Impacts of changing agricultural land-use practices on municipal groundwater quality: Woodstock, Ontario

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Abstract The primary groundwater supply for the City of Woodstock, Ontario is drawn from a well field situated in a rural setting outside the city limits. Nitrate concentrations in several of the wells have exceeded the Ontario Drinking Water Guidelines leading to significant concern regarding the long-term water quality of this key supply. The source of nitrate may be related to historical agricultural land-use practices. In an attempt to reduce nitrate levels in the municipal wells, nutrient loadings on the agricultural land within the immediate vicinity of the well field are being significantly reduced through alternative cropping and fertilizing practices. To evaluate the success of these pro-active agricultural land-use practices a multi-faceted investigative approach has been adopted. A key component of this approach involves a detailed hydrogeologic investigation to: (a) improve the conceptual model of the groundwater flow system; (b) estimate the nitrate mass present in the subsurface; and (c) quantify the spatial nitrate mass loading from the agricultural land under investigation. In concert with these data, a three-dimensional flow and transport model is currently under development with the objective of predicting the magnitude and timing of the influence of these land-use changes on the nitrate concentrations extracted by the municipal well field. This paper presents an outline of the novel land-use management strategy employed by the County of Oxford, which oversees the City of Woodstock water supply, hydrogeological details of the various field investigations, and preliminary field results.

Key words agriculture; City of Woodstock, Canada; field investigations; hydrogeologic conceptual model; municipal groundwater; nitrate

INTRODUCTION

In order to evaluate the effectiveness of alternative agricultural land-use management practices designed to reduce nutrient loading to groundwater resources, a thorough understanding of the groundwater flow system and solute transport behaviour must be developed and linked to a comprehensive monitoring programme. This paper presents details of an investigative monitoring strategy that is being employed within the capture zone of a rural municipal well field near Woodstock, Ontario, Canada, where steps are being taken to reduce nitrate loading to the subsurface. Preliminary results of the detailed hydrogeological investigation are presented and discussed within the context of a conceptual model of the groundwater flow system.

Thornton well field

The City of Woodstock is located about 220 km west of Toronto in southwestern Ontario. Two well fields, situated in a rural setting, are used as the primary source of public water supply for the 34 000 Woodstock residents. One of these well fields, the Thornton Well Field (Fig. 1), is located just south of the city's boundary and supplies 56% of the city's water with an average annual extraction rate of 4300 m^3 day^{-1}. This area has been the subject of previous studies (Heagle, 2000; Sebol, 2000; Padusenko, 2001), which focused on developing an initial conceptual model of the groundwater flow system and mapping the regional occurrence of nitrate. As part of these initial studies, a network of 20 monitoring locations was instrumented with 32 wells. Data collected from these monitoring wells provided information on regional groundwater flow and the spatial distribution of nitrate within the capture zone of the Thornton wells. This information formed the basis for the current field investigations.

The site is located in a glacial setting referred to as an interlobate zone where deposition occurred during subsequent ice advances from different directions (Krzyszkowski & Karrow, 2001). This depositional environment is the major cause for

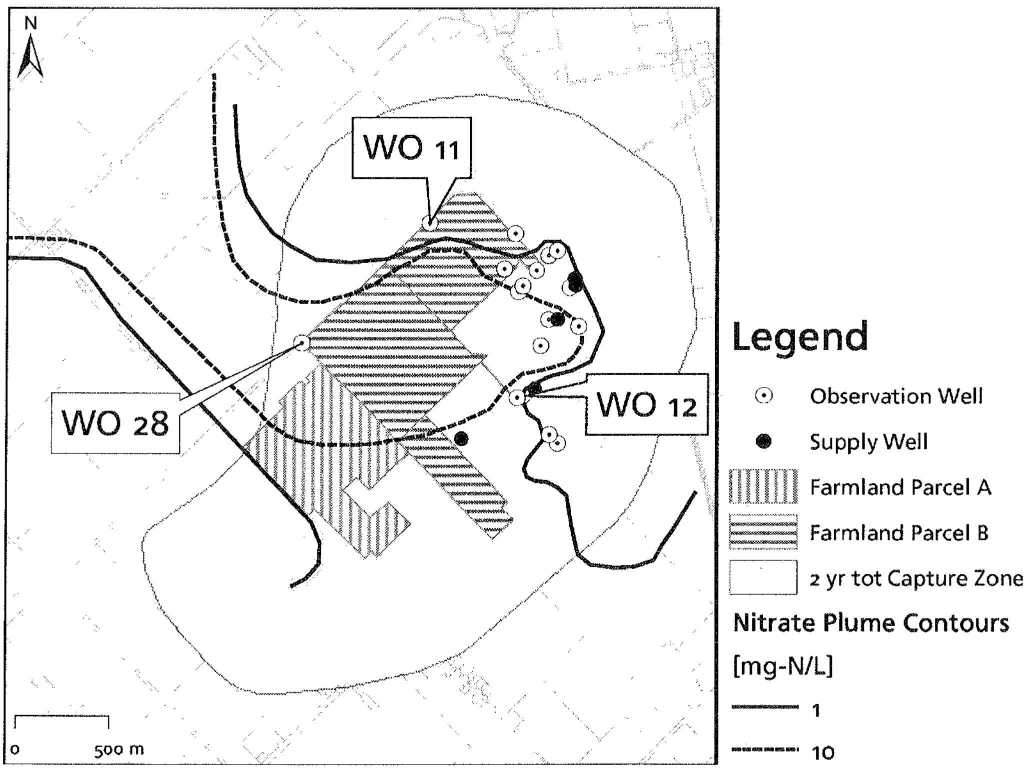

Fig. 1 Map of the Thornton Well Field. The supply wells for the City of Woodstock and numerous observation wells are shown. The recently purchased farmland (Parcels A and B) are indicated. The 2-year time of travel (tot) capture zones were extracted from a wellhead protection study performed by Golder Associates Ltd. (Golder, 2001). Nitrate concentration contours (1 and 10 mg-N l^{-1}) were taken from Padusenko (2001) and are based on the maximum concentration observed at each monitoring location.

spatial heterogeneity in the overburden and resulted in an undulating topography (over 40 m of local relief), and a complex intermingling of granular aquifers and low permeability aquitard units. The wells of the Thornton Well Field are completed in the glacial overburden, which ranges in thickness between 30 m and 70 m within the study area. Two wells (Well 1 and Well 5) are screened in a lower sand and gravel aquifer directly above carbonate bedrock at a depth of about 30 m below ground surface (bgs). All the other wells are screened in an upper sand aquifer (Wells 3, 8 and 11) with depths of ~20 m bgs. In proximity of the well field there is evidence to suggest that both aquifers are hydraulically connected (Fig. 2).

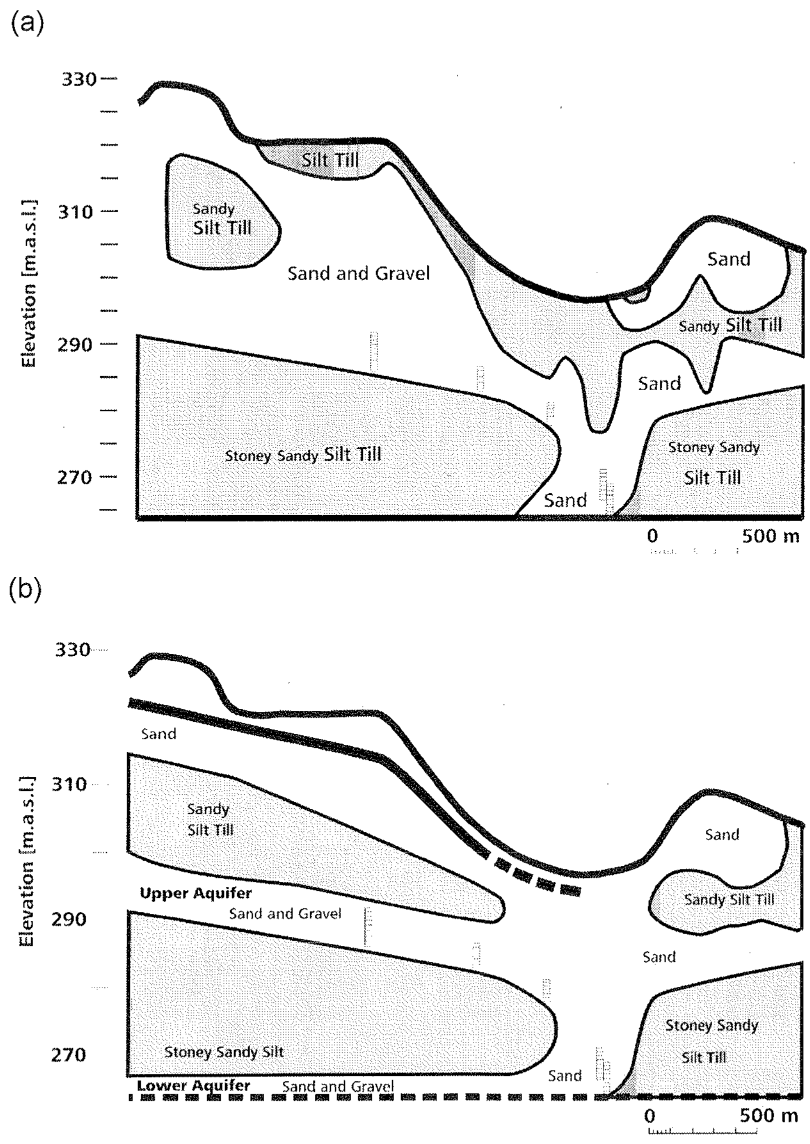

Fig. 2 Cross section of the conceptual hydrostratigraphic model through the five supply wells of the Thornton Well Field (indicated as screened intervals): (a) initial conceptual model after Padusenko (2001); and (b) revised conceptual model as a result of the findings discussed in this paper.

Since 1975 the nitrate concentrations in all five extraction wells have been gradually increasing to a point that wells 1, 3 and 5 now exceed the Ontario drinking water guideline of 10 mg N l^{-1} (Fig. 3). Currently, water from the Thornton Well Field is blended with water from the second well field in order to achieve acceptable concentrations prior to distribution.

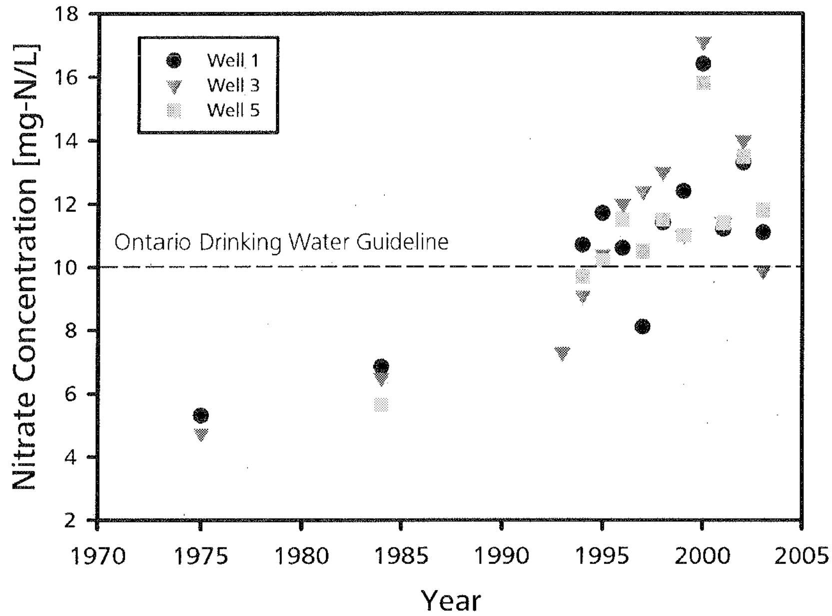

Fig. 3 Maximum annual nitrate concentrations (mg N l^{-1}) observed at three of the five extraction wells in the Thornton Well Field.

The primary source of nitrate is suspected to be agricultural activity since 82% of the land-use within the capture zone of the well field is agriculture. The nitrate plume, as mapped by Padusenko (2001), is evolving from the west into the study area and may be drawn into the Thornton Well Field through a connection between the aquifers in proximity of the supply wells (Figs 1 and 2). The County of Oxford purchased two parcels of farmland totalling 275 acres (111 ha) within the 2-year time of travel capture zone of the combined influence from all of the wells (Golder, 2001) with the intention of reducing excess nitrogen loading near the well field. The land has been subsequently rented back to farmers with restrictions placed on the amount of fertilizer that can be applied.

On one 95-acre (38-ha) parcel of farmland (Parcel A, Fig. 1) fertilizer application is timed to maximize crop uptake. The farmer managing this parcel of land was required to develop a Nutrition Management Plan (NMP) based on the guidelines provided through the Ontario Ministry of Agriculture and Food (OMAF, 2004). The NMP is intended to assist farmers in optimising the use and management of all nutrients within the overall agricultural operation.

On the other parcel of farmland comprising 180 acres (73 ha, Parcel B, Fig. 1) minimal nutrient inputs are prescribed. The soil was tested extensively across the fields to determine the spatial distribution for nutrient requirements. Based on the soil test data, minimum nutrient requirements were determined relative to the selected crop type. Fertilizer is being applied with the aid of a global positioning system- (GPS-) assisted fertilizer spreader, and detailed loading records are being collected for subsequent use in mass loading estimates. Considering the tight restrictions on fertilizer applications in Parcel B, the County of Oxford subsidizes the agricultural activity by renting the land for less than market value.

Study objective and methodology

The overall study objective is to evaluate the effectiveness of the pro-active modifications to the land-use practice on the nitrate concentrations within the Thornton Well Field. The study has been designed to: provide an estimate of nitrate mass presently in the subsurface; quantify the spatial distribution of nitrogen loading within the purchased land area; develop a monitoring strategy to evaluate the effectiveness of the changes in agricultural land-use practices; and predict the impact on the water quality in the municipal wells.

The first phase of the study involved a detailed hydrogeological investigation focused on enhancing the understanding of the groundwater flow system and mapping the spatial distribution of nitrate mass in the unsaturated zone. Field work involved installation of a deep monitoring well cluster designed to improve our understanding of the complete sequence of hydrostratigraphic units and determine the nature of vertical hydraulic gradients, physical parameters and nitrate concentrations at a key location within the study area. In addition, geophysical techniques, including surface electromagnetic surveys (EM 34) and terrain resistivity profiles were conducted at various locations to assist in mapping the lateral continuity of the near surface sediments and soil moisture content distributions. Sediment cores were also collected at several spatial locations across the agricultural fields to provide additional stratigraphic information and soil water nitrate concentrations.

This paper reports on the preliminary results, interpretations and implications of this phase of the field investigation and discusses the subsequent components of the overall study in relation to these results.

RESULTS AND DISCUSSION

Because this well field is located in a complex glacial environment, the spatial variability of stratigraphic layers and the hydraulic parameters of the sediments are extremely high. A major focus of the field activities was to better delineate the main aquifer and aquitard units within the study area. A brief summary of the results from these activities is provided below.

To augment information obtained from the existing network of >30 monitoring wells installed during previous investigations, which were primarily restricted to the upper 20 m of the overburden sequence, a deep borehole (70 m) was completed to bedrock at the western edge of the purchased land parcels (WO 28, Fig. 1) and instrumented with a cluster of four wells. The deepest well in this cluster was installed

3 m into bedrock, two wells were placed in a lower highly-productive aquifer just above bedrock at ~67 m, and the remaining well was installed in an upper aquifer at a depth of 30 m. Geometry of the well cluster, piezometric levels and the hydrostratigraphic sequence are shown in Fig. 4. The surface elevation at the location of WO28 is approximately 30 m higher than at the Thornton Well Field.

The hydraulic head data suggest the presence of perched conditions in several of the aquifer units with a significant amount of unsaturated sediment separating the water bearing strata. The two main aquifer units (upper and lower) are not in direct hydraulic connection in this part of the study area. Pressure conditions indicate flow

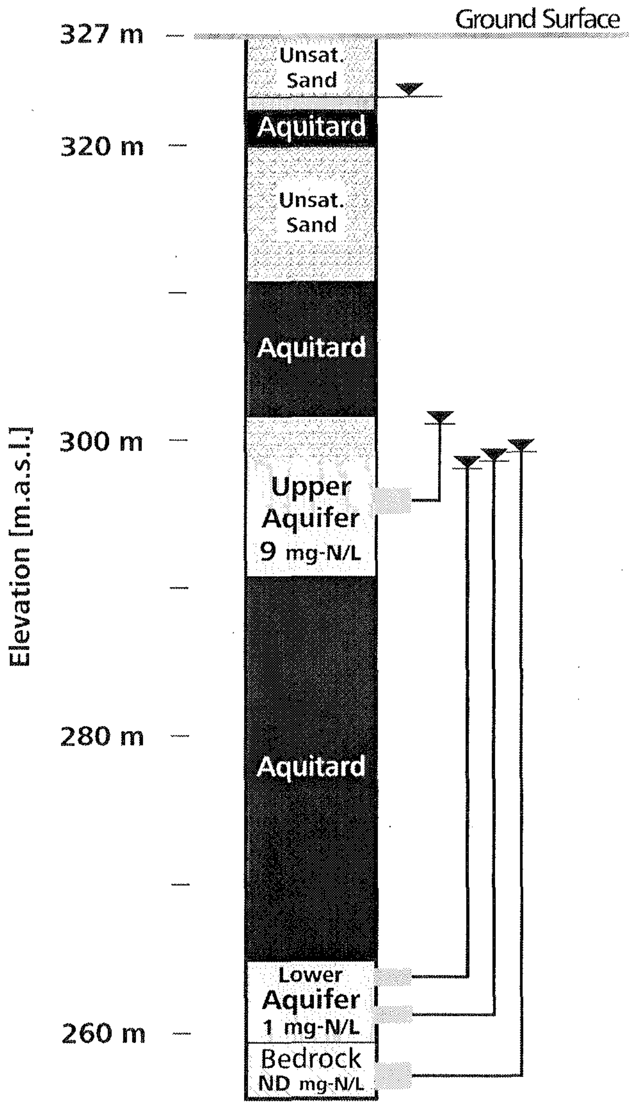

Fig. 4 Stratigraphic log of borehole WO 28 showing the location of the screened intervals, the associated water level for each observation well, and the nitrate concentration measured in each water bearing zone.

into the lower aquifer. This is in direct contrast to the flowing artesian conditions present in the lower aquifer in the vicinity of the Thornton Well Field (Padusenko, 2001).

This deep well installation produced two key pieces of site information. The first piece of information is the documented presence of the Lower Aquifer at this location, which was not included in previous conceptual models (Fig. 2(a)). This indicates that this deeper aquifer unit is more laterally extensive than was previously thought. The second key piece of information was that the shallow groundwater flow system appears to be isolated by a thin aquitard unit above the underlying aquifers suggesting that little downward nitrate mass flux occurs in this region. Because shallow groundwater flow systems transmit and distribute infiltrating contaminants deeper into the flow system, characterizing the nature of the shallow flow system is important and is discussed in more detail below. Geochemical data suggest that both the shallow water table system and the upper aquifer have elevated levels of nitrate. Because unsaturated conditions exist between the shallow system and the upper aquifer unit, it is likely that the elevated nitrate levels observed in the upper aquifer at this location are due to land-use activities outside and upgradient of the parcel of land owned by the County (Fig. 1). This regional inflow of nitrate mass may be contributing to the high nitrate concentrations observed in the Thornton wells. The lower aquifer, however, shows no signs of elevated nitrate, supporting the conclusion that the two aquifers are hydraulically isolated from each other in this area and that nitrate mass moving into the capture zone of the wells is predominantly located in the shallower units.

Geophysical mapping of the shallow subsurface

To develop a more complete picture of the spatial distribution of the shallow aquitard unit, two complimentary geophysical techniques were used: electrical resistivity and surface electromagnetics (McNeil, 1980; Loke, 2004). Both of these techniques were effective at distinguishing the moisture content contrast between the wet topsoil material above the aquitard and the dry sandy sediments below the aquitard.

Five electrical resistivity lines were surveyed using a 5 m electrode spacing which provides a penetration depth of ~30 m (McNeil, 1980). All survey lines began at WO 28 since the presence of the aquitard at this location was known (Fig. 5). Figure 6 illustrates the electrical resistivity results from line 1. In general, areas of high electrical conductivity, which were encountered at shallow depths, correspond to high moisture contents. Along most of the length of this survey line a sharp conductivity contrast is present between 5 and 8 m bgs indicative of lower moisture contents in the sandy sediments below the aquitard. At ~680 m along this survey line, high electrical conductivity values are found at greater depths suggesting the edge of the aquitard has been reached (i.e. a window has been located) and that the sandy sediments have increased moisture contents. Further along this line (780–1000 m) a low conductivity zone reappears indicating the discontinuous nature of this shallow aquitard.

An electromagnetic survey (Geonics EM 34) was performed over the 20 acres (8 ha) area indicated on Fig. 5 using two transmitter/receiver spacings (10 and 20 m) and two operational modes (horizontal or vertical). Figure 5 presents the EM 34 survey results for a 20 m spacing and a vertical operational mode on a 20 × 50 m grid. This configuration provides the deepest range of penetration of the four modes used. These measurements suggest extensive areas of low conductivity between 10 m and 30 m bgs near the topographic high, and high conductivities in regions to the north of the surveyed area. These findings are consistent with the resistivity survey results (Fig. 6) and further assist in delineating the continuity of this critical shallow aquitard unit that may play an important role in the control of the subsurface migration of infiltrating nitrate mass.. Based on all of these data, an undated hydrogeological conceptual model is shown in Fig. 2(b).

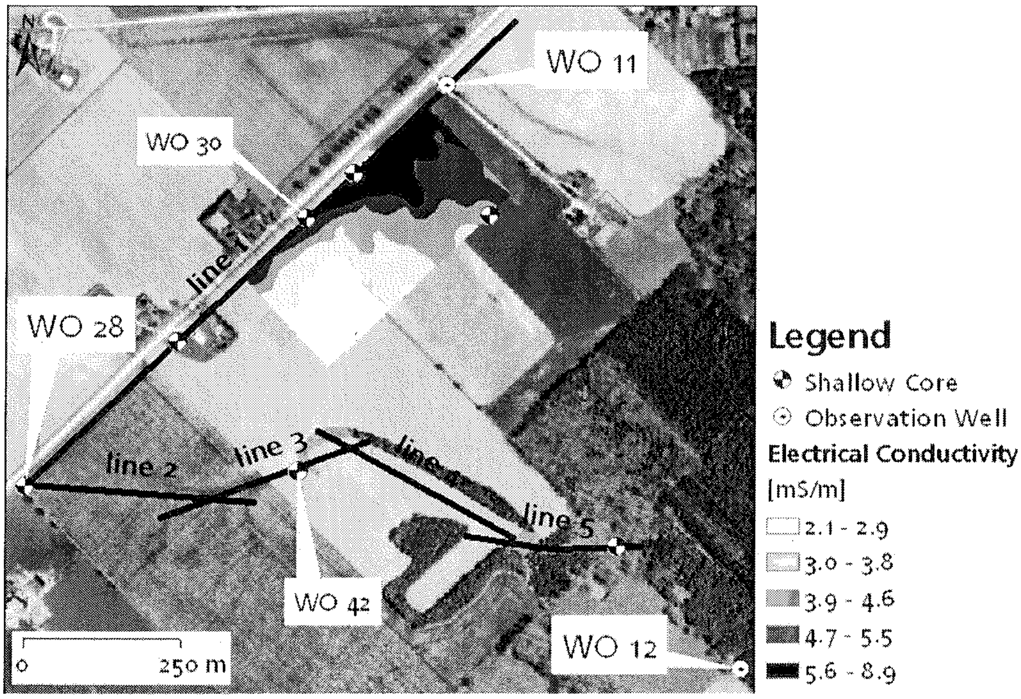

Fig. 5 Location of the five resistivity survey lines, and the area covered by the EM survey.

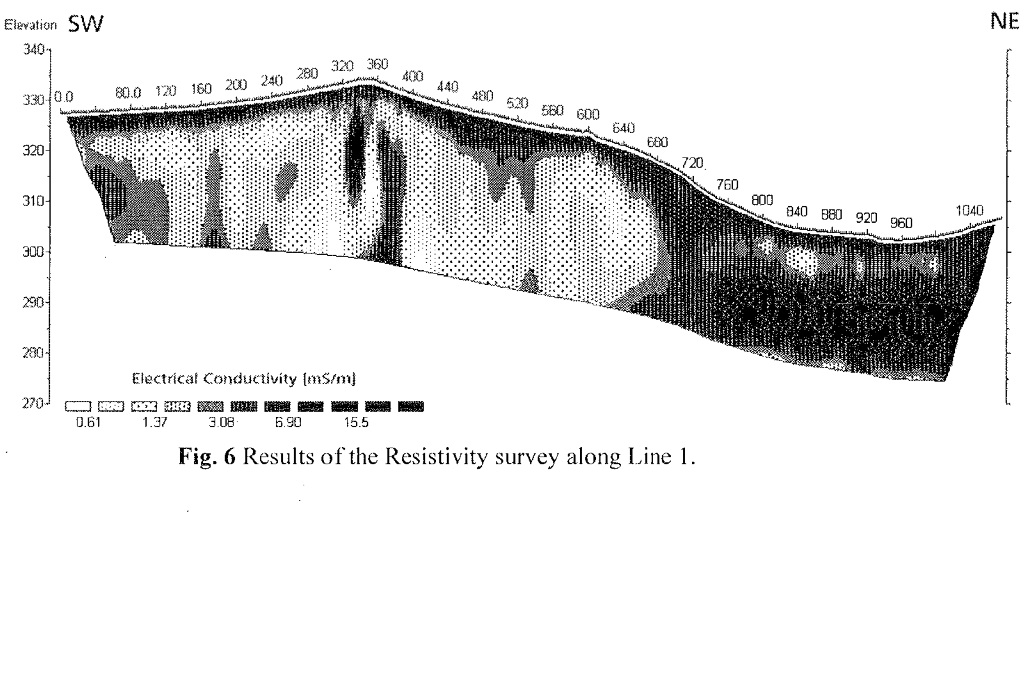

Fig. 6 Results of the Resistivity survey along Line 1.

Hydraulic response

To further investigate the vertical hydraulic connection between the different hydrostratigraphic units, the hydraulic response of this multi-layered aquifer system to recharge events was monitored with pressure transducers placed in wells at various spatial locations within the study area. Figure 7 presents an example of the temporal profile of hydraulic head at two discrete depths in wells WO 11 and WO 12 (see Fig. 1 for well locations) along with daily precipitation data. At WO 11 water levels at both depths responded rapidly to precipitation events indicating a direct hydraulic connection, while the water levels at WO 12 showed a very weak response (seasonal trend) to precipitation events. These findings once again emphasize the need to understand the hydraulic connections between various aquifer units since these connections control the contaminant migration pathways from the surface (source) to the extraction wells (receptor).

Soil water analyses

Another critical characteristic required to estimate the temporal impact of land-use changes on the nitrate concentrations in the extracted water at the Thornton Well Field is the mass of nitrate stored in the subsurface system prior to changes in land-use. The nitrate concentrations observed in the network of wells can be used to estimate the nitrate mass present in the saturated zone; however, a large portion of the subsurface system at this site is unsaturated (Figs 2 and 4). To estimate the mass stored in the unsaturated zone, soil cores were extracted below the root zone at several locations across the fields to establish vertical profiles of pore water nitrate concentrations. Representative locations were selected based on the presence or absence of the shallow aquitard,

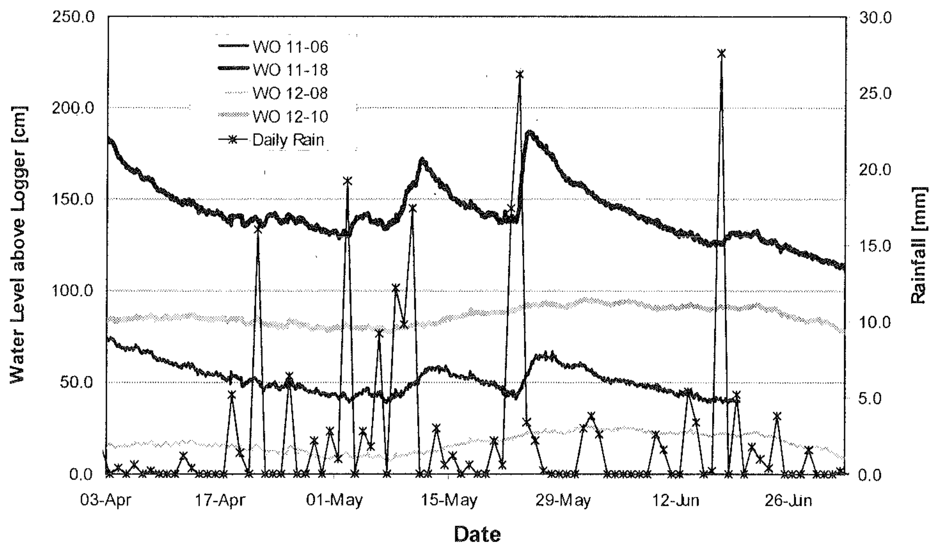

Fig. 7 Water level response at two discrete depths in wells WO 11 and WO 12 (see Fig. 5 for locations). Monitoring piezometers WO 11-06, and WO 12-08 are the shallow piezometers at each location.

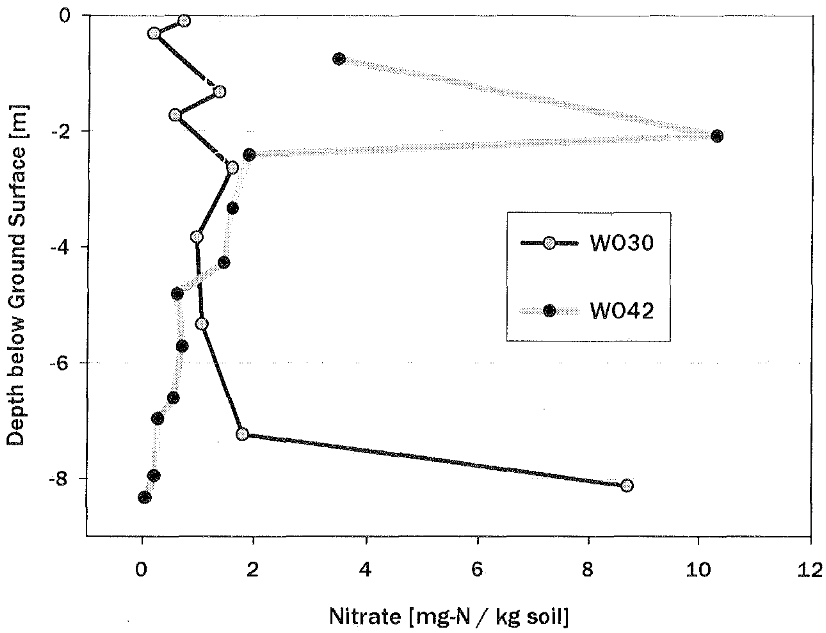

Fig. 8 Example bulk soil nitrate concentration profiles. Core WO30 was extracted from a location where sand overlies the shallow aquitard which was present at a depth of 8 m, and Core WO42 was extracted from a location where the upper 8m consists of silty till material. Core locations shown on Fig. 5.

electrical resistivity and electromagnetic survey data, analytical soil data, transient hydraulic response data, and anecdotal evidence from local farmers. Due to variations in subsurface geology, surface topography and nutrient loading, the vertical profiles of stored nitrate in the unsaturated zone are also highly variable as indicated in Fig. 8.

Because these core data represent a "snap shot" of the near surface nitrate concentration profiles, supplementary soil cores will be extracted in proximity to previous core locations to observe the change in land-use practices on the near surface nitrate distribution below the root zone over time.

SUMMARY

Understanding the spatial overburden heterogeneity with some degree of certainty in complex glacial aquifer/aquitard systems is a difficult task. Although an initial hydrogeological conceptual model was available for this site (Fig. 2(a)), the information was insufficient to address the overall objectives of this research project and as such additional field activities were undertaken. The independent and complimentary data sets (geophysical surveys, transient hydraulic head fluctuations, and soil water analyses) collected during this initial phase of field activities suggest that it is possible to qualitatively show how the spatial distribution of an aquitard focuses recharge and therefore nitrate mass loading to the aquifer system in the vicinity of the extraction wells. These additional data have allowed a further refinement of the initial conceptual model as shown on Fig. 2(b). Understanding the nature of the various controlling features is a critical step to demonstrate the link between land-use and nitrate concentration changes in the extraction wells.

The data presented in this paper captures some of the findings from the initial phase of this investigation and represents a step towards satisfying the overall study objective. Additional ongoing field investigations include: profiling of the extraction wells to better understand the vertical nitrate flux entering each well screen; estimation of the spatial variability of nitrate mass loading; additional soil water analyses; tile drain characterization and sampling; and direct quantification of groundwater recharge.

Integration of all these different data sets will form the basis for the construction of a three-dimensional flow and transport model (FeFlow, Diersch, 2004) which will be used to make predictions of the magnitude and timing of the influence of these land-use changes on the nitrate concentrations extracted by the municipal well field. These modelling efforts are currently underway.

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