AN INVESTIGATIVE FRAMEWORK FOR ASSESSING THE IMPACT OF CHANGES IN AGRICULTURAL LAND-USE PRACTICES ON MUNICIPAL GROUNDWATER QUALITY: THE WOODSTOCK STUDY

Claus P. Haslauer, University of Waterloo, Ontario, Canada
David L. Rudolph, University of Waterloo, Ontario, Canada
Neil R. Thomson, University of Waterloo, Ontario, Canada

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 is believed to be related to historical agricultural land-use practices. In an attempt to reduce nitrate levels in the municipal wells, nutrient loading on the agricultural land within the immediate vicinity of the well field is 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 framework is being developed. This involves a detailed hydrogeologic study to develop a conceptual model of the groundwater flow system, an estimate of the spatial nitrate-mass loading from the agricultural land under investigation and predictions of the magnitude and timing of the influence of these land-use changes on the nitrate concentrations extracted by the municipal well field. This presentation includes an outline of the novel land-use management strategy employed by the County of Oxford which oversees the City of Woodstock water supply, hydrogeologic details of the various field investigations, and preliminary results.

RÉSUMÉ

La source principale d'approvisionnement en eau potable de la ville de Woodstock en Ontario provient d'un champ de puits situé à l'extérieur de la ville, en milieu agricole. La concentration en nitrates dans plusieurs des puits excède la norme ontarienne pour l'eau potable, ce qui soulève beaucoup de préoccupations à l'égard de la pérennité de cette ressource clé. La source de nitrates serait liée aux pratiques agricoles passées. Dans le but de diminuer le taux de nitrates dans les puits municipaux, la charge de nutriments ajoutée aux champs agricoles à proximité du champ de puits est réduite grâce à l'utilisation de pratiques agricoles alternatives. Afin d'évaluer le succès de ces pratiques agricoles pro-actives, une étude hydrogéologique est présentement en cours afin de développer un modèle conceptuel de l'écoulement de l'eau souterraine, d'estimer la masse de nitrates provenant des terres agricoles à l'étude et de prédire l'importance et la chronologie de ces pratiques sur la qualité de l'eau dans le champ de puits. La présentation inclut un résumé de la stratégie innovatrice d'aménagement du territoire employée par le Comté d'Oxford, des détails hydrogéologiques provenant des différents relevés de terrain et des résultats préliminaires de l'analyse numérique.

1. INTRODUCTION

The effectiveness of alternative agricultural land-use management practices to reduce nutrient loading to groundwater resources shall be assessed. For this evaluation a comprehensive monitoring program in addition to a thorough understanding of the groundwater flow system and solute transport behaviour is required.
This extended abstract presents the development of an investigative monitoring strategy that is being employed within the capture zone of a municipal well field near Woodstock, Ontario. Preliminary results of a detailed hydrogeological investigation designed to evaluate the influence of significant reductions in nutrient loadings on lands within the capture zone will be presented and discussed.

2. THE THORNTON WELL FIELD

The City of Woodstock is located about 220 km west of Toronto in south-western Ontario. Two well fields are used as the sole source of public water supply for the 34,000 Woodstock residents. The Thornton Well Field (Figure 1), located just south of the city's boundary, supplies 56% of the water with an average annual extraction rate of 4,300 m^3/day. The area has been the subject of previous studies (Sebol 2000, Heagle 2000, Padusenko 2001), which focussed on developing an initial conceptual model of the groundwater flow system and mapping the regional occurrence of nitrate.
Two wells in this well field (Well 1 and Well 5) are screened in a lower sand and gravel aquifer directly above bedrock at a depth of about 30 m below ground surface. All the other wells are screened in an upper sand aquifer (Wells 3, 8 and 11) with depths of ~20 m. In proximity of the well field there is evidence to suggest that both aquifers are hydraulically connected (Figure 2). The site is located in a glacial morphologic setting referred to as an interlobate zone with deposition occurring during different ice advances from different directions (Krzyszkowski and Karrow, 2001), which is the major cause for spatial heterogeneity in the overburden. The site has an undulating surface topography with over 40 m of local relief.

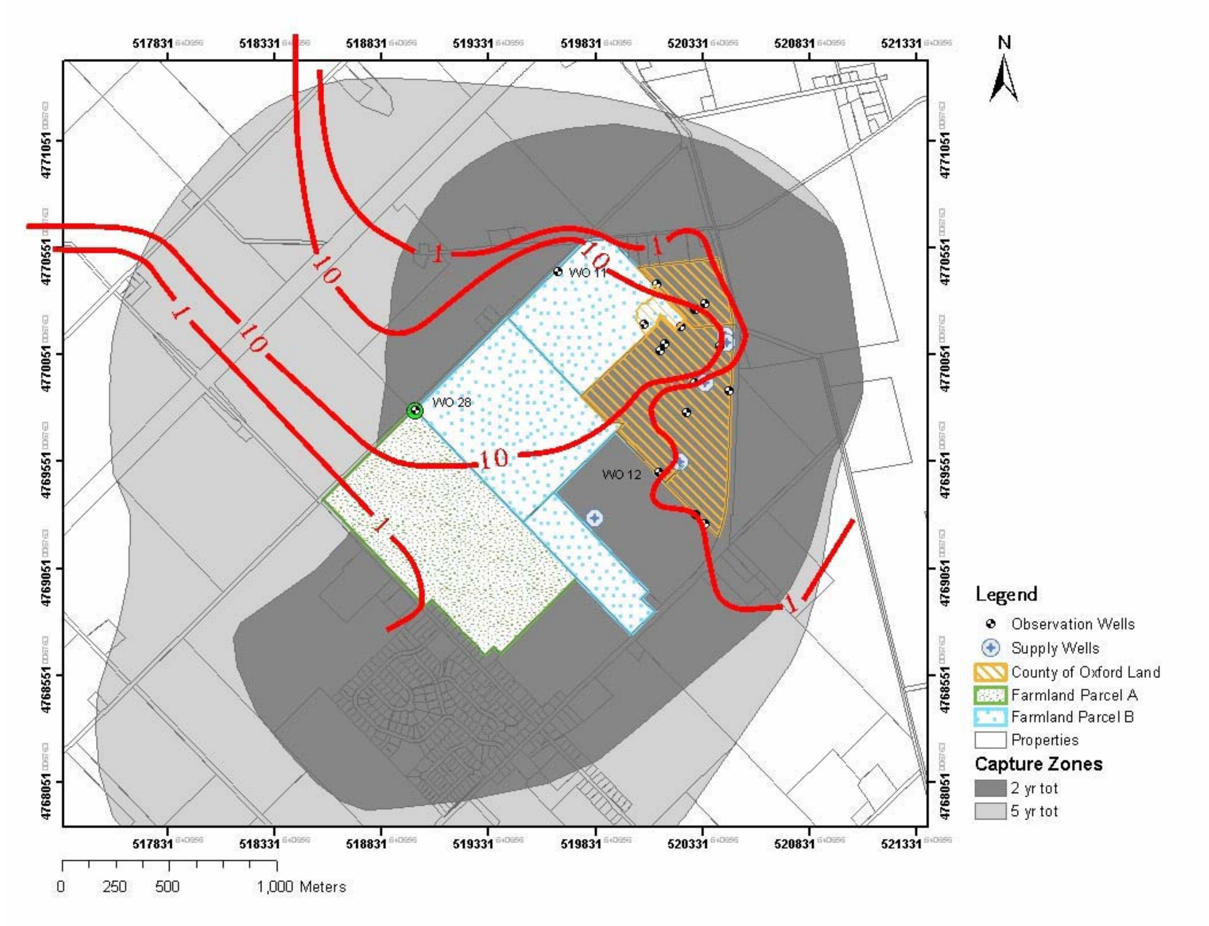

Figure 1. Map of the Thornton Well Field. The supply wells for the City of Woodstock and numerous observation piezometers are shown. The land historically owned by the County of Oxford and the recently purchased farmland (Parcels A and B) are indicated. The 2-year and 5-year time of travel (tot) capture zones were extracted from a wellhead protection study performed by Golder Associates Ltd. (Golder, 2001). Nitrate concentration contours (1 and 10 mg-N/L) were taken from Padusenko (2001) and are based on the maximum concentration observed at each monitoring location.

Since 1975 the nitrate concentrations in all five extraction wells have gradually increased towards and for some wells above the drinking water guideline of 10 mg N/L (Figure 3). In fact over the last decade the nitrate concentrations in Wells 1, 3 and 5 have been constantly above the guideline. Currently, water from the Thornton Well Field is blended with water from the second well field in order to achieve acceptable concentrations.

The primary source of nitrate is suspected to be agricultural activity since this is the dominant land-use within the capture zone of the well field. The nitrate plume, as mapped by Padusenko (2001), is evolving from the west into the study area and is believed to be drawn into the Thornton Well Field through a connection between the aquifers in proximity of the supply wells (Figure 1 and Figure 2).

The County of Oxford, the agency responsible for the water supply for the City of Woodstock, purchased two parcels of farmland totalling 275 acres (111 hectares) within the 2-year time of travel capture zone (Golder, 2001, Figure 1) 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 parcel of farmland (Parcel A, Figure 1) the stipulation is that a strategy has to be established so that fertilizer application is timed to maximize uptake by the crops. The farmer managing this parcel of land was required to develop a standard 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 (Parcel B, Figure 1) minimal nutrient inputs are prescribed. Extensive nitrogen soil testing was carried out across the fields to determine the nutrient requirements on

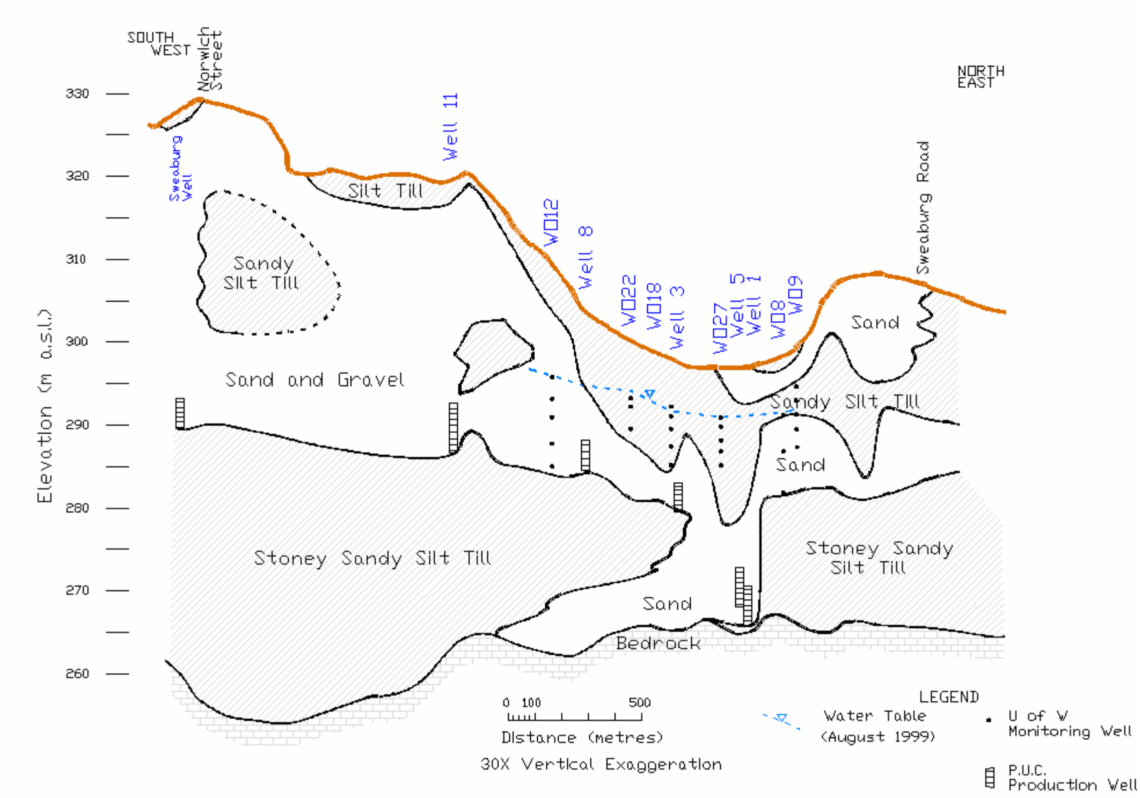

Figure 2. Cross section of the conceptual hydrostratigraphic model through the five supply wells of the Thornton Well Field (after Padusenko, 2001).

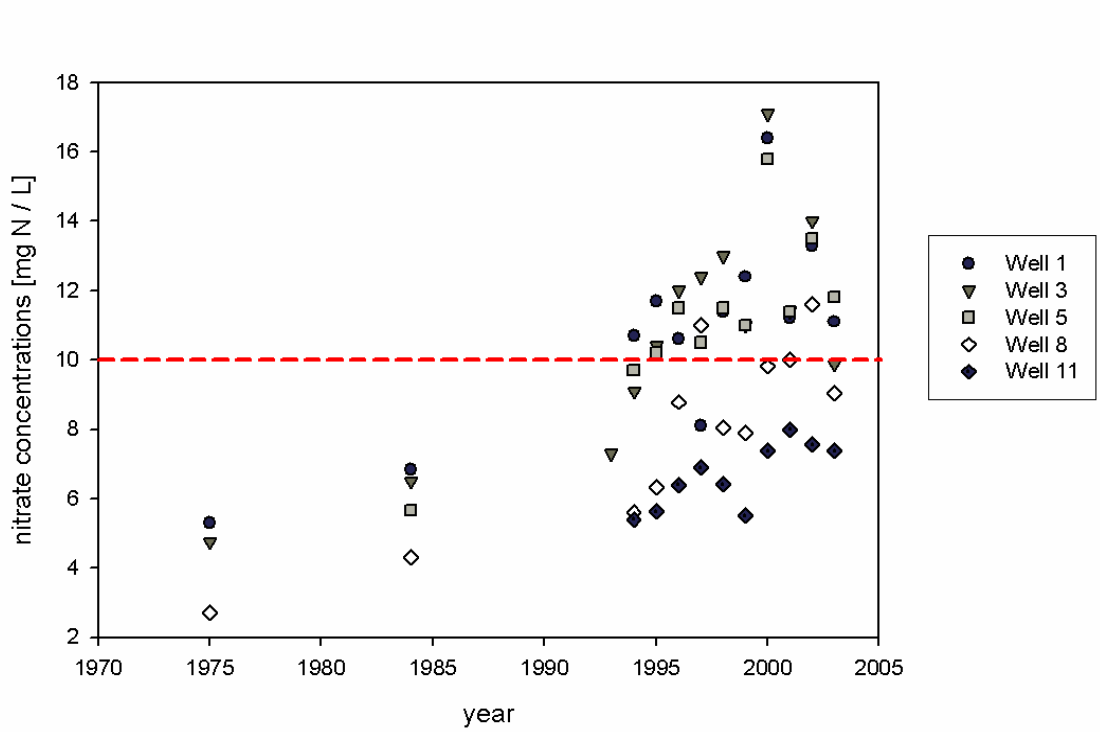

Figure 3. Maximum annual nitrate concentrations (mg N/L) observed at the five extraction wells in the Thornton Well Field.

a spatially distributed scale. 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 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 accepting a lower than market value for the rental of the land. The farm operator is maintaining detailed records of crop production.

3. GOAL OF THIS STUDY

The overall goal of this study is to evaluate the effectiveness of the pro-active modifications to the land-use practice on the nitrate concentrations extracted from the 5 wells within the Thornton Well Field. The current study has been designed to provide a comprehensive picture of 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 to predict the impacts on the water quality in the municipal wells. An important component will be the ability to forecast the degree and timing of these effects. Ideally, recommendations will be given on how to reduce the nitrate concentrations in the supply wells by means of a source water protection strategy that permits sustainable agricultural activity within the capture zone of the well field.

To satisfy the overall goal the following actions are being undertaken:

- The local hydrogeology is being further assessed through drilling, sediment coring, monitoring well and lysimeter installation, and geophysical surveying.
- Information on the source loading is being obtained by mapping the temporal and spatial variations of nitrate concentrations at tile drain outlets, and within the monitoring well and lysimeter network.
- The mass of nitrate stored in the unsaturated zone is being determined by soil-water analysis. This data is critical to estimate the timing and magnitude of the response at the supply wells due to land-use changes.
- Depth-discrete measurements within the municipal production wells are being undertaken to determine where the highest mass flux of nitrate is entering the wells
- A fully three dimensional, variably saturated groundwater model (flow and transport) is being constructed to simulate the impact of reduced nitrogen loading in the effluent from the municipal supply wells.

4. SUMMARY OF ACTIVITIES TO DATE

The spatial variability of stratigraphic layers and the hydraulic parameters of the sediments are extremely high because the study site is located in a complex glacial environment. Discontinuities in the different hydrostratigraphic units result in the formation of areas of direct connection between the aquifers. These connections or windows provide the potential for rapid downward migration of surface contamination and represent areas of significant concern (Frind, 2002). Locating these features is a significant challenge and is an important primary focus of the field activities.

4.1 Installation of multi-level wells

The installation of multi-level wells provide key information including: (1) establishment of the hydrostratigraphic sequence in areas where subsurface data was limited, (2) determination of the water table depth and variations in vertical hydraulic gradients, and (3) the vertical variation of nitrate concentrations. The new wells installed as part of this current study, augment a network of more than 20 monitoring wells installed during previous investigations.

The first of the new installations involved the drilling of a deep borehole (70 m) completed to bedrock at the western edge of the purchased land parcels (WO 28, Figure 1). The objectives of this installation were to determine hydrogeologic parameters that were not well known in the area: the depth to bedrock, the continuity of key hydrostratigraphic units that are encountered in the vicinity of the well field, the vertical piezometric conditions along the lateral boundary of the study area, and the nitrate concentrations in various water bearing units to quantify the mass-influx of nitrate. The "direct air rotary method" was used to drill a hole large enough to complete the installation of a 4-well monitoring cluster. A log is shown in Figure 4. The deepest well was installed 10 ft. (3 m) into bedrock. Two wells were placed in a lower, very productive aquifer that was found just above bedrock at approximately 220 ft. (67 m). The fourth well was installed in an upper aquifer at a depth of 100 ft. (30 m).

The bedrock well will provide insight into whether or not groundwater flow from the bedrock is influencing the quality of the deep aquifer encountered both at WO 28 and at the Thornton Well Field. The lower confined, highly productive (estimated potential between 400 to 600 gal/min (1.5 to2.3 m^3/min)) aquifer directly above bedrock is encountered frequently in south-western Ontario (Bajic, 2004; Sharpe and Russell, 2004). Prior to drilling this well it was assumed that this lower aquifer was present only locally around the supply wells 1 and 5. The new well WO 28 suggests that it may be is more spatially extensive.

The upper aquifer corresponds in elevation and hydraulic head with the aquifer being used by adjacent farmers for their residential and livestock supply, but its yield is orders of magnitude less than the lower aquifer.

Both of these main aquifers are isolated by two layers of aquitard material (Figure 4). Between these two aquitards is a zone of highly conductive material (gravely sand), that was found to be dry. Nitrate concentrations in these aquifers do not suggest a connection between them at well WO 28. In the vicinity of the well field the upper and the lower aquifer are connected, thus the separating aquitard is not continuous. Understanding these

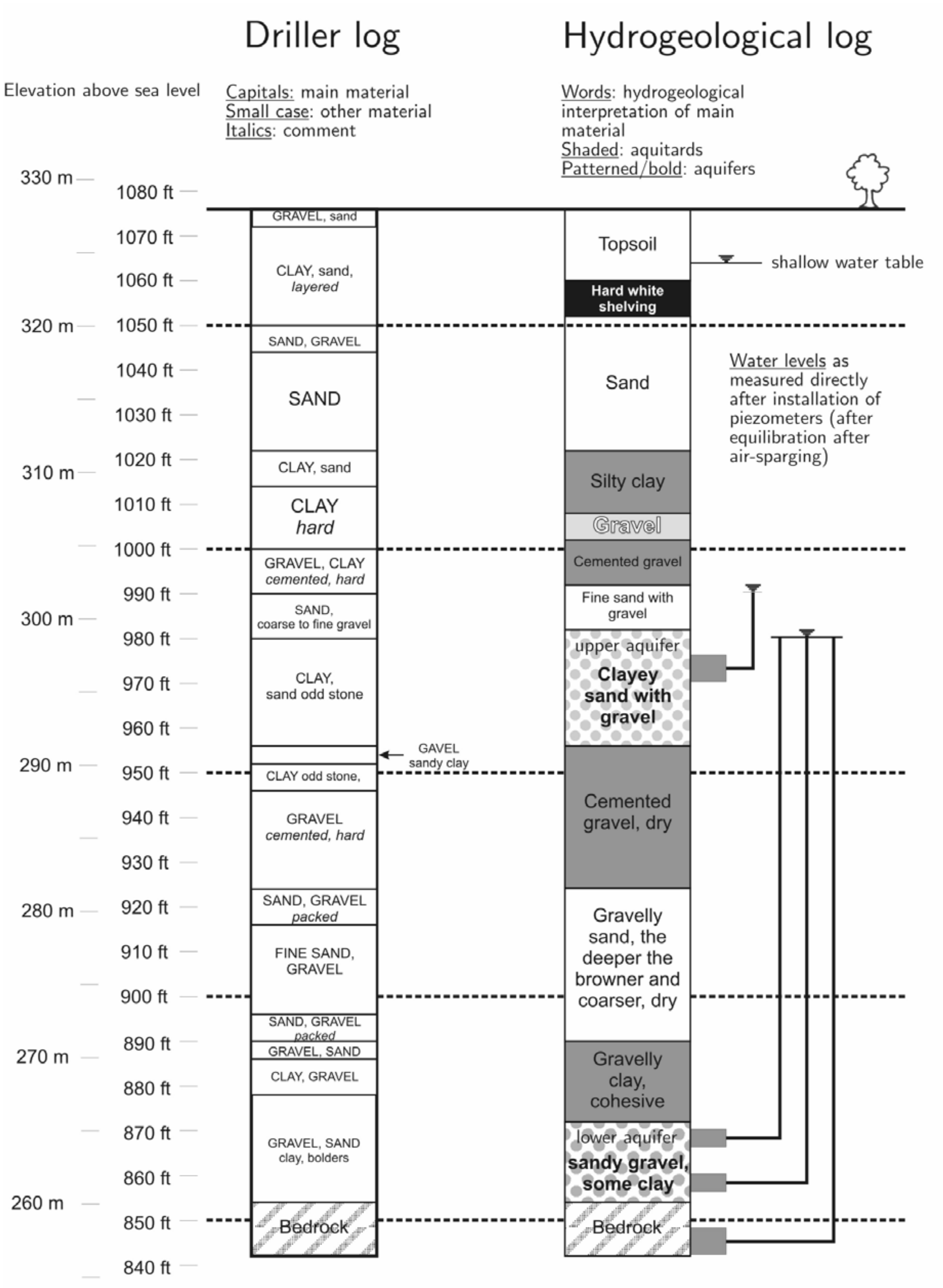

Figure 4. Stratigraphic logs of borehole WO 28. Shown is the driller-log, the interpreted hydrogeological log, and the location of the screened interval and associated water level for each observation well.

complexities and their implications are essential to the goal of this project.

The hydraulic head profile in the multilevel wells suggests a downward gradient from the upper aquifer into the lower aquifer. Within the Thornton Well Field, however, the two wells completed in the lower aquifer (Well 1 and Well 5) are flowing artesian wells, whereas the wells in the upper aquifer are not, indicating a strong upward gradient in the vicinity of the well field.

4.2 Influence of shallow sediments on the nitrate plume

During the course of drilling Well WO 28, a shallow, hard clay aquitard was found at a depth of 20 ft. (6 m) below ground surface (Figure 4). Although a monitoring well has not yet been installed in the aquifer material above this aquitard unit, drill cuttings indicated the aquifer material is saturated suggesting a shallow perched aquifer. Beneath this aquitard unit, the sandy sediments appeared to be unsaturated to a depth of 100 ft. (30 m) where the piezometric surface in the upper aquifer was encountered (Figure 4).

The lateral extent and continuity of this aquitard is considered to be crucial since it likely controls the distribution of nitrogen-rich recharge from the root zone into the local aquifer system by redistributing the nutrient mass flux towards discontinuities where deeper infiltration can occur.

In order to develop a more complete picture of the distribution of this shallow aquitard unit, terrain resistivity is being used to map the shallow subsurface between several of the existing boreholes. This information, currently under interpretation, may assist in the subsurface mapping of the perched aquifer system and in the detection of windows in the aquitard that may be focussed points of deeper recharge.
In an attempt to determine the hydraulic response of the multi-layered aquifer system to recharge events, groundwater levels are being monitored with pressure transducers at several locations in both shallow and deep aquifer units above and below the shallow aquitard.. These data are being compared to precipitation data collected from an on site rain gauge to identify locations where rapid hydraulic response can be observed indicating direct connection to the near surface sediments. This information will also aid in the location of areas of rapid recharge, which are believed to significantly influence the mass loading of nitrate to the subsurface environment.

Figure 5 shows the temporal profile of hydraulic head at wells WO 11 and WO 12 along with daily precipitation data. Well WO 11 reacts strongly to rainfall events whereas well WO 12 shows a very weak change in water levels. This may be due to the discontinuous nature of the aquitard unit. Around the location of WO 12 the water bearing zones seem well protected to recharge, which is not true for the area in the vicinity of WO 11.

Soil cores are being taken to depths of 10 m at several locations across the fields to establish vertical profiles of pore water nitrate concentrations representative of “initial conditions”. Locations of interest were chosen where the shallow aquitard was found to be continuous and discontinuous, based on cores, resistivity profiles, transient water level data and farmers’ knowledge of dry areas. These data from the cores provide an indication of the total nitrate mass stored in the vadose zone, which is critical to the long-term impacts on the municipal well field. Additional soil cores will be extracted at selected times to determine if the change in land-use practices is influencing the mass loading of nitrate past the root zone.

5. BUILDING A SIMULATION MODEL

Based on currently available data a flexible simulation model is being constructed using a fully 3D, finite element, flow and transport model (FEFlow). The numerical model is being created to predict the timing and the magnitude of the impact of the decrease in nitrogen loading. It will be used to minimize and ideally reduce nitrate concentrations in the supply wells by adjusting pumping schemes and mass loading scenarios for fertilizer application.

6. SUMMARY

A thorough understanding of hydrogeology is the basis for the prediction of hydrogeologic parameters (quantity and quality). The current study improved the understanding of the hydrogeology of the site by employing a variety of tools: drilling, coring and installation of advanced monitoring wells, geophysical surveys and transient hydraulic head-monitoring.

Research was conducted in the deep and the shallow system. The existence of the shallow aquitard was shown, its extent is currently being mapped and its influence of pathways for nutrient contamination is under investigation. The perception of the extent of the lower aquifer and its chemical evolution along the flow path was changed. Determination of the extent and continuity of hydrogeologic layers was a crucial factor to understand contaminant pathways.

Mass loadings into the system are being estimated through the combination of hydraulic measurements and soil core nitrate mass mapping.

It is planned to investigate more thoroughly in the quantification of the amount of nitrate stored in the unsaturated zone and the recharge rate into the aquifers. Approaches to determine the continuity of the lower aquifer will be undertaken.

These advanced field methods are being used as remote sensors for observations of change of nitrate concentrations within the system. Integration of all of the different data-sets will form the basis for a fully physically based three-dimensional predictive computer model for sustainable groundwater management.

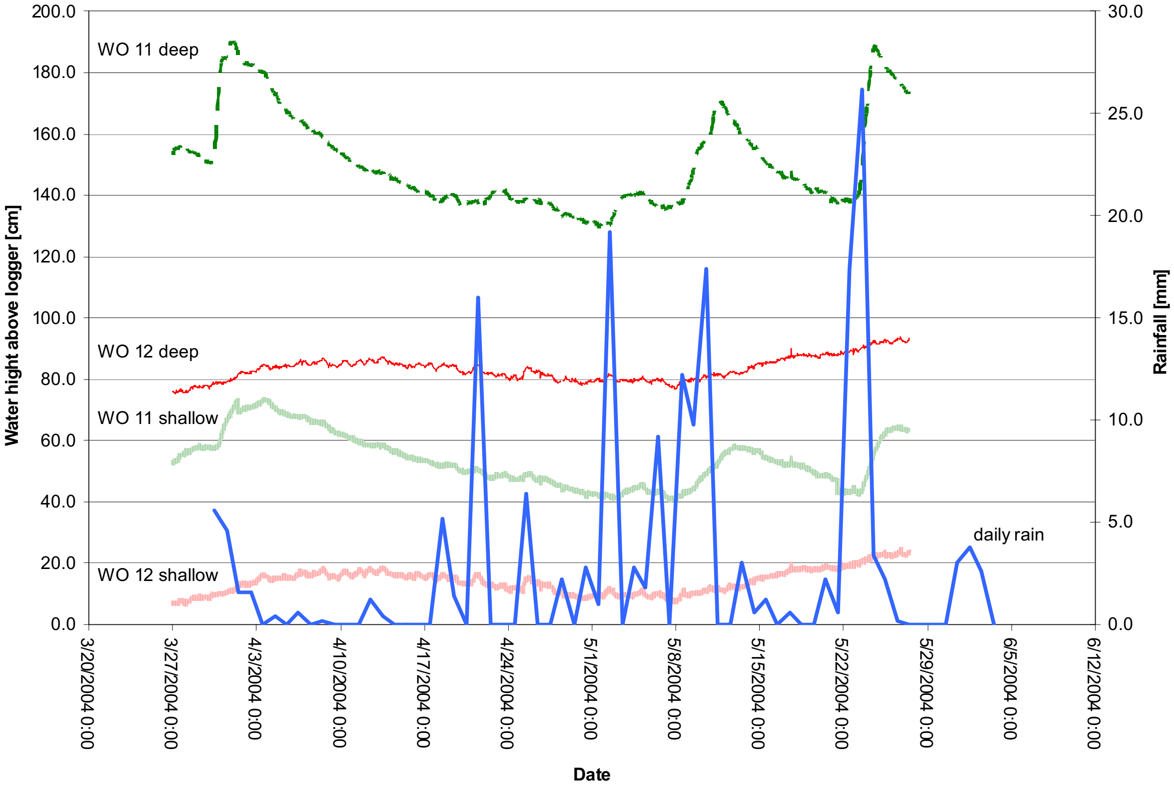

Figure 5. Transient Water levels for multilevel wells WO 11 and WO 12 as well as daily rainfall depths for the month of April 2004. At each location a shallow and a deep piezometer were monitored.

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