DRINKING WATER
SOURCE PROTECTION
ACT FOR CLEAN WATER

Thames-Sydenham and Region Source Protection Committee

Upper Thames River Source Protection Area

Amended Proposed

Assessment Report

Revised - August 12, 2011

APPROVED

4.0 Vulnerability Assessment

ST. CLAIR CONSERVATION

LOWER THAMES VALLEY CONSERVATION AUTHORITY

UPPER THAMES RIVER CONSERVATION AUTHORITY

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Conservation ONTARIO

Thames – Sydenham and Region
Upper Thames River Conservation Authority
1424 Clarke Road, London, ON, N5V 5B9

July 4, 2011

Dear reader

Re: **Upper Thames River Amended Proposed Assessment Report posted for comments**

The Thames-Sydenham and Region Source Protection Committee has posted the enclosed report for review and comment by stakeholders. This report includes updates and amendments to the Proposed Assessment Report for the Upper Thames River Source Protection Authority. Comments received through the first posting (draft proposed report) were considered by the Source Protection Committee and the report has been revised. Comments received in response to the second posting were submitted with the Proposed Assessment Report to the Ministry of the Environment (MOE).

Based on directions from the Director of Source Protection Programs Branch, MOE, updates and amendments were made to the Proposed Assessment Report to include further technical work conducted. These include the Tier 2 water budget drought scenario analysis, the delineation, vulnerability assessment and threats assessment of WHPA-E, and threats assessment of sewer line threats. The updates and amendments made are summarized in Appendix 4. This version of the Assessment Report once approved will be used by the Source Protection Committee for the development of the Source Protection Plan which is to be submitted to the MOE in August 2012.

The Amended Proposed Assessment Report for the Upper Thames River Source Protection Area represents a significant milestone in the Source Protection Committee's progress in the completion of the first Source Protection Plans for the Thames-Sydenham and Region. The Source Protection Committee realizes that this report is a "living document" which may be updated as more information becomes available in the future.

We hope that you have had an opportunity to attend previous open houses that were held throughout the region, and plan to attend the open houses to be held in July 2011. More information on this assessment report and the past and current consultation is available on the web site given at the bottom of this letter.

Yours truly,
THAMES-SYDENHAM and REGION

Robert Bedggood, Chair
Source Protection Committee

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4.0 Vulnerability Assessment

In order to protect drinking water sources it is necessary to identify areas where activities can affect the drinking water sources. The Clean Water Act refers to these areas as *Vulnerable Areas* and requires that they be identified in the Assessment Report. The Vulnerability Assessment section of the Assessment Report summarizes the work to delineate these *vulnerable areas* which was undertaken through various studies. The studies involved the operating authorities of the water systems and were undertaken through partnerships involving the Conservation Authorities in the region. The Clean Water Act also requires that these *vulnerable areas* be assessed to determine their relative level of vulnerability. There are four types of *vulnerable areas* which must be identified and assessed:

- *Intake Protection Zones* (*IPZ*)
- *Wellhead Protection Areas* (*WHPA*)
- *Highly Vulnerable Aquifers* (*HVA*)
- *Significant Groundwater Recharge Areas* (*SGRA*)

Activities in these *vulnerable areas* will be reviewed to determine the *risks* that they pose to the drinking water sources. The vulnerability of the area, combined with the hazard associated with the activity, provide a relative indication of the level of *risk* associated with a *threat*. The *Source Protection Plan* is focused on reducing the level of *risk* associated with *threats*. As such, the identification of the *vulnerable areas* and the assessment of vulnerability are cornerstones to the development of the *Source Protection Plan*. There are no surface water intakes located within the UTRSPA, and therefore no *IPZ* related to surface water intakes are delineated wthin this SPA.

Each type of *vulnerable area* is described in the following sections which summarize the identification and assessment of the vulnerability within the areas.

4.1 Peer Review of Vulnerability Assessment

All aspects of the vulnerability assessment are subject to a thorough peer review process. This process is described in Peer Review of Vulnerability Assessment, Terms of Reference (March 2008). This process includes the forming of a peer review committee comprised of four professionals with extensive experience in one or more of the areas related to the vulnerability assessment of the *vulnerable areas*. Two members of the committee are professional geoscientists familiar with the assessment of groundwater vulnerability; one with experience related to *Groundwater Under the Direct Influence* (*GUDI*) wells, while the other is also a member of the peer review committee for the Water Budget work. The third member of the peer review committee has extensive experience related to the surface water vulnerability assessment and is working on similar projects in other regions. A fourth member joined the committee in the peer review of vulnerability assessment studies of groundwater systems spanning the County of Oxford and Perth County in the Upper Thames River Source Protection Area (*SPA*) and the Lake Erie Source Protection Region (*SPR*). The peer review committee reviewed each technical report, met with the consultants and project teams to discuss the project and submitted comments based on their review and the discussion. Comments were considered and responded to by the consultant or project team members. These comments and the responses form part of the peer review record along with the terms of reference for the peer review committee discussed above. The peer review process added considerable value to the technical report by ensuring that the work was well documented.

One point that involved considerable discussion by the peer reviewers was the uncertainty analysis undertaken in the technical studies. The *rules* allow for uncertainty to be determined as either high or low. While it was generally reported that the uncertainty associated with the vulnerability assessment or delineation of the *vulnerable areas* was acceptable for the intended purpose, there was a wide variation in what consultants viewed as a low level of uncertainty. The uncertainty reported in this report reflects that which has been identified in the technical reports. However, following the completion of the peer review of all of these studies, it has been suggested that the peer reviewers provide a relative comparison of the uncertainty of the projects so that a consistent interpretation between studies is available. This may result in changes to the uncertainty reported in this Assessment Report, which would be documented in a subsequent amendment to the Assessment Report.

4.2 Intake Protection Zones

An *Intake Protection Zone* (*IPZ*) is delineated around an intake in a surface water body. In the Upper Thames River Source Protection Area there are no surface water intakes. Although many of the municipalities in the region rely on surface water, the intakes are located in other Source Protection Areas.

4.3 Wellhead Protection Areas

Wellhead Protection Areas or *WHPAs*, as they are often referred to, are the *vulnerable areas* which are delineated around groundwater sources of drinking water. Wells are used to extract the water from aquifers in the ground where water is contained in spaces, voids or fractures in the soil or rocks. Often many wells are used in an area to extract sufficient water to supply the needs of the customers. Multiple wells in an area are often referred to as a wellfield.

A *WHPA* can be delineated through one of the methods identified in Rule 42:

- A computer based three-dimensional groundwater flow model;
- Two-dimensional analytical model;
- Uniform flow method; or
- Calculated fixed radius method.

In the Upper Thames River Source Protection Area, *WHPAs* have been delineated using computer based three-dimensional groundwater flow models as discussed in the Technical Studies section below. The models are used to calculate the time it takes for water to travel to the wells through the aquifer. For each well or wellfield, three areas are delineated based on the time of travel, while one is a fixed radius around the wells.

WHPA-A – 100 m fixed radius around each well
WHPA-B – 2 year time of travel to the well, excluding the area of WHPA-A
WHPA-C – 2 to 5 year time of travel to the well
WHPA-D – 5 to 25 year time of travel to the well

Two other *WHPAs (E* and *F)* can be delineated for wells which are under the direct influence of surface water (*Groundwater Under the Direct Influence* or *GUDI*). These are further described in Section 4.3.4.

4.3.1 Technical Studies

The models used to delineate the time of travel based zones were originally developed through the county groundwater studies. The models for the systems in the Upper Thames River Source Protection Area were developed in the Middlesex-Elgin Groundwater Study, Final Report, July 2004; Perth County Groundwater Study, Final Report April, 2003; Phase II Groundwater Protection Study County of Oxford, March, 2001. Through *MOE* technical studies the models were updated and refined by Dillon Consulting Limited as part of a project led by the City of London, Golder Associates Limited led by the County of Oxford and Schlumberger Water Services (Perth County) led by the Upper Thames River Conservation Authority and Lotowater Technical Services Incorporated led by Thames Centre. Two *GUDI* system studies each were led by the County of Oxford and the St. Clair Region Conservation Authority (SCRCA). Dillon Consulting Limited carried out the work for these two studies. The third *GUDI* study was conducted by the Upper Thames River Conservation Authority. The final draft vulnerability reports are listed in Table 4-1 below.

Table 4-1 Summary of Technical Reports for UTR Municipal Systems

Report Reference	Consultant	Date	UTR Groundwater Intake Municipal Systems
London, Middlesex Centre & Thames Centre Wellfield Source Protection Study Vulnerability Assessment Report	Dillon Consulting Limited	October 2009	Birr, London Back up wells (Fanshawe and Hyde Park), Melrose
London, Middlesex Centre & Thames Centre Wellfield Source Protection Study Vulnerability Assessment Report: Thorndale and Dorchester	Dillon Consulting Limited	March 2010	Dorchester and Thorndale
Source Protection Technical Studies - Report on the Groundwater Vulnerability Assessment for the Wellhead Protection Areas in the County of Oxford	County of Oxford	April 2011	Beachville, Embro, Hickson, Ingersoll, Innerkip, Lakeside, Mount Elgin, Tavistock, Thamesford and Woodstock
Vulnerability Assessment - Perth County Municipal Drinking Water Systems	Schlumberger Water Services	March 2010	Mitchell, Sebringville, Shakespeare, St. Pauls, St. Marys and Stratford
Town of St. Marys Wellhead Protection Area Modelling: Draft Calibration and WHPA Delineation Technical Memorandum	Schlumberger Water Services	July 2010	St. Marys
St. Marys Well 1 WHPA E Delineation Draft	Upper Thames River Conservation Authority	April 2011	St. Marys (*GUDI* study)
WHPA-E Delineation and Vulnerability Assessment – Thamesford, Woodstock and Tillsonburg Municipal Water Supplies.	Dillon Consulting Limited	May 2011	Thamesford and Woodstock (*GUDI* study)
WHPA-E and F Delineation and Vulnerability Assessment – Dorchester, Fanshawe and St. Marys Municipal Water Supplies.	Dillon Consulting Limited	May 2011	Dorchester, Fanshawe and St. Marys (*GUDI* study)

Through the peer review of the Perth study (SWS, 2010) it was identified that the uncertainty associated with the St. Marys WHPA was too great to rely on for Source Protection Planning. A single layer model, originally developed by International Water Consultants in 2002, had been used in the subsequent studies for delineation of time of travel based capture zones. The SWS work utilized the same model; however the pumping rates were altered. Although this model was conservative, there was a concern that it may be overly conservative. The Town and the

Source Protection Committee agreed that it was necessary to improve the understanding of the hydrogeology of the area. As a result, Schlumberger Water Services (SWS) was retained by the town to refine the conceptual understanding and develop a numerical model which could be used to delineate the WHPAs for the St. Marys system (Town of St. Marys Wellhead Protection Area Modelling- Conceptual Model Report, SWS, May, 2010). Schlumberger compiled groundwater investigation reports and data from the area, and consulted with other researchers who were working in the area. This information was used to develop a conceptual model which was peer reviewed prior to the completion of computer modelling. Results from the model were discussed with the peer reviewers and scenarios were developed to explore the uncertainties in the delineation of the WHPA. The scenarios were assessed to ensure that they were equally likely through the use of the calibration statistics. Due to the uncertainty associated with this fractured rock aquifer, these scenarios were included in the delineation of the WHPA. Those scenarios which resulted in a significantly poorer calibration were not included in the WHPA delineation. This results in the reasonably conservative WHPA shown in Map 4-1-21. The consultants, peer reviewers, project team, and Source Protection Committee are satisfied that this WHPA is adequate for the purposes of Source Protection Planning.

The Thames Centre systems in Dorchester and Thorndale also were the subject of additional study. Since the Thorndale modelling was completed in the original Middlesex-Elgin Groundwater Study completed by Dillon and Golder Associates, 2004 report, the municipality has progressed with providing municipal water to the rest of the village and an additional subdivision is currently under development. This has significantly increased the future pumping rates used for the previous modelling. The March 2010 report noted above includes the results from re-running the model based on new forecasts for future water needs. Dorchester was also the subject of refined estimates of future water use as well as modelling refinements through an external peer review undertaken (Frind and Associates, 2008).

Planned wells in existing systems in Woodstock and Mount Elgin were considered through updated modelling undertaken by Golder Associates (April 2011) following well tests undertaken on these planned wells. Previous models were updated to include the additional well and appropriate changes to planned pumping rates.

4.3.2 WHPA-A

WHPA-A is a fixed 100 metre radius around the well(s) and is not a function of modelling. Locations of the wells were confirmed with the municipality and compared against orthographic imagery. A circle with a 100 m radius was delineated around the well using Geographic Information System (GIS) tools. This zone is shown with the other parts of the *WHPAs* in Maps 4-1-1 to 4-1-23.

4.3.3 WHPA-B, WHPA-C and WHPA-D

The *WHPAs* in the Upper Thames River Source Protection Area were delineated with computer models as discussed earlier in the technical studies section. This work involved the development of a conceptual groundwater flow model based on current understanding of the local groundwater flow conditions and the aquifer properties. The aquifer locations and extents are conceptualized at this stage. A computer model was then developed based on the conceptual understanding. United States Geologic Survey (*USGS*) *MODFLOW* numerical groundwater flow model was developed through previous studies (Middlesex-Elgin Groundwater Study (2004), Perth County Groundwater Study (2003), and the Phase II Groundwater Protection Study, County of Oxford (2001)). Additional refinement of the modelling has been completed on many of the systems since these investigations were completed. Any new or proposed wells within the existing systems were added to those models. The models were calibrated and *MODPATH* was used to simulate particle movement in the capture zones. These results were used to determine the extent of the travel time based *WHPA*. This estimates the horizontal travel time (within the aquifer) to the well. The model is run in reverse to determine where particles arriving at the well within the specified travel time could have originated.

The *WHPAs* in the Upper Thames River Source Protection Area are illustrated in Maps 4-1-1 to 4-1-23.

4.3.4 WHPA-E and WHPA-F

Two other *WHPAs (E* and *F)* can be delineated for wells which are under the direct influence of surface water (*Groundwater Under the Direct Influence* or *GUDI*). There are *GUDI* wells in Dorchester, London Fanshawe back up wellfield; Thamesford; Woodstock; and St. Marys. Systems were previously assessed through requirements of the Safe Drinking Water Act, 2002 (subsection 2(2) of O. Reg. 170/03) to determine if they are *GUDI*. Operators of systems that are designated as *GUDI* are required to determine if there are surface water bodies or water courses which can deliver surface water to the well, effectively short circuiting the natural protection assessed in the vulnerability assessment. Should a surface water system influence effectively bypass the aquifer's protection, a *WHPA-E* must be delineated. Rule 49(3) states that a *WHPA-E* is to be defined if the interaction between surface water and groundwater has the effect of decreasing the time of travel of water to the well when compared to the time it would take water to travel to the well if the raw water supply for the well was not under the direct influence of surface water.

Rule 50 (1), (2) and (3) require that *WHPA-F* be delineated if a *WHPA-E* is delineated, and the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside the other parts of the *WHPA*. *Issues* are discussed in Section 5 – Issues Evaluation.

The work on *GUDI* systems has been undertaken in the Thames-Sydenham and Region Source Protection Region. The systems outlined in Table 4-2 are included in this project. Additional work is planned for the First Nations *GUDI* system in the Lower Thames Valley SPA.

Table 4-2 Thames-Sydenham and Region GUDI wells

GUDI wells in the Upper Thames River Source Protection Area (UTRSPA)	
London and Middlesex systems	Dorchester (overburden wells 2PW-1, 3PW-1, 3PW-2B, 3PW-4A, 3PW7 and 3PW-8)
	London back up well supply Fanshawe (Fanshawe wells 1, 2, 3, 4, 5 and 6)
Oxford systems	Thamesford Wells 1 and 2 (often referred to as overburden wells or River Wells)
	Woodstock (Wells 1, 2, 3, 4, 5, 8 - Thornton and Tabor wellfields)
Town of St. Marys system	St. Marys (Wells 1 and 3)

The *WHPA-E* represents the extent of influence of a surface water feature on the affected well. According to Technical Rule 47 (5), the *WHPA-E* is delineated as an *Intake Protection Zone-2* (*IPZ-2*) as if the intake was located at the point where surface water would flow into the groundwater (i.e. the point of interaction). In the event that the point of interaction is not known, the closest point in the surface water body to the well is used.

A general description of the *WHPA-E* delineation methodology in the Upper Thames River SPA is provided below, followed by system specific information. Vulnerability scoring for *GUDI* systems is described in Section 4.3.5.

As per Rules 65 and 66, *WHPA-E* is the area within each surface water body that contributes water to the intake based on a surface water travel time of at least two hours, and a certain setback where it abuts land. The distance that *WHPA-E* extends upstream from the point of groundwater and surface water interaction depends on the time it takes for the drinking water treatment plant operators to respond to an adverse condition or emergency (such as a spill). The Technical Rule 66 requires that a minimum of two hours be used as the response time. Discussions with the *GUDI* system operators determined that a longer time was not required. As such, a 2 hour travel time was used to delineate *WHPA-E*. The travel time was estimated using stream velocity at bank full stage. It is widely accepted that bank full stage can be approximated by a 2 year return flow, but can vary dependent upon the nature of the watercourse from less than the two year flow, to as high as the five year flow.

Where the delineation abutted land, as per Rule 65 (1) for *IPZ-2* delineation, it was delineated to a setback of 120 meters (measured to the high water mark of the surface water body) or the Conservation Authority Regulatory Limit (for floodplains), or the greater of the two. Further, the *WHPA-E* was extended to include areas that contribute water to *WHPA-E* through a natural or anthropogenic pathway, as per Rules 72 and 73. Transport pathways are typically any structure, land alteration or condition resulting from naturally occurring process or human activity which would increase the probability of a contaminant reaching a drinking water source. Transport Pathways include tile drainage and other drainage works. Parcels immediately adjacent to watercourse buffers and regulated areas have been considered in the *WHPA-E* delineation, and not included in the WHPA-E unless they are believed to be connected due to transport pathways (tile drainage). These parcels have been trimmed to the subwatershed boundary outside of which water is assumed to be directed away from the intake. Also, storm sewersheds which outlet into the *WHPA-E* were included within the *WHPA-E* (within the 2 hour travel time to the intake), as per Rule 65 (2). This is due to their direct connection to a watercourse by storm sewers. The storm sewershed is the catchment area drained by the storm sewer.

The delineation and the assigning of vulnerability scores are influenced by the type of intake. Type C intakes are located in rivers and neither the direction nor the flow of water at the intake is affected by a water impoundment structure. Type D is an intake not already defined by the other Types, for example, an inland lake. In the Thames-Sydenham and Region the *GUDI* wells are considered Type C or D intakes as per the Technical Rules.

According to Rule 47 (6), the *WHPA-F* is delineated as an *Intake Protection Zone-3* (*IPZ-3*), as if the intake were located at the nearest point to the well in the surface water body. As per Rule 70, the *IPZ-3* is composed of the area within each surface water body that may contribute water to the intake, and a setback on land. This setback is 120 meters (measured to the high water mark of the surface water body) or the Conservation Authority Regulatory Limit (for floodplains), or the greater of the two. As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside the other parts of the *WHPA*.

A description of the delineation methodology specific to each *GUDI* system in the Upper Thames River SPA is provided below. Vulnerability scoring for *GUDI* systems is described in Section 4.3.5.

Dorchester *WHPA-E*

The Dorchester system, operated by the Municipality of Thames Centre, consists of nine wells of which six are *GUDI* (wells 2PW-1, 3PW-1, 3PW-2B, 3PW-4A, 3PW7 and 3PW-8). The wells are located in Dorchester, east of Dorchester Road and south of Byron Avenue. Several surface water bodies are present in the area and include Big Swamp Drain, Tap Municipal Drain and Lawton Drain. They combine and discharge into the South Thames River via an outlet from the Dorchester Mill Pond. The Dorchester Swamp, which discharges into these drains, is a predominant feature in the wellhead protection areas.

Intake Type

The delineation of *WHPA-E*, conducted by Dillon Consulting Limited, is based on the locations of the nearest surface water body to the wells, and an intake Type C (located in a river and neither the direction nor the flow of water at the intake is affected by a water impoundment structure). Based on available information, the Dorchester wells were projected to the Big Swamp Drain. These well projections were used as the 'surrogate' intake locations for the *WHPA-E* delineation.

Extent up Surface Water Bodies

In order to delineate the area within the Big Swamp Drain and its tributaries that may contribute water to the well's closest in-stream point within a 2 hour travel time, hydrologic and hydraulic analyses as well as a field trip were conducted. There was no model available for the Big Swamp Drain to simulate hydrologic and hydraulic analyses. Therefore, for the hydrologic analysis, empirical equations combined with a field visit were used to estimate the required 2-year flow. The Moin Index Flood Method (IFM) and the Primary Multiple Regression Method (PMRM) were used to calculate bankfull 2 year flow in the Big Swamp Drain and its tributaries (Lawton Drain, Tributary 'A' and Tap Drain). The more conservative flow (i.e. the larger flow) between IFM and PMRM methods was used for velocity, and eventually travel time analysis. For the hydraulic analysis, instream velocities were estimated by using Manning's Equation combined with the GIS data and field observations. Further, a field survey of the Big Swamp Drain and its tributaries was conducted in March 2011 by the consultant. For each cross-section of interest, the physical condition was noted and the bank and channel geometry was estimated, where possible.

Setbacks on Land, Storm Sewersheds and Transport Pathways

Where the delineation abutted land, it was truncated to the greater of either the setback of 120 meters (measured to the high water mark of the Big Swamp Drain) or the Conservation Authority Regulatory Limit. Further, the tile drainages, channels and ditches were examined for transport pathways. Tile drains and roadside ditches that can contribute water to *WHPA-E* within a 2 hour travel time were examined and included into the *WHPA-E* delineation where applicable. The available tile drain GIS layer did not include the outlets of the tiles, therefore an assumption was made that the tiles drain in the same direction as the general slope of the land. Tiles that touch the 120 m buffer or the Regulation Limits and located within 2 hour travel time from the intake were included in the *WHPA-E* delineation. A stormwatershed east of Oakwood Dr. is located very close to the Big Swamp Drain. However, based on the Dorchester stormwatershed map its outfall is downstream of the well projection, i.e. flows away from the 'surrogate' intake. Based on available information, no stormwatersheds were included in the delineation as transport pathways.

Final WHPA-E Delineation

The final delineation considers the local watershed boundaries, such that only areas that can contribute overland flow to the well are included in the delineation. The Dorchester *WHPA-E* is shown in **Map 4-1-2a**. Vulnerability Scoring is described in Section 4.3.5.

WHPA-F

As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside *WHPA-A to E*. No *issues* were identified for the Dorchester well supply system. Therefore a *WHPA-F* was not required to be delineated.

Fanshawe *WHPA-E*

The Fanshawe wells are part of the City of London's back up wells. There are six wells that draw water from an unconfined sand aquifer. All six wells are classified as *GUDI*. Five of these wells are located within the boundaries of the Fanshawe Golf Course and one pumping well is located just west of Clarke Road. No drains or creeks flow through the wellfield capture zone. However, several ponds and small ditches are present within the previously delineated *WHPA*. These ponds appear to have a limited catchment area, and are essentially surface exposures of the water table.

Intake Type

The delineation of *WHPA-E*, conducted by Dillon Consulting Limited, is based on the locations of the nearest surface water body to the wells, and an intake Type D (inland lakes). Based on available information, the Fanshawe wells were projected to nearby water bodies. These well projections were used as the 'surrogate' intake locations for the *WHPA-E* delineation.

Extent up Surface Water Bodies

During a field survey, several additional ponds and wetland areas, beyond those identified in the MNR watercourse mapping, were observed around the well houses. In particular, small ponds were observed west of Well 5 and Well 6. All of these features are considered to be points of interaction or transport pathways between surface water and the well. There are no streams which contribute to the ponds and therefore no travel time analysis is required. The well operator indicated that from time to time pumps must be turned on to eliminate standing water around the pump houses.

Setbacks on Land, Storm Sewersheds and Transport Pathways

The Fanshawe *WHPA-E* delineation includes a setback of 120 m along the abutted land measured from the high mark of the Fanshawe ponds and the area that contributes water to *WHPA-E* through transport pathways. A 120 m setback from the surface water features located in *WHPA-A* and *WHPA-B* (which are considered the zone of interaction) constitute the final *WHPA-E*. It should be noted that local watershed boundaries (quarry limits on west and east side) take priority over the extent of 120 m buffer, and therefore, *WHPA-E* was clipped on the west and east side.

Transport pathways which were observed in the zone of interaction were also included into *WHPA-E*. These are the wetland areas within the study area. Based on available information, no other transport pathways such as drainages, channels and ditches, or stormwatersheds were included in the delineation.

Final WHPA-E Delineation

The final delineation considers the local watershed boundaries, such that only areas that can contribute overland flow to the well are included in the delineation. The Fanshawe *WHPA-E* is shown in **Map 4-1-4a**. Vulnerability Scoring is described in Section 4.3.5.

WHPA-F

As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside *WHPA-A* to *E*.

Based on the issues evaluation conducted (see Section 5), organic nitrogen was identified as a water quality *issue*, which may be due to anthropogenic causes, at the Fanshawe wells. However, organic nitrogen likely originates from the area immediately attached to the well field (i.e. within *WHPA-A* through *E*). Therefore no *WHPA-F* delineation is required.

St. Marys *WHPA-E*

The Town of St. Marys wells consist of three pumping wells, two of which (Well 1 and Well 3) are identified as *GUDI*. Several surface water features including Skinner, Sheldon, Rolston and Waghorn Drains, Trout Creek, Otter Creek and the Thames River cross the St. Marys *WHPAs*.

Intake Type

The intake type is based on the location of the nearest surface water body to the wells. Well 1 is adjacent to Trout Creek and Well 3 is adjacent to the North Thames River. As such an intake Type C (located in a river and neither the direction nor the flow of water at the intake is affected by a water impoundment structure) was used to determine the appropriate rules to apply to the delineation of *WHPA-E* for both wells.

The delineation of that portion of the *WHPA-E* related to the St. Marys Well 1 was completed by the Upper Thames River Conservation Authority (with input from Schlumberger Water Services (SWS)), while the delineation of that portion of the *WHPA-E* related to Well 3 was completed by Dillon Consulting Limited in a separate study. Both studies included work on the *WHPA-E* extent up surface water bodies, setbacks on land, transport pathways and storm sewersheds. The final delineation of *WHPA-E* for the St. Marys *GUDI* wells incorporates the delineations from both studies.

St. Marys Well 3 was projected to the nearest water body, the North Thames River. This point was used as the surrogate for an intake and the *WHPA-E* was delineated from this point. Well 1 was the subject of previous investigations to determine the location of surface water interaction. In the past, the river reach within the general vicinity of the well was the subject of investigation and exploration to locate a point of interaction without success. These well projections which were used to determine the surrogate intake location would have been in the area where the past investigation did not identify a pathway or other interaction point. As such additional work was undertaken by SWS to identify the area within which it is likely that the interaction could occur. This area of potential interaction was used to delineate the *WHPA-E*.

Extent up Surface Water Bodies

The area within the surface water bodies and their tributaries that may contribute water to the surrogate intake was based on a 2 hour time of travel.

a) Delineation of the WHPA-E extent up Trout Creek and its tributaries

The interaction of the surface and groundwater in the St. Marys Well 1 has been the subject of much investigation in the past. This previous exploration focused on trying to locate a potential transport pathway in or near the watercourse in the vicinity of the well. The cause of this interaction or the location at which the interaction occurs could not be determined.

According to the Technical Rules, in the event that the point of interaction is not known, the closest point in the water body to the well is to be used. This would establish the point within the area of the previous investigation. In 2007, Schlumberger Water Services (SWS) conducted a study to determine the area within which it is likely for the point of interaction to occur. This area was called the zone of potential groundwater/surface water interaction. It was determined by comparing surface water elevation levels and groundwater hydraulic heads. If the water elevation in the stream was higher than the hydraulic head in the groundwater at the interface, then it was concluded that water moved from the stream into the groundwater. Stream elevation and bedrock groundwater equipotential maps were examined. Based on review of the available data, a reach along Trout Creek was identified to likely contribute surface water to the groundwater system, and then subsequently to Well 1. Therefore the zone of interaction included Trout Creek and overbank areas a few kilometers upstream of Well 1, and a few hundred meters downstream of this well. In other words, the upper end of the zone of interaction occurs approximately where 14 Line crosses Trout Creek, and the lower end occurs approximately where Church Street North crosses Trout Creek. The SWS study showed that the interaction could be significantly more removed from the well than the nearest point to the well in the water body. As a result it was determined that the *WHPA-E* should be delineated upstream from the zone of potential groundwater/surface water interaction and include the zone of potential interaction. This provided a conservative, but reasonable start for the travel time determination.

The UTRCA conducted the remaining work to delineate the Well 1 *WHPA-E* portion. A 2 hour time of travel up Trout Creek was estimated using Wildwood Dam discharge and stream guage data, as well as HEC-RAS model output. The Wildwood Dam discharges to Trout Creek upstream of the upper end of the zone of interaction (near 14 Line), and upstream of the St. Marys Well 1. There is a stream gauge on Trout Creek at the upper end of the zone of potential interaction near 14 Line, and another stream guage downstream of the confluence of Trout Creek and the North Thames River (but upstream of the Well 3). By examining flows at these two guage stations after Wildwood Dam operations, it was concluded that discharges from the dam occur well within the 2 hour time of travel from the zone of interaction. While this analysis was not performed for bankfull conditions, the discharge volumes are high enough that it is reasonable to arrive at the same conclusion if 2 year flow bankfull conditions were considered. Similarly, by examining the velocities produced by the HEC-RAS model of Trout Creek between Wildwood Dam and the confluence with the North Thames River, it was found that the 2 hour travel time for a 2 year flow from the outlet of the dam is well into the zone of potential interaction. The residence time of Wildwood reservoir is much greater than 2 hours, being in the order of days. Thus any potential contamination occurring upstream of the dam could not make it to the zone of interaction within the prescribed 2 hour limit. It was therefore concluded that the entire length of Trout Creek downstream of Wildwood Dam be included in the *WHPA-E* of St. Marys Well 1.

A 2 hour time of travel up the smaller tributaries that feed Trout Creek was estimated using Manning’s equation. This equation was used to calculate velocities and therefore travel times based on the lengths of the tributaries. Cross sections and channel slope are taken from Ontario Base Mapping, and the depth of water in the channel is assumed to be equal to the bank elevation of the most upstream cross section for bankfull flow, based on observed local conditions. Cross sections are assumed to be trapezoidal, with stream widths estimated from aerial photography. Stretches of Birches Creek and Ralston Drain, as well as stretches up tributaries to Birches Creek were included in the delineation. The stretches of Birch Creek tributaries beyond the 2 hour travel time were excluded. The travel time of an unnamed tributary which enters the Trout Creek from the north to the zone of potential interaction was estimated to be approximately half an hour. As the hydrology is quite similar in other areas of this subwatershed below Wildwood Dam, and because the travel distances for other tributaries to the zone of potential interaction are shorter, it was concluded that all additional tributaries, aside from the previously discussed Birches Creek and Ralston Drain, are within the 2 hour time of travel.

b) Delineation of the WHPA-E extent up North Thames River and its tributaries

In order to delineate the area within the surface water bodies and their tributaries that may contribute water to the respective well's closest in-stream point within the 2 hour time of travel, hydrologic and hydraulic analyses as well as a field trip were conducted. The hydrologic analysis helps to estimate a 2 year flow or, as it commonly referred to, bank full discharge. The 2 year flow in the North Thames River and flow change locations along the North Thames River were gathered from the HEC-RAS model calibrated and used by the Upper Thames River Conservation Authority (UTRCA) for flood plain mapping of the area. For small tributaries and for reaches where the existing model did not provide coverage, these empirical equations were used: Moin Index Flood Method (IFM) and the Primary Multiple Regression Method (PMRM) to determine the 2 year flow. The more conservative flow (i.e. the larger flow) between IFM and PMRM methods was used for velocity, and eventually travel time analysis. For the hydraulic analysis of the North Thames River, the HEC-RAS model was used to estimate flow velocities. For the hydraulic analysis of the smaller tributaries, instream velocities were estimated by using Manning's Equation combined with the GIS data and field observations. A tributary field survey was conducted in March 2011 by the consultant. For each cross-section of interest, the physical condition was noted and the bank and channel geometry was estimated, where possible. The 2 year flow velocities were calculated for Otter Creek, Flat Creek, Tributary A, Avon River and Tributary B.

Setbacks on Land, Storm Sewersheds and Transport Pathways

Similar methodologies were used in both studies to determine setbacks on land and extensions to include transport pathways and storm sewersheds. Where the delineation abutted land, it was truncated to the greater of either the setback of 120 meters (measured to the high water mark of the North Thames River, Trout Creek and their tributaries) or the Conservation Authority Regulatory Limit. A number of stormwater outfalls are located in close proximity to the St. Marys wells, and several outlet to Trout Creek within the zone of potential interaction for Well 1. Travel velocities within urbanized areas with sewersheds can be relatively high due to surface grading and storm sewer conveyance. Based on the analysis of available data, all St. Marys stormwatersheds with outfalls upstream of the Well 3, and both upstream and downstream of Well 1 on Trout Creek were included in *WHPA-E*. This results in an overlap of areas around the confluence of the North Thames River and Trout Creek.

Further, tile drainage, channels and ditches were examined for transport pathways. Tile drains and roadside ditches that can contribute water to *WHPA-E* within a 2 hour travel time were examined and included into the *WHPA-E* delineation where applicable. The available tile drain GIS layer did not include the outlets of the tiles, therefore an assumption was made that the tiles drain in the same direction as the general slope of the land. Tiles that touch the 120 m buffer or the Regulation Limits and located within 2 hour travel time from the intake were included in the *WHPA-E* delineation.

While valley slopes and flood plain areas drain directly to the watercourses, wetlands should be screened to determine if they are connected either by natural or anthropogenic transport pathways. There are 2 such wetland areas within the study area. One is at the headwaters of both a watercourse which drains south to Trout creek, and a second watercourse which drains to Wildwood Reservoir. The area draining to Wildwood Reservoir is beyond the area which could flow to the zone of interaction within the 2 hour operator response time. Therefore the part of this wetland area draining to Wildwood Reservoir has been trimmed from the area to be included in *WHPA-E* using catchment areas available with the watercourse information. The other area is between Birches Creek and a tributary north of Birches Creek. Review of the tile drainage information indicates that part of this area is tile drained. The entire area is included in the *WHPA-E*.

Final WHPA-E Delineation

The final delineation considers the local watershed boundaries, such that only areas that can contribute overland flow to the well are included in the delineation. The St. Marys *WHPA-E* is shown in **Map 4-1-21a**. Vulnerability Scoring is described in Section 4.3.5.

WHPA-F

As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside *WHPA-A to E*. No *issues* were identified for the St. Marys well supply system. Therefore a *WHPA-F* was not required to be delineated.

Thamesford *WHPA-E*

The Thamesford well supply system is comprised of 3 wells located near County Road No. 19, north and south of the Canadian Pacific Railway alignment. Two of the wells, Well 1 and Well 2 are classified as *GUDI* wells. Both wells pump water from an alluvial sand and gravel unconfined aquifer. Below the alluvial aquifer are silty tills, which overlay the bedrock limestone aquifer. Both wells are located near the Middle Thames River, with Well 1 and 2 being 20 m and 40 m south of the river, respectively. In addition to the river, there is a small tributary that flows into the Middle Thames River, and is within 70 m of the wells. Based on the close proximity of these wells to the river and their *GUDI* status, a *WHPA-E* is required.

Intake Type

The delineation of *WHPA-E*, conducted by Dillon Consulting Limited, is based on the locations of the nearest surface water body to the wells, and an intake Type C (located in a river and neither the direction nor the flow of water at the intake is affected by a water impoundment structure). Based on available information, the Thamesford wells 1 and 2 were projected to the nearest shore of the Middle Thames River. These well projections were used as the 'surrogate' intake locations for the *WHPA-E* delineation. In addition, the small tributary located around 70 m away from the wells was also considered as potentially having a hydraulic connection to the wells based on its close proximity.

Extent up Surface Water Bodies

In order to delineate the area within the Middle Thames River and its tributaries that may contribute water to the well's closest in-stream point within a 2 hour travel time (based on a 2 year bankfull flow), hydrologic and hydraulic analyses as well as a field trip were conducted.The travel time analysis for the Middle Thames River was completed using the HEC-RAS model (hydraulic analysis). For small tributaries and for reaches of the Middle Thames River not covered through HEC-RAS modeling, the travel time analysis (2-year flow) for was conducted using empirical equations (hydrologic analysis) combined with a field visit. The Moin Index Flood Method (IFM) and the Primary Multiple Regression Method (PMRM) were used to calculate bankfull 2 year flow in the Middle Thames River tributaries of Daymun Drain, George Roberts Drain, Arthur Vanatter Drain, 12^{th} Concession Drain, Mcdonald Drain, Nissouri Creek and the watercourse just southwest of Wells 1 and 2. The more conservative flow (i.e. the larger flow) between IFM and PMRM methods was used for velocity, and eventually travel time analysis. For the hydraulic analysis, instream velocities were estimated by using Manning's Equation combined with the GIS data and field observations. Further, a field survey of the Middle Thames River and its tributaries was conducted in March 2011 by the consultant. For each cross-section of interest, the physical condition was noted and the bank and channel geometry was estimated, where possible.

Setbacks on Land, Storm Sewersheds and Transport Pathways

Where the delineation abutted land, it was truncated to the greater of either the setback of 120 meters (measured to the high water mark of the Middle Thames River) or the Conservation Authority Regulatory Limit. Further, the tile drainages, channels and ditches were examined for transport pathways. Tile drains and roadside ditches that can contribute water to *WHPA-E* within a 2 hour travel time were examined and included into the *WHPA-E* delineation where applicable. The available tile drain GIS layer did not include the outlets of the tiles, therefore an assumption was made that the tiles drain in the same direction as the general slope of the land. Tiles that touch the 120 m buffer or the Regulation Limits and located within 2 hour travel time from the intake were included in the *WHPA-E* delineation. Based on available information, no stormwatersheds were included in the delineation as transport pathways.

Final WHPA-E Delineation

The final delineation considers the local watershed boundaries, such that only areas that can contribute overland flow to the well are included in the delineation. The Thamesford *WHPA-E* is shown in **Map 4-1-16a**. Vulnerability Scoring is described in Section 4.3.5.

WHPA-F

As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside *WHPA-A to E*. The only *issue* identified for the Thamesford well supply system (manganese) is naturally occurring (see Section 5). No other *issues* were identified for this system. Therefore a *WHPA-F* was not required to be delineated.

Woodstock *WHPA-E*

The water supply for Woodstock is predominantly supplied by the Thornton and Tabor rural wellfields, which are located east and southeast of the community of Sweaburg. Wells 1, 3, 5 and 8 of the Thornton wellfield and Wells 2 and 4 of the Tabor wellfield have been designated as *GUDI* wells. Nitrate has been identified as an anthropogenic raw water quality issue for both the Thornton and Tabor systems.

The Thornton Wells 1, 3, 5 and 8 draw water from a sand and gravel unconfined aquifer. The pumping test conducted during the *GUDI* study identified a strong hydraulic connection between the aquifer and the local wetland. During periods of pumping, the water table fell below the ground surface resulting in a predominant downward movement of groundwater flow. When the pumping of the well field was stopped, springs and localized ponding occurred, as the groundwater levels rose above the ground surface in some areas.

The Tabor Wells 2 and 4 also draw water from a sand and gravel unconfined aquifer. Water level data suggests a predominant downward movement of groundwater flow.

Intake Type

The delineation of *WHPA-E*, conducted by Dillon Consulting Limited, is based on the locations of the nearest surface water body to the wells, and the intake type. For the purpose of the *WHPA-E* delineation, the Thornton and Tabor *GUDI* wells are classified as a Type D (inland lakes) surface water intake. A Type D designation is deemed appropriate as both wellfields are near the Sweaburg Wetland.

Extent up Surface Water Bodies

The *WHPA-E* delineations are completed separately for the two wellfields of Thornton and Tabor.

The Thornton Wells 1, 3, 5 and 8 are located within 25 to 100 m of a wetland and other surface water bearing features such as creeks, ditches and ponds. Two waterbodies were identified as potential areas of groundwater-surface water interactions: a Cedar Creek tributary and the Sweaburg wetland. Through field investigations, previous reports and communications with various technical staff, a creek running between Wells 1 and 5, a ditch near Well 1, and a pond close to Well 3 were identified and included in the *WHPA-E* delineation. During the field visit, it was confirmed that there is no surface water flow from the adjacent wetlands (which is down slope of the wellfield) to the wells. Rather, surface water flow is away from the wells, towards the wetland. Based on this information, the Sweaburg wetland is not expected to decrease the time of travel for surface water to migrate to the well, and it was not included in the delineation.

For the Tabor Wells 2 and 4, two waterbodies were identified as potential areas of groundwater-surface water interactions: a ditch along Cedar Line that is part of a tributary fed by two ponds (located 0.5 to 1 km south of the wellfield), and a small creek near Well 2 that seems to be spring-fed. During a field survey conducted to investigate these waterbodies, the ditch (along the west of Cedar Line), ponds (south of Wells 2 and 4) and a small creek (near Well 2 that discharges to a ditch along River Road) were identified and included in the *WHPA-E* delineation.

Setbacks on Land, Storm Sewersheds and Transport Pathways

Where the delineation abutted land, the Thornton *WHPA-E* was truncated to a setback of 120 meters, measured to the high water mark of the creek, ditch and pond located near Thornton Well 3. The west side of Sweaburg Road is downstream of the wells and therefore *WHPA-E* was clipped to the east side of the road. This assumption is supported by observed direction of flow in the creek during the field visit.

Based on available information, no tile drained areas or stormwatersheds were included in the Thornton *WHPA-E* delineation as transport pathways.
Where the delineation abutted land, the Tabor *WHPA-E* was truncated to a setback of 120 meters, measured to the high water mark of the tributary, two ponds and the small creek. Cedar Line is a local watershed boundary, and therefore *WHPA-E* was clipped to the road on the west side. This assumption is supported by observed direction of flow in a culvert across Cedar Line, during the field visit.

Based on available information, no tile drained areas or stormwatersheds were included in the Tabor *WHPA-E* delineation as transport pathways.

Final WHPA-E Delineation

The final delineation considers the local watershed boundaries, such that only areas that can contribute overland flow to the well are included in the delineation. The Thornton and Tabor *WHPA-Es* are shown in **Map 4-1-17a**. Vulnerability Scoring is described in Section 4.3.5.

WHPA-F

As mentioned earlier, *WHPA-F* is only delineated if the well is subject to *issues* (known to be partially or wholly due to anthropogenic causes), which originate from outside *WHPA-A to E*. Elevated nitrate levels are identified as an *issue* for the Woodstock-rural well supply system (see Section 5). Information from the University of Waterloo suggests that the nitrate may have originated from surface runoff of adjacent farm fields, and infiltrated into the aquifer. Since the nitrate originates from areas within the *WHPA-A* to *E*, a *WHPA-F* was not required to be delineated.

4.3.5 Vulnerability Assessment of the WHPA

Within the *WHPA-A to D* zones, the vulnerability must be assessed using one of the four methods described in Rule 37 of the *Technical Rules: Assessment Report*:

- *Intrinsic susceptibility index* (*ISI*).
- Aquifer vulnerability index (*AVI*).
- Surface to aquifer advection time (*SAAT*).

- o *Surface to well advection time* (*SWAT*).

Rule 15.1 also allows the use of a method which is equivalent or better than these methods provided the reason for the use of this method is documented in the Assessment Report and the Director has provided approval for the use of the alternative method.

Three methods have been used to identify vulnerability in *WHPAs* in the UTRSPA. Intrinsic Susceptibility Index (*ISI*) was used for the vulnerability assessment in the municipal systems in Perth County and the City of London-Middlesex County. The County of Oxford used AVI methodology throughout most of the wells with the exception of SWAT that was used in Ingersoll and Woodstock systems.

The ISI and AVI methods are index methods based on the Ministry of the Environment's (*MOE*) Water Well Information System (*WWIS*) which contains borehole information collected at the time of the well construction. The MOE undertook a project to characterize the materials identified in this database so that a 'k' value can be assigned to each material identified in the well log. The 'k' value is then multiplied by the thickness of the material in metres and summed over the depth to the aquifer of interest or the water table. The main difference between the ISI approach and AVI method is that the ISI method takes into account the location of the water table. Therefore, in order to apply the ISI method the water table must be calculated, if this has not previously been done. In the AVI method, the scores are summed to the aquifer. The sum results in a score which is then categorized as high, medium or low as identified in Rule 38 (1). The *ISI and AVI* of the Study *Wellhead Protection Areas* are shown for Middlesex in Maps 4-1-1 through 4-1-7; Oxford 4-1-8 through 4-1-17; and Perth 4-1-18 through 4-1-23. The AVI of the Oxford Study Wellhead Protection Area is shown in Maps 4-1-8 through 4-1-10 and 4-1-12 through 4-1-16.

Professional judgement had a wider degree of variability throughout the various studies and is difficult to summarize in general. The actual studies should be reviewed for more clarification but examples of the rationale are included below. Rationale for decisions using professional judgement included the utilization of cross-sections throughout the wellfield to identify the production aquifer, calculating ISI / AVI scores to the production aquifer, hand contouring to allow interpretation of the hydrogeology and to exclude outliers rather than utilizing computer algorithms. For the uncertainty, a low uncertainty was sometimes assigned to areas, where the underlying ISI / AVI value was clearly within the class boundaries and a high uncertainty, where the ISI / AVI value was close to the class limit. For example, if a vulnerability value is based on a value of 150, it is very unlikely that changing the input parameters for the calculated value would result in an ISI of lower than 80, thus changing the vulnerability class. In areas where the ISI / AVI appeared to be a function of a computer algorithm or poor well log, professional judgement was used either to include or exclude a data point. In general, a conservative approach was incorporated during this review.

As part of an MOE pilot project, the County of Oxford was selected to receive funding to complete a Surface to Well Advection Time (*SWAT)* study to compare to previously completed vulnerability studies (AVI method) and further assess and delineate existing vulnerability in WHPA areas. WHPA *SWAT* is the time it takes for a particle of groundwater to move from the ground's surface to the well. The *SWAT* is comprised of two major components: (1) the time it takes for a particle to move from the ground's surface to the water table in the unsaturated zone (UZAT), and (2) the time it takes for a particle of water to move from the intersection of the water table to the well (WWAT). Two sites were selected for the pilot study to provide contrasting hydrogeological settings including an unconfined sand and gravel aquifer in Woodstock and a multi-aquifer bedrock supply well in Ingersoll. At Ingersoll and Woodstock, the *SWAT* methodology was used to assess the vulnerability of the municipal groundwater wells. A grid of particles to be released at the water table was established. Particles were spaced evenly apart in the area around each well. The travel time of each particle to move from its original position to the water table was then calculated, in order to determine WWAT. *WWIS* data was used for static water levels. UZAT is calculated by considering the depth to the water table, the moisture content and the infiltration rate.

Like the *ISI* and *AVI*, the *SWAT* is also categorized into high, medium, or low vulnerability. Travel time is represented in years and is mapped as: less than 5 years (high), 5 to 25 years (medium), or greater than 25 years (low). A *SWAT* of greater than 25 years represents a low intrinsic vulnerability. The vulnerability is illustrated for each system in the vulnerability maps in Appendix 1. The systems which were assessed using SWAT are illustrated in Maps 4-1-11 and 4-1-17.

Professional judgement is an accepted practice in the process and its documentation varied to some degree between studies. In some cases, systems were applied a low uncertainty because they were felt to be modelled using a consistent and well documented modelling procedure, based on sound hydrogeological interpretations and were considered as having a relatively low level of uncertainty. In many cases, professional judgement was evaluated on individual parameters - the reliability of the numerical model, for example input parameters such as the presence of data gaps, interpreted groundwater flow direction and on the WHPA size. Furthermore, the reliability of the model was judged on the presence of data gaps and on the calibration results. Some evaluations on WHPA uncertainty were based on the size of the WHPA. The rationale for larger size of WHPA is generally associated with a lower uncertainty, since even significant changes of the hydrogeologic parameters, such as conductivity or recharge, result in a relatively small percentage change of the size and shape of the respective WHPAs. The same input parameter changes applied to a small WHPA could however, change size and direction of the WHPA considerably. A high uncertainty therefore, was more associated with smaller WHPAs. For the London-Middlesex systems, there is considerable uncertainty in the recharge and hydraulic conductivity values used. For the Perth systems, all capture zones in fractured bedrock are considered to have high uncertainty. At Stratford, the uppermost bedrock zone is fractured and assigned a higher conductivity than the fresh bedrock below it. At St. Marys fractured bedrock layers were modelled with higher conductivity values. There is a higher uncertainty associated with hydraulic conductivity values and this uncertainty was considered in the WHPA delineation. Similary for the Oxford systems, uncertainty in bedrock fracture increased the uncertainty in hydraulic parameters. For the Oxford systems, in many cases the contact lines between areas of different vulnerability were irregular, and appeared to reflect the grid system and/or the interpolation algorithms associated with presenting the vulnerability information in a GIS system. Smoothing was done in an attempt to have the vulnerability contact lines reflect a more natural condition. For example, a 'saw-tooth' line contact was adjusted into a smooth line contact, similar to how the contacts are shown in geological and hydrogeological maps.

Adjustments to vulnerability to reflect transport pathways (*WHPA-A to D*)

Following the assessment of intrinsic vulnerability, information on constructed *transport pathways* is reviewed in order to examine whether an increase in the vulnerability score in the *WHPA-A to D* due to the presence of the *transport pathways* is needed. The discussion of transport pathways for *WHPA-E* (related to*GUDI* wells) are discussed separately in Section 4.3.4. *Transport pathways* are man-made constructions such as oil wells, pipelines or excavations that may circumvent the natural protective layers above a groundwater aquifer. While the Technical Rules 39-41 define the elements to be considered for increasing the vulnerability rating, they do not address the criteria that should be applied in order to increase the vulnerability. The Technical Rules do not clarify the area of influence of different types of transport pathways within which the vulnerability is to be increased. Some alternatives for considering transport pathways focus on the assumption that it is not the individual occurrence of a feature, but the increased density of the features in an area which affects the vulnerability. The vulnerability of the aquifer should only be increased in areas where the natural vulnerability is well understood and the potential characteristics of the transport pathways is such that an increase in aquifer vulnerability is likely to result due to a change from transport pathways. The methodology to reflect wells as transport pathways was applied slightly different in each of the studies and reflect the differences in the nature of the aquifers and the needs of the municipalities.

Modification of the groundwater vulnerability is performed by increasing the vulnerability of the underlying groundwater vulnerability map from either a low to moderate value, moderate to high value or low to high value. An initial groundwater vulnerability value of high cannot be increased. The Thames-Sydenham and Region SPC proposed a standardized methodology (Approach to Consideration of Transport Pathways in the Vulnerability Assessment of Groundwater Based Vulnerable Areas, May 2009) for the recommended changes to groundwater vulnerability. One recommendation was that changes should be applied where the system operator is concerned about activities being undertaken in areas which could pose a higher risk to the system than reflected by the vulnerability assigned to the area in which the activity is occurring.

Factors such as hydrogeological conditions, type and nature of *transport pathways*, and cumulative impact of these pathways are considered. Water wells can be *transport pathways* if they are not properly constructed or maintained. An inventory of *transport pathways* was completed by the consultant and reviewed with the system operators. Within a zone of vulnerability, transport pathways such as abandoned wells or quarries can eliminate partially or entirely the protective layers above the aquifers and form a direct conduit between the ground surface and the aquifer. Such features were felt to significantly increase the vulnerability of a localized zone, and this should be reflected in the vulnerability assessment of the area. Identifying the locations of wells in WHPAs, assessing their current state, and properly decommissioning abandoned or poorly constructed wells would help to reduce the risk that these potential conduits pose to the groundwater system. The process is based on professional judgement. The uncertainty due to fracture in bedrock is considered in the WHPA delineation.

London, Middlesex Centre & Thames Centre Wellfields

Many of the identified *transport pathways* in London, Middlesex Centre & Thames Centre Wellfield Source Protection Study Vulnerability Assessment Report were not considered significant, as these features are of shallow construction relative to the thickness (30 to 50 m) of the clay till aquitard that overlies the pumped aquifer, or there were few transport pathways documented or the area already had a high vulnerability and therefore could not be increased in vulnerability to reflect the *transport pathway*. *Transport pathways* in this study area that are deemed to penetrate into the aquifer include both potable water wells and oil and gas wells. The density of these wells appears to be low based on the available data, and therefore an increase in the vulnerability of the aquifer is not considered necessary. Potential areas that may warrant a vulnerability increase include former and current wellfields where the potential for yet to be discovered former wells exists.

For discussion purposes, systems with similar aquifers are summarized together with respect to transport pathways - bedrock (Thorndale), deeper overburden (Birr, London - Hyde Park back up wellfield and Melrose) and shallow overburden aquifers (Dorchester and London - Fanshawe back up wellfield).

Thorndale derives its drinking water from a bedrock aquifer. See Appendix 1 Map 4-1-7. The mapped extent of the area where *transport pathways* exist (which involved conservatively assigning a potential water well location at each developed property) is deemed conservative.

Furthermore, the degree to which any *transport pathway* has on reducing the natural protection of the overlying aquitard is difficult to assess, mainly due to limited information on the geology of the area.

The rationale for the decision to leave the vulnerability unchanged for Thorndale was that there is already uncertainty associated with the prediction of the capture zones, and that this uncertainty is greater than the effect that transport pathways would have on the vulnerability evaluation. In addition, the only transport pathway type that would potentially be considered to increase the vulnerability would be private wells as these are the only features that would penetrate into the bedrock aquifer below. Most of the properties that may potentially use private wells, or may have abandoned wells on their premises, are those along Fairview and Thorndale Roads. The density of these properties over the entire capture zone is not high, and therefore the risk of significantly increasing the vulnerability of the aquifer is deemed low. Nevertheless, sporadic occurrences of *E. coli* and Total Coliforms have been detected in the raw water. The source of the impacts is not known; however, a report by Lotowater (2009) suggests that it is possible that these parameters may be introduced into the aquifer from any nearby poorly constructed wells. No data are available that indicate that the nearby private wells act as transport pathways; however, future actions such as inspections or sampling could be performed to determine if the local wells are a source of the coliform impacts. The significance of the *E. coli* and Total Coliform concentrations in the raw water is addressed in the Issues Evaluation assessment. More recent discussions with the municipality suggest that the possible pathway may have been eliminated through well decommissioning in the area, however a longer period of monitoring is necessary before the results can be considered conclusive.

Birr, London-Hyde Park (back up wellfield) and Melrose derive their water from a deeper, confined, overburden aquifer. The decision was made to leave the vulnerability unchanged with respect to *transport pathways* for the above stated reasons and more specific rationale is included as follows. The decision to not modify the groundwater vulnerability based on the location of potential transport pathways both horizontal and vertical was confirmed through discussions with the municipality.

The community of **Birr** is supplied in part by one well that pumps from a confined overburden sand and gravel aquifer and was first developed in 1975. Eighteen lots along Gwendolyn Court are serviced by the municipal system**.** The remainder of the community is serviced by individual private wells. Several potential transport pathways were identified within the capture zones A to D. Areas where the likelihood of improperly abandoned wells is greatest are within *WHPA-A* which already received the highest vulnerability score. See Appendix 1 Map 4-1-1.

The community of **Kilworth-Komoka** was supplied by three wells that pump from a confined overburden sand and gravel aquifer. That well system was decommissioned in October 2010, and the community is now served by the Lake Huron Primary Water Supply System under the Middlesex Centre Distribution System.

The **London-Hyde Park (backup well)** was drilled to a depth of approximately 37 m. Clayey and bouldery till was encountered in the top 20.7 m, overlying 16.6 m of sand and gravel. See Appendix 1 Map 4-1-5. The groundwater vulnerability values were not modified to take into account transport pathways. The rationale for this decision was that there is already a large uncertainty associated with the prediction of the capture zones, and that this uncertainty is far greater than the effect that transport pathways would have on the vulnerability evaluation. In addition, considering that the system is used for emergency back-up purposes only, the need to adjust the vulnerability rankings was deemed unnecessary.

The community of **Melrose** is supplied by two wells that pump from a confined overburden sand aquifer. See Appendix 1 Map 4-1-6. The system services a residential subdivision of 64 lots, occupied by approximately 224 residences. While it is possible that abandoned wells may exist along Vanneck Road in Melrose**,** the portion of this area that falls within the most sensitive zones (*WHPA - A* and *WHPA - B*) already is classed as highly vulnerable, and the vulnerability value cannot be increased. Septic systems are present on all developed lots within the capture zones; however, the relatively shallow depth (<1 m) would be insufficient to cause an increase in the groundwater vulnerability.

Dorchester and London-Fanshawe (back up wellfield), have shallow overburden aquifers. The vulnerability of these aquifers within the WHPA-A to D is already considered high for both systems.

The **Dorchester** system obtains water from nine production wells that pump from both a shallow unconfined sand and gravel aquifer and a deeper confined bedrock aquifer. See Appendix 1 Map 4-1-2. The wells are located in two wellfields. Well Field 2 consists of one production well. Well Field 3 consists of five overburden production wells and two bedrock production wells. The overburden groundwater supply is classified as being *GUDI* (Groundwater Under the Direct Influence of Surface Water) while the bedrock groundwater supply is classified as "groundwater" (i.e., non- *GUDI*). Even though there are numerous transport pathways within the Dorchester WHPA-A to D, the intrinsic vulnerability of the aquifer within these WHPA is already high. Therefore, the aquifer vulnerability cannot be increased, and the final aquifer vulnerability remains the same as the results of the initial groundwater vulnerability assessment. The transport pathways related to *GUDI* wells are described in Section 4.3.4.

The City of London operates a back up wellfield referred to as **London - Fanshawe**, located just west of Fanshawe Lake. See Appendix 1 Map 4-1-4. This wellfield is used in case of supply interruptions from either the Lake Huron or the Elgin Area Primary Water Supply Systems. The wellfield consists of six high capacity wells, each capable of pumping at 3,200 L/minute from an unconfined overburden sand aquifer. Five of these wells are located within the boundaries of the Fanshawe Golf Course, and one pumping well is located just west of Clarke Road. The transport pathways related to *GUDI* wells are described in Section 4.3.4.

Oxford Wellfields

The County of Oxford systems are comprised of deep bedrock wells (Beachville, Embro, Hickson, Ingersoll, Innerkip, Lakeside, and Mount Elgin), a combination of overburden and bedrock systems (Tavistock - intermediate overburden and bedrock; Thamesford shallow overburden and bedrock; and Woodstock with bedrock and shallow overburden wells). The County evaluated transport pathways by plotting well locations (based originally on the MOE Water Well Information System), information on the location of sanitary sewers, septic systems, storm water infiltration facilities, pits and quarries and the location of oil wells, within 100 m of

WHPAs on maps and aerial photographs. The hydrogeologist retained for the study reviewed the maps and identified areas where the vulnerability scoring should be adjusted based on his professional judgement.

The **Beachville** water system is supplied by one bedrock production well with casing set to a depth of approximately 33 m and a total well depth of approximately 91 m. See Appendix 1 Map 4-1-8. The water system supplies a population of approximately 180. The Beachville well was incorporated into the Ingersoll Groundwater Model for the purpose of delineating the WHPA (Golder Associates 2001). Potential transport pathways are mostly limited to the relatively high density of private wells and septic systems located along County Road No. 9 (Beachville Road). The vulnerability was already high within this area, so adjustments to the vulnerability mapping/scoring to account for the transport pathways were not necessary.

The **Embro** water system is supplied by two bedrock wells located near the pump house in the central part of the village. The wells are cased to depths of approximately 38 m and completed as open hole in the bedrock to depths of approximately 60 m. See Appendix 1 Map 4-1-9. The water system supplies a population of approximately 830. The water well records at the Embro well site indicate that the overburden sequence above bedrock consists mostly of low hydraulic conductivity deposits (described as clay, hardpan and till). Other than septic systems, there is no evidence of significant transport pathways within the WHPA and no adjustments to the vulnerability index mapping were made.

The **Hickson** water system services the King subdivision on the east side of the village and is supplied by one bedrock well. See Appendix 1 Map 4-1-10. The water system supplies a population of approximately 100. The Phase II Groundwater Protection Study (2001) report indicates that the well is cased to a depth of 33.5 m and completed as open hole to a depth of 53 m. The review of transport pathways information indicates that there are approximately 12 wells located in the 2 year TOT zone; the 2 year TOT extends through the centre of the village where there are numerous septic systems. As a result, the AVI vulnerability mapping across Zone B was increased from low to moderate, resulting in an increase in the intrinsic vulnerability score from 6 to 8 in Zone B. Vulnerability scores are 4 in Zone C and 2 in Zone D.

The **Ingersoll** water system is supplied by 7 bedrock production wells (**Wells 2, 3, 5, 7, 8, 10, 11**) each at a different location. See Appendix 1 Map 4-1-11. Well 8 is located in the northeast part of the town on the north side of the Thames River. The other wells are located south of the Thames River. The wells are cased to depths ranging from approximately 21 m (Well 3) to 60 m (Well 2). The depth to the bottom of the wells ranges from approximately 109 m (Well 5) to 140 m (Well 2). The water system supplies a population of approximately 13,600. According to the Phase II Groundwater Protection Study (2001), the groundwater model used to delineate the Ingersoll WHPA is based on a four-layer conceptual model with one overburden layer and three bedrock layers. The overburden layer is characterized in accordance with the lower hydraulic conductivity till units that occur over most of the model area, with some higher conductivity areas to account for the presence of glacial outwash and modern fluvial sediments in the vicinity of the Thames River. The WHPA for six of the seven Ingersoll wells show some overlap/interaction with one or more of the others. Adjustments to groundwater vulnerability due to transport pathways is shown in Appendix 1 Map 4-1-11. Transport pathways were considered for each of the WHPA as follows:

- The Phase II study also notes that the capture zone for **Well 2** is affected by two private industrial wells in the vicinity. An adjustment from low to medium vulnerability category was made in the west central portion of the WHPA (north side of Victoria Road/Road 60) to account for private wells (potential transport pathways) serving a settlement in that area (WHPA-D). An adjustment from low to medium vulnerability category was also made to account for private wells on Clarke Road (vicinity of Whiting Street) in the south part of the WHPA (WHPA-D, where it overlaps with the WHPA for Well 10).
- No adjustments were made for **Well 3** for transport pathways.
- A number of private wells exist within the WHPA for **Well 5**, based on information available from the water well record database. However, the number and density of wells were not considered sufficient to warrant an adjustment to account for potential transport pathways.
- No adjustments were made to the mapping for **Well 7** to account for transport pathways.
- An adjustment was made to the vulnerability mapping within the **Well 8** WHPA to account for the concentration of private wells on North Town Line Road as potential transport pathways. The adjustment results in a change in vulnerability score in WHPA-

C from 2 to 6 (low to medium vulnerability category); and in WHPA-B the score has been adjusted from a 6 to an 8 (low to medium vulnerability category).

- The **Well 10** WHPA overlaps the portions of the WHPAs for Wells 2, 5 and 11. The adjustment in vulnerability category for potential transport pathways (private wells) on Clarke Road near Whiting Street (noted in the discussion above for Well 2) also applies to the WHPA for Well 10. The area affected by the adjustment for potential transport pathways includes portions of Well 10 WHPA-B, C and D, with a change of low to medium vulnerability in these zones. The resulting vulnerability scores for this area are 8 for the portion within WHPA-B, 6 for the portion within WHPA-C and 4 for the portion within WHPA-D. The remainder of WHPA-B and the other portions of WHPA-C and WHPA-D have vulnerability scores of 6.
- The WHPA for **Well 11** extends approximately 2.5 km to the southeast and is overlain in parts by the WHPAs for Well 3 and Well 10. No adjustments were made to the vulnerability mapping for transport pathways.

The **Innerkip** water system is supplied by two bedrock wells southwest of the village, on the east side of County Road 4. . See Appendix 1 Map 4-1-12. The water system supplies a population of approximately 950. Well 1 is cased to a depth of approximately 19 m with open hole in the bedrock to a depth of 34 metres. Well 2 is cased to a depth of approximately 16 m with open hole in the bedrock to a depth of 35 m. Potential transport pathways within the WHPAs appear to be limited to a few rural private wells and no adjustments to the mapping were made to account for these pathways.

The **Lakeside** water system is supplied by a bedrock well located on the east side of the community. See Appendix 1 Map 4-1-13. The water system supplies a population of approximately 310. The well is cased through a sequence of mainly fine-grained sediments to a depth of approximately 90 m, and completed as open hole in the bedrock to a depth of approximately 100 m. There appear to be few, if any, potential transport pathways in the WHPA.

The **Tavistock** water system is supplied by one overburden (Well 1) and two bedrock production wells (Well 2A, Well 3). See Appendix 1 Map 4-1-15. The water system supplies a population of approximately 2,660. The wells are located in close proximity to each other at a site near the water tower in the south-central part of the town. The overburden well is screened over a depth interval from approximately 16.5 – 19.5 m and is considered to be a completion in the intermediate aquifer. Well 2A is cased to a depth of 41 m and completed as an open well in bedrock to a depth of approximately 62 m. Well 3 is cased to a depth of approximately 35 m and completed as an open well in bedrock to a depth of approximately 48 m. Private wells occur within the WHPA, however, the number and location of the wells were not considered sufficient to warrant an adjustment to the vulnerability. The existing sewage lagoons were also not considered to be a transport pathway as it is understood that the lagoons are excavated no more than about 2 m below the surface, are lined with a clay barrier, and do not penetrate the confining till layer that overlies the intermediate overburden aquifer.

The **Thamesford** water system is supplied by one bedrock well (Well 3 – Stanley Street) and two overburden wells (Wells 1 and 2 - commonly referred to as the River Wells). See Appendix 1 Map 4-1-16. The water system supplies a population of approximately 2000. The bedrock well is located in the northwest part of the community; the overburden wells are located in the northeast part of the community, adjacent to the Thames River. The Stanley Street well is cased to a depth of approximately 25 m and completed as an open bedrock well to a depth of approximately 78 m. The overburden wells are completed in gravel and sand with screen depth settings from approximately 6 – 14 m below surface (shallow aquifer). Potential transport pathways within the WHPA appear to be limited to a few private wells. No adjustments were made to account for these pathways. The transport pathways related to *GUDI* wells are described in Section 4.3.4.

The **Mount Elgin** water system is supplied by one bedrock well (Well 3) and one planned well to come on line located on the north side of the village. See Appendix 1 Map 4-1-14. The water system supplies a population of approximately 370. Well 3 is cased to a depth of approximately 55 m and completed as an open hole in bedrock to a depth of 60 m. Well 5 is undergoing an evaluation for possible connection to the water system. A WHPA has been delineated and is included in the Assessment Report as a planned system. The remaining well (Well 6) will either be retained for monitoring purposes or decommissioned. The Mount Elgin WHPA is based on a forecast pumping rate of 176 m^3/day (2 L/s) and the two WHPAs extend approximately 6 km to the north of the well. The WHPA occurs mostly in a rural area and potential transport pathways appear to be limited to a few private wells. The Mount Elgin wells are completed in the upper bedrock. The available mapping indicates more than 30 m of overburden in the WHPA and most of this appears to be low permeability material (tills, etc.). The County of Oxford landfill is located within the 25 year time of travel for well 5 however the landfill excavation is shallow. Therefore, the landfill was not considered to be a transport pathway, with respect to the WHPA.

The water supply system serving the City of **Woodstock** and the community of Sweaburg is supplied by two major wellfields (Thornton and Tabor - wells 1-5, 8 & 11 and a planned well has been added) completed in the overburden aquifer system southwest of the City and three bedrock wells within the City (wells 6, 7, & 9). See Appendix 1 Map 4-1-17. The water system supplies a population of approximately 36,600. The Thornton and Tabor wells are completed in sand and gravel and screened between 13-32 m below the surface and the bedrock wells are open hole between 20-63 m below surface. Adjustments to the vulnerability mapping were made in three areas to account for *transport pathways*. These areas include:

- The sand/gravel pits located in WHPA-B of the well 2 and 4 of the Tabor wellfield: vulnerability categories were adjusted from medium to high, resulting in an increase in vulnerability score from 8 to 10
- The village of Sweaburg to account for a higher density of existing private wells and septic systems in WHPA-B of the wells 1, 3, 5, 8 and 11 of the Thornton wellfield; vulnerability categories were adjusted from medium to high, resulting in an increase in vulnerability score from 8 to 10
- The Pattulo Avenue/Greenly Line portion of WHPA-C and D from bedrock Well 9, to account for a high density of private wells; in WHPA-C, vulnerability categories were adjusted from low to medium, resulting in an increase in vulnerability score from 2 to 6, while in WHPA-D, vulnerability categories were adjusted from low to medium, resulting in an increase in vulnerability score from 2 to 4.

Perth Wellfields

Approximately 80% of the domestic and municipal wells in Perth County are deep bedrock wells with 30 to 50 m of overburden comprised of clay or clay till and limited areas of sand and gravel. All municipal systems in Perth County are developed in bedrock aquifers. The Perth County

Groundwater Study (2003) identified abandoned wells as significant transport pathways and were identified as a 'threat' in the report (p.3-5). Due to the identified sensitivity of deep wells, the consultant identified non-municipal water wells in the WHPA as *transport pathways* and included a buffer around the pathway. Horizontal pathways or shallow wells were not identified as *transport pathways* as these features are believed to be shallow and are well separated from the aquifers supplying the municipal systems. The approach taken in the most recent study was to identify all non-municipal water wells within the WHPA and increase the vulnerability within a 50 m buffer by one level for wells reaching the same aquifer as the drinking water system. The buffer size has been chosen as half of the high vulnerability radius (WHPA-A) around the municipal wells. The buffer, based on the consultant's best professional judgement, may help offset well record location errors, and result in a closer look at the buffer area. Each occurrence of water wells within the 25-year capture zone was discussed with the well operator prior to increasing the vulnerability. This adjustment was supported by the Source Protection Committee who discussed the importance that private wells within the WHPA need to be properly constructed, well maintained and, if no longer needed, be properly decommissioned.

The **Mitchell** municipal wellfield is located in the Town of Mitchell. The water supply system is comprised of four wells, which supply water to a population of approximately 4,000 people. All four bedrock wells produce water from depths between 24 to 60 m. See Appendix 1 Map 4-1-18. Transport pathways were discussed with the well operator of the Mitchell well. Only one transport pathway was identified during this discussion, represented by a well, located in the WHPA-B of well 4. Upon further investigation, this well was found to be screened in the same aquifer as the municipal aquifer. As a result, the vulnerability of the well and a surrounding 50 m buffer (which overlaps WHPA-C also) was increased from low to a medium vulnerability, resulting in an increase in vulnerability score of 6 to 8 in WHPA-B, and 4 to 6 in WHPA-C.

The Town of **St. Marys** water supply is obtained from three groundwater wells referred to as Well Number 1, 2a, and 3 and services a population of approximately 6,200. The wells are completed in bedrock. The casing extends into bedrock to a depth of 12 to 18 m. They continue through the bedrock to a depth of between 45 and 47 m as open holes. See Appendix 1 Map 4-1-21. It was determined through previous work that the system is a *GUDI* system. The transport pathways related to *GUDI* wells are described in Section 4.3.4. The following were considered as transport pathways in WHPA-A to D:

- Monitoring wells are located within the WHPA-A (100 m radius) of well 1, however, the vulnerability is already high and cannot be increased.
- There are private wells within the WHPA-B, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 6 to 8. Also in WHPA-B, private wells occurring in a vulnerability category of medium resulted in a category of high, and an increase in vulnerabiity score from 8 to 10.
- There are private wells within the WHPA-C, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 4 to 6. Also in WHPA-C, a private well occurring in a vulnerability category of medium resulted in a category of high, and an increase in vulnerabiity score from 6 to 8.
- There are private wells within the WHPA-D, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 2 to 4.

St. Pauls drinking water system consists of a single well serving a population of approximately 90 people. This drinking water system consists of a 70.4 m deep drilled bedrock well. See Appendix 1 Map 4-1-22. Potential transport pathways within the St. Pauls capture zone consist of a variety of unused/ abandoned dug wells throughout the town, which were identified by the water well technician. As these wells occur within the 100 m radius, having already a vulnerability score of 10, there is no further vulnerability increase.

The **Sebringville** drinking water system includes one well serving a population of approximately 90 people. The Black Creek subdivision well reaches a depth of 55.5 m. The overburden has an average thickness of 20 m across Sebringville. See Appendix 1 Map 4-1-19. A few potential transport pathways were identified by the municipality, including unused/ abandoned dug wells found in the Sebringville community and some tile drains in the 5-year and 25-year capture zones. These features have not been located yet and are, therefore, not included at this time. However a few private wells, the locations of which are known, are identified as transport pathways. The vulnerability category around these transport pathways in WHPA-D was increased from low to medium, resulting in an increase in vulnerability score from 2 to 4.

The **Shakespeare** well system is located in bedrock which is found at considerable depths in this area and serves a population of approximately 220. The Miller well is 85 m deep and is being protected by approximately 44 m of overburden material, consisting of silt, sandy silt and sand lenses. The bedrock completion is open hole. See Appendix 1 Map 4-1-20. The area around Shakespeare has a low vulnerability. Transport pathways were discussed with the well technicians for the Shakespeare municipal system. Given the considerable depth of the aquifer, only abandoned bedrock wells are anticipated to represent a significant risk. Within the modest area covered by the Miller well capture zone, no potential transport pathways have been identified.

The City of **Stratford** currently encompasses 6 wellfields with a total of 11 wells. This supply provides drinking water to a population of approximately 30,460 people. All wells pump water from the bedrock aquifer. The bedrock contact is located at a depth of 33 m (Romeo #4) to 47 m (Dunn well). All wells are cased to the bedrock and then completed as open hole, with a total well depth of 139 m at the deepest well. See Appendix 1 Map 4-1-23. The largest concern for the Stratford water supply system is non-municipal private wells which are completed to the bedrock aquifer. There is currently a ban on the installation of any well within the Stratford area as a protective measure. However, geothermal wells supersede this ban under the Green Energy Act and have been installed west of the Romeo wellfield into the same depth as the municipal aquifer; exact locations are yet to be determined. A number of wells have been decommissioned in Stratford and the abandonment records will need to be considered in subsequent Assessment Reports. A municipal monitoring well is located in the Romeo wells WHPA, to the west of Romeo Street and to the south of Vivian Street. A water level transducer is installed on this well to record water level data. The monitoring well is part of the municipal system and is inspected every week as per the Permit to Take Water, and is not considered as a transport pathway.

The following were considered as transport pathways in the City of Stratford WHPA:

- There are private wells within the O'Loane Well WHPA-B, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 6 to 8.
- There are private wells within the Mornington Well WHPA-B, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 6 to 8.
- There are private wells within the Mornington Well WHPA-C, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 4 to 6.
- There are private wells within the Mornington Well WHPA-D, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 2 to 4.
- There are private wells within the Romeo Well WHPA-B, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 6 to 8.
- There are private wells within the Romeo Well WHPA-C, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 4 to 6.
- There are private wells within the Romeo Well WHPA-D, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 2 to 4.
- There are private wells within the Dunn Well WHPA-D, due to which an adjustment in vulnerability category was made from low to medium, resulting in an increase in vulnerability score from 2 to 4.

Vulnerability Scoring within WHPA-A, B, C, D

Vulnerability of an area within a *WHPA* is assigned a score of 2 to 10 dependent on the *WHPA* zone that it is within (*WHPA-A*, *WHPA-B*, *WHPA-C*, *WHPA-D*), the method used to assess vulnerability (such as *ISI, AVI* or *SWAT*), and the vulnerability category (high, medium or low). Table 4-3 summarizes the possible vulnerability scoring using *ISI*, *AVI* or *SWAT*, according to the *Technical Rules: Assessment Reports*. A higher score signifies a greater vulnerability to contamination.

Table 4-3 WHPA vulnerability scoring (Technical Rules Table 2 a and b)

Groundwater Vulnerability Category	Vulnerability Score			
	WHPA-A	WHPA-B	WHPA-C	WHPA-D
Using ISI and AVI				
High	10	10	8	6
Medium	10	8	6	4
Low	10	6	4	2
Using SWAT				
High	10	10	8	6
Medium	10	8	6	4
Low	10	6	2	2

The results of the vulnerability assessment for the *WHPA* in the Upper Thames River Source Protection Area are shown in the vulnerability maps in Appendix 1 (Maps 4-1-1 to 4-1-23). Vulnerability scores for the UTRSPA are summarized below in Table 4-4.

Table 4-4 List of Groundwater Wells and Vulnerability Scores for WHPA-A, B, C, D

Groundwater Intake	Vulnerability Score				Vulnerability Comments
	WHPA-A	WHPA-B	WHPA-C	WHPA-D	H= high, M= moderate, L= Low
London Middlesex Study					
Birr	10	6	4	2	Vulnerability is low
Dorchester Overburden & Bedrock	10	10, 6	8, 4	6, 2	Vulnerability is high in overburden and low in bedrock
London Back Up Wells Fanshawe & Hyde Park	10	10, 8, 6	8, 6, 4	doesn't exist for Fanshawe 6, 4, 2	High for Fanshawe, reaches steady state at WHPA-C
Melrose	10	10	8,6	6,4,2	H for WHPA-B, H and M for WHPA-C; H, M and L for WHPA-D
Thorndale	10	6	4	2	Vulnerability is Low in WHPA

Table 4-4 List of Groundwater Wells and Vulnerability Scores for WHPA-A, B, C, D

Groundwater Intake	Vulnerability Score				Vulnerability Comments
	WHPA-A	WHPA-B	WHPA-C	WHPA-D	H= high, M= moderate, L= Low
Oxford Study					
Beachville (larger and smaller)	10	8, 6	8, 4	6,4,2	High for WHPA-B & C; High, Medium & Low for WHPA-D, (Smaller WHPA) Medium for part of WHPA-B & low for WHPA-C & D
Embro	10	6	4	2	L for all WHPA-D
Hickson	10	8	4	2	M for part of WHPA-B but all included as moderate, L for WHPA-C & D
Ingersoll	10	10, 8, 6	6, 2 (H & L SWAT)	8*, 6*, 4*, 2	Ingersoll was completed with SWAT Table 2b. WHPA values different. H, M, & L for WHPA-B; M & L for WHPA-C & D
Innerkip	10	8	8, 6	4, 2	WHPA-B: M, WHPA-C: H & M; WHPA-D: M & L
Lakeside	10	6	4	2	WHPA-B-D all low vulnerability
Mount Elgin	10	6	4	2	WHPA-B-D all low vulnerability
Tavistock	10	6	4	2	WHPA-B-D all low vulnerability
Thamesford (bedrock & overburden WHPA)	10	10*, 8*, 6	10*, 8*, 4	10*, 8*, 4, 2 No D for over-burden	WHPA-B-D bedrock well are all low vulnerability; WHPA-B-D are all high for overburden wells
Woodstock	10	10, 8, 6	8,6, 2	10*, 8*, 6*, 4, 2	Woodstock was completed with SWAT. WHPA values table 2b.WHPA-B: H, M, & L; WHPA-C: M & L; & WHPA-D: M, L (H, M & L in overlap wells)
Perth Study					
Mitchell	10	6	4	2	WHPA-A-D vulnerability is low
Sebringville	10	10	4	2	WHPA-A-D are all in low vulnerability areas. WHPA-B appears to be beneath WHPA-A
Shakespeare	10	6	4	2	WHPA-A-D are all in low vulnerability areas.
St. Pauls	10	6	4	2	WHPA-A-D are all in low vulnerability areas.
St. Marys	10	10, 8, 6,	6, 4	6, 4, 2	WHPA B and D- high, medium and low vulnerability, WHPA-C has medium and low vulnerability areas
Stratford	10	6	4	2	WHPA-A-D vulnerability is low

*Note: These vulnerability scores for these WHPA are a result of overlapping areas.

Vulnerability Scoring within *WHPA-E*

The vulnerability score of a *WHPA-E* is calculated as per the Technical Rules on vulnerability scores for *Intake Protection Zone-2* (*IPZ-2*). A higher score signifies a greater vulnerability to contamination. The vulnerability score must be calculated based on the vulnerability of the source and the area in the *WHPA-E,* which in turn are based on a number of factors described below. The vulnerability score is a product of the area vulnerability factor and the source vulnerability factor. **Table 4-5** summarizes the vulnerability scores of the *GUDI* well systems in the UTRSPA.

Table 4-5 List of GUDI Wells and Vulnerability Scores for *WHPA-E*

GUDI Well System	Intake Type	*WHPA-E* Area Vulnerability Factor	*WHPA-E* Source Vulnerability Factor	*WHPA-E* Vulnerability Score
Dorchester	C	7.0	0.9	6.3
London Back Up Wells - Fanshawe	D	7.0	1.0	7.0
St. Marys	C	8.0	0.9	7.2
Thamesford	C	7.0	0.9	6.3
Woodstock – rural - Thornton	D	7.0	1.0	7.0
Woodstock – rural - Tabor	D	7.0	1.0	7.0

Area Vulnerability factor: According to the *Technical Rules*, the area vulnerability factor for a *WHPA-E* is assigned in the same manner of assigning a factor to a surface water intake *IPZ-2*. Therefore the area vulnerability factor for a *WHPA-E* ranges between 7 and 9. A higher number corresponds to a higher vulnerability. The area vulnerability factor is dependent on the percentage of area that is land in the *WHPA-E*, land cover, soil type and permeability of the land, slope of any setbacks, and the hydrological and hydrogeological conditions in the area that contribute water to the area through *transport pathways*. The above mentioned criteria have been given equal weight based on professional judgement.

Source Vulnerability factor: According to the Technical Rules, the area vulnerability factor for a *WHPA-E* is assigned based on the type of intake. The source vulnerability factor for a Type C intake can be 0.9 or 1.0 and is based on certain criteria: depth of the intake from the top of the water surface, distance of the intake from land, and number of recorded drinking water issues related to the intake. The source vulnerability factor for a Type D intake can be 0.8 to 1.0 and is based on the same criteria.

The consideration of the above criteria in assigning area and source vulnerability factors to each *GUDI* system's *WHPA-E* is described below.

Dorchester WHPA-E Area and Source Vulnerability Factors

The Dorchester *WHPA-E* consists primary of the Dorchester swamp, wetlands and agricultural lands. Soils are predominantly organic and fine sand loam with high runoff potential. A number of agricultural tile drainages cross the *WHPA-E*. The surficial geology consists of mainly glacial outwash sand deposits. Modern alluvium, consisting mainly of silty sand, occurs within the floodplains of the Big Swamp Drain and its tributaries. *WHPA-E* is relatively flat with 73% of its area having overland slopes less than 1%. From a range between 7 and 9, an area vulnerability factor of 7 (low value) was assigned to the Dorchester *WHPA-E*. The decision was mainly based on flat topography, low soil permeability and low percentage of urban area.

The Dorchester *GUDI* wells pump water from a shallow overburden unconfined aquifer consisting of glaciofluvial sand and gravel. The overburden thickness is in the order of 24 m at the well fields. In the general vicinity of the well field, the aquifer varies in thickness from 4 m to 17 m. A relatively homogenous till underlies the sand and gravel aquifer. The wells are located about 100 to 200 m from the Big Swamp Drain. Considering that the wells are not located in the immediate vicinity of the Big Swamp Drain and no historical drinking water issues were recorded, a source vulnerability factor of 0.9 was assigned to *WHPA-E*. The factor, which is at the low end of the recommended range for a Type C intake, reflects the condition that the well does not pump directly from surface water, has no water quality issues and is located relatively far from the potential surface sources of contamination.

Fanshawe WHPA-E Area and Source Vulnerability Factors

The *WHPA-E* is mostly cultivated grass (golf course) and roads, with forests and some waterbodies. The soils are mainly sandy loams. The soils are moderately to well permeable. Overland slopes are mild, mainly less than 5%. A number of kettle ponds are located around the well field. These kettles generally contain less than 1 m of standing water and are disconnected and do not have outlets. These ponds are vertically hydraulically connected to the water supply. The pumped aquifer consists of a 15 m to 20 m thick deposit of unconfined sand and gravel. The water table is fairly shallow, being approximately 1 m to 5 m below surface. From a range of 7 to 9, an area vulnerability factor of 7 (low value) was assigned to the Fanshawe *WHPA-E*. The decision was mainly based on low percentages of paved areas, high permeability of soils, and mild slopes.

Considering that the aquifer is very shallow (1 to 5 m), the Fanshawe wells are located in the immediate vicinity of kettle ponds, the identified drinking water *issue* (organic nitrogen) and Type D intake, a high source vulnerability factor of 1.0 was assigned. This high factor considers that the wells pump groundwater that is susceptible to water quality impacts from surface water contamination.

St. Marys WHPA-E Area and Source Vulnerability Factors

The St. Marys *WHPA-E* primarily consists of the urban land uses of St. Marys and agricultural land upstream of St. Marys. Soils are predominantly clay loam and silty loam with relatively poor permeability. A number of agricultural tile drainages cross the *WHPA-E*. The *WHPA-E* has generally mild slopes, mainly less than 5%; however in areas close to the river channel slopes may be steep. From a range between 7 and 9, an area vulnerability factor of 8 (middle value) was assigned to the St. Marys *WHPA-E*. The decision was mainly based on percentage of urban area and concentration of transport pathways (St. Marys stormwatersheds and tile drainages), low permeability of soils and relatively steep slopes.

The wells pump water from the bedrock which is relatively deep around the wells. The zone of interaction with the surface water is located several hundreds metres away from the well projections. The major source of water to the well is attributed to groundwater, however, a small, and unknown portion of water may potentially originate from a surface water source. No drinking water issues were recorded in the St. Marys wells. Considering that the wells are located in deep bedrock, and the zone of interaction is several hundreds meters away from the wells and no historical drinking water issues were recorded, a source vulnerability factor of 0.9 was assigned to *WHPA-E*. The factor is at the low end of the recommended range for a Type C intake.

Thamesford WHPA-E Area and Source Vulnerability Factors

The *WHPA-E* is mostly agricultural, with some wetlands and forests. The overburden in the area is part of the Oxford Till Plain, which consists of sandy-silt to clayey silt soils. Alluvial and glaciofluvial sand and gravel are observed in the drainage channels and valleys. The topography is relatively flat. A large number of agricultural tile drainages and some road ditches exist in *WHPA-E*. From a range between 7 and 9, an area vulnerability factor of 7 (low value) was assigned to the Thamesford *WHPA-E*. The decision was mainly based on flat topography, low percentage of water in the area and low to moderate soil permeability.

Both Thamesford wells are installed in alluvial sands and gravels in an unconfined aquifer. Well 1 is 14.5 m deep and Well 2 is 9.4 m deep. The two wells are located close to the Middle Thames River, with Well 1 and Well 2 being approximately 20 m and 40 m away from the river, respectively. In addition, there is a tributary approximately 70 m south of the wells. Raw water in the wells may be vulnerable to contamination from these surface water features; however, no existing drinking water issues were recorded. Considering that no drinking water issues were recorded and wells are relatively deep, a source vulnerability factor of 0.9 was assigned to *WHPA-E*. The factor, which is at the low end of the recommended range for a Type C intake, reflects the condition that the potential vulnerability of the well to surface water impacts may be low.

Woodstock WHPA-E Area and Source Vulnerability Factors

Both the Thornton and Tabor wellfield *WHPA-Es* encompass a high percentage of rural land. The land cover is predominantly forest for Thornton wellfield, and agriculture for Tabor wellfield. Soils are very permeable, being predominantly sandy loam for Thornton wellfield and loam for Tabor wellfield. No tile drainages within *WHPA-E* were mapped or observed for either wellfield. The topography is moderately flat for both systems, with 98% of their areas having overland slopes less than 5%. Considering these criteria, an area vulnerability factor of 7 (lowest value) was assigned to the Thornton and Tabor wellfields *WHPA-Es*. The decision was based on the percentages of land, relatively high permeability of soils, flat slopes and absence of transport pathways (i.e. tile drainages).

The depth of the Thornton wells ranges from 11 to 32 m below ground surface. The Tabor wells are approximately 14 to 24 m deep. The Thornton and Tabor wells are located very close to the surface water features. Nitrate was identified as a drinking water issue for both wells. Considering these criteria and the intake type (D), a source vulnerability factor of 1.0 (highest value) was assigned for both wellfields.

4.3.6 Uncertainty in WHPA Vulnerability

Based on our understanding of the Technical Rules, the uncertainty assessment is to include the following:

- an evaluation of the uncertainty associated with the assessment of the vulnerability of groundwater within the area of interest (low, medium, high vulnerability);
- an evaluation of the uncertainty associated with the delineation of the WHPA; and
- an assignment of an uncertainty rating (high or low) for each vulnerable area (WHPA).

The *technical rules* states that an analysis of the uncertainty, characterized as high or low, shall be made with respect to the delineation and assessment of groundwater *wellhead protection areas*. The factors to be considered in the analysis include:

- o the distribution, variability, quality and relevance of data used;
- o the ability of the methods and models used to accurately reflect the flow processes in the hydrological / hydrogeological system;
- o the quality assurance and quality control procedures applied;
- o the extent and level of calibration of models; and
- o the accuracy of the groundwater vulnerability categories to effectively assess the relative vulnerability of underlying hydrogeological features.

For uncertainty in vulnerability scoring for *WHPA-E* associated with *GUDI* wells, the accuracy to which the area vulnerability factor and the source vulnerability factor effectively assesses the relative vulnerability of the hydrological features must also be considered.

The evaluation of uncertainty varied between studies and is discussed in Appendix 13.

The peer reviewers have had considerable discussion with the consultants who have undertaken the studies for both surface water and groundwater vulnerability assessment in the Thames-Sydenham and Region. Through that discussion it has become apparent that there is considerable subjectivity to the assignment of the uncertainty factors. It is important to understand that a high uncertainty associated with any aspect of the work does not suggest that the conclusions are inappropriate for the purposes that the results are being used. This is merely an acknowledgement of the potential for a better understanding with further analysis or data. If it were identified that the uncertainty was too great, additional work would have been undertaken to reduce the level of uncertainty. Availability of data to support additional work would also need to be considered. Even with the completion of additional work, it is unlikely that all uncertainty can be eliminated. The Source Protection Committee is satisfied that the uncertainty of the vulnerability assessment is low enough for the purposes intended.

4.4 Highly Vulnerable Aquifers

As discussed earlier, there are four methods with which the vulnerability of an aquifer can be assessed. These methodologies were applied to the assessment of the *wellhead protection areas* as discussed above. These same methodologies can be applied, on a much larger scale, to the assessment of the vulnerability (or intrinsic susceptibility as it is also referred to) of the first significant aquifer across the entire Source Protection Region. Areas which are identified through these methods as being highly vulnerable, and the aquifers beneath them, are to be identified as *Highly Vulnerable Aquifers* according to Rule 43 of the *Technical Rules: Assessment Report*.

In the Thames-Sydenham and Region, *Highly Vulnerable Aquifers* (*HVA*) were mapped using the Intrinsic Susceptibility Index described above. *ISI* was available across the entire region from the county groundwater studies. In some local areas the other vulnerability assessment methodologies (*AVI* and *SWAT*) have been calculated and mapped, however they have not been applied across the entire region. A seamless product across the region is needed. It is acknowledged that there will likely be challenges in matching the vulnerability assessment map discussed here, with the mapping products developed by neighbouring source protection regions. This will need to be considered in subsequent Assessment Reports after all of the neighbouring regions' products have been developed. This will present a challenge for municipalities which are within more than one Source Protection Region. These differences will also need to be considered in the development of the *Source Protection Plan* in those areas.

In determining which vulnerability assessment method to apply in the region it was also important to consider the data which are available to support the methodology. As the data necessary to apply other methods were not available in many of the areas, it was not possible to apply the other methods across the entire region without undertaking considerably more work. As such, *ISI* was used to assess the vulnerability in the Thames-Sydenham and Region.

Although the county groundwater studies followed a consistent terms of reference and methodology and were reviewed through an *MOE* developed peer review process, there were significant challenges when edge-matching the work between adjacent studies. Many of the products developed through the groundwater studies (such as water table elevation and overburden thickness) were edge-matched in the Southwest Region Edge-Matching Study Results (Waterloo Hydrologic Inc., 2005). *ISI*, however, was not able to be seamlessly matched throughout the region. Instead, a product was developed which identified the areas of overlap between study areas where the *ISI* index was one or two levels different (Map 18 of Appendix 5). In order to use this product to describe the intrinsic vulnerability in the region, it needed to be updated to ensure seamless mapping across the entire region. Further, it is important that consistent methodologies be applied to all areas within the region. The work described in this section is described in detail in the Highly Vulnerable Aquifer Identification (Upper Thames River Conservation Authority, November 2009) report.

The *ISI* scores from the wells across the region were obtained from the data of the county groundwater studies. The updated *WWIS* had been corrected to reduce the locational uncertainty of many of the data points. The *ISI* calculations consider the vulnerability only at points where information on the depth and type of materials overlaying the water table is available. The information source for this geologic interpretation was the Water Well Information System (*WWIS*). This database includes a characterization of the materials encountered in the drilling of water wells. Materials are described by the drillers and then entered into this information system along with other details associated with the well, such as the static level of the water in the completed well. As discussed earlier, the *ISI* score had previously been calculated at each well. These data were used as the basis for the initial vulnerability map. Geographic Information System (*GIS*) tools are often used to interpolate values between the discrete points where the value is known. These tools determine the best fit of a surface through the thousands of values across a region. Various computer algorithms are available in the *GIS* programs to undertake this interpolation or smoothing. The county groundwater studies used different tools to undertake this smoothing of the *ISI*. For a seamless product across the entire Source Protection Region it was necessary to use the same algorithms across the entire region. The ‘Natural Neighbour’ method was used by many of the studies to provide an interpolation of data between neighbouring water well locations. In some of the studies, the results were similar to a computer algorithm method. Natural Neighbour is, however, simpler to apply with fewer options as to how to apply the method. This is an advantage as this method will be better able to be reproduced and updated in the future. Natural Neighbour was therefore used for the seamless update of the *ISI* across the region.

Another difference between the studies was in which values of intrinsic vulnerability were interpolated. In some studies the *ISI* scores were interpolated, whereas other studies interpolated an index which represented whether the score was high, medium or low. As discussed above, an *ISI* score of less than 30 results in a high vulnerability. These were assigned an index value of 1, whereas medium vulnerabilities were assigned an *ISI* of 2 and lows were assigned an *ISI* of 3. In many of the county groundwater studies, these 1, 2 and 3 values were interpolated across the study areas. This resulted in a continuously variable surface with values ranging from less than 1 to greater than 3. It was therefore necessary to determine the breakpoints between high, medium and low within this continuous surface to determine where the lines should be between the high, medium or low area. In investigating this, the study team found that this was not well documented and that it was apparent that various breakpoints were used for the separation of high, medium and low areas. For the purposes of this update, the scores were interpolated rather than the index values, allowing the breakpoints specified in the *rules* to be used in the delineation between high, medium and low vulnerability.

As discussed above, an *ISI* score is only calculated at points where the WWIS contained information. Even with the extensive number of wells which were used, there are areas where there are no wells to define the vulnerability. A simple illustration of this is to consider where wells are generally located. They will normally be located in an area where there are homes or other buildings. The buildings tend to be located close to the roads. As a result, areas between the roads tend not to have many wells. Sand and Gravel information from the Surficial Geology (*OGS*) was used to define features which were not well represented in the *ISI* data. In some areas, the Surficial Geology defined sand and gravel areas suggest that small areas of high vulnerability identified through the *ISI* mapping may be more extensive or connected to other areas which the *ISI* had identified as high vulnerability. This required professional judgement through an extensive comparison of the well records within and around these features to determine whether areas of *highly vulnerable aquifers* were missed in the *ISI* mapping that was developed. This work was undertaken by the region's staff hydrogeologist and was peer reviewed as described in the peer review section above. Where the sand and gravel information agreed with the water well records, the extent of the surficial geology feature (sands and gravels) was used to connect smaller pockets of high vulnerability. Where water well information did not seem to agree with the surficial geology information, examination of the well record and air photo interpretation were used to determine if the well record should be included in the *ISI* interpolation. Further, an assessment as to whether the sand and gravel area identified in the surficial geology features is likely to contain an aquifer was also undertaken where these areas were being added to the highly *vulnerable areas* identified through the seamless *ISI*. Where individual pixels smaller than 200 m square were identified in the seamless *ISI* mapping they were screened out.

The areas where the *ISI* score was calculated or interpolated to be less than 30 are identified as *Highly Vulnerable Aquifers*. The use of a second data source (surficial geology features) and professional judgement to supplement and confirm the results of the *ISI* work give more certainty to the areas delineated as *Highly Vulnerable Aquifers*. This also resulted in a more comprehensive identification of *highly vulnerable aquifers* across the region than could be provided by the *ISI* information calculated and interpolated from well locations. Map 4-3-2 illustrates the *highly vulnerable aquifers* within the Upper Thames River Source Protection Area. All HVAs are assigned a vulnerability score of 6 according to the technical rules.

These areas of high vulnerability identified as *HVA*s were overlaid over the areas of medium or low vulnerability from the seamless *ISI* developed as described above to produce a seamless vulnerability mapping across the region. In this manner, areas identified as *Highly Vulnerable Aquifers* were assigned a vulnerability of high. Those areas which were not identified as *highly vulnerable aquifers* retained the low or medium vulnerability from the seamless vulnerability mapping. The resulting regional scale map is included as Map 4-3-1.

4.4.1 Uncertainty of HVA

The uncertainty associated with the delineation of HVA is largely associated with the uncertainties related to the data sets used. The use of a second information source greatly reduces the uncertainty associated with the HVA, especially in the areas where the 2 data sources agree. This is described in detail in the Highly Vulnerable Aquifer Identification report (UTRCA, 2009) and summarized in Appendix 13. Although there is still a high level of uncertainty, the Source Protection Committee is satisfied that the uncertainty of the HVA is low enough for the purposes intended.

4.5 Significant Groundwater Recharge Areas

Significant Groundwater Recharge Areas or *SGRA*s are delineated through the Water Budget Process. In the Upper Thames River Source Protection Area these were delineated through the Tier 2 Water Budget. The delineation of the *SGRA*s is described in detail in Section 3 – Water Budget and Water Quantity Stress Assessment.

Rule 44 defines *Significant Groundwater Recharge Areas* as those areas where the recharge is:

1) more than 1.15 times the average recharge in the area or
2) 55% or more of the volume determined by subtracting the annual evapotranspiration for the whole of the related groundwater recharge area from the annual precipitation for the whole of the related groundwater recharge area.

For the purposes of identifying SGRA in the Upper Thames River Source Protection Area, areas were assessed to determine if they exceeded 1.15 times the average recharge of the SPA (method 1 above). The areas which meet this criterion are shown in Map 4-2-1 which shows the delineated *SGRA*. Map 4-2-1 filters out areas which are based on single grids from the analysis (less than 25 ha in area).

Rule 46 allows professional judgement in the determination of areas deemed to exhibit significant recharge or not. For example, if an area is known to provide significant recharge on a local scale due to is unique physiography, but does not show up as significant using the methodology described above, it can be changed in the SGRA mapping to be significant. In the modelling done for SGRA determination in the TSR, river valleys and flood plain areas were shown to be SGRAs. In the opinion of some of the Water Budget Peer Review Committee (PRC) members, these areas are more appropriately defined as groundwater discharge rather than recharge areas, due to their low elevations and to the general groundwater hydraulic gradient towards them. However, there is also a body of research which shows that river valley areas can potentially exhibit both types of behaviour, dependent upon the season, and other PRC members felt it was appropriate to consider them as recharge areas. In the end it was agreed that they would be considered discharge areas, and thus removed from the SGRA mapping in Map 4-2-1.

Vulnerability within these *Significant Groundwater Recharge Areas* was assessed using the *ISI* developed for delineation of the *Highly Vulnerable Aquifers*. The combined *HVA* and seamless *ISI* map (Map 4-3-1) was used to assess the vulnerability of the *SGRA*s. *SGRA*s which have a high vulnerability are assessed a vulnerability score of 6, while medium areas are scored 4, and low areas are scored 2. The vulnerability of the *SGRA*s is illustrated in Map 4-2-2.

It is important to note that overlaying the groundwater vulnerability onto the *SGRAs* creates “overlay artifacts” or “sliver polygons”. This occurs where the boundary of a contiguous groundwater vulnerability area falls close to the boundary of the *SGRA*. Since the datasets do not perfectly align to each other, the slight gaps and overlaps between the boundaries create small, uniquely valued polygons. In some cases, these polygons will be assigned a vulnerability score of 6 (i.e. potential for moderate or low threats) but have areas less than 1 square meter in size. This should be considered in policy development and implementation.

4.5.1 Uncertainty of SGRA

The uncertainty associated with the delineation of the SGRA is discussed in the Significant Groundwater Recharge Area technical memorandum (UTRCA, May 2010). Recharge is a difficult parameter to estimate. The recharge used in the delineation of the SGRA for the Upper Thames River Source Protection Area is derived from a calibrated surface water model which was coupled with a calibrated groundwater model. While the calibration of both models reduces the uncertainty in the recharge, the resulting SGRA still has a degree of uncertainty. The Source Protection Committee is satisfied that the uncertainty of the SGRA is low enough for the purposes intended.

4.6 Data Gaps and Next Steps

The data gaps encountered in the assessment of vulnerability are listed in Table 4-6.

Table 4-6 Vulnerability Assessment Data Gaps Relevant to the Upper Thames River SPA

Data Gap	Description
Groundwater model parameters (vertical and horizontal hydraulic conductivity, recharge, hydraulic head)	Lack of data; might be an opportunity for future monitoring and testing
WHPA Transport Pathways	Locations of water, oil and gas wells in WHPA
Edge-matching of HVA and SGRA with neighbouring regions	This work will be considered when neighbouring regions' HVA and SGRA maps are complete
Water well data in portions of SPR, for HVA determination	Lack of data; might be an opportunity for future monitoring
Aquifer mapping	Better understanding of the conceptual geologic model including mapping of the lateral extent of the aquifers and aquitards and recharge areas feeding these aquifers