Groundwater Vulnerability Study - March/Nepean Formation Aquifer

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ABSTRACT
An aquifer vulnerability study was undertaken on a regional bedrock aquifer that provides drinking water to a number of Eastern Ontario municipalities. The study included field data acquisition, numerical modelling and Wellhead Protection Area delineation. Aquifer vulnerability scores were assigned to various zones within the Wellhead Protection Areas and vulnerability maps were produced.

RÉSUMÉ
Une étude de vulnérabilité de périmètre de protection de puits de captage d'eau a été entreprise pour un aquifère de roc profond régional qui fournit l'eau potable à un nombre de municipalités de l'est Ontarien. L'étude consistait en une collected de données de terrain, une modélisation numérique et une délinéation des aires de protection des puits. Un pointage a été développé pour assigner un indice de vulnérabilité des aires protection et une carte de vulnérabilité des aires de protection à été produite

1 INTRODUCTION

A significant regional aquifer occurs within the basal Paleozoic Nepean and March Formations in much of central Eastern Ontario. This productive aquifer provides good quality water for a number of local municipalities, including the Village of Merrickville, and the Town of Kemptville, the subjects of this study. Both municipalities draw water from the aquifer using communal well systems.

The aim of the investigation, conducted for the Mississippi Rideau Source Protection Region (MRSPR) and funded by the Ontario Ministry of the Environment (MOE) under the Ontario Source Protection Technical Studies Grant Program, was to map groundwater vulnerability within the catchments of the municipal wells servicing these two communities. Comparatively little hydrogeological information was available for the March/Nepean aquifer, particularly in regards to horizontal and vertical hydraulic gradients, locations of recharge area(s) and the rate of propagation of water. A better understanding of these processes was required to assess the vulnerability of the aquifer system that supplies water to the municipal wells and to enable appropriate source water protection planning.

The study included the construction of two boreholes, borehole geophysics and installation of screened monitors at discrete intervals in each borehole. Hydraulic testing was performed on selected monitors and a water quality sampling program, including isotope analysis was conducted. A three-dimensional, finite difference groundwater flow model was developed and calibrated to static water levels from available data, to hydraulic heads measured in the multi-level monitoring wells, and to groundwater residence times estimated from the isotope data.

Wellhead Protection Areas (WHPAs) were delineated for both shallow and deep takings at each of the three municipal wells in North Grenville and the municipal wells in Merrickville-Wolford. Groundwater vulnerability maps for the shallow and deep bedrock aquifers were then generated using accepted methodologies.

2 LOCATION AND WATER SUPPLY SYSTEMS

Merrickvile-Woolford is located about 55 kilometres southwest of downtown City of Ottawa and is comprised of the former Village of Merrickville (Merrickville) and the Township of Wolford. The boundary of Merrickville-Wolford is shown on Figure 1. The current population of the municipality is approximately 2,870, of which about 1,000 live in the area serviced by the Merrickville Water Supply System.

Groundwater is pumped through three wells, all located within a 60 metre radius on a single property. The water from the wells is disinfected and conducted to an underground storage reservoir. The water is pumped from the reservoir to the distribution system using a high lift booster pump. The three Merrickville wells are permitted for a maximum of 4,295 cubic metres per day (m^3/day). Actual average day consumption in 2006 was 394 m^3/day.

North Grenville is located approximately 40 kilometres south of the City of Ottawa and 18 kilometres to the east of Merrickville. North Grenville is comprised of the former Town of Kemptville (Kemptville) and the Townships of Oxford on Rideau and South Gower. The boundary of North Grenville is shown on Figure 1. The current population of North Grenville is approximately 14,200, of which approximately 3,400 live in the area serviced by the Kemptville Water Supply System.

The Kemptville Water Supply System consists of three supply wells referred to as the Alfred Street Well, Kernahan Street Well and Van Buren Street Well. The wells are between 62 and 110 metres deep and are permitted for 2,946 m^3/day (Alfred Street) 1,964 m^3/day (Kernahan) and 1,309 m^3/day (Van Buren).

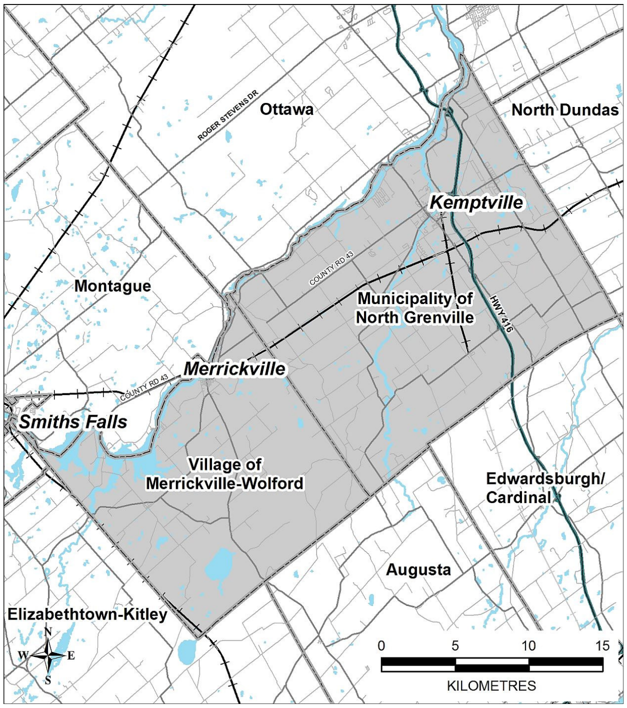


Figure 1. Study Location

3 PHYSICAL SETTING

3.1 Physiography

The dominant physiographic features in the study area are the Rideau River which flows through North Grenville and Merrickville-Wolford, and Kemptville Creek which flows through Kemptville and the former Township of Oxford on Rideau, within North Grenville. The Rideau River flows from southwest to northeast through the study area and ultimately discharges to the Ottawa River. Kemptville Creek flows to the north and discharges to the Rideau River northeast of Kemptville.

In general, the ground surface is highest near the western boundary of the study area, and lowest near the eastern boundary. The total change in relief across the study area is approximately 75 metres. The ground surface in the vicinity of the Rideau River and Kemptville Creek is slightly lower than the surrounding areas. The local topography in North Grenville and Merrickville-Wolford is relatively flat lying, and ranges from approximately 90 metres above sea level (masl) to 100 masl in North Grenville and from approximately 110 masl to 120 masl in Merrickville-Wolford.

Chapman and Putnam (1984) categorized the physiography of Southern Ontario into 55 separate regions. Merrickville-Wolford is located within the Smiths Falls Limestone Plain Region. Due to the flat topography, shallow soils and large areas of exposed bedrock, drainage in low-lying areas is typically poor. As such, wetlands and bogs are common features throughout this physiographic region, as seen in the southern half of Merrickville-Wolford. North Grenville is located primarily in the Edwardsburg Sand Plain Region, while the western edge is within in the Smiths Falls Limestone Plain Region. The Edwardsburg Sand Plain is generally characterized by glaciofluvial sand deposits overlying bedrock, till or clay. The topographic relief in this region is relatively small (i.e., less than 35 metres), and sand ridges or moraines are found in areas of higher elevation.

3.2 Surficial Geology

According to the Ontario Geological Survey (2003), the surficial geology in the study area consists primarily of glacial till deposits, offshore marine clay deposits and near shore fine to medium sand deposits. In general, the overburden in the western half of the study area is thin (i.e., less than two metres), while in the eastern half, local areas of increased overburden thickness are present (i.e., up to approximately 20 metres).

The till deposits within the study area consist of occasional to numerous cobbles and boulders in a sandy silt to clay matrix. The topography associated with these deposits is generally flat to hummocky with the exception of the drumlinized portions which may show moderate local relief.

The silt and clay deposits within the study area are found in areas along Kemptville Creek and the Rideau River, near the north and eastern end boundaries of the study area, and in other localized areas, typically where the ground surface elevation is less than 105 masl. The silt and clay deposits are occasionally overlain locally by thin sand layers. The upper part of the unit is generally mottled or laminated, reddish brown and bluish grey. At depth, it is often uniformly blue-grey clay.

Portions of the eastern half of the study area have surficial deposits of fine to medium grained sand, which is calcareous and commonly fossiliferous. The unit generally occurs as sheets or bars and is associated with glaciofluvial materials.

3.3 Bedrock Geology

The sequence of sedimentary rock underlying the study area (from oldest to youngest) is Nepean Formation (sandstone), March Formation (sandstone/dolostone), Oxford Formation (dolostone) and Rockliffe Formation (limestone/shale). These formations are interpreted to dip approximately three metres per kilometre towards the southeast.

The Nepean Formation Sandstone overlies the unevenly eroded Precambrian granitic basement within the study area. Williams (1991) describes the Nepean sandstone as white to cream coloured, weathering to grey. It is generally thick-bedded; however, portions are thinly-bedded and water-bearing. The cementing minerals include both calcite and quartz. The thickness of the Nepean Formation is difficult to ascertain precisely as there are very few drill holes that have been reported to penetrate the entire formation. Across the study area, the Nepean Formation thickens towards the east (Williams, 1991), and is likely approximately 50 metres thick in the central part of the study area. The Nepean Formation is absent in certain places, as evidenced by the small knobs of Precambrian granite found south of Kemptville. It should be noted that significant thickness of limestone and sandstone have been reported by drillers in very close proximity to these knobs, and their presence is not considered to be an indicator of an overall thinning of the Nepean Formation.

The Nepean Formation is conformably overlain by the younger March Formation, which is characterized by interbedded quartz sandstone and dolostone. The lithology of the quartz sandstone beds of the March Formation are similar to those of the underlying Nepean Formation, while the lithology of the dolostone beds of the March Formation are similar to those of the overlying Oxford Formation (Williams, 1991). As a result, the March Formation is referred to as a transitional unit between the Nepean Formation and the Oxford Formation. The contact between the March and Oxford Formations is marked by the upper limit of the common occurrence of quartz sand (Williams, 1991). By extrapolation from recorded drill holes (Williams, 1991) and from boreholes drilled in this study, the thickness of the March Formation is interpreted to be approximately 20 to 30 metres across much of the study area.

The March Formation is conformably overlain by the younger Oxford Formation. The Oxford Formation consists mainly of thin to thickly bedded dolostone. Shaley interbeds up to 30 centimetres in thickness occur within the Oxford Formation (Williams, 1991). The Oxford formation is absent in the western third of the study area, and by extrapolation from recorded drill holes (Williams, 1991) thickens to approximately 100 metres at the mid-point of the eastern edge of the study area.

The Rockliffe Formation lies unconformably on the Oxford Formation. This formation contains a sequence of limestone, sandstone, and shale. The lower portion of the sequence contains interbedded shale and sandstone, while the upper portion contains additional interbeds of limestone (Williams, 1991). Within the study area, the Rockliffe Formation is found only along portions of the eastern and northern study area boundaries.

3.4 Hydrogeology

Extensive deposits of coarse and permeable overburden, capable of supplying sufficient quantities of groundwater for domestic use, are not prevalent in the study area. For this reason, bedrock aquifers are considered the principal aquifers for water supply.

The shallow bedrock aquifer is the primary source of water for private water supply wells (Geo-Analysis and J.L. Richards and Associates Limited, 1992) and is interpreted to correspond with the upper part of the Oxford Formation. Typical well yields reported for this aquifer are between 45 to 115 L/min (Geo-Analysis and J.L. Richards and Associates Limited, 1992). Drillers' records indicate that water bearing zones occur at distinct depths within the formation, with water being found within a network of fractures, possibly enhanced by carbonate dissolution, and possibly associated with shale partings (Williams, 1991).

A bedrock aquitard is interpreted to lie within the lower part of the Oxford Formation and the upper part of the March Formation (Raven Beck, 1996). Its presence is indicated by strong vertical gradients across this zone and by flowing artesian conditions observed in some wells completed below the aquitard, (i.e., the Alfred Street and Kernahan municipal wells in Kemptville).

The deep bedrock aquifer is interpreted to be present within the lower part of the March Formation and within the Nepean Formation. This aquifer is generally associated with sandstone rather than dolostone or limestone, and is attributed both to the Nepean Formation (e.g., Brandon, 1960) and to the March Formation (e.g., Wilson, 1946, J.D. Patterson, 1991). Flow within this aquifer is mainly through fractures, as the primary porosity of the sandstone has been reduced by cementation. The aquifer tends to be most productive at the contact between the Nepean Formation and overlying March Formation and at the contact of the Nepean Formation with the underlying Precambrian rock (Brandon, 1960). Using 5 metres test-interval straddle packers, Raven Beck (1996) measured a transmissivity of approximately 600 metres squared per day (m2/day) over the upper 50 metres of the Nepean Formation, and found enhanced permeability at the March formation/Nepean Formation contact. Well statistics indicate that yields are high, ranging from 150 to 4,450 litres per minute (Brandon, 1960; Oliver, Mangione, McCalla & Associates 1990, 1991; Geo-Analysis and J.L. Richards and Associates Limited, 1992). This aquifer is the primary source of water for large commercial/municipal groundwater supply systems, including the municipal wells at Kemptville and Merrickville.

4 STUDY RESULTS

4.1 Borehole Construction and Geophysics

The Merrickville borehole was located within 20 to 75 metres of the town's three production wells. In Kemptville, the borehole was constructed in a municipal easement to the north of the Town.

Flowing conditions were encountered in both boreholes. At MW06-1 in Merrickville, the artesian head was contained within the surface casing, which had a stick-up of 0.7 metres. At MW06-2 in Kemptville, it was necessary to extend the surface casing four metres above the ground surface to contain the head.

A suite of downhole geophysical logging tools and techniques were employed at both borehole locations. These included optical and acoustic televiewer logging, natural gamma and apparent conductivity logging; caliper logging; borehole fluid temperature, resistivity and conductivity logging and a heat-pulse flow meter log.

The geophysical logging indicated that the majority of the water bearing structures are within 10 degrees of horizontal, suggesting that the major permeability is related to bedding or bedding partings. The logging clearly delineated the depths of major fractures, which determined locations for the placement of the screened intervals.

Flow in both boreholes was determined to be upward, with formation water entering the borehole from fractures/joints close to the bottom of the boreholes, and exiting the borehole in fractures/joints close to the bottom of the casing. This information is important, as the well casing in the six municipal wells in the two municipalities is relatively short, and the wells are therefore open to the shallower bedrock aquifer. If the water level in a particular well is lowered below the upper fractures through pumping, water will move into the wellbore from the upper bedrock aquifer.

After the geophysical program was completed, both boreholes were reconstructed as multi-level monitoring wells, with three screened intervals in each borehole. The three intervals in the Merrickville borehole and the upper and lower interval in the Kemptville borehole corresponded to major or minor flow zones as identified in the geophysical surveys. The middle screened interval in the Kemptville borehole was placed within the intervening aquitard.

4.2 Water level Monitoring and Hydraulic Testing

Water levels were collected from all screened intervals. The results confirm that the gradients were upward in both locations. The head difference between the deep and shallow monitors was 3.5 metres in Merrickville and 4.0 metres in Kemptville. This data suggests a degree of hydraulic isolation between the deep and shallow bedrock aquifers. The data also provide justification for exercising caution in the interpretation of deep groundwater flow directions from water well data.

Rising head tests were performed on selected monitoring intervals to provide additional information on the horizontal hydraulic conductivity of the bedrock adjacent to the selected monitoring well intervals. The results suggest that the hydraulic conductivity in the deep fracture zones is in the range 10^{-4} metres per second (m/sec) to 10^{-5} m/sec, while the hydraulic conductivity of the intervening aquitard in Kemptville was determined to be two to three orders of magnitude lower, at about 10^{-7} m/sec.

4.3 General Chemistry and Isotope Sampling

Groundwater and surface water samples were collected from various monitors, municipal wells and surface water locations and analyzed for parameters that included general chemistry, oxygen-18/deuterium ($^{18}O/^{2}H$), tritium (^{3}H), and helium-3 (^{3}He).

The surface water samples, as expected, contained lower concentrations of sodium, magnesium, alkalinity, hardness, conductivity, sulphate and chloride compared to the groundwater samples. The groundwater results for the nine sample locations show relatively consistent concentration for most parameters. Overall, the general groundwater chemistry was typical of that observed in the Oxford, March and Nepean Formations (Golder et.al, 2003).

The isotope results indicate that there is a consistent $^{18}O/^{2}H$ signature in the groundwater supplying the Merrickville municipal wells, suggesting that the groundwater is well mixed and that the aquifers are recharged at a distance from the municipal wells.

The groundwater samples collected from the Kemptville monitoring well nest all plot together below the Local Meteoric Water Line (LMWL), which may indicate some evaporation of the recharge water prior to infiltration. The groundwater sample collected from the Kernahan Street Well in Kemptville does not plot in the same location as the others. This well was deepened from 67.8 metres to 110 metres in 1981 in an attempt to increase the yield. The deepest monitor in MW06-2 (MW06-2A) has a screened interval of 56.39 to 71.63 metres below ground surface (mbgs). The observed difference in the $^{18}O/^{2}H$ signature between the intervals of MW06-2 and the Kernahan Street Well may indicate that the majority of the water taken from the Kernahan Street Well comes from below 71.73 metres. This is further supported by the elevated conductivity and chloride concentrations relative to the MW06-2 intervals, which may also indicate deeper, older, slightly more mineralized groundwater.

Differences in the $^{18}O/^{2}H$ signature between the groundwater samples collected from MW06-1 in Merrickville and MW06-2 in Kemptville suggests the water recharging these locations originates from separate sources (i.e., separate recharge areas).

The samples for ^{3}He were collected using diffusion samplers prepared and provided by the G.G. Hatch Stable Isotope Lab at the University of Ottawa. The diffusion samplers consist of a diffusion membrane and a copper tube reservoir. The diffusion samplers were deployed in the monitoring wells, within the screened interval, and left in place for 11 days to allow the concentration of gasses in the air in the copper reservoir to equilibrate with the concentration of gases in the groundwater in the test interval. The concentration of ^{3}He in the collected sample was then determined by the lab using a magnetic sector mass spectrometer.

The helium isotope ^3He is a daughter product of the decay of ^3H. The concentration of ^3H in the groundwater is measured in the lab. The measured ^3He in the air sample (collected from the diffusion sampler) is corrected by the lab to account for atmospheric ^3He that is dissolved at the time of recharge. Any ^3He above the concentration expected to dissolve from the atmosphere is assumed to be from the decay of ^3H. This concentration is referred to as the tritiogenic ^3He. The estimated concentration of tritiogenic ^3He is used with the measured concentration of ^3H to estimate the groundwater residence time according to equation 1:

$$t = T^{1/2}/\ln 2 \times \ln(1+{}^3He\ tri/{}^3H) \qquad [1]$$

where:
t = groundwater residence time
$T^{1/2}$ = half life of ^3H (12.43 years)
^3He tri = tritiogenic ^3He (helium from the decay of ^3H)
^3H = measured ^3H concentration in groundwater

The resulting groundwater residence times (Table 1) indicate that the groundwater from MW06-1 in Merrickville becomes progressively older with depth to a maximum estimated age of approximately 45 years. The deepest interval in MW06-2 in Kemptville has a similar age of approximately 40 years; however, the age of the middle interval was estimated to be approximately 44 years. The middle interval at MW06-2 (17.7 mbgs to 21.7 mbgs) was purposely installed in an area where no potential flow zones were identified by the geophysical logging. As such, due to the relatively low groundwater velocities anticipated in this interval, the groundwater residence time is expected to be higher. The youngest groundwater at MW06-1 and MW06-2 was found in the upper interval, and had an estimated residence time of approximately 12.3 years and 18.6 years, respectively.

Table 1. Tritium/Helium3 Age Dating Results.

Sample Location	Screen Depth (metres below ground surface)	Groundwater Residence Time (years)*
MW06-1A	45.4 to 49.5	45.4
MW06-1B	19,8 to 24.1	17.7
MW06-1C	6.0 to 10.1	12.3
MW06-2A	56.4 to 71.6	39.6
MW06-2B	17.7 to 21.9	44.3
MW06-2C	8.7 to 12.8	18.6

*Residence times plus or minus 2.9 to 4.4 years

4.4 Groundwater Flow Modeling

Numerical models were developed to simulate the 3-D distribution of hydraulic head in the study area, and, for the purpose of WHPA delineation, to track particles backwards from the Kemptville and Merrickville municipal wells, through the associated groundwater velocity vector field. The flow modelling was performed using MODFLOW (McDonald and Harbaugh, 1988), while the particle tracking was performed using MODPATH (Pollock, 1994). The primary source of geologic and hydrogeologic data that was used to construct the model was the MOE's Water Well Information System (WWIS). This data in the WWIS comes primarily from drilled water well logs submitted by the drilling contractor after completion of a well.

The numerical model domain was constructed as a volume bounded on top by the ground surface, on the sides by the 60 km by 42 km rectangle shown as Figure 2, and on the bottom by a plane set 50 metres below the assumed contact between the March and Nepean Formations. The boundaries of this domain were chosen in part to be coincident with inferred flow lines (particularly on the southern boundary, and western half of the northern boundary, and in part to be sufficiently remote from the wells as to minimize boundary effects.

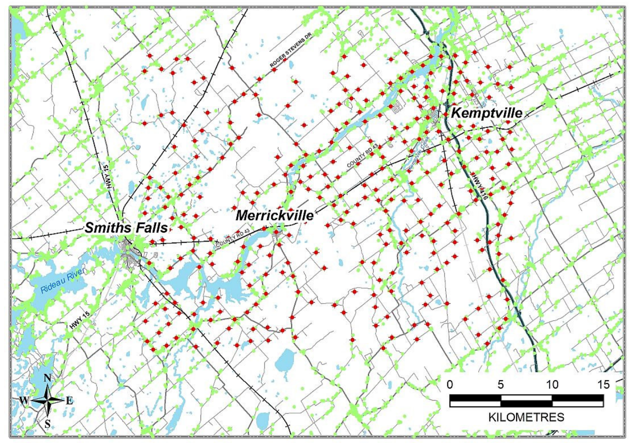


Figure 2. Numerical Model Domain (symbols are WWIS wells used in model)

The domain was divided into 114 rows and 123 columns. The row/column width was set equal to 100 metres in close proximity to the well fields, and increased by a factor of ten percent per row/column outside of these areas. The model domain was divided into 10 layers of grid blocks, whose thicknesses were selected to best match observed geologic and hydrogeologic boundaries.

The bedrock aquifers were assigned a hydraulic conductivity of $5x10^{-5}$ m/sec, while the aquitard was assigned a hydraulic conductivity of $5x10^{-8}$ m/sec. The five metre thick contact zone within the deep bedrock aquifer was assigned a hydraulic conductivity of $8x10^{-4}$ m/sec. This hydrostratigraphic profile corresponds to that measured in packer tests across the Oxford/March/Nepean sequence by Raven Beck (1996), and verified by drilling observations and hydraulic testing carried out in this study. Vertical bedrock hydraulic conductivity was assumed ten times lower than horizontal.

Recharge was initially established using consideration of local topography and geology, and was refined through adjustments during the calibration process.

Parameter variations from the calibrated flow model were undertaken to incorporate uncertainty in the WHPA delineation. A total of eight simulated cases were considered. In these scenarios, the hydraulic conductivity for various zones was increased or decreased by up to one order of magnitude and recharge was varied by up to 50 percent. Some of the scenarios included a "window" of enhanced permeability located under the Rideau River. While no direct evidence of this window was obtained, it was considered important to include scenarios with it present, due to the similarity of the calibration results of the simulations with and without the "window".

The eight groundwater flow simulations with associated backwards particle tracking were repeated using rates of 1,309 m^3/day, 1,363 m^3/day, 1,816 m^3/day for the Kernahan, Van Buren and Alfred Street wells respectively in Kemptville and a combined rate of 520 m^3/day for the three Merrickville wells.

4.5 WHPA Delineation and Vulnerability Mapping

WHPA delineation was undertaken for each of eight water "takings". These included shallow and deep aquifer takings for the Merrickville well field, and shallow and deep aquifer takings for each of the three Kemptville municipal wells. The WHPAs were mapped as a smoothed polygon containing the projection onto a horizontal plane of all of the time-truncated particle traces from each of the simulations. The truncation times considered were 2 years, 5 years, and 25 years for WHPA Zones B, C, and D, respectively, as established in the Assessment Report: Draft Guidance Module 3 – Groundwater Vulnerability Analysis (MOE, October 2006).

Groundwater vulnerability mapping was performed over the area of the model domain using the Intrinsic Susceptibility Index (ISI) method carried out on a 100 metre grid. The ISI provides a quantitative measure of the degree of protection afforded an aquifer by the overlying geologic material: the higher the index, the greater the degree of protection.

Intrinsic vulnerability scores were calculated for the shallow takings using the shallow aquifer vulnerability mapping. Likewise, intrinsic vulnerability scores were calculated within WHPA Zones B, C, and D for the deep water takings using the deep aquifer vulnerability mapping. The larger of these two scores, on a pixel-by-pixel basis, was taken as the intrinsic vulnerability score for the combined deep and shallow water taking (i.e., for the production well as a whole).

The final intrinsic vulnerability scoring maps are presented as Figure 3 (Kemptville) and Figure 4 (Merrickville).

4.6 Uncertainty Assessment

In general, the shallow systems are better characterized than the deep. This is a reflection of the fact that there are more shallow water wells in the WWIS than deep wells, that static water levels measured in open holes become less representative of true hydraulic heads with increasing depth of the open hole, and that the shallow flow system is more strongly influenced by the well characterized local topography and drainage. The lack of hydraulic head data in the deep aquifer is the most obvious data gap identified in this study.

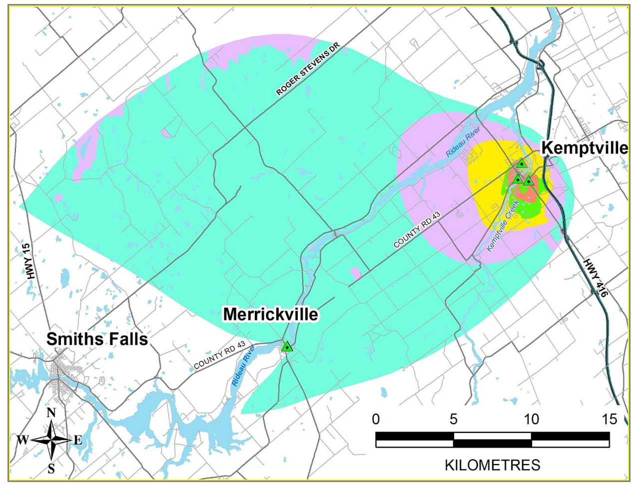


Figure 3. Intrinsic Vulnerability Scoring - Kemptville

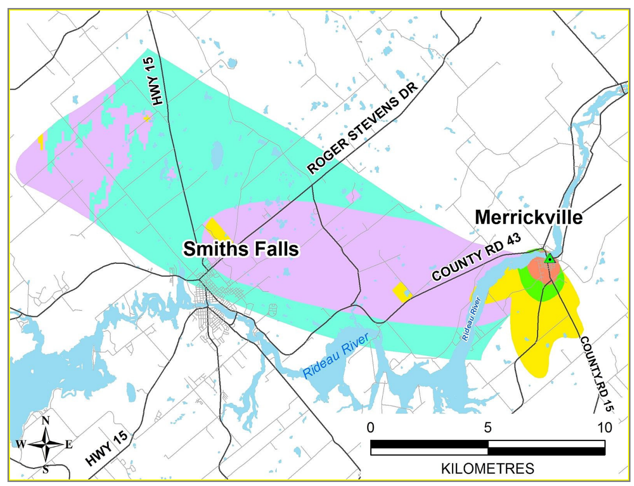
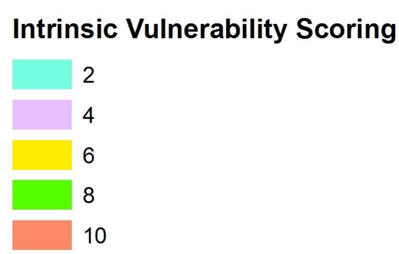


Figure 4. Intrinsic Vulnerability Scoring - Merrickville



5 DATA GAPS

Two significant data gaps were identified in this study.

Very little hydraulic head information for the deep aquifer is available in either municipality. This data would provide much greater certainty with respect to the groundwater flow direction in the deep bedrock aquifer, which could reduce the size of WHPAs.

Detailed overburden information (soil type and thickness) for the area in and surrounding Kemptville would be helpful. This data would provide greater certainty of the shallow aquifer vulnerability in close proximity to the three Kemptville municipal wells considered in this study.

6 LESSONS LEARNED

The use of isotopes for characterizing the groundwater at discrete depths was considered a success. The age dating using ^3H and ^3He isotopes added considerable confidence in the determination of groundwater travel times, which is obviously critical for accurate WHPA delineation.

It is clear that the application of the groundwater vulnerability studies to planning decisions, a part of the Ontario Source Protection Initiative that is only just underway, is focussed on vulnerability Zones A and B (100 metre radius and 2 year time of travel). Therefore, when considering allocation of scarce resources for additional data collection, emphasis should be placed on more clearly defining the characteristics of these areas.

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