Predicting Effects of Agricultural Beneficial Management Practices on Water Supply Wells using Numerical Modelling

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ABSTRACT
Agricultural Beneficial Management Practices (BMPs) were implemented within the capture zone of water supply wells at a field site in southern Ontario, Canada, in an attempt to reduce nitrate concentrations in wells impacted by non-point source contamination. A 3-dimensional, variably-saturated, flow and transport model (FEFLOW) was subsequently applied and predicted the effects of current and future BMP scenarios on the water quality. Simulations indicate reductions in nutrient applications can reduce nitrate concentrations in the supply wells. Complex glacial deposits and large depths to water influenced the timing and magnitude of the simulated improvements.

RÉSUMÉ
Des pratiques de gestion bénéfiques (PGB) agricoles ont été appliquées dans la zone de capture de puits d'approvisionnement au sud de l'Ontario, Canada, affin d'essayer de réduire la concentration de nitrate provenant de sources non-ponctuelles. Un modèle tridimensionnel (FEFLOW) a été appliqué au site et a prédit les effets de scenarios de PGB sur la qualité d'eau dans les puits. Les simulations indiquent que réduire l'application de nutriment peut réduire les concentrations de nitrate. La complexité des sédiments glaciaires ainsi que de grande profondeur de la nappe phréatique ont influencé le temps et le montant de l'amélioration simulée.

1 INTRODUCTION

High or increasing concentrations of contaminants originating from non-point sources (e.g. road de-icing chemicals and excess nutrients from agricultural areas) in water supply wells are a major concern for water supply management. One approach to address this problem is the adoption of Beneficial Management Practices (BMPs). For agricultural areas impacted by excess nitrate applied as fertilizer, BMPs consist of optimized management of inorganic fertilizer and animal manure inputs in order to reduce contaminant loadings to aquifers (Wassenaar et al. 2006).

The implementation of BMPs can affect both land use management and water quality, so it has potentially significant health and economic impacts. Therefore, the areas to be targeted with BMPs and what constitutes an admissible contaminant loading need to be carefully defined. Unfortunately, the effects of changes in land-use practices are usually slow (Tomer and Burkart 2002) and difficult to monitor. Consequently, there is a need to develop approaches and long-term predictive tools to support the decision making process regarding the use of BMPs. In this context, a physically-based, 3-dimensional, flow and transport model was developed and applied to a well field impacted by agriculturally-derived nitrate.

2 STUDY AREA

The study area encompasses the region surrounding the Thornton Well Field, located in an agricultural setting within a complex glacial aquifer system in southern Ontario, Canada (Figure 1). This well field currently provides around 7,000 m^3/day to the city of Woodstock (County of Oxford 2009). An increasing trend in nitrate concentrations was observed in this well field since the 1970s and it eventually exceeded the drinking water limit of 10 mg NO_3-N/L in the mid 1990s. After that, pumping rates were reduced and the concentrations in the supply wells have ranged between 6 and 12 mg NO_3-N/L.

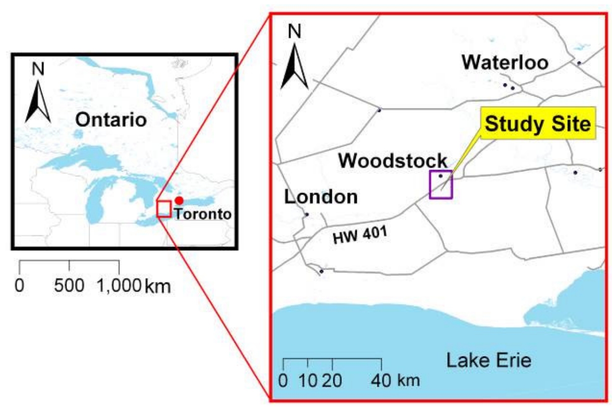

Figure 1. Location of the study area (adapted from Haslauer, 2005)

In order to address this water quality problem, in 2003 the County of Oxford purchased two parcels of farmland (Figure 2) located within the two year time-of-travel capture zones estimated as part of a well head protection study performed by Golder Associates Ltd (Golder Associates 2001). The parcels were rented back to farmers under some restrictions with the objective of implementing BMPs to reduce the input of nitrate to the aquifer. In one parcel (Parcel A, 38 ha) a nutrient management plan was developed to maximize crop uptake. On the other parcel (Parcel B, 73 ha) minimum nutrient inputs were prescribed (Haslauer 2005).

The field site has an extensive monitoring network and several previous studies were conducted in this area to characterize the site hydrogeology (Padusenko 2001; Haslauer 2005), geochemistry (Sebol 2000; Heagle 2000), and the recharge and nitrate mass loadings before and after implementation of BMPs (Bekeris 2007; Koch 2009). Hydrogeological conditions at the study site are complex due to the nature and variety of glacial deposits at the site. The hydrogeological conceptual model developed for the area has five interconnected aquifers and four aquitards, extending from ground surface to the bedrock, as shown in Figure 3.

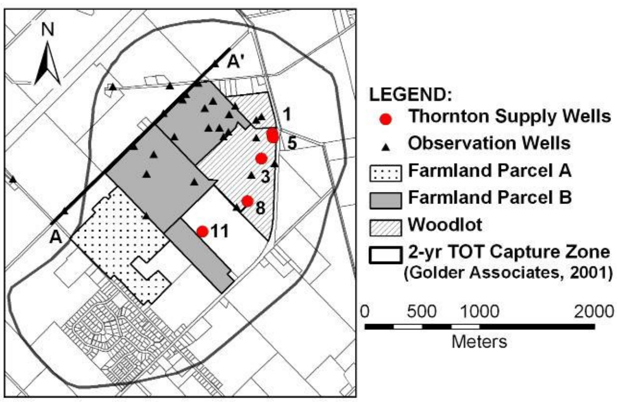

Figure 2. Thornton well field and parcels A and B (Adapted from Haslauer, 2005)

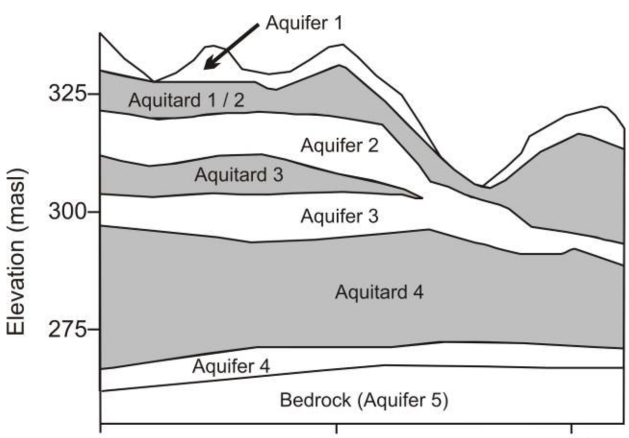

Figure 3. Cross section A-A' (Adapted from Koch, 2009)

High concentrations of nitrate are limited to the top three aquifers, including the one in which the supply wells are screened (Aquifer 3). Geologic interpretation of the available data indicates there is a hydraulic connection between ground surface and the deeper aquifer units in some areas of the site. The complexity of the site meant that a numerical model was necessary to evaluate current and future conditions.

3 NUMERICAL MODELLING

In order to predict the potential impact of BMPs on the supply wells, the available field data was integrated into a physically-based three-dimensional numerical model.

The approach taken was to accurately model groundwater flow on a regional-scale (3100 ha area) around the Thornton Well Field and then simulate nitrate transport within a more detailed local sub-area (700 ha). The use of two different model domains (Figure 4) is necessary in this case because the high spatial resolution required to simulate nitrate transport would be computationally prohibitive at the regional scale. All simulations were performed using FEFLOW (Diersch 2006), which is a finite-element model that can simulate saturated and unsaturated flow and transport of dissolved constituents.

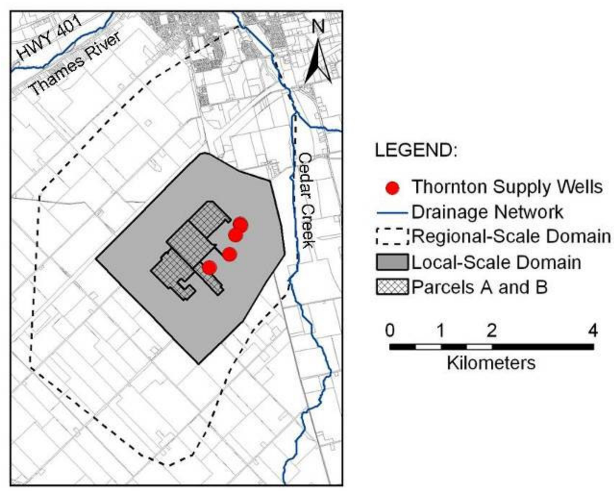

Figure 4. Regional-scale and local-scale model domains

3.1 Regional-Scale Flow Model

The regional-scale model considered saturated flow only and was calibrated to averaged observed hydraulic head data deemed to represent steady or long-term conditions. These observed hydraulic heads were monitored continuously at 34 screen locations in 25 wells using pressure transducers and corrected by regular manual measurements.

The recharge rates used in the model were based on values estimated from field data, presented by Bekeris (2007) and Koch (2009). The distribution of recharge across the model domain was based on previous 1-D simulations performed by Padusenko (2001) using HELP (Schroeder et al., 1994) that considered near-surface soil type, crop type and topography.

The calculated hydraulic heads from the regional-scale model were then used to define the flow boundary conditions for the local scale model.

3.2 Local-Scale Flow and Transport Model

The local-scale model encompasses the well field and the critical farm properties (Parcel A and B) where land-use changes have occurred and other areas that are potential targets for future implementation of land-use changes.

The local-scale model simulates variably-saturated flow, so the flow through the unsaturated zone is taken into account. This capability is important because transport through the unsaturated zone is expected to contribute to the time lag between changes in land use practices and the changes in concentrations at the supply wells. For this site, the unsaturated zone thickness ranges from 1 to 36 m, with an average of 11 m, based on water level data from 35 well locations across the site.

Nitrate transport is simulated only below the root zone and there is no evidence of significant denitrification in the aquifer. Therefore, nitrate was simulated as a conservative tracer. The transport surface boundary condition was defined from the up-scaled nitrate mass loading distribution below the root zone calculated from previous studies for the area. Porewater concentrations in agricultural areas ranged between 1.3 and 69.9 NO_3-N mg/L (Bekeris 2007; Koch 2009). In urban and woodlot areas, the concentration of nitrate in the recharge water was assumed to be 2.0 NO_3-N mg/L.

The transport boundary conditions for the local-scale model domain vertical boundaries (inflow and outflow) were defined based on observed concentrations from the vast monitoring well network at this site and then were kept constant for all simulated scenarios. This assumption implies that no changes in land use are expected in areas outside the local-scale model domain and their contributions to nitrate input to the aquifer are in equilibrium. The specified concentrations assigned to these boundaries were calibrated to produce nitrate distributions in the aquifer in which the pumping wells are screened (Aquifer 3) and concentrations on the supply wells similar to conditions observed in the field before the application of BMPs. The initial nitrate distribution in the local model domain (i.e., before the changes in land use were implemented) was estimated considering steady-state flow and transport using pre-BMP boundary conditions.

Changes in land use were represented by altering nitrate mass loading relative to the pre-BMP values in selected areas within the 2-year time of travel around the well field.(Figure 5). All other boundary conditions were kept the same. The change in nitrate concentrations at the surface was considered instantaneous for simulation purposes.

The following simulations were performed:

- Scenario 1 (Base Case): Represent the expected impact in supply wells under current BMPs, based on mass loadings measured in the field on Parcels A and B (Koch 2009). This data was collected approximately 5 years after BMPs were implemented and were assumed to remain the same for the rest of the simulation period (Figure 6).
- Scenario 2 (Additional Area): Represents an alternative scenario in which an additional area, indicated in Figure 5, is targeted with BMPs. The same pre- and post-BMP mass loading estimates for parcel B are assumed for this hypothetical scenario (Figure 7).
- Scenario 3 (Minimum Load): Represents an alternative scenario in which Parcels A and B are decommissioned from agricultural use and measures are taken to minimize nitrate loading in these areas. The nitrate concentration input in this scenario are assumed to be 2.0 mg/L for the rest of the simulation period (Figure 8).

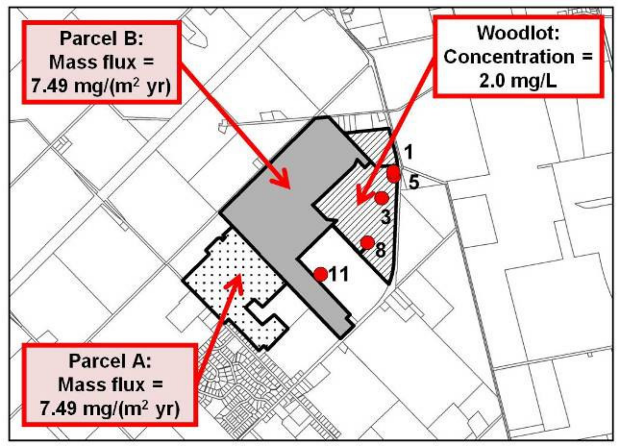

Figure 5. Pre-BMP conditions for all scenarios (only key areas of interest are shown). Mass fluxes obtained from Koch (2009)

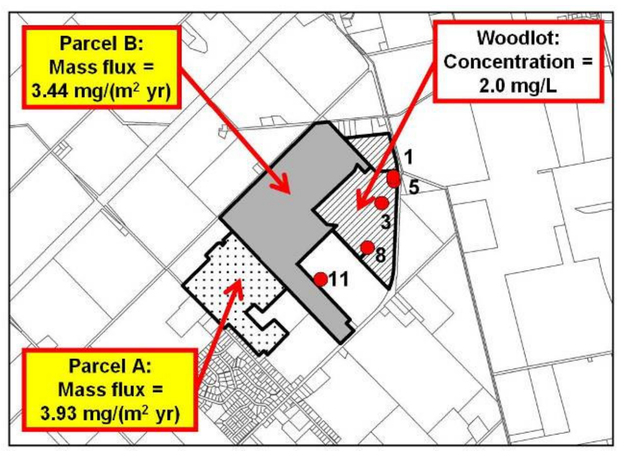

Figure 6. Scenario 1: Base case (Mass fluxes obtained from Koch, 2009)

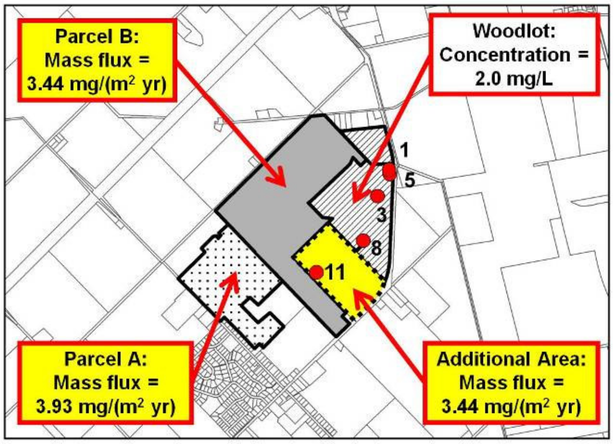

Figure 7. Scenario 2: Additional area (Mass fluxes obtained from Koch, 2009)

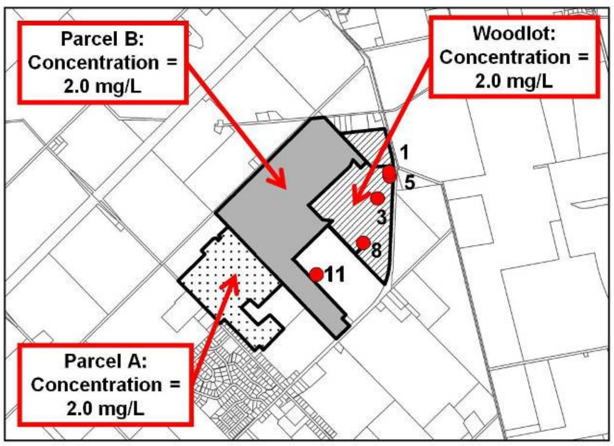

Figure 8. Scenario 3: Minimum load

4 RESULTS

Figures 9 to 12 show that the concentration at the supply wells as a function of time due to changes in nitrate input at the surface. The final (steady-state) concentrations for each scenario are presented in Figure 13.

In the Base Case scenario, the average concentrations for the 5 supply wells at steady state are expected to drop from 8.4 NO_3-N mg/L to 6.6 NO_3-N mg/L, representing a 22% reduction. For the alternative scenarios “Minimum Load” and “Additional Area”, the estimated final average concentrations are 5.3 NO_3-N mg/L (37% reduction) and 6.0 NO_3-N mg/L (29% reduction), respectively. The “Additional Area” scenario did not show improvements at Wells 1/5 and 3 when compared to Base Case conditions; however, concentrations at Wells 11 and 8 decreased significantly. The different response in the concentration profile relates to the position of the additional area with respect to the supply well capture zones. From a water management perspective this aspect may not be important as long as the average concentration produced at all wells is optimized. These results indicate that the implementation of BMPs in selected areas within the capture zones is a promising strategy to reduce nitrate concentrations at the supply wells.

A significant time is required for changes in land use to affect concentrations in the municipal wells. As an example, six to seven years are expected to elapse before a change in 1.0 NO_3-N mg/L takes place at the fastest responding well (Well 3).

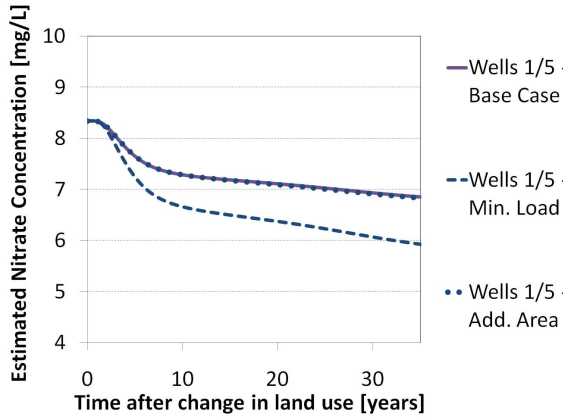

Figure 9. Nitrate concentrations for Wells 1 & 5 in after changes in land use

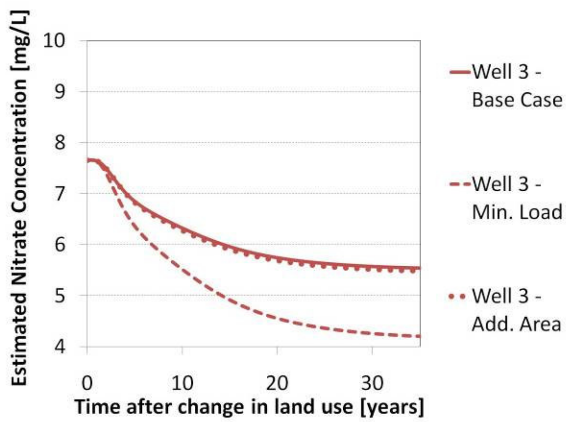

Figure 10. Nitrate concentrations for Well 3 after changes in land use

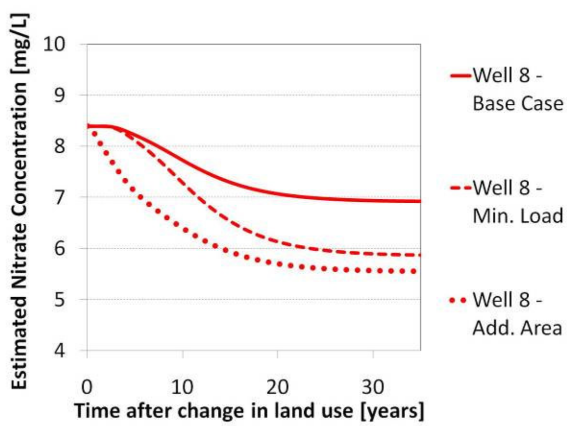

Figure 11. Nitrate concentrations for Well 8 after changes in land use

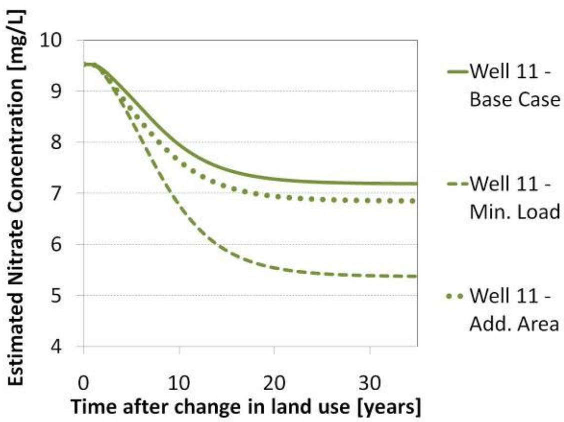

Figure 12. Nitrate concentrations for Well 11 after changes in land use

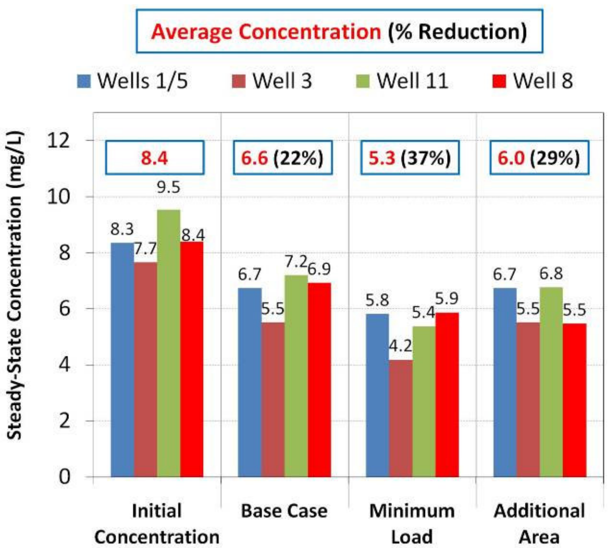

Figure 13. Final (steady-state) concentrations for alternative scenarios

5 SUMMARY AND CONCLUSIONS

A numerical model (FEFLOW) was applied to an agricultural setting within a complex glacial aquifer system to simulate the effects of BMPs on nitrate concentrations at supply wells.

This approach integrates field data into a physically-based model which can estimate the magnitude and timeframe of changes in concentration considering both the saturated and the unsaturated zone. It also provides a method to estimate the effects of different management alternatives which may assist the decision making process regarding the management of groundwater supplies. This approach can be generalized and applied at other well fields affected by non-point sources of contaminants.

The obtained results indicate that the implementation of BMPs in selected areas within the capture zone is a promising strategy to reduce nitrate concentrations at supply wells. For the particular case of the Thornton well field, a significant reduction (22%) is expected due to current nutrient management practices. Changes in the concentrations at the wells are expected to be relatively slow due to the legacy of nitrate stored in the saturated and unsaturated zone. Simulated concentrations at the wells approach steady-state conditions at around thirty five years after changes in land use.

Finally, before using these results to make decisions related to the well field management or land use practices it is important to estimate the uncertainty associated with these simulation results. The sensitivity of the model results to model parameters should also be assessed. This information can provide valuable input to assist with further data collection efforts that can be used to reduce model uncertainty.

ACKNOWLEDGEMENTS

Financial support for this project was provided by the County of Oxford, Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), Ontario Ministry of the Environment (MOE), Canadian Water Network (CWN), and Canada Foundation for Innovation (CFI). The authors thank Jacqueline Davidson for her help in translating the abstract.

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