Final Report

# Updated Vulnerability Analysis for the Kelso and Campbellville Wellfields, Regional Municipality of Halton, Ontario

Prepared for:

Conservation Halton
2596 Britannia Road West
Burlington, Ontario L7P 0G3

Prepared by:

Earthfx Incorporated
3363 Yonge Street
Toronto, Ontario M4N 2M6

February 2015

Earthfx Incorporated
Earth Science Information Systems

March 22, 2015

Mr. Jacek Strakowski, Hydrogeologist
Conservation Halton
2596 Britannia Road West
Burlington, Ontario
L7P 0G3

**RE: Updated Vulnerability Analysis for the Kelso and Campbellville Wellfields**

Dear Mr. Strakowski:

Earthfx Incorporated is pleased to submit our final report on the updated vulnerability analysis for the Kelso and Campbellville municipal wells in the Town of Milton.

The update was conducted to assess the water quality vulnerability capture zones of the wells using the new integrated surface water/groundwater surface water model developed for the Tier 3 Water Budget study. The Tier 3 model provides an improved representation of the hydrogeology, climate, transient reservoir operations and surface water flow system.

The model was run under transient conditions for a 28-year period with average climate conditions so as to account for the large fluctuations in groundwater levels, surface water flows and seasonal variations and operations of the Kelso reservoir. The report describes the methods used and model results and presents updated maps of the capture zones and vulnerability scores.

We trust this work report meets with your satisfaction. If you have any questions, please call.

Yours truly,

Earthfx Incorporated

Dirk Kassenaar, M.Sc., P.Eng.
President, Earthfx Inc.

E.J. Wexler, M.S.E., M.Sc., P.Eng.
Vice-President, Earthfx Inc.

3363 Yonge St., Toronto, Ontario, Canada M4N 2M6
Tele: 416.410.4260 e-mail: info@earthfx.com
www.earthfx.com

# Table of Contents



# Tables

# Figures

# 1 Introduction

The Regional Municipality of Halton operates the Kelso and Campbellville wellfields in the northwest portion of the Sixteen Mile Creek watershed (Figure 1, Figure 2, and Figure 3). Water quality and quantity issues within the wellfields have been the subject of recent Source Water Protection studies, a program funded by the Province of Ontario under The Clean Water Act. Source Water Protection studies are considered a first step in a multi-barrier approach to ensuring safe drinking water.

## 1.1 Background

Earthfx conducted a water quality vulnerability analysis for the Halton wells in 2010, and a Tier 3 water quantity assessment in 2013, described in more detail below. The model created for the Tier 3 quantity assessment included numerous improvements and the findings of the study indicated that surface and groundwater flow conditions fluctuate significantly in a complex transient manner due to the reservoir operations, reservoir geometry and the valley system aquifer configuration. These findings justified an update of the earlier water quality vulnerability analyses.

## 1.2 Water Quality Vulnerability Analysis

Threats to municipal water quality are assessed as part of a Source Water Protection study. Specifically, Part V of the Technical Rules for Assessment Reports (MOE, 2009) defines three categories of vulnerable areas with respect to groundwater drinking water sources that are in need of delineation. These include:

1. highly vulnerable aquifers;
2. significant groundwater recharge areas; and
3. wellhead protection areas.

Part V of the Technical Rules for Assessment Reports defines the various types of wellhead protection area (WHPA) zones and approved methods for WHPA delineation. Part VII defines the rules for assigning groundwater vulnerability scores to subzones within the WHPAs based on a variety of approved vulnerability scoring methods. This study was conducted in accordance with these technical rules.

# 2 Previous Studies

## 2.1 2010 Wellhead Protection Area Delineation and Vulnerability Assessment

In 2010, Earthfx conducted a Source Water Protection vulnerability analysis for the municipal wells in the Kelso and Campbellville wellfields (Earthfx, 2010). A steady-state model was developed for the “South Halton” area (Figure 4) using the U.S. Geological Survey (USGS) MODFLOW code. Average annual groundwater recharge to the model was determined using an independently developed hydrologic model based on the USGS Precipitation-Runoff Modelling System (PRMS). The PRMS model covered all of Halton Region as well as the northern part of the City of Hamilton and was calibrated to observed flows at 23 Water Survey of Canada stream gauges. The groundwater model was calibrated to 3205 observed static groundwater levels obtained from the Ministry of Environment (MOE) Water Well Information System (WWIS). Simulated groundwater discharge to streams was compared against estimated baseflow at four key gauges in the South Halton model area.

Wellhead protection areas were delineated as the 2, 5, and 25 year time-of-travel zones as determined using the steady-state groundwater model. Virtual particles were released at the wells and tracked backwards through the simulated flow system. The time-of-travel zones were drawn as an envelope encompassing the particle locations projected onto a two-dimensional map at the different times and are shown on Figure 5. The capture zones for the Kelso wells are quite large and extend up the Campbellville re-entrant valley. As will be discussed further on, the large extent is primarily due to the assumption, based on reported information at the time, that Kelso reservoir was not hydraulically connected to the aquifer in which the municipal wells were screened.

Aquifer vulnerability was assessed based on the time-of-travel from the surface to the well using the surface to well advective time (SWAT) method. Travel times through the unsaturated zone (UZAT) were estimated using a simplified approach, outlined in MOE (2008), and based on recharge rates and porosity values. Travel times from the water table to the wells (WWAT) were determined by releasing virtual particles at the water table and tracking them until they reached a municipal well. Vulnerability classes (high, medium, and low) were assigned to each model cell based on the SWAT values (e.g., cells with less than a 5 year SWAT value were assigned a rating of high, while cells with a SWAT value between 5 and 25 years were assigned a rating of medium). Finally, the 2, 5, and 25 year WHPAs were intersected with the High, Medium, and Low vulnerability zones. Each subarea formed was assigned a vulnerability score between 2 and 10, as outlined in MOE (2008). Final vulnerability scoring is shown in Figure 7.

## *2.2 Tier 3 Water Budget and Local Area Risk Assessment for the Kelso and Campbellville Municipal Wells*

A second component of the Source Water Protection process is the assessment of potential risks to municipal water supplies from a water quantity perspective. This analysis requires an in-depth understanding of the water budget in the local area surrounding the municipal wells. A three-tiered approach has been defined under the Clean Water Act for the purpose of preliminary screening, followed by an in-depth risk assessment. Tier 1 and 2 level water-budget studies were completed for the watersheds in this study area (Halton-Hamilton Source Protection Staff, August, 2010) based on the PRMS and MODFLOW models described in Earthfx (2010). The Upper West Branch subwatershed of Sixteen Mile Creek was identified as moderately stressed at the Tier 2 level. Accordingly, a Tier 3 assessment was conducted for the subwatershed with a particular focus on the areas surrounding the Campbellville and Kelso (Milton) municipal wells (Earthfx, 2014) (the Walkers Line wells are outside the stressed subwatershed and are expected to be decommissioned). The Tier 3 study area showing the model extents and the wellfield locations is shown in Figure 1.

To conduct the Tier 3 analysis, Earthfx developed an integrated groundwater/surface water model of the Kelso and Campbellville area using the USGS GSFLOW code. The model, described in Earthfx (2013) represented a 270 $km^2$ area straddling the Niagara Escarpment. The model consisted of eight hydrostratigraphic layers and used cells as small as 5 m by 5 m in the wellfield. The GSFLOW code incorporates the PRMS and MODFLOW-NWT codes as submodels. Information is passed between the submodels such that there is instantaneous feedback between the groundwater and surface water systems in each time step. Soil water processes and cascading overland flow were simulated using the PRMS submodel. Routing and groundwater interaction with all mapped streams, wetlands, quarry lakes, ponds and reservoirs were represented. Stage in the Kelso and

Hilton Falls reservoirs, and all other lakes and wetlands were dependent on upstream inflows, direct precipitation, evaporation, and gains/losses to groundwater. Outflow rates from the lakes and wetlands were stage-dependent; releases from the two reservoirs and an upstream diversion structure were regulated by operating rule curves. Other key inputs included NEXRAD precipitation data and detailed land use information. The groundwater submodel uses MODFLOW-NWT, a much more stable version than used in the previous work that allowed simulation of groundwater flow and spring discharge all along the edge of the Niagara Escarpment.

The Tier 3 integrated GSFLOW model represents a significant improvement over previous WHPA, Tier 1 and Tier 2 modelling efforts in the study area particularly in the way that recharge and groundwater/surface water interaction was simulated. The Model Development and Calibration Report (Earthfx, 2013) covered all aspects of data compilation, conceptualization, model construction and calibration of the fully integrated surface water/groundwater model used in this risk assessment. Significant findings include a better understanding of:

- local geology in the vicinity of the Kelso wellfield;
- the role and influence that the operation of Kelso reservoir has on wellfield water levels;
- the regional groundwater flow system including the role of wetlands and stream channel/aquifer interaction;
- the distribution and transient nature of recharge; and,
- the seasonality of both the extents and quantity of groundwater discharge to wetlands and riparian areas.

The incorporation of the transient recharge, groundwater flow, reservoir management, and pumping data are a major improvement over the steady-state analysis presented in earlier modelling reports from the area. Simulations with the integrated model matched seasonal response including the spring freshet. Wetlands in the upland area fill during the spring months and provide baseflow and groundwater recharge through much of the summer. The model was calibrated to reservoir discharges and observed streamflow at the gauge on Sixteen Mile Creek. Filling of the Kelso and Hilton Falls reservoirs was very sensitive to correctly representing runoff, wetland attenuation, seasonal discharge from quarries, and the operation of diversion structures. Simulated groundwater levels matched the seasonal response in observation wells and showed that the Kelso reservoir was likely hydraulically connected to the wellfield through a glacial meltwater channel that breached the confining unit. Drawdowns near the well were sensitive to reservoir operation as well as antecedent conditions in the upstream areas. Further discussions of the Tier 3 work including risk assessment simulations of future water use and extreme drought can be found in Earthfx (2014)

# 3 Need, Objectives, and Approach

## *3.1 Need*

As noted, the integrated groundwater/surface water model developed for the Tier 3 study represented a significant improvement over the steady-state model used in the Tier 1 and 2 studies particularly in the way groundwater recharge and groundwater/surface water interaction were represented. The advances in understanding suggest that a re-evaluation of the original WHPAs and vulnerability scoring would be justified. In particular, the Tier 3 study noted that groundwater levels and, accordingly, the rate and direction of groundwater flow was highly dependent on changes in stage in the Kelso reservoir. The outlines of the time-of-travel zones would also vary over time as a consequence of the change in the groundwater velocities. A steady-state model cannot capture the highly transient nature of the flow system and the time-varying shape of the WHPA zones at the Kelso wells.

Although all groundwater systems are transient in nature, the degree of change at the Kelso wells was felt to be unusual enough to merit additional analysis of both natural seasonal variability and variation due to the large operational change in reservoir water levels. This degree of variability implies that there is no representative average reservoir condition under which steady-state simulations would represent the system. The reservoir is never kept at an average “half full” level, and operations indicate that the levels are not even kept at low and high levels for an equal 6 month time period. Most significantly, the modelling clearly demonstrated that during high water levels there is significantly greater leakage from the reservoir through the shallow groundwater system. This “short circuiting” would significantly affect time-of-travel and the outlines of the WHPAs.

### *3.2 Objectives*

The primary objective of this study is to re-assess and update the water quality vulnerability status of the Kelso and Campbellville wells using the new model and understanding of the wellfields. The objectives include completion of the WHPA vulnerability assessment as outlined in Part V and Part VII of the Technical Rules for Assessment Reports.

### *3.3 Approach*

The proposed approach is based on using the GSFLOW model to estimate the extents of the capture zones under transient seasonally-fluctuating conditions. The transient simulation approach is not considered a “worst case” analysis. The transient model simulations are based on average climate conditions and normal reservoir operating rules.

The simulation approach involves cycling average seasonal climatic inputs, pumping rates and reservoir operations throughout a long term transient simulation. Particles are released on a monthly basis into the pumping wells, and are tracked backwards through the fluctuating flow field. The WHPA capture zones are outlined by mapping the extents of the particle positions at the prescribed assessment times.

## 4 Updated Vulnerability Analysis

### *4.1 Simulation of Groundwater and Surface Water Flow*

To obtain results comparable to a steady-state analysis (i.e., measurements of long-term average as opposed to sampling the full range of possible conditions), a period of near-average climate conditions was selected from the historic data set. Climate data for the selected four-year period (WY1972-WY1976), was used as input to the GSFLOW model and cycled seven times to create the simulated 28-year near-average conditions for the particle-tracking simulations. Figure 8 shows daily precipitation (rainfall plus snowfall) and daily snowfall for the four-year period.

Official reservoir operating rules, rather than historic actual gate openings and closings, were used to control the structures at the Kelso and Hilton Falls reservoirs and the diversion structure upstream of the Hilton Falls reservoir. Figure 9 shows the simulated lake stage in Kelso reservoir for 1972-1976 where the lake fills based on the simulated inflows from upstream and the timing of gate openings and closings are controlled by the operating rules. (Note, the use of dates herein refers to the simulation times with the cycled climate inputs rather than real calendar dates).

All other aspects of the GSFLOW model are as described in Earthfx (2013) including the simulation of wetlands, streams, quarry ponds, and the groundwater system. Simulated heads in January 1976 (Figure 10) are typical of winter conditions with Kelso and Hilton Falls reservoirs at their winter low stage. Figure 11 shows simulated heads in July 1976 which are typical of summer conditions with Kelso and Hilton Falls reservoirs at their summer high stage. Water levels in the Kelso wellfield increase about 3.0 m from winter to summer.

### *4.2 WHPA Delineation*

Part V of the Technical Rules for Assessment Reports defines the different zones surrounding a municipal well that make up a WHPA. The WHPA-B, WHPA-C, and WHPA-D zones are based on the time-of travel to the well. These are listed in Table 1 and shown schematically in Figure 12b.

Table 1: Time of Travel (ToT) zones and corresponding sensitivity zones.

| Zone Name | Delineation Method |
|---|---|
| WHPA A | 100-metre radius |
| WHPA B | 0 to 2-year ToT zone (outside WHPA A) |
| WHPA C | 2 to 5-year ToT zone |
| WHPA D | 5 to 25-year ToT zone |

Capture zones and time-of-travel zone analyses were conducted using version 6.0 of the USGS MODPATH code (Pollock, 2012). MODPATH uses simulated heads and flow rates from the MODFLOW-NWT sub-model along with estimates of aquifer porosity to calculate average groundwater velocities for every cell in the model grid. MODPATH uses these velocities to track virtual particles backwards from the municipal supply wells to their point of entry into the groundwater flow system (as shown schematically in Figure 12a). Whenever a virtual particle crosses the boundary of a finite-difference cell, the particle location and time are recorded. The points are then linked to form pathlines. Multiple virtual particles are released to ensure that all likely pathways are defined. MODPATH can also be used to track particles from points along the water table (where water enters the groundwater system) to a discharge point such as a stream or well. The technique was applied to determine surface to well advection times (as discussed further on).

The newer version of the MODPATH code can track particles in a transient flow field. The simulation is broken down into a series of daily time steps during which flow rates remain constant. The position of the water table and the saturated thickness of the shallow aquifer are also assumed to remain constant within the one-day period. Particle paths are computed for each time step (just as for the steady-state case) until the end of the time step is reached. A new velocity distribution is calculated for the next time step and the particles are moved along their calculated path. Particles can be tracked forward or backward through the time-varying flow field. Pathlines are terminated when they exit the model boundaries or after specified lengths of time.

To delineate the time-of-travel zones, 49 virtual particles were placed along each of the four outer faces of the cells containing a production well. For the Kelso wells, 196 particles were placed in Layer 5 and another 196 particles in Layer 6 so that a total of 1176 particles were used for Wells 3, 4, 5, and 6 (as Well 3 and Well 6 share the same cell). Groups of 1176 particles were released every 30.43 days over a four-year period and each particle in the group was tracked backwards in time for 28 years or until the particle exited a model boundary (i.e., a point of recharge). A similar process was carried out for the Campbellville wells. Visualizing the paths of the large number of particles can be difficult, so Figure 13 shows the pathlines after 25 years of travel for four releases from the Kelso wells spaced three months apart. These particular releases took place in January, April, and July, and October of the third year (release 25, 28, 31, and 34 in year 26). The figure shows wide variation in the pathlines in the wellfield vicinity. Less variation in the pathlines is shown away from Kelso reservoir and the wellfield but the small variations in the flow field in the release area affect the paths and ultimate destinations of the particles.

Time-of-travel zones were created by drawing polygons around the well and the endpoint positions that encompassed all particle locations at 2, 5, and 25 years from the initial release dates. Figure 14 shows all the backward particle tracks from the wells at the end of 25 years of travel for all particles released over the four year period. The 25-year time-of-travel zone shown in the figure encompasses over 56,400 individual pathlines.

Final WHPAs based on the time-of-travel zones are shown in Figure 15 for the Kelso and Campbellville municipal wells. WHPA-A zones, based on the 100-metre radius around the wellhead, have been added to each figure. The particle pathways and WHPA zones shown in these figures are more complex than shown in the MOE sketch (Figure 12b) due to the time-varying flow field, as well as local variation in aquifer and aquitard properties and recharge rates.

It should also be noted that each time-of-travel zone is based on the vertical projection of the three-dimensional particle tracks onto a two-dimensional map. This has little effect when dealing with unconfined aquifers, but is a very conservative assumption when dealing with municipal wells screened in confined aquifers. The vertical travel time through the confining units can add years to the actual time of travel from the surface. The difference between the time of travel represented by the WHPA zones and the actual time of travel was considered when assigning vulnerability scores to subzones within the WHPAs, as described in the following section.

## *4.3 Vulnerability Assessment*

### 4.3.1 Overview

Part IV of the Technical Rules for Assessment Reports defines areas of high, medium, and low groundwater vulnerability for each of the allowed assessment methods. The purpose of a vulnerability assessment is to identify those zones within the WHPAs that are particularly sensitive to contamination from a surface source.

The Technical Rules for Assessment Reports outline multiple methods for the assessment of the vulnerability. The Surface to Well Advective Time (SWAT) method was chosen for this project because it is numerically consistent with the numerical model used to delineate the WHPAs and is also consistent with the method used in the previous work (Earthfx, 2010).

For the SWAT method, the classification is based on actual travel times from the surface to the well as follows:

(a) areas of high vulnerability are those areas with travel times less than 5 years;
(b) areas of medium vulnerability are those areas with travel times greater than or equal to 5 years but less than or equal to 25 years, and
(c) areas of low vulnerability are those areas with travel times greater than 25 years.

These zones are shown schematically in Figure 12c.

Surface to well advective travel times (SWAT) consists of two components, the vertical travel time through the unsaturated zone above the water table (unsaturated zone advective time or UZAT) and the travel time from the water table to the well through the saturated zone (water table to well advective time or WWAT). Determining vertical time of travel through the unsaturated zone is highly complex and depends on the unsaturated hydraulic conductivity of the soil, soil moisture, and tensions (i.e. negative pressure-heads) in the unsaturated zone. Unsaturated hydraulic conductivity and pressure-head can be related to moisture content through characteristic curves developed for each soil type. Unfortunately, the data on unsaturated soil properties is very limited and calculation of unsaturated travel times would be highly uncertain.

### 4.3.2 UZAT Analysis

As an alternative to complex unsaturated flow calculations, Guidance Module 3 (MOE, 2006) suggests a simplified method wherein the annual rate of groundwater recharge is assumed to be an approximation for the average rate of moisture movement through the unsaturated zone. Accordingly, UZAT values can be estimated as:

$$UZAT = \frac{d_{wt} \cdot \theta_m}{q_z} \qquad \text{(Eq. 1)}$$

where:

UZAT = advective time of travel through the unsaturated zone
$d_{wt}$ = depth to the water table
$\theta_m$ = mobile moisture content
$q_z$ = infiltration rate

Infiltration rates were obtained from the daily groundwater recharge values computed by the PRMS model averaged over the 28-year period. Average groundwater discharge to surface was subtracted from these rates to determine the net infiltration rates shown in Figure 16. Depth to the water table, shown in Figure 17, was estimated by subtracting the simulated groundwater levels in Layer 1, averaged over the 28-year period, from land surface elevation. Guidance Module 3 (MOE, 2006) suggests values for mobile moisture content based on soil type as shown in Table 2. These values are related to field capacity or specific retention of the soil. Estimated values for mobile moisture content, based on the MOE values and soils mapping is shown in Figure 18.

Table 2: Mobile moisture content values based on soil description (from MOE, 2006)

| Overburden Material | Mobile Moisture Content |
|---|---|
| Sand | 10% |
| Loam | 25% |
| Clay | 40% |

UZAT times, in years, were calculated for the Kelso and Campbellville area and are shown in Figure 19. Most of the area has low UZAT values due to thin overburden and generally sandy soils in the Campbellville re-entrant. The Kelso wellfield area, however, has high UZAT values due to the thicker overburden in the area, depressed water levels, and clayey soils. UZAT times increase significantly to the east of the wellfield where the aquifer is confined by Halton Till.

It should be noted that the protection afforded by long-travel times in the unsaturated zone is reasonable when considering a contaminant that is leached by precipitation, such as road salt or agricultural pesticides or fertilizers. Surface releases of contaminated fluids (e.g., a spill from a wastewater lagoon or a leaky storage tank), however, can locally saturate the soil and contaminants can move downward through a sandy or sandy-silt soil in orders of magnitude less time (i.e., hours or days rather than years). Fractures and macro-pores can also result in rapid movement through the unsaturated zone. Therefore, if the contaminants of concern in a particular area are likely to be released by spills and leaks rather than leaching, it would be a reasonably conservative assumption to omit UZAT times from the SWAT analysis. To be consistent with previous studies, however, the SWAT times calculated for this update included both UZAT and WWAT values.

#### 4.3.3 WWAT Analysis

WWAT values were determined by releasing virtual particles from cells in the uppermost active groundwater model layer (i.e., the layer containing the water table) within a buffer around the 25-year time of travel zone. Extents of the areas around the Kelso and Campbellville WHPAs in which particles were released are shown in Figure 20. Particles were released on a monthly basis with 25 particles released in each model cell for a total of more than 3,427,800 particles. The particles were forward-tracked from the water table to their point of discharge, either a stream, lake/wetland, or well. The times-of-travel for the over 380,130 particles ending up in the cells containing the municipal wells were recorded and then assigned back to the originating cell. Where more than one particle from a cell ended up in a municipal well, the minimum time of travel was assigned to the cell.

Simulated WWAT values for particles arriving at the Kelso and Campbellville wells are shown in Figure 21. The travel times are generally less than 25 years with a few exceptions (magenta areas) that have WWAT values close to or greater than 25 years. The white areas on the map within the 25-year ToT zone are areas where the particles released at the water table did not arrive at any of the municipal wells and, presumably, discharge to a stream or wetland or exit the wellfield study area. These areas were considered to have extremely low vulnerability.

The use of WWAT values allows the intrinsic vulnerability to be expressed in terms of travel times as opposed to other methods which use relative index values. It should be recognized, however, that the advective travel times are calculated without consideration of the nature of the potential contaminants, release mechanisms, and attenuation processes (e.g., diffusion, dispersion, adsorption and chemical transformation).

The SWAT (UZAT + WWAT) times, shown in Figure 22, were reclassified and used to delineate areas of high (0-5 year SWAT), medium (5-25 year SWAT), and low (>25 year SWAT) vulnerability as shown schematically in Figure 12c. Maps of vulnerability zones based on SWAT values are shown in Figure 23. Areas with no shading within the 25-year ToT zone were not assigned vulnerability scores because the forward tracking indicated that the particles did not discharge to the municipal wells.

### *4.4 Transport Pathways Analysis*

Adjustments to the vulnerability scores were needed to account for the presence of transport pathways (i.e., constructed preferential pathways) that may bypass the natural protective geologic layers. Preferential pathways can include improperly constructed or decommissioned wells, pits and quarries, ditches, and pipeline bedding for storm and sanitary sewers. According to Technical Rule 39, the vulnerability of an area identified as low vulnerability can be increased to medium or high vulnerability because of the presence of a transport pathway that is anthropogenic in origin.

Similarly, an area assigned a medium vulnerability can be increased to high vulnerability (Rule 40). The assessment of increased vulnerability considers:

a. hydrogeological conditions;
b. the type and design of the transport pathways;
c. the cumulative impact of the transport pathways; and
d. assumptions used in the assessment of groundwater vulnerability.

With respect to the last item, it should be noted that in this analysis of SWAT times, unsaturated zone travel times (UZAT) were set equal to zero. Therefore, constructed pathways that could possibly reduce unsaturated zone travel times, such as pipeline bedding and excavations above the water table, would not result in an increase in the vulnerability scores already assigned. The focus, therefore, was on identifying those constructed pathways that could reduce travel times in the saturated zone. These included:

- deep wells that may leak or have been improperly abandoned;
- pits and quarries that breech the upper confining unit;
- landfills located in former pits or quarries that may breach the upper confining unit; or
- other deep excavations.

### 4.4.1 Pits and Quarries

The primary transport pathways identified within the WHPAs were active and former pits and quarries. Based on aerial photography and a map of pits and quarries produced by MNR, there were five locations that intersected the WHPAs (Figure 24).

### 4.4.2 Deep Private Domestic Water Wells

Improperly constructed or decommissioned wells can potentially provide a pathway for contaminants to deeper zones within the unconfined aquifers or to the underlying confined aquifers. The risk posed by water wells in the area was assessed using the MOE WWIS database.

The potential for a water well to affect the Kelso and Campbellville municipal wells was based on two criteria: 1) whether the well is connected to the same aquifer as the municipal wells, and 2) the likely condition and quality of well construction. To evaluate the first criterion, the screened interval for each private well was queried and any that had an open interval or screen penetrating the three overburden aquifer layers in the Campbellville re-entrant was considered to be connected.

Ontario Regulation 903 (Wells) under the Ontario Water Resources Act was enacted in 1990 and set minimum standards for the construction and proper decommissioning of all types of wells. Private wells installed after 1990 were assumed to be of higher quality construction and, therefore, less likely to have failures of the casing or annular seals. Dug wells and wells constructed prior to the introduction of pitless adaptors (in the early 1980s) were considered to represent higher risk for the introduction of contaminants; these wells are categorized as being of poor construction. Wells that fall between the construction dates of 1980 and 1990 were considered to be of moderate construction quality. Wells were assigned a risk level of high, medium, or low according to the framework presented in Table 3.

Table 3: Framework for Risk Level Assignments to Other Wells

| | Poor Construction | Moderate Construction | Proper Construction |
|---|---|---|---|
| **No Connection to Aquifer** | Low | Low | Low |
| **Likely Connection to Aquifer** | High | Medium | Medium |

Eighty-four wells were identified within the Kelso and Campbellville WHPAs. The numbers of wells with low, moderate and high risk ratings are summarized in Table 4. Thirty-nine high risk wells were identified, which likely do not meet the current MOE well standards and could possibly be in connection with the aquifer used for municipal supply. Well locations are shown in Figure 24.

Table 4: Number of Wells Assigned to each Risk Level in WHPAs

| | Risk Levels | | |
|---|---|---|---|
| | **High** | **Moderate** | **Low** |
| **WHPA-A** | 16 | 5 | 3 |
| **WHPA-B** | 16 | 10 | 22 |
| **WHPA-C** | 7 | 3 | 2 |
| **WHPA-D** | 0 | 0 | 0 |
| **Totals** | **39** | **18** | **27** |

### 4.4.1 Adjustment of Vulnerability Zone Ratings

Vulnerability scores were increased (i.e., from low to medium, or medium to high) within the footprints of the quarries and pits intersecting the WHPAs as shown in Figure 25. Zones that had low vulnerability because particles released in these areas ended at points other than the municipal wells also had their ratings adjusted to medium.

The vulnerability within a 30 m radius of each of the wells identified within the WHPAs with a risk level of moderate or high were also increased by one level (i.e., from low to medium, or medium to high). The 30 m radius was selected based on the recommended setback distance from contamination sources under Ontario Regulation 903. It should be noted that many of the moderate and high risk wells were located within areas that were already at the highest vulnerability scoring of 10. The vulnerability zone rating for the area around wells with a risk level of low was left unchanged. The increased vulnerability scoring around the wells within the delineated WHPAs is presented in Figure 25.

Natural preferential pathways, such as erosion or fracturing of the confining units, can be accounted for explicitly in the numerical models where known. Despite efforts to characterize the geology of the study area, it is still unlikely that the subsurface conditions will ever be known with high enough certainty to be able to directly account for all such local-scale phenomena in the vulnerability assessments. Because of the uncertainty inherent in all these assessments, as discussed further below, the results of the TOT and SWAT analyses should best be viewed as a tool for identifying the higher risk areas that should receive priority for contaminant risk assessment, improved water quality monitoring and decommissioning of abandoned wells. Areas identified as moderate and low vulnerability will still require land-use planning and water quality monitoring.

## 4.5 Vulnerability Scoring

Finally, the vulnerability zones were superimposed on the WHPA time-of-travel zones. The vulnerability zones and WHPA polygons were intersected to create subzones around the high, medium, and low vulnerability zones within each WHPA zone as shown schematically in Figure 12d. Vulnerability scores are assigned to each subzone based on values provided in the Technical Rules for Assessment Reports as listed in Table 5.

Table 5: Vulnerability Scoring Matrix.

| | | | Surface to Well Advective Time (SWAT) | | |
|---|---|---|---|---|---|
| | | | High<br>0 to 5 years | Medium<br>5 to 25 years | Low<br>> 25 years |
| WHPA | A | within 100-m radius | 10 | 10 | 10 |
| | B | 100 m radius to 2-year ToT | 10 | 8 | 6 |
| | C | 2-year to 5-year ToT | 8 | 6 | 2 |
| | D | 5-year to 25-year ToT | (6) | 4 | 2 |

Results for the Kelso and Campbellville wells with and without transport pathway adjustment are shown in Figure 26 and Figure 27. The distribution of the vulnerability scores appears complex because of the aquifer geometry and assumed distribution of hydraulic conductivity values. In general, areas with highest vulnerability scores (10) are centred in the WHPA-A zones around the well and in areas west of Kelso reservoir and near the eastern boundary of the Halton Crushed Stone Quarry. The remaining area in the WHPA-B is has moderate scores of 6 to 8. The WHPA-C and WHPA-D are dominated by low scores (2 to 4).

## 4.6 Uncertainty Assessment

### 4.6.1 Overview

There is a degree of uncertainty associated with the ToT, SWAT and vulnerability scoring analyses; however, it is difficult to provide a quantitative assessment of the level of uncertainty. As an alternative, qualitative analysis of the available data and methods of analysis can be used to characterize the level of uncertainty as low or high. General discussions of uncertainty related to the earlier model were provided in Earthfx (2010). The Technical Rules (MOE, 2009) specify that the following factors should be considered in an uncertainty analysis for WHPA delineation and vulnerability assessments (Rule 14):

1. The distribution, variability, quality and relevance of data used in the preparation of the assessment report;
2. The ability of the methods and models used to accurately reflect the flow processes in the hydrological system;
3. The quality assurance and quality control procedures applied;
4. The extent and level of calibration and validation achieved for models used or calculations or general assessments completed; and
5. The accuracy to which the groundwater vulnerability categories effectively assess the relative vulnerability of the underlying hydrogeological features. (Subrule 5 applies only to the vulnerability scoring.)

### 4.6.2 Uncertainty Related to Data Distribution

Appendix 6 of the MOE Guidance Module (MOE 2006) indicates that it would be reasonable to expect a low level of uncertainty in areas where data density is high, where detailed hydrogeologic studies have been conducted, and where numerical models have been developed. This study generally satisfies these criteria. With regards to data density, there are a number of high-quality boreholes in the immediate vicinity of the Kelso wells. There are a reasonable amount of MOE WWIS data to the west and east of the wellfields, but there is relatively less data in the immediate vicinity of the Niagara Escarpment, which is intersected by the capture zones. There is a reasonable amount of continuous monitoring data (lake stage and groundwater levels at the municipal wells, near the quarries, and at the Mohawk racetrack) that was used to calibrate the transient model, but the areal coverage is still small compared to the size of the model area. An additional source of uncertainty, not discussed in Earthfx (2010), are quality issues related to the climate data which is a primary input to the integrated model. Detailed discussions of the climate data are provided in Earthfx (2013).

The intrinsic biases in the MOE WWIS well log data is a recognized source of uncertainty. In general, well owners only drill as deep as necessary, often completing the borehole in the top of the first aquifer encountered. This has resulted in a general tendency to record the extent of low permeability materials overlying the aquifers, but the wells provide limited information on the total thickness of the aquifer or on the properties of deeper aquifers and aquitards. Municipal wells are often located in deeper aquifer systems, below the level most commonly drilled for small private well supplies. Other biases, such as the lack of geologic training for drillers and the poor sampling techniques associated with water well drilling methods, also add to the level of uncertainty.

One key issue identified in Earthfx (2010) was uncertainty in the time-of-travel and WWAT analyses related to a lack of well data needed to accurately map the discontinuous till units. While the Halton Till is relatively thick in the eastern portion of the study area, it thins to the west and becomes patchy in the vicinity of the Kelso wellfield. Gaps in the tills allow more rapid travel of contaminants to the deeper wells. Considerable effort was expended to obtain and review additional borehole data for the Tier 3 study to improve the understanding of the local geology in the Kelso area and reduce this uncertainty. Improvements were made to the Tier 3 model during the course of model calibration to specifically address the issue of breaches in the till layers and the degree of hydraulic connection between Kelso reservoir and the municipal wells.

### 4.6.3 Uncertainty Related to the Ability of the Methods and Models to Accurately Reflect Flow Processes in the Hydrological System

As noted above, considerable effort was made to improve the understanding of the area for the Tier 3 study. Numerous improvements were made to the geologic, hydrostratigraphic, and numerical models. Of these, the most important was the use of the integrated model to better represent recharge and runoff processes and improve the representation of groundwater/surface water interaction with the model. As a result, the numerical model produced better matches to the observed water levels, streamflow, baseflow, lake stage, and wetland response as described in Earthfx (2013).

With respect to the WHPA delineation, one recognized area of uncertainty is that flow patterns change over time as a result of seasonal and annual variation in groundwater recharge. The highly transient nature of the flow system and the time-varying shape of the WHPA zones at the Kelso wells could not be captured with a steady-state model. Accordingly, the objectives of this study were to analyze how the outlines of the time-of-travel zones would vary over time, incorporate that information into the delineation of the WHPA zones, and, thereby, reduce the level of uncertainty.

#### 4.6.4 Uncertainty related to the Extent and Level of Calibration/Validation of the Models

Calibration of the integrated surface water/groundwater model is discussed in great detail in Earthfx (2013). Maps comparing observed and simulated static water levels and hydrographs comparing streamflow, baseflow, lake stage, and wetland response were prepared and showed a good match was achieved through the calibration and verification process.

Even though overall uncertainty has been reduced due to a better representation of the physical system with the calibrated model, the ability of the flow model to exactly reproduce all local flow patterns and transient response is still limited. Subtle variations in the flow directions near the wells, caused by local variation in aquitard or aquifer thickness, aquifer and aquitard hydraulic conductivity values, and/or recharge rates can lead to significant changes in the flow paths of the particles. Therefore, some level of uncertainty remains with regard to defining the three-dimensional flow patterns and determining ToT zones to a high level of precision.

There are additional factors that increase the uncertainty in calculating travel times. For example, the times of travel scale linearly with the porosity of the formations and are highly sensitive to the values assumed. Porosity values are not used in the flow model and are, therefore, not part of the normal model calibration process (they are, however, a key input to the particle tracking model). No specific measurements of porosity were available for this study, so values for the various formations were estimated based on published values (e.g., Freeze and Cherry, 1979, p. 37). To be conservative, we used values that were lower for the till aquitard layers (assuming that the tills behave as fractured media), thus resulting in greater velocity and therefore shorter travel times.

#### 4.6.5 Uncertainty Related to the Accuracy to which Groundwater Vulnerability Categories Assess the Relative Vulnerability of the Underlying Hydrogeological Features.

Of the recommended methods listed in the Technical Rules for Assessment Reports (MOE, 2008), the WWAT component of the SWAT method is by far the most scientifically sound. It is based on assessing travel times using locally-determined hydraulic properties that have been adjusted and refined through model calibration. The model that the WWAT analyses was based on was developed using recognized hydrogeologic and hydraulic principles and have been calibrated to match the observed heads and, more importantly, the model was calibrated to best match the observed directions of flow and transient groundwater response by carefully representing factors that influence flow patterns such as local variations in aquifer properties, recharge rates, aquifer and aquitard thickness and continuity as well as the effects of pumping from nearby wells and the influence of streams. However, as indicated by the discussions above, it is difficult to quantitatively assess the certainty of the ToT zones and it is even more difficult to assess uncertainty in the WWAT values within the ToT zones.

The use of SWAT zones to subdivide areas within the ToT zones adds another level of uncertainty because the SWAT results cannot be field-verified or easily tested. The assignment of high vulnerability scores to the 100-m radius, regardless of actual travel times, is an implicit recognition that the level of uncertainty is unacceptable when it comes to potential sources of contamination in close proximity to the wells. The creation of multiple small zones whose boundaries may shift (as pumping rates change or as new data become available) will also present a difficult challenge to municipal planners responsible for incorporating these discontinuous areas into municipal plans.

### 4.6.6 Uncertainty Level Assignment

An uncertainty factor of "high" or "low" was assigned to each vulnerable area delineated based on the results of the uncertainty analysis as per Rule 15. Results of the uncertainty analysis and final uncertainty factors for each wellfield are provided in Table 6.

Table 6: Summary of uncertainty analysis for WHPA delineation.

| Uncertainty Element | Kelso | Campbell-ville |
|---|---|---|
| Distribution, variability, quality and relevance of data | Low | Low |
| Ability of the methods/models to accurately reflect flow processes | Low | Low |
| Quality assurance and quality control procedures applied. | Low | Low |
| Extent and level of calibration and validation achieved for models used or calculations or general assessments completed. | Low | Low |
| Accuracy to which the groundwater vulnerability categories assess the relative vulnerability of the underlying hydrogeological features | High | High |
| **Overall** | **Low** | **Low** |

As can been seen, despite the inherent uncertainty associated with analyzing flow in the subsurface and all numerical models, the first four categories have been assigned a low level of uncertainty primarily to reflect the level of effort and the sophistication of the methods and models relative to other Source Water Protection studies. The inherent uncertainty related to the subdivision of the WHPAs into subzones is still felt to be high despite the more detailed transient analyses applied in this study. Overall, the level of uncertainty is felt to be much lower than other studies.

# 5 Summary

The purpose of this analysis was to update the delineation of the wellhead protection areas and vulnerability scores for the Kelso and Campbellville wells. Motivation for this work included (1) an improved understanding of the hydrogeology of the Kelso wellfield area and, in particular, a recognition that the wells were better connected hydraulically to the Kelso reservoir; (2) a recognition, based on results of the Tier 3 study, that groundwater levels and the rate and direction of groundwater flow was highly dependent on changes in stage in Kelso reservoir. The outlines of the time-of-travel zones also vary over time as a consequence of the change in the groundwater velocities. The steady-state model developed by Earthfx (2010) cannot capture the highly transient nature of the flow system and the time-varying shape of the WHPA zones at the Kelso wells.

The Tier 3 integrated groundwater/surface water model (described in Earthfx, 2014) better represents the local hydrogeology of the Kelso wellfield and was applied to determine the time-varying flow patterns needed to delineate transient WHPAs. A period of near-average climate conditions (1972-1976) was selected form the historic data set so that results comparable to an average steady-state analysis could be obtained. The climate data for WY1972-WY1976 was used as input to the GSFLOW model and cycled seven times to create the simulated 28-year near-average conditions for the particle-tracking simulations.

Capture zones and time-of-travel zone analyses were conducted using version 6.0 of the USGS MODPATH code (Pollock, 2012) which can track particles in a transient flow field. Groups of 1274 virtual particles were released every 30.43 days over a four-year period from the model cells containing the Kelso and Campbellville wells. Every particle in the group was tracked backwards in time for 28 years or until the particle exited a model boundary. Time-of-travel zones were created by manually drawing polygons around the well that encompassed all particle locations at 2, 5, and 25 years from the initial release dates.

Surface to well advective travel times (SWAT) were then assessed to determine (1) the vertical travel time through the unsaturated zone above the water table (UZAT) and (2) the travel time from the water table to the well through the saturated zone (WWAT). Determining vertical time of travel through the unsaturated zone is highly complex; simplified methods using the annual rate of groundwater recharge were applied to map the UZAT values. WWAT values were determined by releasing virtual particles from cells in the uppermost active groundwater model layer within the 25-year time of travel zone on a monthly basis over a four-year period. Over 3,427,800 particles were forward-tracked from the water table to their point of discharge. Of these, over 380,130 particles ended up in the cells containing the municipal wells. The minimum particle travel time was assigned back to the originating cell. Simulated travel times were generally less than 25 years. The UZAT plus WWAT values were used to delineate areas of high (0-5 year SWAT), medium (5-25 year SWAT), and low (>25 year SWAT) vulnerability. The vulnerability zones values within areas considered to be potential anthropogenic transport pathways, primarily active or former gravel pits and quarries, were adjusted upwards. The vulnerability zones and WHPA polygons were intersected to create subzones around the high, medium, and low vulnerability zones within each WHPA zone and vulnerability scores (2-10) were assigned to each subzone based on values provided in the Technical Rules.

The uncertainty related to the transient WHPA analysis and vulnerability scoring was assessed in a qualitative manner. Despite the inherent uncertainty associated with analyzing flow in the subsurface and all numerical models, the uncertainty related to the WHPA delineation and SWAT analysis was assigned a low level of uncertainty primarily to reflect the level of effort and the sophistication of the methods and models. The inherent uncertainty related to the subdivision of the WHPAs into subzones is still felt to be high despite the more detailed transient analyses applied in this study. Overall, the level of uncertainty is felt to be much lower relative to other Source Water Protection studies.

A comparison of the previous 2010 vulnerability assessment and the updated 2015 assessment is shown in Figure 28. The updated vulnerability zones cover a smaller area, but with a higher vulnerability score within that area. As outlined, numerous changes in the model combine to account for the differences, including significant changes in the surface water representation (Note: Some of the changes reflect complex interactions such as surface water leakage that may not show up clearly at the comparison map scale that is presented).

These analyses are a first, but very important, step in conducting a risk-based assessment of potential threats to the municipal supply wells from past, current, or future land-use activities. Further steps include conducting a contaminant threats inventory (as per the MOE Issues Evaluation/Threats Inventory Guidance Module) and conducting a parcel-by-parcel risk analysis based on the hazard to human health posed by contaminants on the site and the vulnerability of the drinking water source (as per the MOE Water Quality Risk Assessment Guidance Module).

# 6 Limitations

Services performed by Earthfx Incorporated were conducted in a manner consistent with a level of care and skill ordinarily exercised by members of the environmental engineering and consulting profession. This report presents the results of data compilation and computer simulations of a complex hydrogeologic setting. Data errors and data gaps are likely present in the information supplied to Earthfx, and it was beyond the scope of this project to review each data measurement and infill all gaps. Models constructed from these data are limited by the quality and completeness of the information available at the time the work was performed. Computer models represent a simplification of the actual hydrologic and hydrogeologic conditions. The applicability of the simplifying assumptions may or may not be suitable to a variety of end uses.

This report does not exhaustively cover an investigation of all possible environmental conditions or circumstances that may exist in the study area. If a service is not expressly indicated, it should not be assumed that it was provided. It should be recognized that the passage of time affects the information provided in this report. Environmental conditions and the amount of data available can change. Any discussion relating to the conditions are based upon information that existed at the time the conclusions were formulated.

This report was prepared by Earthfx Incorporated for the sole benefit of Conservation Halton. Any use which a third party makes of this report, any reliance thereon, or decisions made based on it, are the responsibility of such third parties. Earthfx Incorporated accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions taken based on this report.

Report prepared by:

Dirk Kassenaar, M.Sc., P.Eng.
President, Senior Hydrogeologist

E.J. Wexler, M.Sc., M.S.E., P.Eng.
Vice President, Senior Hydrogeologist

Mike Takeda, M.A.Sc.
Hydrogeologist

Peter John Thompson, M.A.Sc.
Hydrologist

# 7 References

Earthfx Inc., 2010, Vulnerability Assessment and Scoring of Wellhead Protection Areas, City of Hamilton, Ontario: prepared for the City of Hamilton.

Earthfx Inc., 2013, Tier 3 Water Budget and Local Area Risk Assessment for the Kelso and Campbellville Groundwater Municipal Systems: Model Development and Calibration Report, prepared for Halton Region Conservation Authority, 310 p.

Earthfx Inc., 2014, Tier 3 Water Budget and Local Area Risk Assessment for the Kelso and Campbellville Groundwater Municipal Systems, prepared for Halton Region Conservation Authority, 170 p.

Halton-Hamilton Source Protection Staff, 2010, Report on the Tier 1 Water Budget and Water Quantity Stress Assessment for the Halton-Hamilton Source Protection Region and Report on the Tier 2 Water Budget and Water Quantity Stress Assessments for the Upper West Branch of Sixteen Mile Creek and Middle Spencer Creek Subwatersheds.

Halton-Hamilton Source Protection Committee, 2012, Assessment Report for the Halton Region Source Protection Area (Version 2.1).

Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process: USGS Techniques and Methods 6-A16.

Leavesley, G.H., Litchty, R.W., Troutman, B.M. and Saindon, L.G., 1986, Precipitation-Runoff Modeling System: User's Manual. USGS Water Resources Investigations Report 83-4283.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008, GSFLOW: Coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240 p.

Niswonger, R.G., Panday, S., and Ibaraki, M., 2011, MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6–A37, 44 p.

Niswonger, R.G. and D.E. Prudic, 2005, Documentation of the Streamflow-Routing (SFR2) package to include Unsaturated Flow beneath Streams- a modification to SFR1; U.S. Geological Survey Techniques and Methods 6-A13, p. 50.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: USGS Techniques and Methods, Book 6, Chapter A19, 62 p.

Ontario Ministry of Environment, 2009, Draft Technical Rules: Assessment Report, Clean Water Act (original release 2006).

Ontario Ministry of Environment, 2011, Technical Rules: Assessment Report, Clean Water Act (original release 2006).

Ontario Ministry of Natural Resources [MNR], 2011, Water Budget & Water Quantity Risk Assessment Guide, Drinking Water Source Protection Program.

# 8 Figures

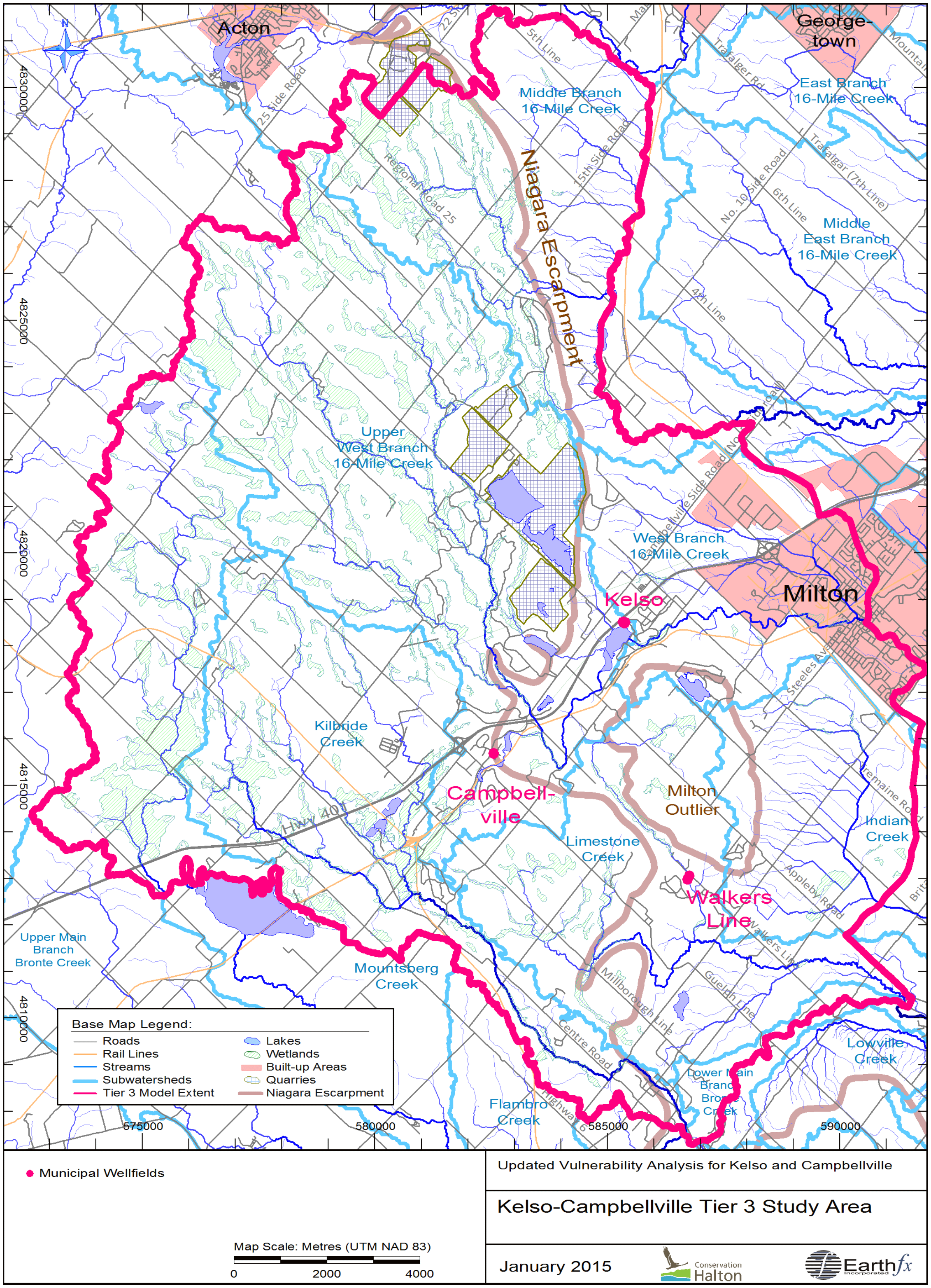


Figure 1: Kelso-Campbellville 2014 Tier 3 Study area (from Earthfx, 2014).


Figure 2: Location of municipal wells in the Kelso wells adjacent to the Kelso reservoir.


Figure 3: Location of the Campbellville municipal wells and Campbellville Pond.

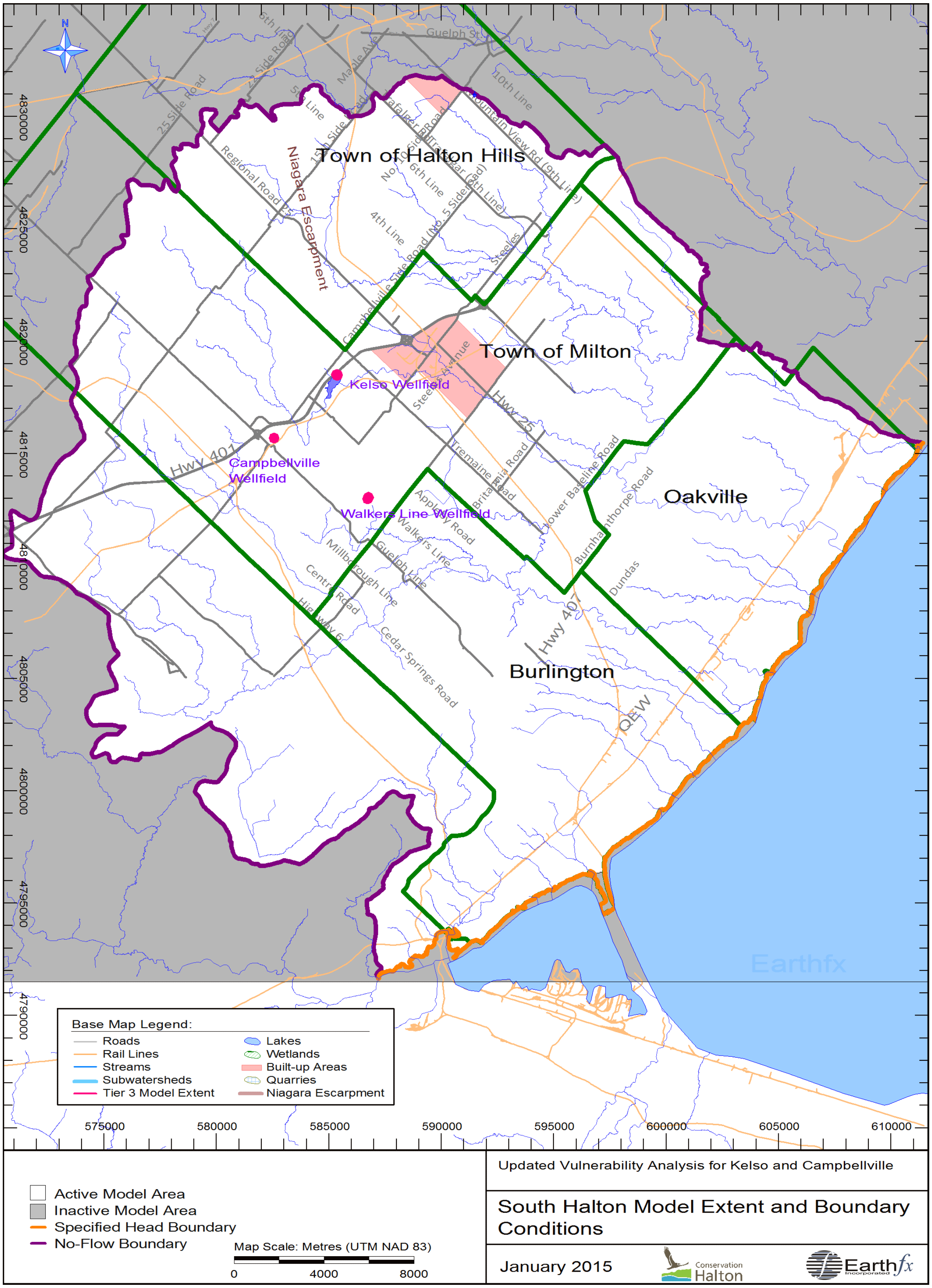


Figure 4: Extent of the 2010 South Halton Model (modified from Earthfx, 2010).

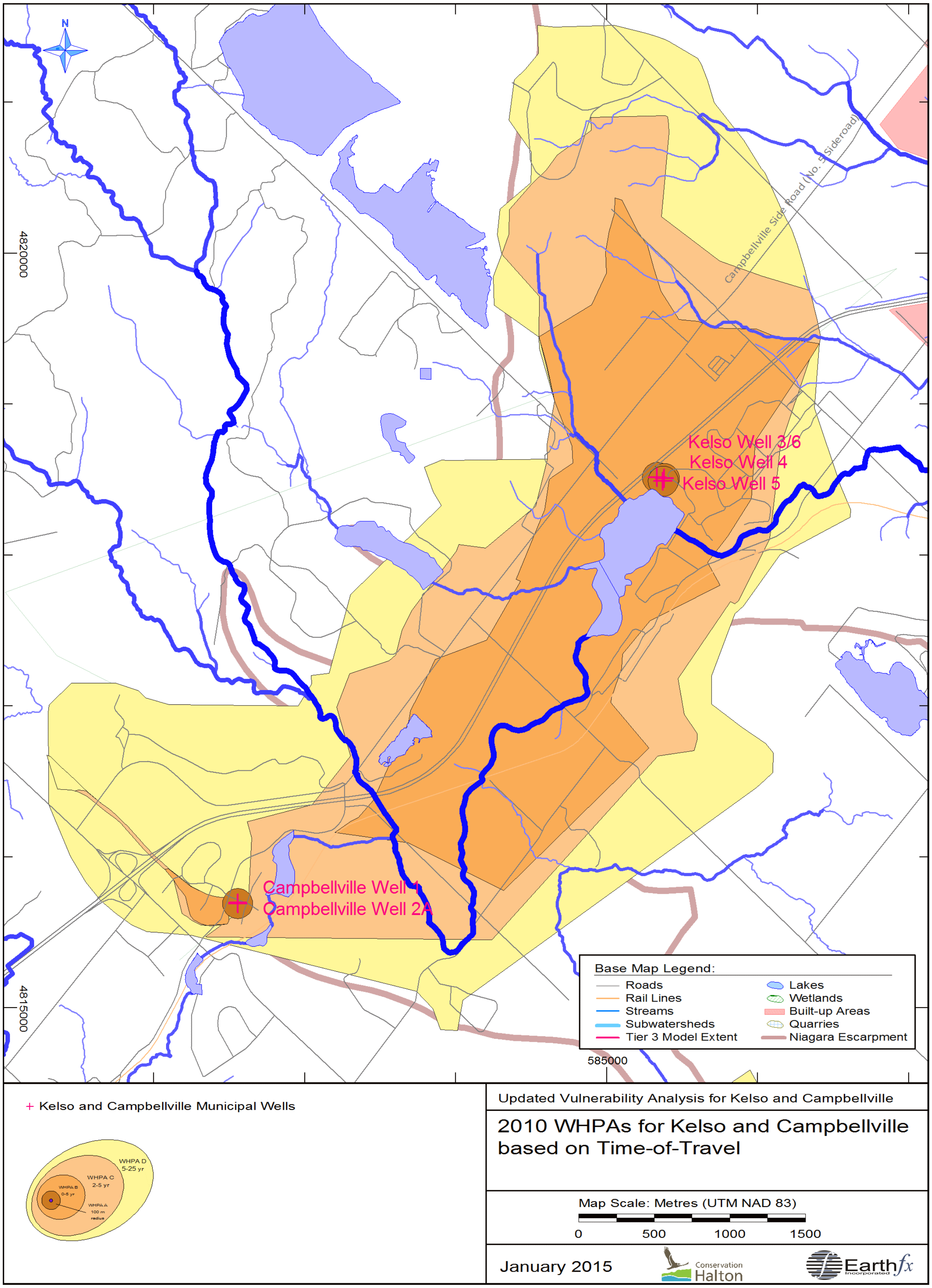


Figure 5: Wellhead protection areas for the Kelso and Campbellville wells based on time of travel (modified from Earthfx, 2010).

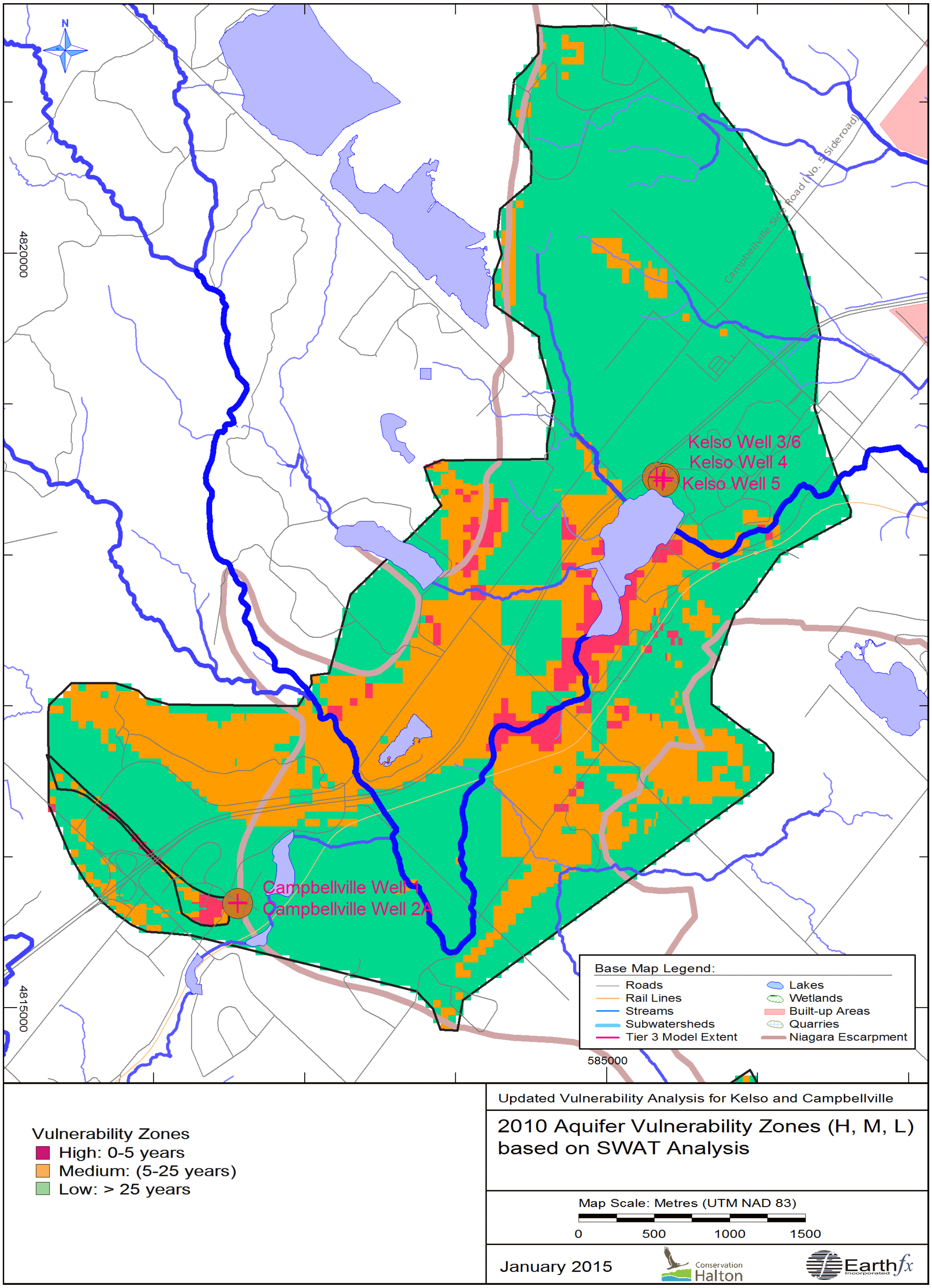


Figure 6: Aquifer vulnerability zones (High, Medium, and Low according to surface to well advection times (SWAT)) for the Kelso and Campbellville wells (modified from Earthfx, 2010).

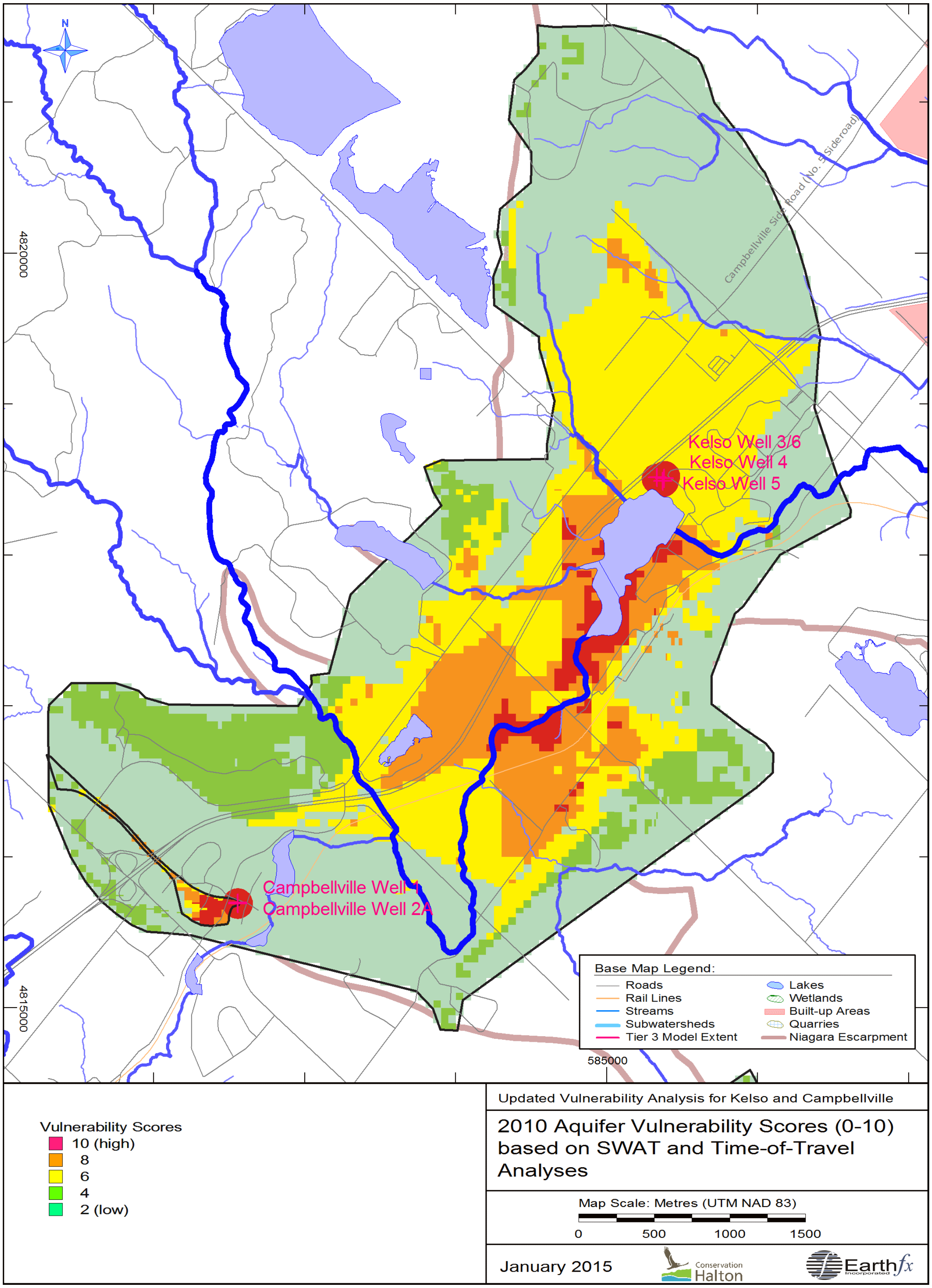


Figure 7: Aquifer vulnerability scores (ranging from 1 to 10) created by overlaying the aquifer vulnerability zones on the time-of-travel WHPAs (modified from Earthfx, 2010).

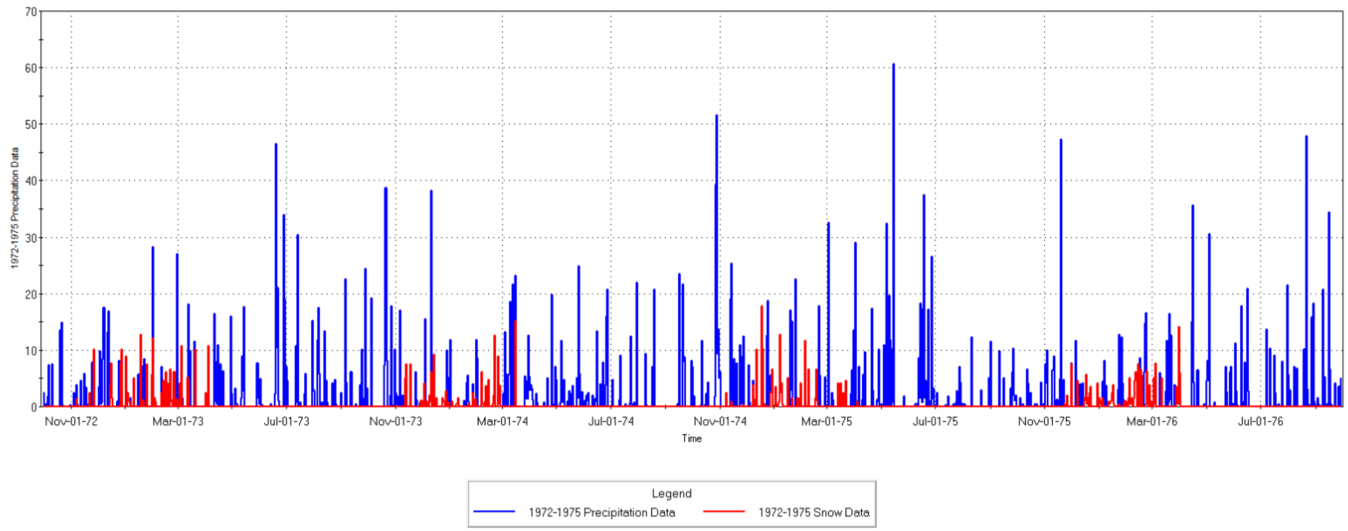


Figure 8: Daily precipitation and snowfall (WY1972-1976), in mm/d.

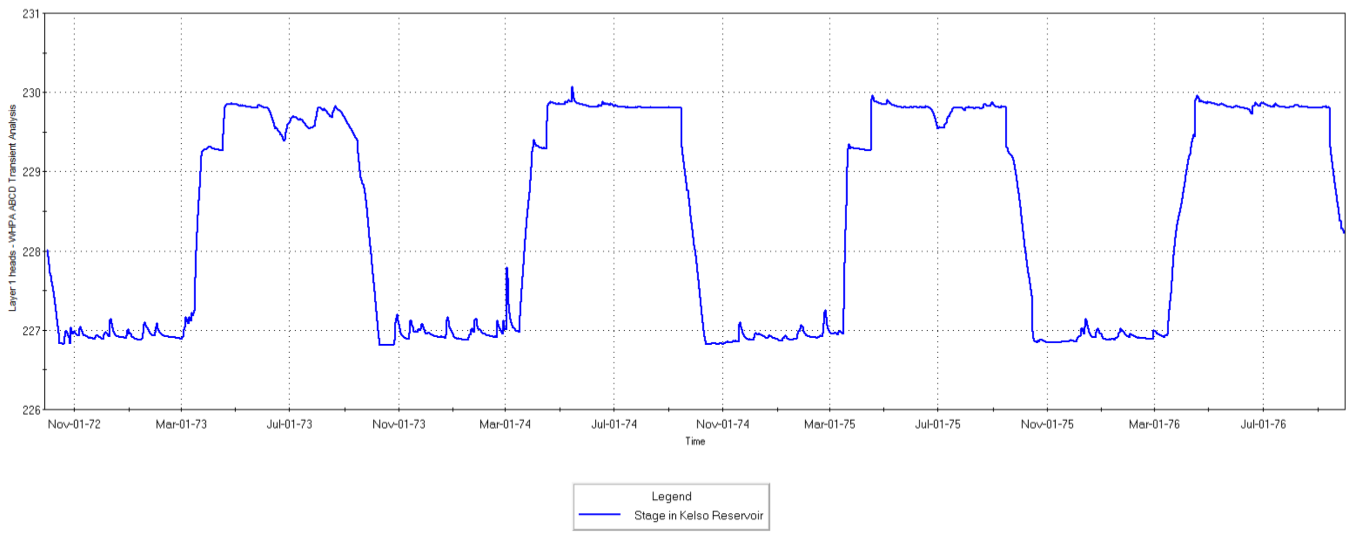


Figure 9: Simulated stage in Kelso reservoir WY1972-1976 with gate openings controlled by operating rules.

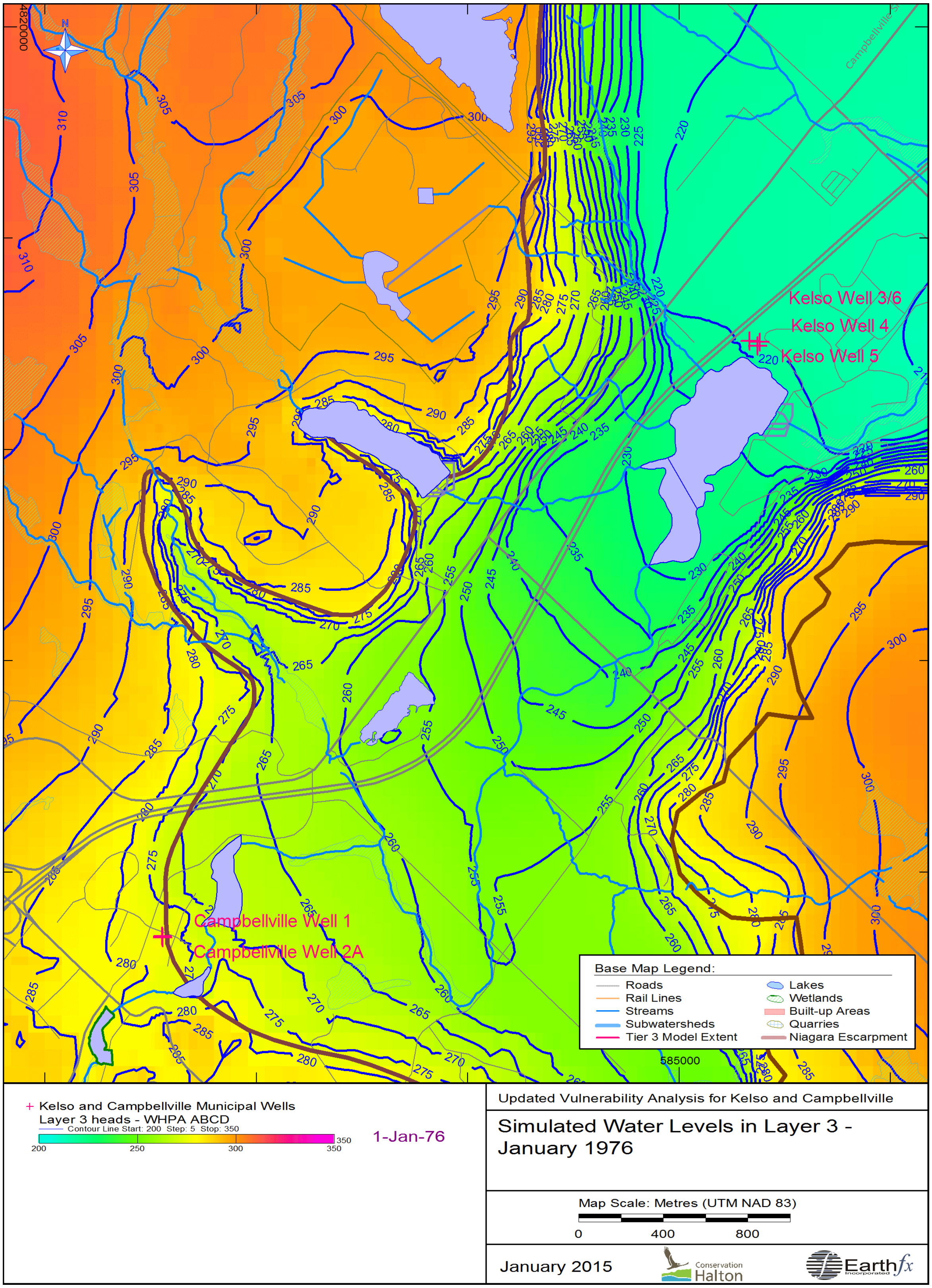


Figure 10: Simulated water levels in January 1976 with Kelso Reservoir at winter low stage.

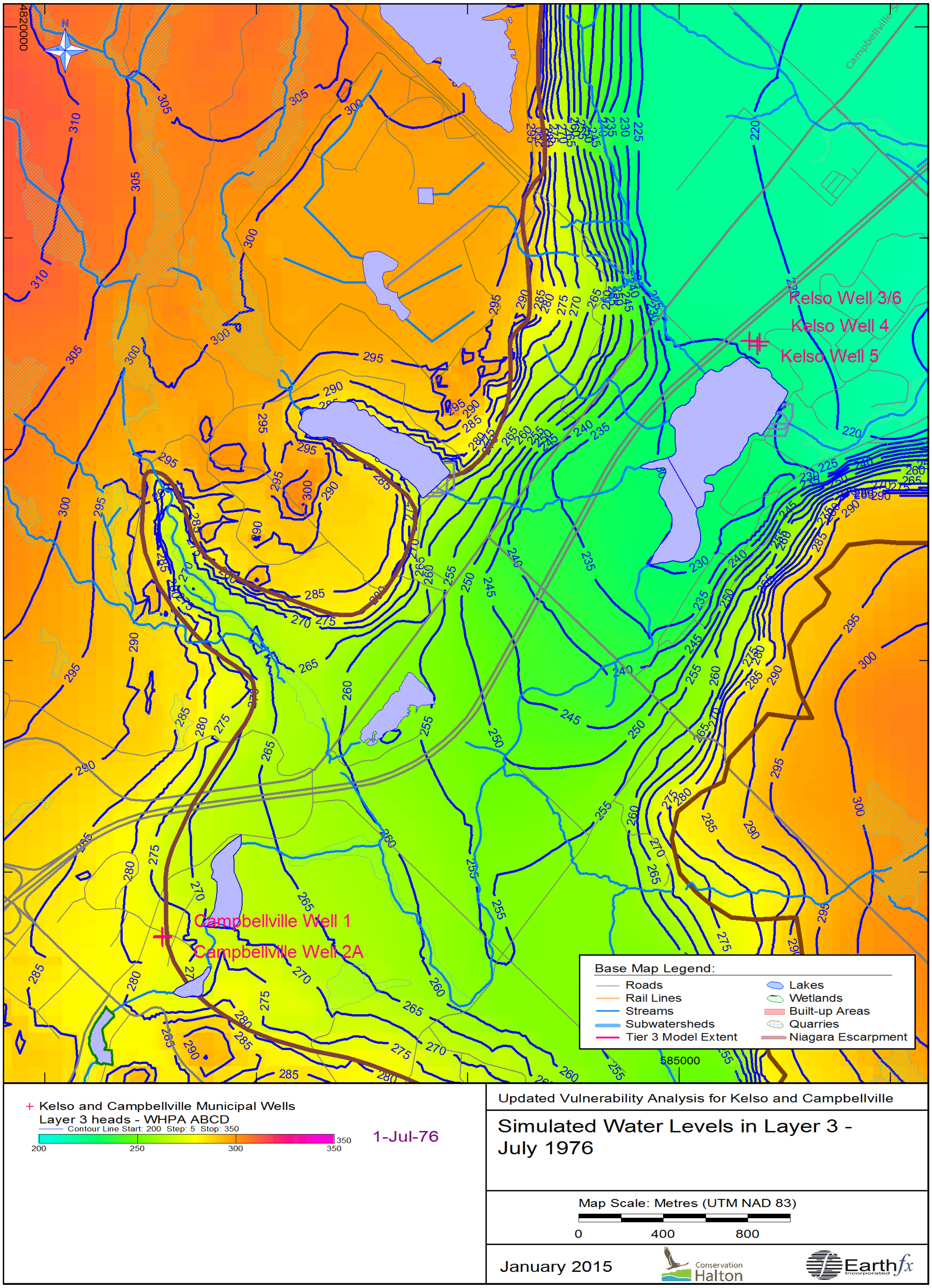


Figure 11: Simulated water levels in July 1976 with Kelso Reservoir at summer high stage.

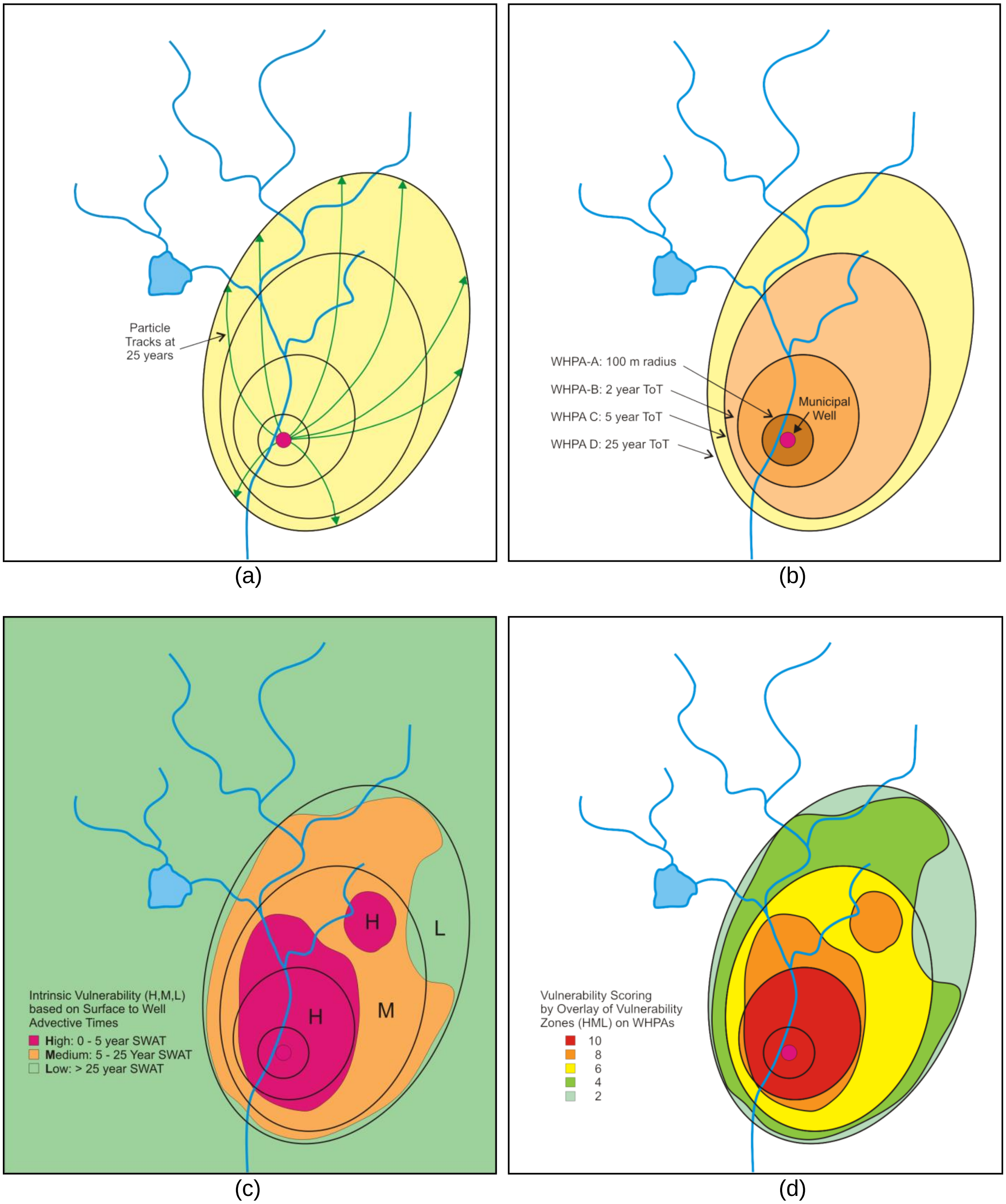


Figure 12: Sketch showing (a) backward tracking of particles from the well to discharge point to define time-of-travel zones (b) time of travel based Wellhead Protection Areas, (c) intrinsic vulnerability zones based on surface to well advection times, and (d) intersection of time-of-travel and WHPAs to assign vulnerability scores.

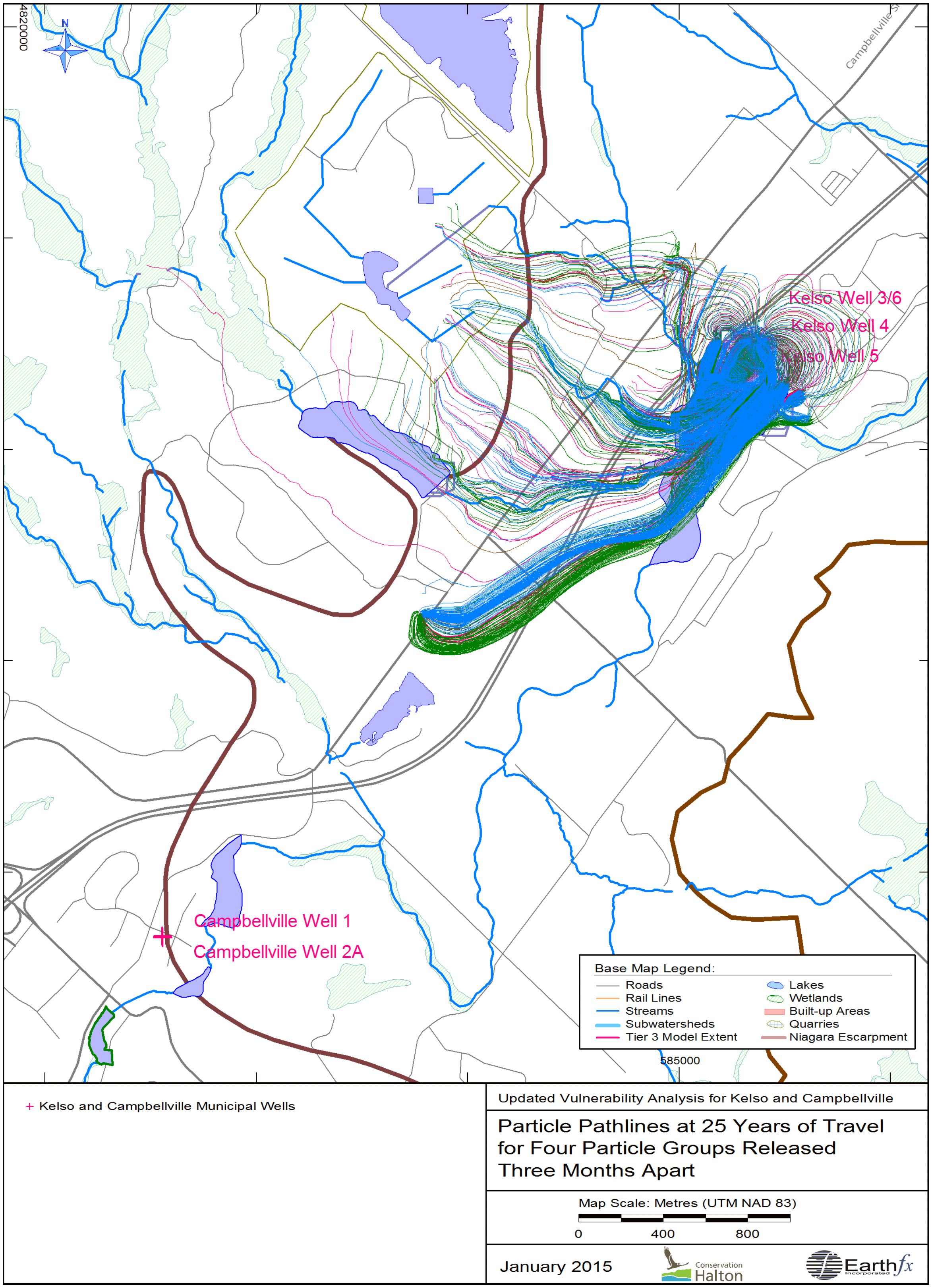


Figure 13: Particle pathlines after 25 years of travel for four particles groups released at the Kelso wellfield three months apart in the third year of the four-year release period.

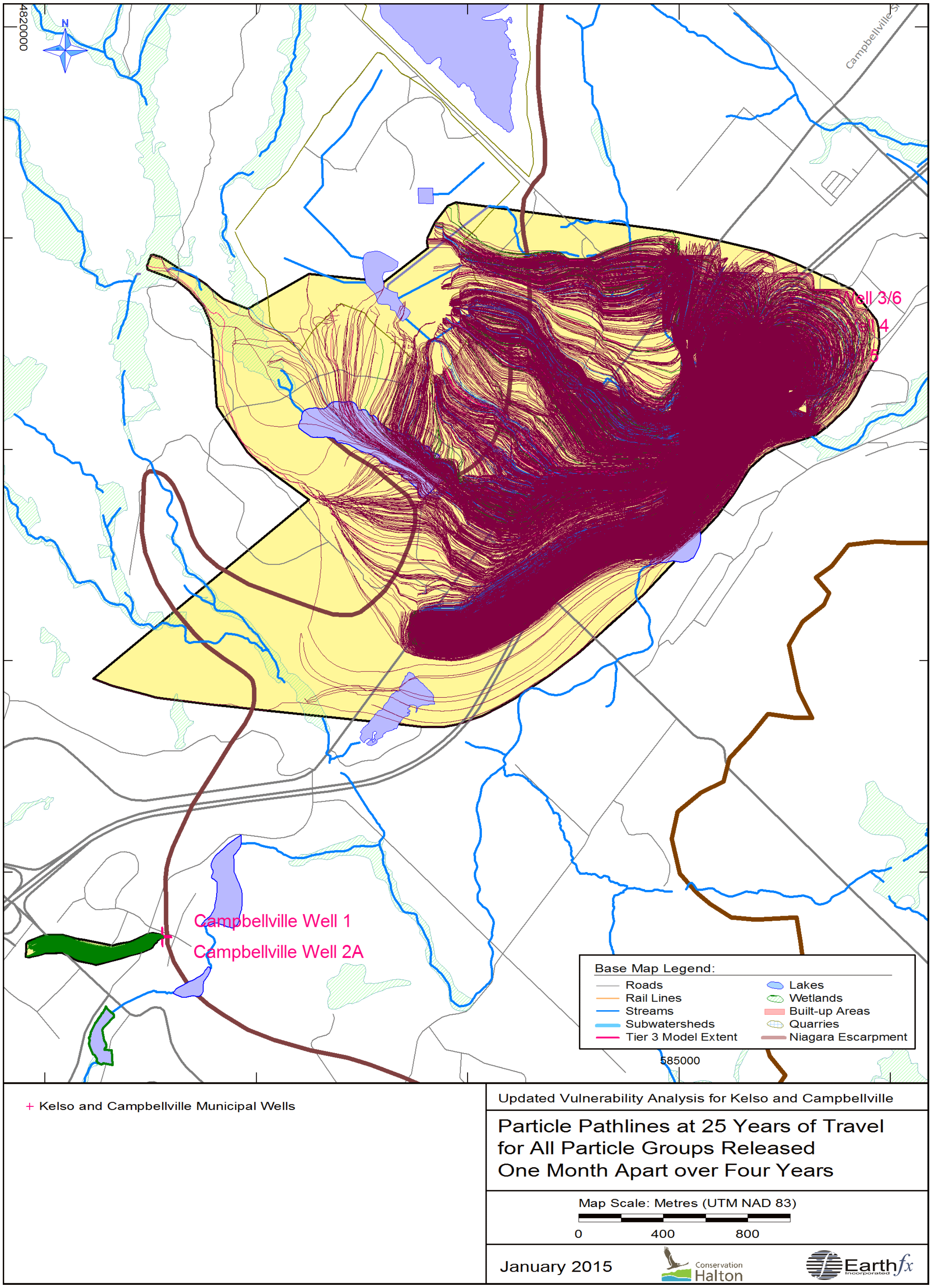


Figure 14: 25-year time-of-travel zone encompassing particle pathlines after 25 years of travel for all particles groups released one month apart over a four-year period from Kelso and Campbellville wellfields.

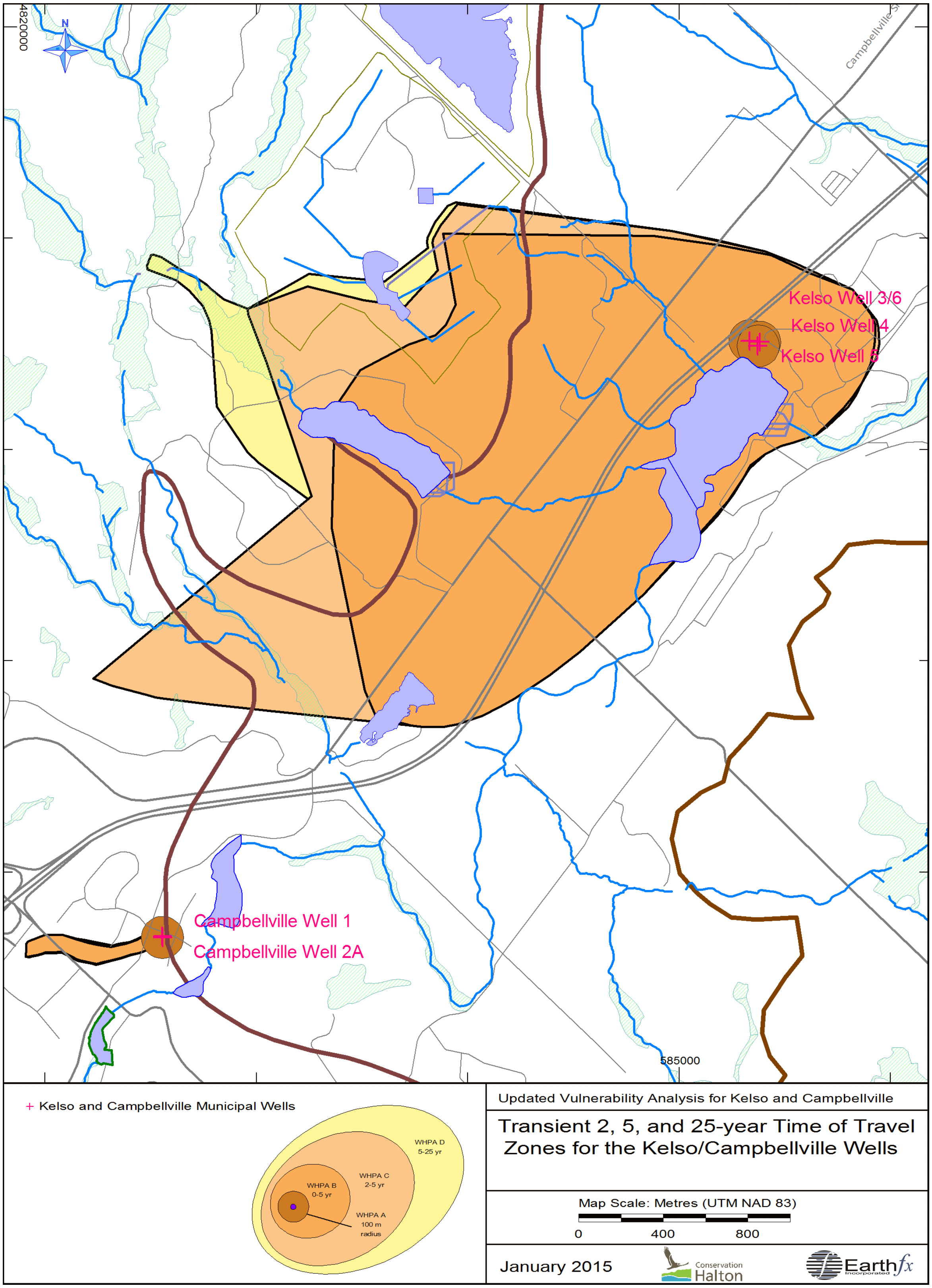


Figure 15: Final 2, 5, and 25 year time-of-travel zones as determined through the transient flow analysis.

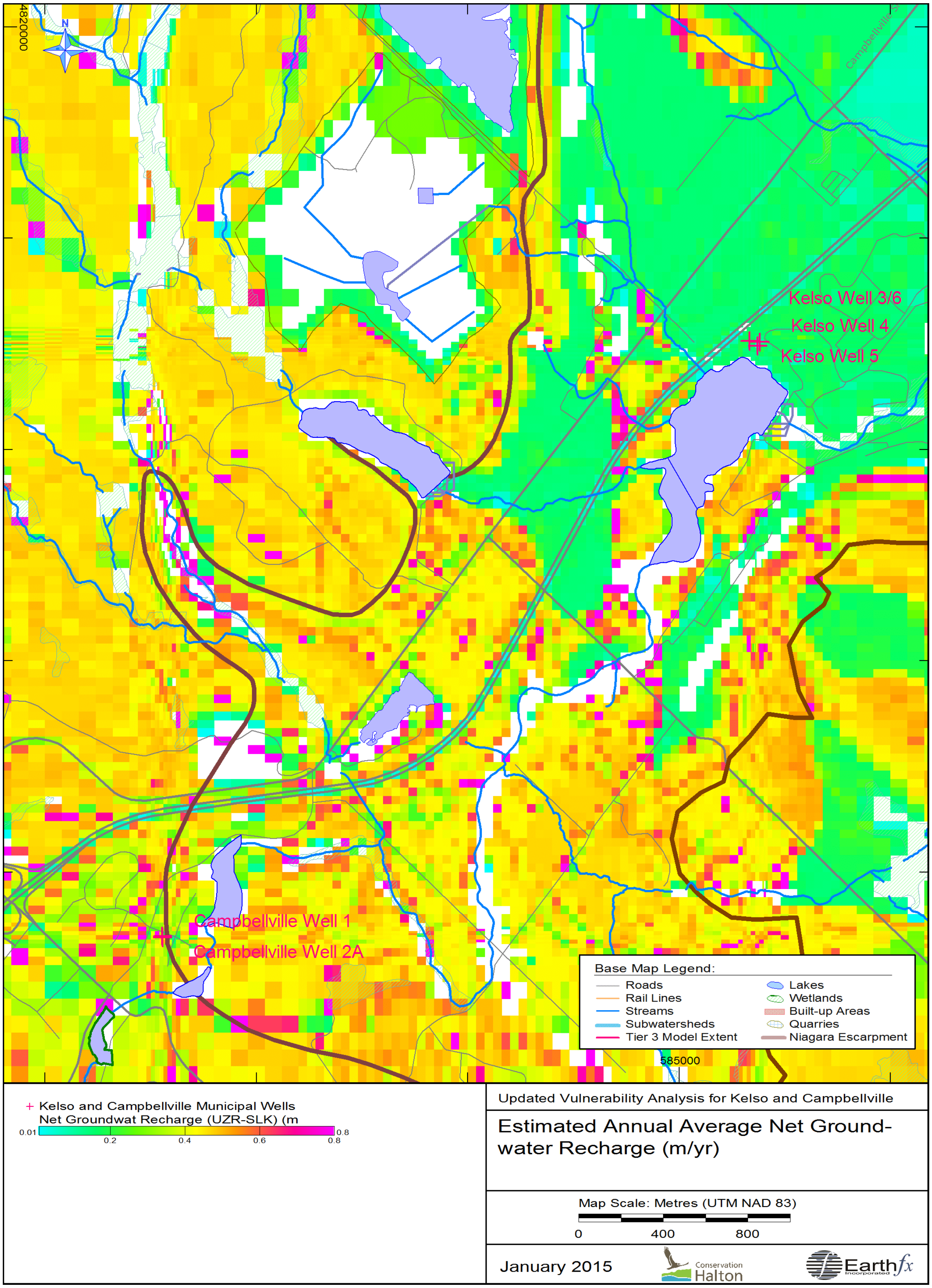


Figure 16: Estimated net groundwater recharge (groundwater recharge minus groundwater discharge to surface), in m/yr, based on long-term GSFLOW simulation.

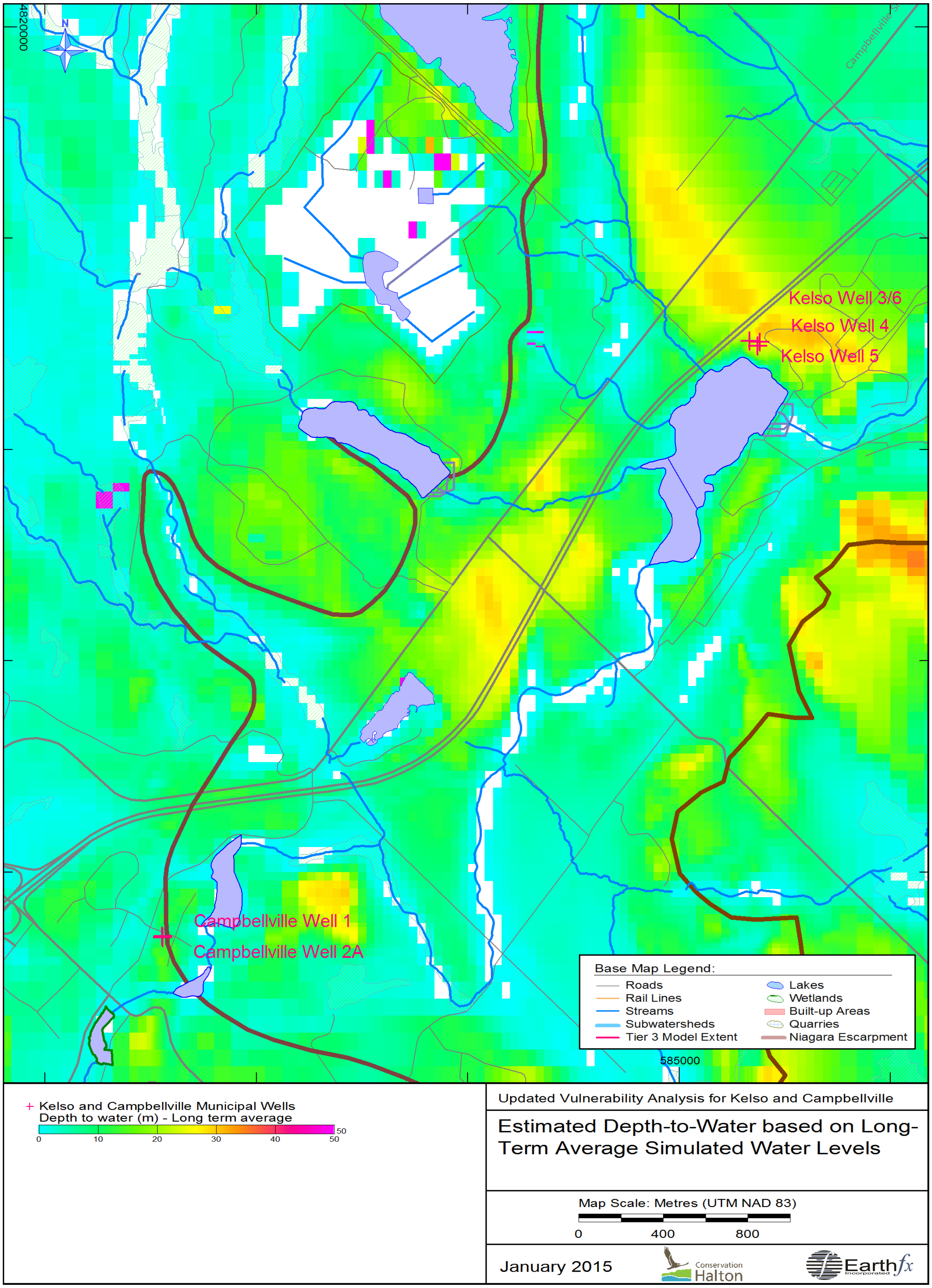


Figure 17: Estimated depth to the water table based on topography and long-term average simulated water levels in Layer 1.

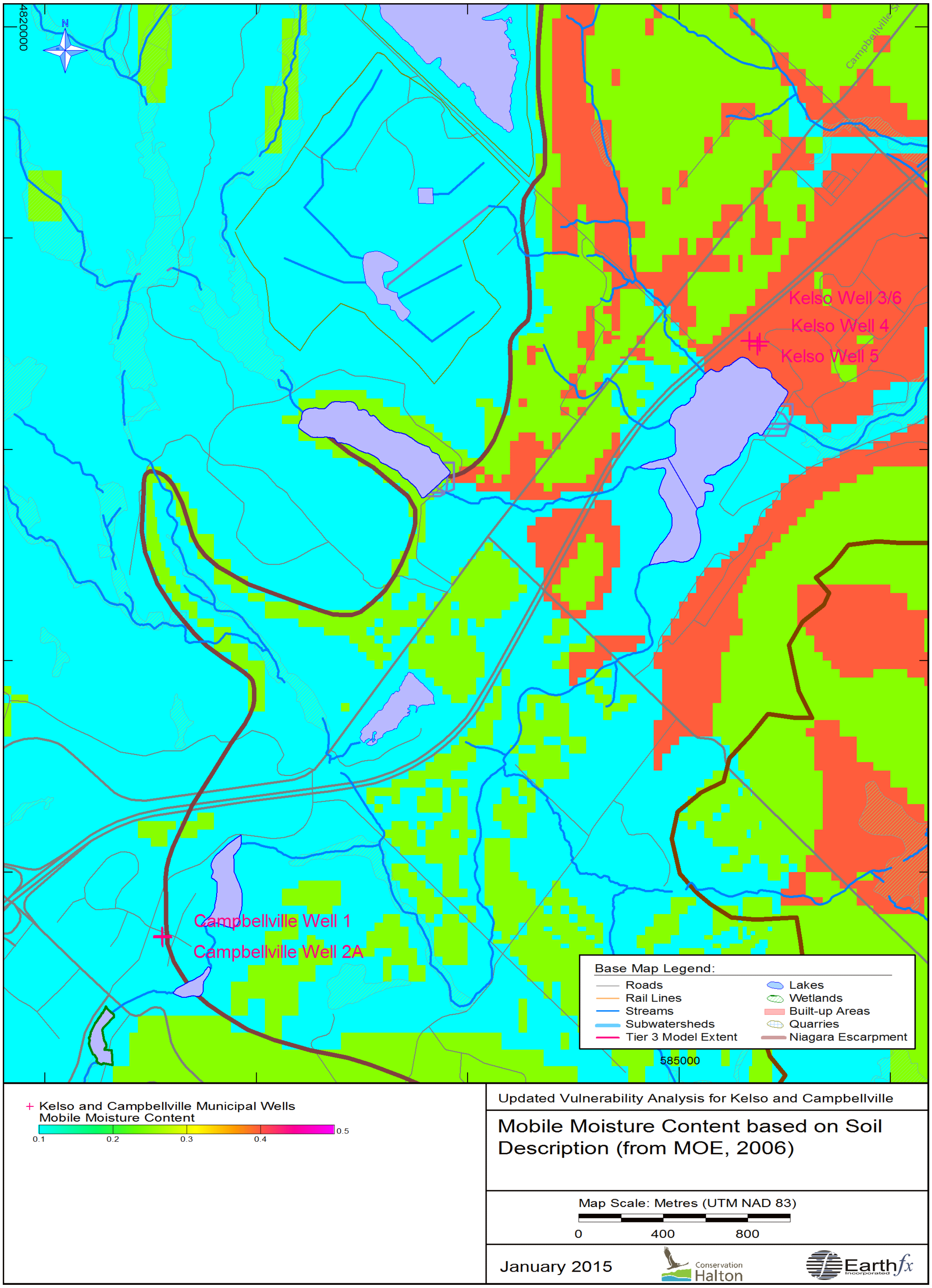


Figure 18: Mobile moisture content based on soil type and values from MOE (2006).

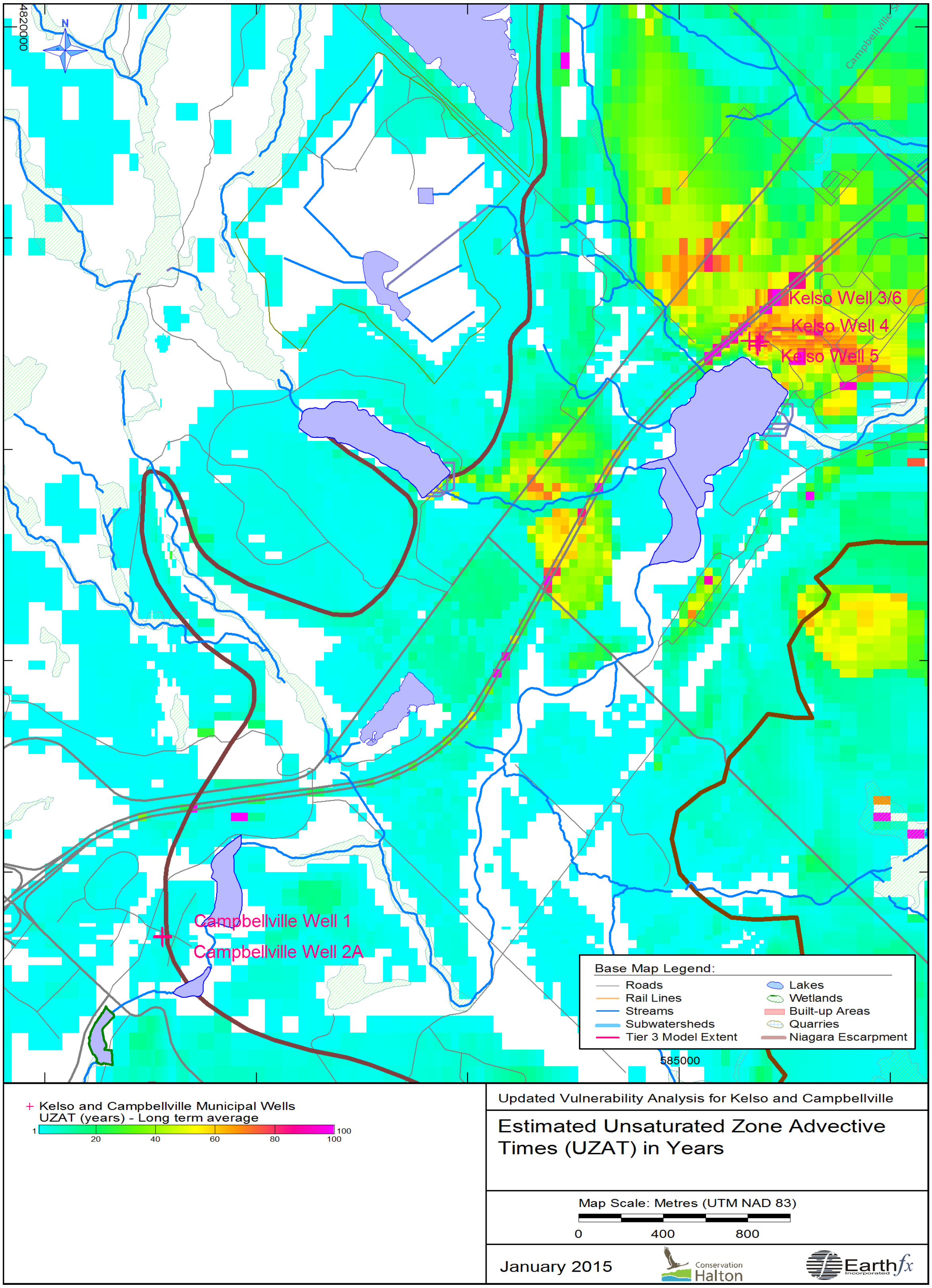


Figure 19: Estimated unsaturated zone advection times (UZAT) in years.

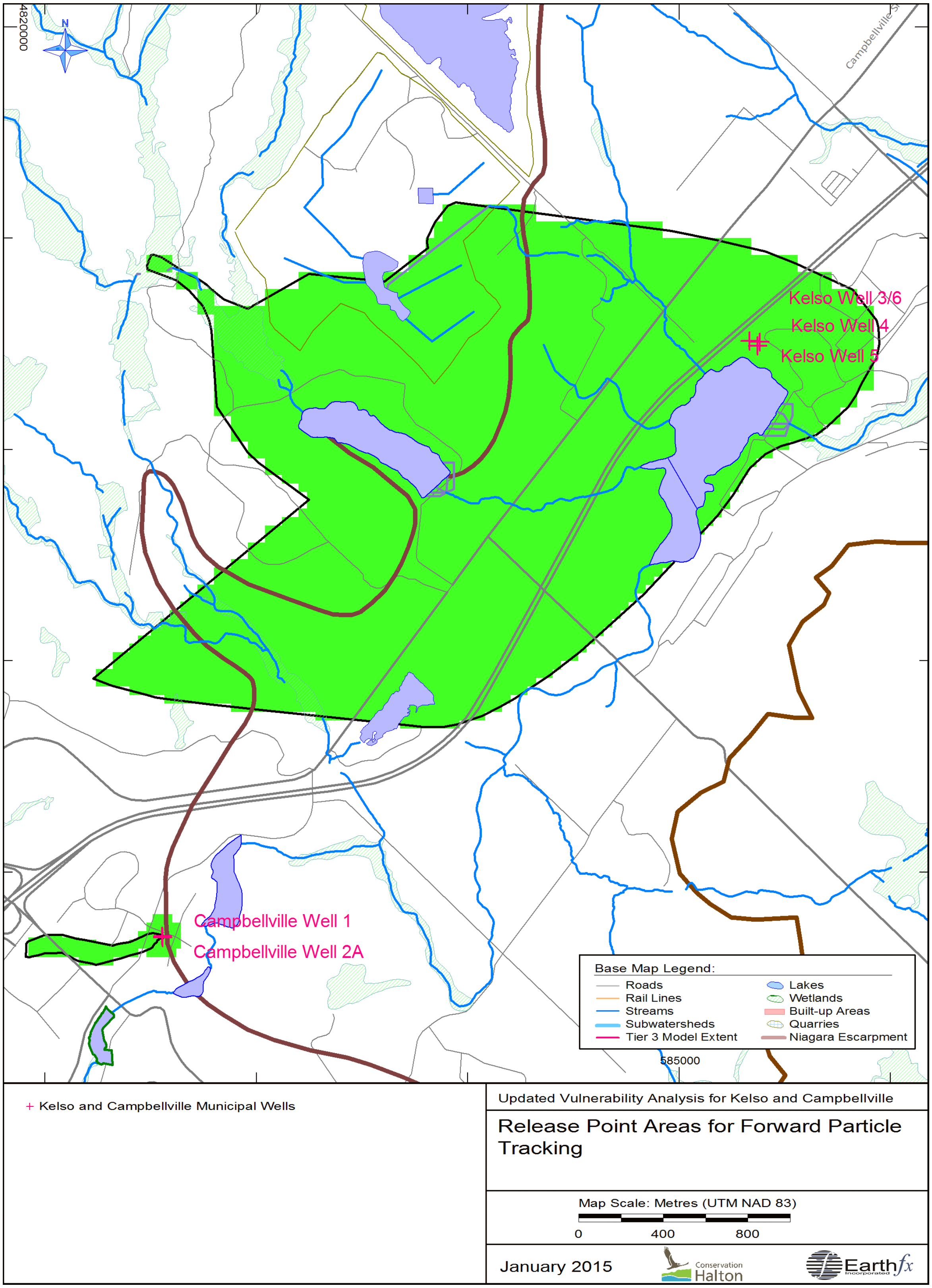


Figure 20: Areas in which particles were released for forward-tracking analysis to determine water table to well advective times (WWAT).

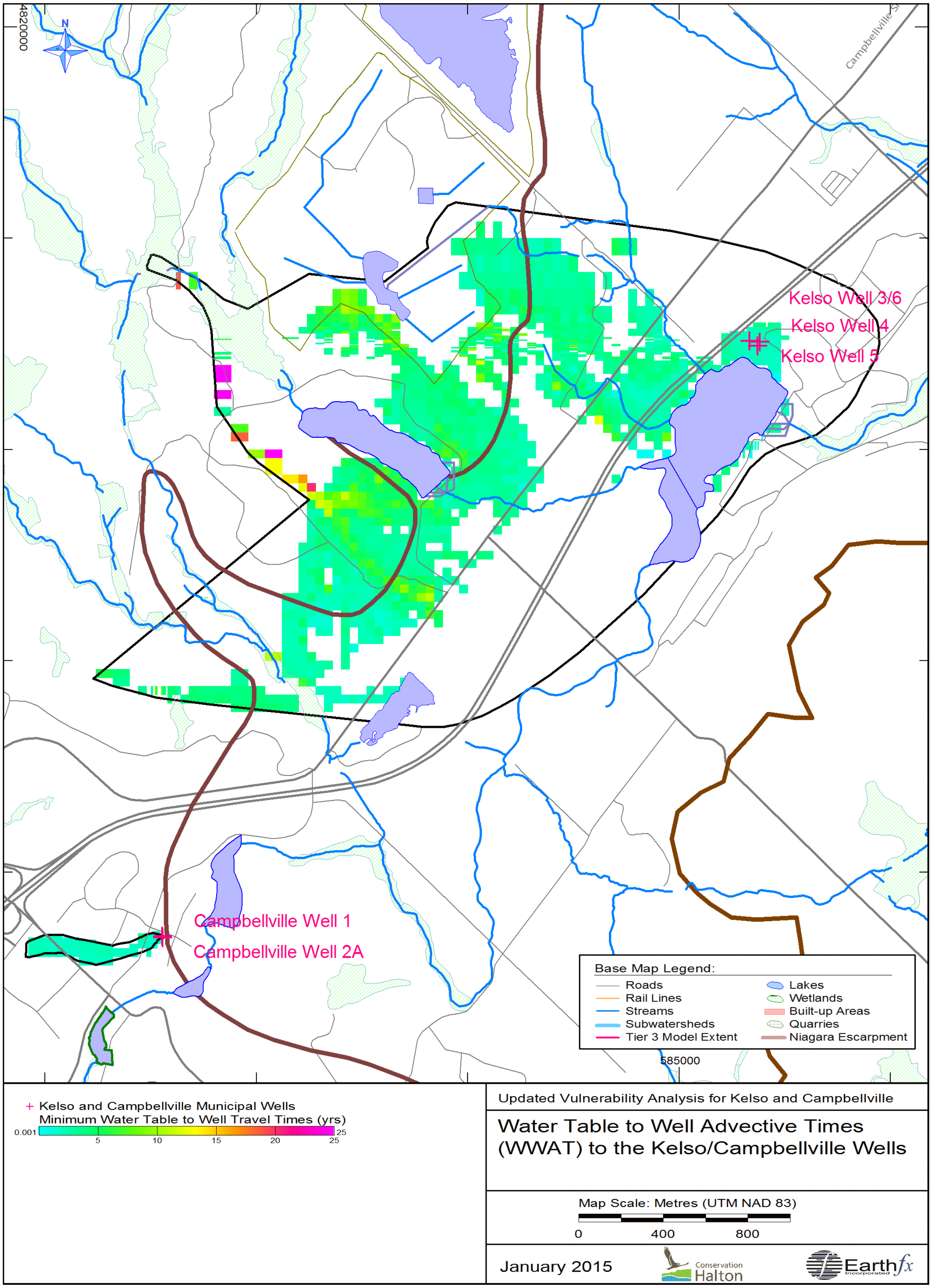


Figure 21: Simulated water table to well advective times (WWAT) based on forward tracking.

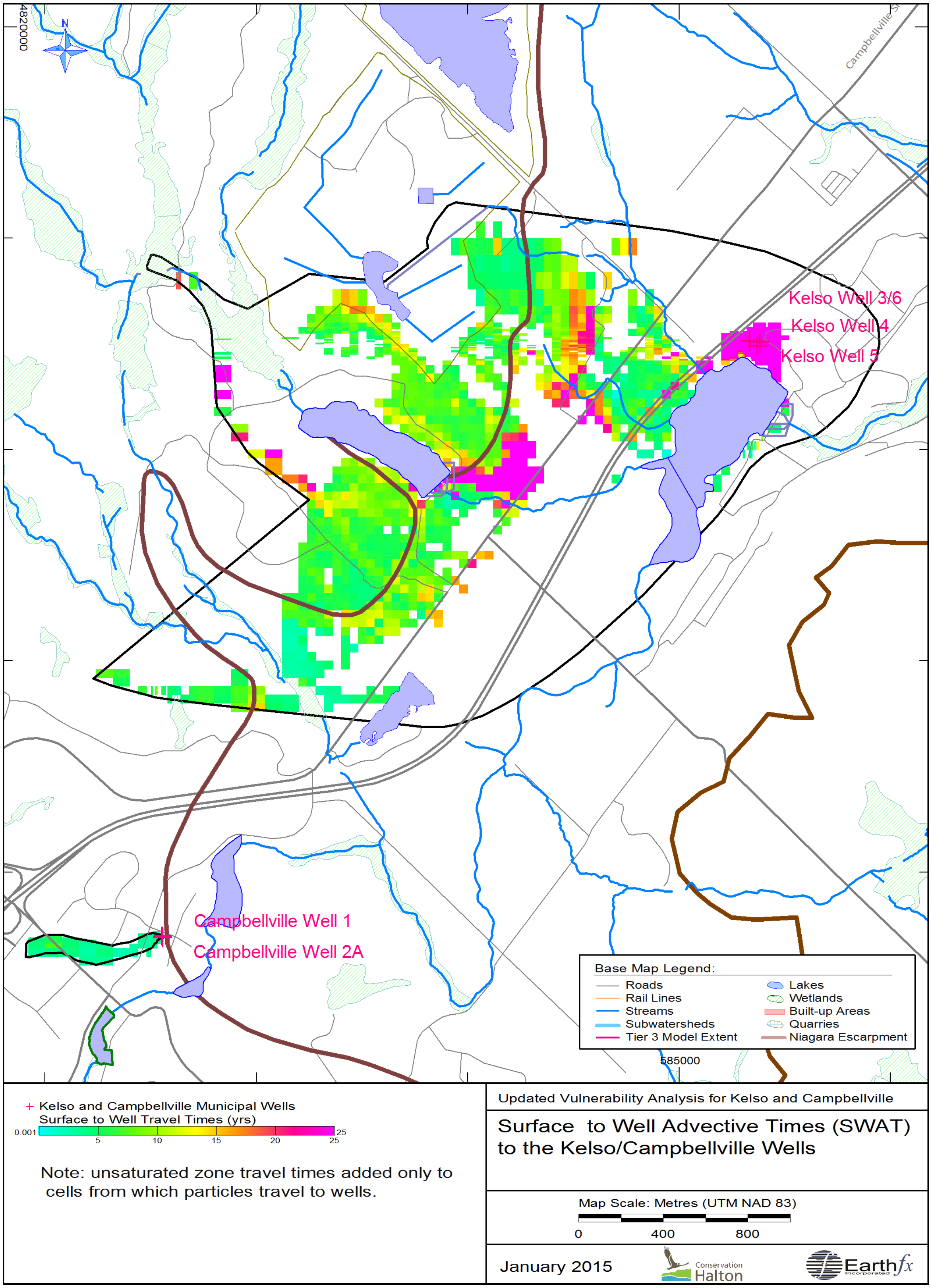


Figure 22: Simulated surface to well advective times (SWAT) based on forward tracking.

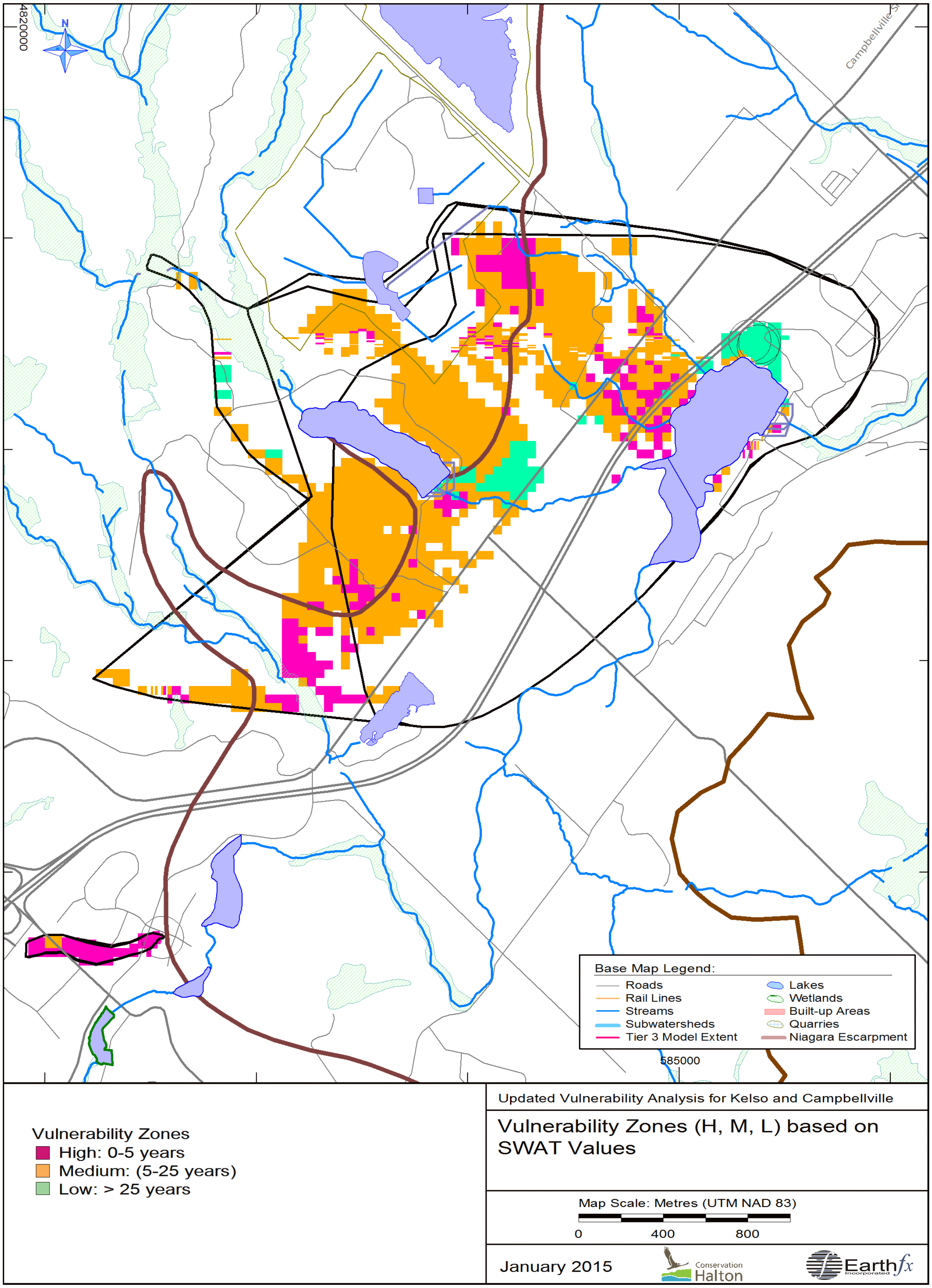


Figure 23: High, medium, and low vulnerability zones based on water table to surface to well advective times (SWAT).

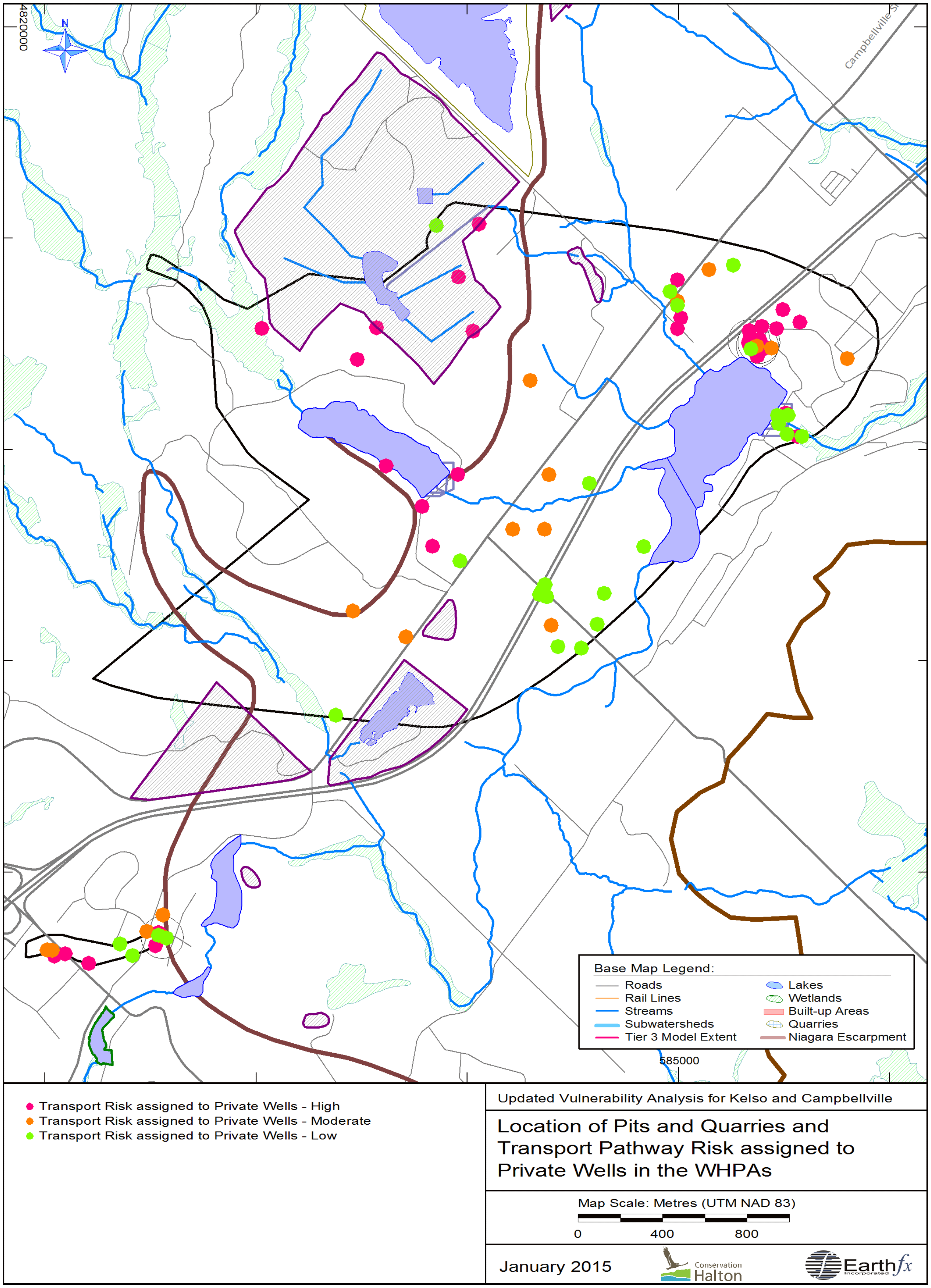


Figure 24: Location of pits and quarries (former and active) and private wells that may pose a transport risk to the municipal wells.

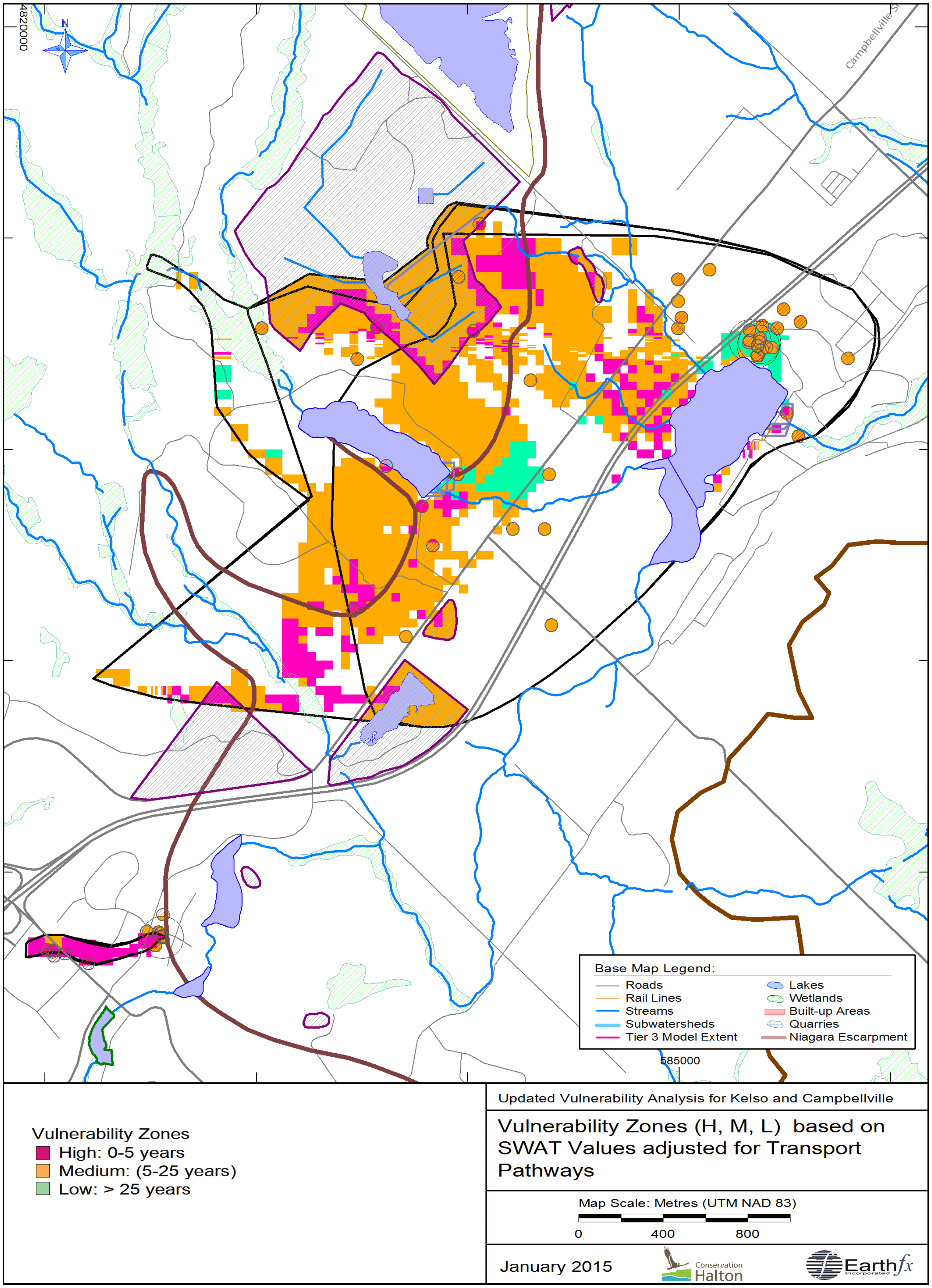


Figure 25: High, medium, and low vulnerability zones adjusted for possible transport pathways associated with pits and quarries and possibly poorly-constructed wells.

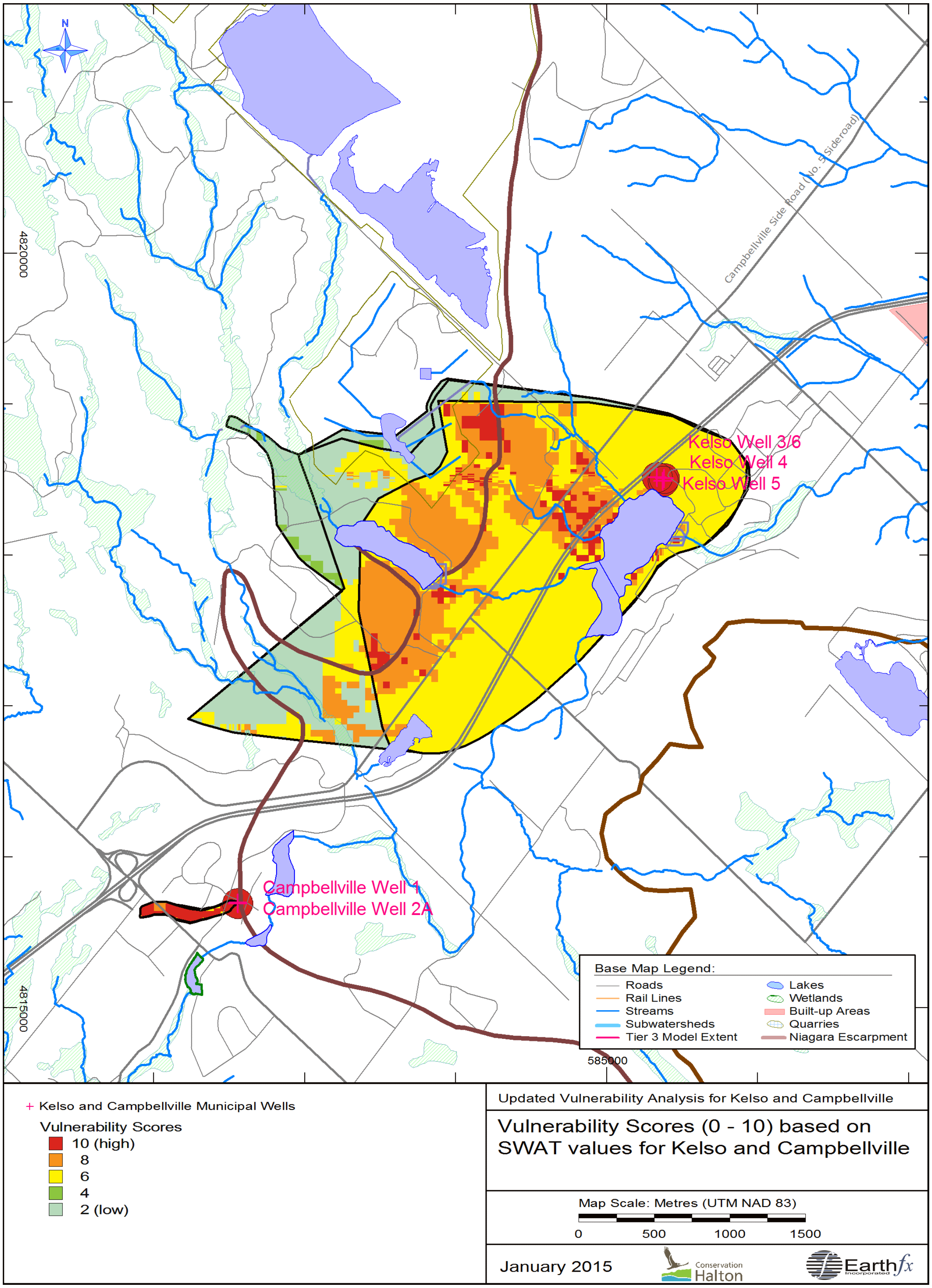


Figure 26: Vulnerability scores (0-10) for Kelso and Campbellville based on water table to well advective times without adjusting for transport pathways.

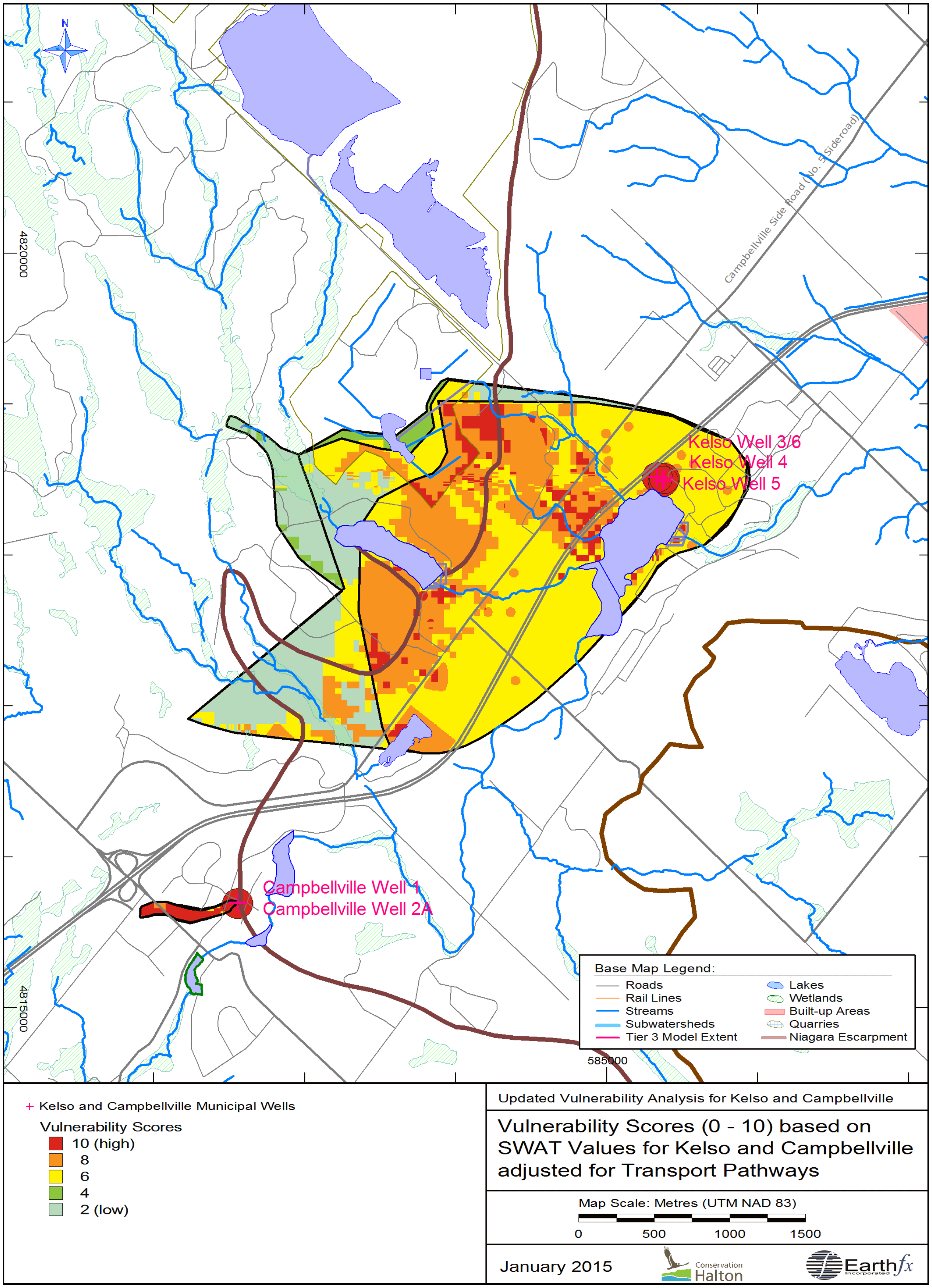


Figure 27: Final vulnerability scores (0-10) for Kelso and Campbellville based on water table to well advective times after adjusting for transport pathways.

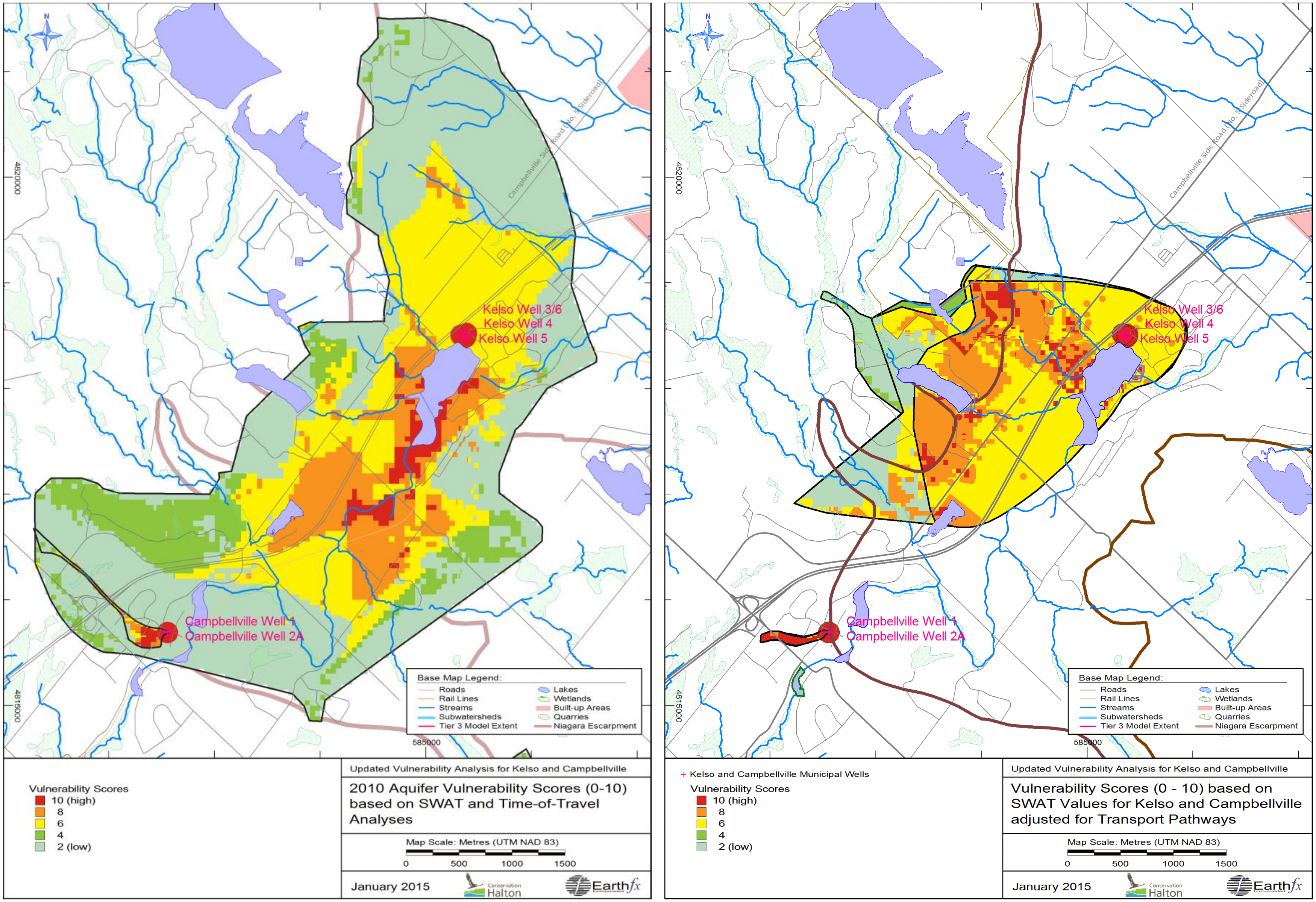


Figure 28: Comparison of 2010 and updated 2015 vulnerability scores at the same map scales.