out or are covered by permeable materials, are speculated to be HVRAs. These permeable formations crop out along the northeastern extent of the watershed.

6) SGRAs that support ecological features were identified in two locations (streams near South Lake and Wilton Creek). Cold-water lakes are present in several locations, but their sensitivity to groundwater input is unclear. Four wetlands were identified (Butternut Creek, Eel Bay/Sydenham Lake, Kingston Mills and Loon Lake wetland) as being both reliant on groundwater inputs and being ecologically significant. Numerous other surface water bodies were identified as potential groundwater discharge areas based on water table gradient information; however, the sensitivity of these features to groundwater is not known.

### 3.7 Bibliography

Cataraqui Region Conservation Authority, 2007, Source Water Protection Water Budget Conceptual Report, March 30, 2007.

Ministry of the Environment, 2007, Water Budget & Water Quantity Risk Assessment – Draft, March 30, 2007.

Ministry of the Environment, 2006. Water Well Information System Database, Ministry of the Environment, ON.

Ministry of the Environment, 2008. Draft Technical Rules Assessment Report.

Ministry of Natural Resources, 2006. Provincial DEM v. 2.0.0. Water Resources Information Program (WRIP).

Ministry of Natural Resources, Land Information Ontario.

Ministry of Natural Resources, 1983, Structural maps for Black River Group, Trenton Group, Ministry of Natural Resources, Petroleum Resources Section, 1983, Scale 1:250 000.

Ontario Geological Survey, 2003. Surficial Geology of Southern Ontario, Miscellaneous Release Data 128.

Ontario Geological Survey, 2003. 1:250-000 Scale Bedrock Geology of Ontario, Miscellaneous Release Data 126.

# PART 4 AQUIFER VULNERABILITY

## 4.1 Introduction

Part 4 identifies the groundwater High Vulnerable Areas (HVAs) within the Cataraqui Source Protection Area (CSPA). HVAs are one of four vulnerable areas that are delineated for input into the assessment report.

## 4.2 Scope and Objectives

The objective of this assessment is to identify regional scale HVAs for the aquifer that is most commonly utilized. In most cases, this is the "first" aquifer encountered during well drilling, which in the CSPA is generally (but not always) the bedrock aquifer. Since there are no regional maps depicting separate hydrostratigraphic units in the bedrock as a function of depth, all bedrock was considered as one aquifer. Furthermore, it was assumed that aquifer protection is provided solely by overburden materials. No attempts were made to differentiate aquifer vulnerability based on overlying lower permeable bedrock zones or vertical groundwater hydraulic gradients; however, at the local scale, these conditions would influence vulnerability.

Two methods were used to conduct the vulnerability assessment: a) MOE Intrinsic Susceptibility Index (ISI) protocol; and b) surficial geology information to qualitatively rank aquifer vulnerability based on the relative permeability of overburden materials. Both methods are endorsed in the draft Technical Rules (June, 2008) for the identification of HVAs.

Considering the complexity of the geology in the CSPA, mapping of HVAs is difficult. Vulnerability scores, which are largely dependant upon the presence and thickness of overlying silt/clay, will vary over distances that are shorter than the spacing between the data points. As a result, the vulnerability mapping produced in the current study depicts the expected vulnerability at the point of information only (at the well for the ISI method and the limits of lithology polygons for surficial geology method). Extrapolation of aquifer vulnerability information beyond the point of information was not conducted as the input data was not of sufficient resolution. Both vulnerability maps, created using the ISI protocol and the surficial geology approach, are best used as data sources for investigators to gain a general sense of the vulnerability of the area. In order to assess aquifer vulnerability at a property scale, additional site-specific information will likely be required.

### 4.3 Previous Work

Aquifer Vulnerability mapping in the CSPA was performed during previous assessments as part of the provincially funded groundwater study program. The current study builds upon information gathered during these previous assessments.

In 2001, aquifer vulnerability mapping using the Aquifer Vulnerability Index (AVI) approach (Stempvoort et al, 1992) was used for the United Counties of Leeds and Grenville groundwater study (Dillon, 2001). The AVI approach is similar to the ISI protocol in that it maps areas by relative vulnerability. Both methods consider the thickness and permeability of material overlying the target aquifer as measured at the well. The equations and relative vulnerability ranking approach are different, and as a result, the outputs of the AVI method are not directly comparable with the ISI protocol. In general, the AVI approach is slightly more conservative. Wells mapped as moderate vulnerability using the ISI protocol may be identified as high vulnerability in the AVI process. In addition, the Dillon 2001 study used kriging to estimate vulnerability between well locations. For the current GVAR study, interpolation of aquifer vulnerability values is based on professional judgment of surficial geology maps rather than computer interpolation of well point data.

Vulnerability mapping in the western half of the Cataraqui Region watershed was produced as part of the Western Cataraqui Region Groundwater Study (Trow, 2007). The following two analysis methods were used: a) MOE Intrinsic Susceptibility Index (ISI); and, b) the United Stated Environmental Protection Agency (US EPA) DRASTIC model. The results of each approach are presented below.

<u>ISI Methodology</u>

The ISI methodology was similar to what is used in the current study, and is therefore not repeated. Using the calculated ISI values at each well, high, medium and low vulnerability values were extrapolated across the study area. The results of the analysis showed large areas of high intrinsic susceptibility. Low and moderate vulnerability scores were present near Kingston and South Frontenac Township. In Loyalist Township, the majority of the area was mapped as high vulnerability.

DRASTIC Methodology

The model assesses vulnerability based on two components: 1) hydrogeological setting parameters; and, 2) seven spatial factors, including depth to water, recharge, aquifer media, soil media, topography, impact of unsaturated zone and hydraulic conductivity of the aquifer (Aller et al, 1985). Each factor is given a weighting between 1 and 5 based on the hydrogeological setting. In the analysis, high weighting (5) was given to depth of water and impact of unsaturated zone, while the lowest weighting (1) was given to topography. All the other factors received moderate weightings (2 to 4). Using this approach, three areas of groundwater sensitivity were identified (low, moderate to high, and very high). A low sensitivity was given to the area that generally corresponded with the Canadian Shield. Moderate to high sensitivity was given to the area underlain by flat-lying Paleozoic bedrock. Very high sensitivity was given to localized areas within the Paleozoic region.

## 4.4 Methodology

In the current study, two different methodologies were used to identify HVAs. The first method followed the MOE Intrinsic Susceptibility Index (ISI) protocol, while the second method was based on a review of surficial geology information. The information provided by the surficial geology method and the ISI method were used together to get a more complete understanding of the vulnerability of the CSPA. A description of both methods is provided below.

### 4.4.1 MOE Intrinsic Susceptibility Index Protocol

The ISI protocol was developed by the MOE in 2002 to facilitate a consistent approach to aquifer vulnerability mapping in Ontario. The method is applied to all provincial groundwater studies. Inputs into the protocol calculations included depth to water table, aquifer depth, and thickness/material type of overburden overlying the aquifer. The permeability of the overburden is a factor of material type and thickness. Aquifer Vulnerability is relatively higher in areas where materials overlaying the aquifer are more permeable or thinner and in areas where the water table is shallow. In general, the ISI protocol is used to describe the vulnerability of the "first" aquifer encountered below ground surface. The methodology is most suited to assessing the vulnerability of an aquifer to contamination from surface or near surface sources.

A summary of the five-step process to generate an aquifer vulnerability map following the MOE protocols is tabulated below. Additional detail is presented in **Appendix C**.

**Table 4.1: Summary of MOE ISI Protocol**

| Procedure | Purpose |
|---|---|
| Step 1: Data Preparation | Application of Geological Survey of Canada (GSC) material code protocols to MOE Water Well Records to improve quality of data. Suspect records are removed. |
| Step 2: Water table Mapping | Determine depth to groundwater near each well. |
| Step 3: Classification of Aquifers and Calculation of ISI value | Identify aquifers in each well, and determine aquifer type (confined, unconfined, semi-confined). Calculate ISI value at each well. |
| Step 4: Categorize vulnerability of well | Class wells based on ISI value<br>ISI <30: High Vulnerability<br>ISI 30 – 80: Moderate Vulnerability<br>ISI >80: Low Vulnerability |
| Step 5: Mapping of ISI values | Map study area based on calculated ISI values to identify regions of similar vulnerability. |

The principal source of information for the ISI protocol is the Ontario water well records. Information on the observed soil conditions, well construction details and depth of water for each well drilled in Ontario is compiled in the MOE Water Well Information System (WWIS). The WWIS is created from information provided by the driller at the time of well construction. Added to this information, is an MOE estimated ground elevation and UTM position for each well. Uncertainty in the elevation and UTM location is reflected through the assignment of accuracy codes. Information in the well records was enhanced through the application of the Geological Survey of Canada (GSC) materials protocol (See **Appendix C**), which is deemed by the MOE to enhance the accuracy of the original well record by simplifying the number of lithological categories reported.

<u>Limitations</u>

The WWIS is the principal data source used in the ISI protocol; however, there are limitations on its accuracy, completeness and representativeness of actual field conditions. Since the well records are based largely on the records of well drillers, the reliability of the records depends upon the diligence and knowledge of the driller, and can therefore vary greatly. A summary of the limitations is shown in the table below.

**Table 4.2: Summary of Data Limitations of MOE Water Well Records**

| Limitation | Possible Effect on Aquifer Vulnerability Mapping |
|---|---|
| Error in description and thickness of unit | ISI values could be either too low or high. Greatest impacts are for wells that have an ISI value near a category boundary. |
| Error in well location and well elevation | Calculated ISI value not representative of conditions. |
| Not all wells represented | Data gaps exist. Overburden wells and shallow bedrock wells created by excavation are under-represented, as well records are often not submitted for older wells. |
| Error in depth to static water levels | Possible overestimation of depth to groundwater. May result in underestimating the aquifer vulnerability. |

To reduce error in the MOE Water Well Records, the data was processed prior to interpretation to remove erroneous and suspicious entries, where practical. The process to remove these questionable data points is based on protocols established by the MOE, which includes:

- Limit analysis to wells that are located with a 30m accuracy
- Remove wells that plot outside the reported lot/concession/township
- Correct well record elevation to ground elevation from DEM
- Apply Sharpe GSC materials protocol to enhance reliability of geologic description.

In addition to limitations of the data used as input into the ISI protocol, there are limitations to the MOE protocol itself. The key limitations and their potential effects are listed in the following table.

**Table 4.3: Summary of Data Limitations of MOE ISI Protocol**

| Limitation | Possible Effect on Aquifer Vulnerability Mapping |
|---|---|
| Calculation of ISI value and grouping into vulnerability categories is purely empirical and is not based on ground-water flow dynamics | Difficult to define what "low, medium, or high" vulnerability means from a risk perspective |
| Method relies heavily on variable quality of well record data | Inaccurate determination of aquifer vulnerability |
| Application of GSC materials protocol causes excessive generalization of conditions | Incorrect identification of presence/thickness of aquitards and aquifers |
| Does not consider effects of vertical groundwater flow gradients | May overestimate vulnerability of aquifer; underestimation also possible |
| Does not consider multiple aquifers | The lower vulnerability of deeper aquifers is not considered in the analysis. |
| Relies on well density and distribution patterns. | Areas that have fewer wells are less understood. |

The combination of these limitations will result in variable degrees of uncertainty associated with the results of the analysis. In general, the ISI protocol will produce low uncertainty in geologically homogenous areas where wells are closely spaced and tap the same aquifer. Unfortunately, many of these assumptions are not applicable in the CSPA because of the complex geology and low development density in many areas. Nevertheless, the ISI protocol results, when used in combination with surficial geology information, can be used to assess general trends and conditions.

### 4.4.2 Surficial Geology Methodology

Information from surficial geology maps can be used to qualitatively assess the vulnerability of aquifers within the CSPA. These maps (**Table 4.4**), which are produced at the 1:50,000 to 1:63,360 scales, are prepared by geologists who specialize in lithological descriptions. Therefore these maps provide better information about shallow geological conditions than would water well records on their own. Application of this method is especially useful in areas where few wells are present (e.g., Canadian shield, between settlement areas, etc.).

Seamless surficial geology mapping created by the Ontario Geological Survey (OGS), 2003 were used to identify large areas that are expected to have a high vulnerability. A reprint of the surficial geology map for the CSPA is presented as **Figure 2.4**. The surficial geology mapping was created by harmonizing geology maps that were originally created in the 1:50,000 and 1:63,360 scales. The maps that were used as the basis for the seamless mapping are listed in **Table 4.4**.

**Table 4.4: Overburden Geology Maps used in Vulnerability Analysis**

| Map | Scale |
|---|---|
| OGS P.2615, Tweed Area (31 C/6), 1983 | 1: 50,000 |
| OGS P.2540 Belleville Area (31 C/3), 1982 | 1: 50,000 |
| OGS P.2587 Sydenham Area (31 C/7), 1984 | 1: 50,000 |
| OGS P.2588 Bath – Yorkshire Island Area (31 C/2; 30 N/13), 1984 | 1: 50,000 |
| GSC 13 – 1965, Gananoque-Wolfe Island | 1: 63,360 |
| GSC Map 6-1970, Brockville and Mallorytown | 1: 50,000 |

Areas mapped as predominantly bare rock, shallow drift (generally <1.5m thick) or sand and gravel were considered to be highly vulnerable because of the lack of low permeability deposits that would impede vertical contaminant migration to the aquifer below. Classification of vulnerability based on surficial geology is shown in the table below.

**Table 4.5: Vulnerability Ranking by Surficial Geology***

| Geological Unit | Vulnerability |
|---|---|
| Precambrian bedrock | High |
| Precambrian bedrock-drift | High |
| Paleozoic bedrock | High |
| Paleozoic bedrock-drift | Moderate |
| Shield-derived silty to sandy till | Moderate |
| Stone-poor silty to sandy till | Moderate |
| Ice-contact stratified deposits | High |
| Moraines, kames and eskers | High |
| Glaciofluvial deposits | High |
| Fine grained glaciolacustrine deposits | Low |
| Coarse glaciolacustrine deposits | High |
| Offshore glaciomarine deposits | Low |
| Nearshore glaciomarine deposits | High |
| Littoral-foreshore deposits | Moderate |
| Eolian Deposits | High |
| Modern Alluvium | Moderate |
| Organic Deposits | Moderate |

*Surficial Geology of Ontario, OGS, 2003

Limitations

The main limitations of this data set are the mapping scale and that the information is on surficial geology conditions only. The original data used to generate the seamless surficial geology map was created at the 1:50,000 and 1:63,360 scales. Therefore, the mapping indicates regional conditions rather than property parcel specific information.

In general, the uncertainty associated with the method is lower in areas of high vulnerability that are produced as a result of thin overburden. Uncertainty is high in areas identified as low to moderate vulnerability, as surficial geology maps only show the soil conditions in the top 1 to 1.5m and do not account for geology at depth. For example, areas mapped as being covered with low permeability clay (which in turn would be identified as low to moderate vulnerability areas) may have bedrock close to surface. In this case, a high vulnerability designation would be more appropriate. At best, in areas of low to moderate vulnerability, the surficial geology method identifies areas of potential low to moderate vulnerability that would need to be confirmed using well data.

## 4.5 Results

The results of the vulnerability mapping are presented as **Figure 4.1** and **Figure 4.2** located in the map pocket at the back of the report text.

ISI Protocol

Mapping of aquifer vulnerability using the ISI protocol is shown in **Figure 4.1**. The map shows that the majority of wells are deemed to have high aquifer vulnerability. A breakdown of the number of wells assessed and the overall percentage of low, moderate and high vulnerability wells is shown in the table below. Overall, the majority of wells (84%) received a high vulnerability ranking. Moderate to low vulnerability conditions were detected in some wells, but the occurrence of these conditions was generally isolated and discontinuous.

| Vulnerability Ranking | # Wells | Total Percentage |
|---|---|---|
| High | 12,955 | 84% |
| Moderate | 2205 | 14% |
| Low | 309 | 2% |
| Total | 15,469 | 100% |

While the CSPA is dominated by high vulnerability areas, areas where clusters of moderate to low vulnerability wells do exist, and are summarized in **Table 4.6**. These locations correspond with areas of relatively thick deposits of clay and silt, or glacial till.

**Table 4.6: Areas of Low to Moderate Vulnerability Wells**

| Municipality | Area |
|---|---|
| Elizabethtown-Kitley | - Parkdale Avenue East & Kelly Road<br>- Between Lyn and Elizabeth Town along Main Street East |
| Front of Yonge | - Highway #2 near Mallorytown |
| Leeds and the Thousand Islands | - Quabbin Road<br>- Seeley's Bay<br>- intersection of Highway #2 and Highway 401<br>- Highway #2 between Clarke Drive and Deer Ridge Drive<br>- Highway 32 and Deryaw Road |
| Township of Rideau Lakes | - Morton<br>- Perth Road Area, south of Westport |
| South Frontenac | - Milburn Road<br>- Moreland-Dixon Road |
| Kingston | - Joyceville Road<br>- Colonel By Lake area (Kingston Mills Road, Highway 15)<br>- Aragon Road<br>- Highway #2 east of Joyceville Road<br>- Abbey Dawn/Highway #2 Area<br>- Sydenham Road/Sunnyside Road/Highway 401 Area<br>- Woodbine Road west of Collins Bay Road |
| Greater Napanee | - Adolphustown<br>- South Shore Road, north of Dorland<br>- Hay Bay North Shore Road, north of Hay Bay |
| Loyalist | - Morven |

Surficial Geology Method

Aquifer vulnerability assessment results based on the surficial geology is shown in **Figure 4.2**. For comparison purposes, the aquifer vulnerability determined at the well using the ISI protocol is also shown. The size of areas identified as high, moderate or low vulnerability is summarized in the table below:

| Vulnerability Ranking | Area | Total Percentage |
|---|---|---|
| High | 2,186 $km^2$ | 61% |
| Moderate | 597 $km^2$ | 23% |
| Low | 784 $km^2$ | 16% |
| Total | 3,567 $km^2$ | 100% |

Areas of high vulnerability correspond with shallow bedrock that is either exposed or thinly covered with glacial drift. Moderate vulnerability was mapped in areas where the bedrock is buried beneath glacial till. Areas that are overlain by glaciolacustrine silts and clays are deemed as low vulnerability. These conditions exist in portions of Loyalist Township, Amherst and Wolfe Islands, City of Kingston and Leeds and the Thousand Islands. In general, many of the areas of low to moderate vulnerability are isolated and discontinuous, reflecting the complex surficial geology of the area. The surficial geology method does not take into account the thickness of the overlying material, but rather its spatial extent only. As a result, many of the areas that are mapped as moderate to low vulnerability will likely have a low accuracy because low permeability materials may only be thin and not provide adequate protection of the underlying aquifers from contamination.

## 4.6 Discussion

An assessment of the vulnerability of the CSPA is best conducted through a review of both the ISI protocol results (**Figure 4.1**) and the surficial geology assessment approach (**Figure 4.2**). Each approach provides slightly different information. The ISI protocol is the best choice to identify areas of low to moderate vulnerability with a high degree of certainty, because it incorporates thickness of the protective overburden. The surficial geology method is the best approach to identify areas of possible low to moderate vulnerability as the method includes spatial data of the extent of low permeability overburden deposits. Confirmation of the potential low vulnerability in these areas would require field studies to investigate the hydrogeological conditions at depth. Both the ISI and surficial geology method are well suited to identify high vulnerability areas; however, the surficial geology approach is better at identifying high vulnerability areas in regions where wells do not exist. Estimation of vulnerability between the well locations in the ISI protocol approach is not recommended because geological conditions change over short distances.

The accuracy of the vulnerability mapping varies as a function of the method used. For areas mapped as highly vulnerable based on surface geology, there is a high confidence in the result. Conversely, for areas mapped as low to moderate vulnerability based on surficial geology, the accuracy is anticipated to be lower. In these areas, the thickness of clay, silt or till (which causes the low/moderate vulnerability ranking) is unknown and therefore the vulnerability is less certain. One exception is in areas where there are clusters of wells that have been mapped as low to moderate vulnerability using the ISI protocol. The higher concentration of data available for these areas increases the confidence in the interpolation. Nevertheless, areas underlain by clay, silt and/or till are deemed to intrinsically have a lower vulnerability than areas of shallow rock or surficial sand.

A comparison of the vulnerability map produced in this study and mapping performed in previous studies shows some similarities and differences. All mapping procedures show that the area is mainly highly vulnerable. However, the area of land shown as high vulnerability is lower in the previous ISI and DRASTIC analyses performed in the Western Cataraqui Groundwater Study. The differences are attributed to both the methodology and the contouring routines. The ISI methodology is more influenced by the depth of overburden than is the DRASTIC methodology, and therefore, shallow soil conditions receive higher vulnerability scores in the ISI approach. Differences in the ISI methodology between this study and the Trow evaluation are believed to be a result of the interpolation program. In the Trow study, interpolation was used to estimate vulnerability between the wells. In the current study, the decision was made to not contour the ISI values at the wells because of the complexity of the geology, which results in changes in the vulnerability over short distances. The density of the well data is not sufficient to represent these sudden vulnerability changes.

## 4.7 Conclusions

Based on the results of the vulnerability assessment, the following conclusions and guidance on application of the study are made.

<u>Distribution of Vulnerability Areas</u>

1) Two methods were used to assess aquifer vulnerability. The first method followed the MOE Intrinsic Susceptibility Index (ISI) protocol while the second method utilized information from surficial geology maps to aid in identifying vulnerable areas. Both methods show that the CSPA is largely in an area of high aquifer vulnerability. Approximately 84% of the known wells were identified as being highly vulnerable using the ISI protocol. Only 2% were identified as having a low vulnerability. Using the surficial geology methodology, approximately 61% of the area was deemed as highly vulnerable, with 16% deemed as having a low vulnerability; however, this method will underestimate the amount of highly vulnerable areas as it does not take into account overburden thickness.

2) Vulnerability rankings change over short distances, reflecting the complex geology of the CSPA. Areas of low vulnerability will be juxtaposed with areas of high vulnerability.

3) Areas of low to moderate vulnerability are most concentrated in parts of Loyalist Township, City of Kingston, and select areas within The Township of Leeds and the Thousand Islands. These low to moderate vulnerability areas are associated with thick deposits of silt and clay.

4) For the purpose of the source protection assessment report, the aquifer vulnerability mapping conducted in this study supersedes earlier vulnerability mapping conducted in the east and western portions of the study. The results of the current study are similar to the previous assessments in that the majority of the area is defined as highly vulnerable.

Application to Source Protection

5) Considering that the vast majority of wells were ranked as highly vulnerable across the CSPA and that low to moderate vulnerability areas only appeared as small and noncontiguous areas, it may be prudent to consider the entire CSPA as being highly vulnerable for the purposes of the Assessment Report and Source Protection planning. While isolated low vulnerability areas exist, they are few and limited in extent, and are not mapable with a high degree of confidence at the property parcel level at which source protection will be applied. This recommendation is further supported by the fact that the high uncertainty associated with mapping low to moderate vulnerability areas based on the surficial geology maps is high, and therefore these areas should also be mapped as highly vulnerable unless future data indicates otherwise.

6) While there are limitations in the application of the vulnerability map, several uses are identified.

- The map can be used to underscore the fact that unlike many other Source Protection Areas in Ontario, the CSPA is intrinsically vulnerable and complex. Land development will require additional study at the local and property parcel scale in order to assess actual vulnerability.

- The map can be used as a guidance tool for future Source Protection activities such as identifying general areas for voluntary-based protection initiatives or for guiding future technical studies.

- The map can be used to identify areas that have the greatest probability of being highly vulnerable (areas of shallow rock and surficial sands and gravels). Future source protection activities such as education programs, spills prevention programs, incentive programs, etc. that target high vulnerability conditions could focus on these areas. Conversely, areas of low vulnerability could be targeted under source protection for the management of transport pathways such as improperly abandoned wells.

- The map can be used to identify areas where the vulnerability is less predictable, such as in areas of clay, silt, or till deposits. In these areas, future studies involving well surveys and test drilling could be conducted to verify vulnerability conditions. Identification and confirmation of low vulnerable areas could be used as input into future land use planning decisions.

7) While the map is regional in nature, it can be used to help assess aquifer vulnerability at more local scales, as long as precautions listed below are followed:

- Interpretation of the map should be performed by a professional geoscientist who is familiar with the local geology.

- When identifying vulnerability zones for a specific area, the location and density of the nearest reported water well ISI value must be considered. Vulnerability conclusions should be based on whether hydrogeological conditions at the closest well point are expected to be similar to what is present at the area of interest. In order to make this determination, consideration should be given to the natural variability in topography and hydrogeology in the area. A review of topography information, soils data, geology maps and air photos would be useful in making these assessments.

- Depending on the purpose of the assessment (i.e., a regulatory vs voluntary action), confirmation of the soil conditions may be required through field sampling.

## 4.8 Bibliography

Aller, Linda, Bennett, Truman, Lehr, J.H., and Petty, R.J., 1985, DRASTIC – a standardized system for evaluating ground water pollution potential using hydrogeological settings, US EPA, EPA/600/2-85/018.

Cataraqui Region Conservation Authority, 2007, Source Water Protection Water Budget Conceptual Report.

Cataraqui Source Protection Area, 2007. Frontenac Islands Groundwater and Aquifer Characterization Study, October, 2007.

Chapman and Putnam, 1984, The Physiography of Southern Ontario, 3rd Edition, Ontario Ministry of Natural Resources.

Dillon, 2001. United Counties of Leeds and Grenville Groundwater Management Study.

Freeze and Cherry, 1979. Groundwater. Prentice-Hall Inc. Englewood Cliffs, New Jersey, U.S.A. 604p.

Golder and Dillon, 2003. Renfrew County – Mississippi – Rideau Groundwater Study, Final Report, September, 2003.

Henderson, 1965, Surficial Geology: Gananoque – Wolfe Island, Geological Survey of Canada.

Henderson, 1972, Surficial Geology: Brockville and Mallorytown, Geological Survey of Canada, Paper 70-18.

Leyland, J.G, 1982. Quaternary Geology of the Belleville Area, Southern Ontario; Ontario Geological Survey, Map P.2540, Geological Series-Preliminary Map, scale 1:50,000. Geology 1981.

Leyland, J.G., and Mihychuk, M., 1983: Quaternary Geology of the Tweed Area, Southern Ontario; Ontario Geological Survey, Map P.2615, Geological Series-Preliminary Map, scale 1:50,000. Geology, 1981.

Leyland, J.G., and Russell, T.S, 1983. Quaternary Geology of the Bath-Yorkshire Island Area, Southern Ontario; Ontario Geological Survey. Map P. 2588, Geological Series-Preliminary Map, Scale 1: 50,000. Geology 1982.

Leyland, J.G., and Russell, T.S, 1983. Quaternary Geology of the Sydenham Area, Southern Ontario; Ontario Geological Survey. Map P. 2587, Geological Series -Preliminary Map, Scale 1: 50,000. Geology 1982.

Ontario Geological Survey, 2003. Surficial Geology of Southern Ontario, Miscellaneous Release Data 128.

Ontario Ministry of the Environment and Energy, 2002; Groundwater Studies, 2001/2002, Technical Terms of Reference with Database Field References, March 2002”.

Ontario Ministry of the Environment and Energy, 2002; Groundwater Studies, 2001/2002, Clarification for TOR sections 2.2.2 and 2.2.3 – GwIS calculation. July 12, 2002.

Stempvoort, Ewert and Wassenaar, 1992. AVI: A Method for Groundwater Protection Mapping in the Prairie Provinces of Canada, National Hydrology Research Institute, Saskatoon.

Trow, 2007, Western Cataraqui Region Groundwater Study, 2007.

## PART 5 RECOMMENDATIONS

Recommendations

The report concludes by making several general recommendations that build upon the findings of this study. These recommendations are:

1) There is a need to improve the understanding of the regional groundwater flow patterns, considering the hydrogeological complexity of the CSPA, and the general lack of good quality groundwater data. Future studies should also focus on understanding groundwater flow within the Nepean Formation aquifer, and in determining the presence and significance of groundwater flow between the watersheds.

2) The relationship between surface water features (lakes, rivers and wetlands) and aquifer recharge should be assessed. The work should include determining the significance that these features have on maintaining seasonal water levels in the aquifer and their contribution to aquifer storage.

3) Significant Groundwater Recharge Areas (SGRA) that were identified in the GVAR study should be confirmed through field investigations. SGRA delineation can also be improved by mapping important groundwater discharge areas, and relating these discharge areas to the recharge areas that support them.

4) Identify SGRAs that provide groundwater recharge to the aquifers that are used by rural settlements serviced by private wells. Protection of these SGRAs will be important to ensure an adequate water quality and quantity to these communities.

5) Identify ecosystems that are sensitive to groundwater contributions, such as cold water streams, or sensitive wetlands. These features may be vulnerable to nearby changes in land use or groundwater pumping.

6) Update the vulnerability maps as additional site specific information becomes available. The study has shown that the majority of aquifers in the CSPA can be considered highly vulnerable; however, aquifer vulnerability at a property parcel level may differ from regional conditions.

# FIGURES

# APPENDIX A

# LIST OF TECHNICAL PAPERS

# APPENDIX B

# GEOLOGICAL SECTIONS

# APPENDIX C

# MOE ISI METHODOLOGY