Determining the influence of surface, unsaturated and saturated processes on source water protection strategies: a multi-model study

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ABSTRACT
A number of groundwater models are now available for source water protection assessments. Most employ simplifying assumptions for representing important hydrologic functions such as surface water or vadose zone flow processes. The objective of this study is, therefore, to assess a selection of models with respect to these assumptions, using a comparative analysis of model responses. For this purpose, simulations results produced using a variably-saturated formulation of the commercial code FEFLOW are compared to those of an advanced research model, HydroGeoSphere (HGS).

RÉSUMÉ
Un certain nombre de modèles de nappe phréatique sont maintenant disponibles pour les évaluations de protection source d'eau. Le plus employez le simplifiant des hypothèses pour représenter des fonctions hydrologiques importantes comme l'eau de surface ou les processus d'écoulement de zone de vadose. L'objectif de cette étude est, donc, d'évaluer une sélection de modèles en ce qui concerne ces hypothèses, en utilisant une analyse comparative de réponses modèles dans la prédiction de bien vulnérabilité. Pour ce but, les résultats de simulations produits en utilisant une formulation variablement-saturée du FEFLOW codé commercial sont comparés à ceux d'un modèle de recherche avancé, HydroGeoSphere (HGS).

1 INTRODUCTION

Source water protection planning (SWPP) is becoming a progressively more indispensible in the province of Ontario and across Canada. Moreover, numerical models are usually an integral part of the SWPP process. However, it is unclear what level of sophistication, based on the physical processes accounted for in a given numerical model, is required for realistic development of SWPPs. For example, the popular USGS model MODFLOW (Harbaugh et al, 2000) is a saturated groundwater flow code that incorporates the influence of surface water processes such as streams using simple boundary conditions and neglects water movement through the vadose zone. It seems intuitively clear that the process simplifications incorporated into models such as MODFLOW will have some influence on the simulated migration of water within the land phase of the hydrologic cycle. Similarly, the numerical scheme used to describe the relationships between pressure head, saturation and unsaturated hydraulic conductivity in the vadose zone also has the potential to impact simulated water flow. The present objective of this study is, therefore, to assess a selection of models with respect to some of these assumptions, using a comparative analysis of model responses in the prediction of steady state flow. For this purpose, simulations results produced using a variably-saturated formulation of the commercial code FEFLOW (Diersch, 2006) are compared to those of an advanced research model, HydroGeoSphere (HGS) (Therrien et al., 2005), which integrates groundwater processes and surface water processes in a rigorous way, and which therefore can be taken as a standard. The long-term objective of this study is to provide a better understanding of what simplifying model assumptions are reasonable and valid in source water protection applications in various hydrologic settings and to provide policy makers guidance in making their model choices.

2 SITE DESCRIPTION

The site used in this research is the Alder Creek Watershed, which covers approximately 79 km^2 within the Grand River basin in Southern Ontario, Canada (Figure 1). This watershed was chosen because it has been reasonably well characterized by previous studies in addition to being the focus of extensive data collection efforts by groups such as the Grand River Conservation Authority (GRCA), the Regional Municipality of Waterloo (RMOW), and the Ontario Ministry of the Environment (MOE). The watershed also contains a number of critical well fields that supply about 30% of the water needs for over 500,000 residents in the Kitchener-Waterloo and surrounding areas, thereby making it a priority candidate for source water protection work. In addition to the Alder Creek and its tributaries, the watershed contains some wetlands in its southern area. However, surface water features are a relatively minor component in the overall water budget of the system.

The Alder Creek Watershed is located in the south-central portion of the Waterloo Moraine which sits along the western edge of the cities of Kitchener and Waterloo. Surface elevations in the Alder Creek Watershed range from about 410 metres in the headwater regions to 290 masl where Alder Creek discharges into the Nith River. Local relief in the watershed ranges up to 30 metres. The overburden, which ranges in thickness from 35 to over 140 metres, is bounded below by the Salina Formation consisting of dolomites and limestone, interbedded with shales and gypsum lenses where the top few metres are fractured (Karrow et al. 1986). The overburden geology of the watershed is highly complex and has been altered by the advance and retreat of several glacial ice sheets that deposited a number of till units. Silty and clayey tills form the major aquitards, while the aquifers consist primarily of reworked tills, glacio-fluvial sands, and gravels (Karrow, 1989).

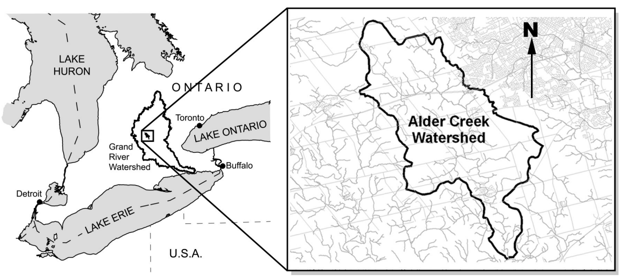

Figure 1. Location of the Alder Creek Watershed.

The complex hydrostratigraphy of the watershed (and the Waterloo Moraine as a whole) has been previously conceptualized as four aquifers bounded by four aquitards (e.g. Martin 1994; Martin and Frind 1998; Radcliffe 2000). The conceptual model employed in these previous studies is also used in this study. As was noted in those previous studies, some of the hydrostratigraphic units present in the system are laterally discontinuous (i.e. they 'pinch out'). Therefore, in order to maintain lateral continuity throughout the subsurface, layers are taken to be continuous in the conceptual model and discontinuities are represented by means of windows in the aquitards and lenses of low-conductivity material in the aquifers, as required. The aquitard windows provide direct conduits between the shallow and deep flow systems, allowing recharge of the deeper aquifers.

2.1 Populating the Models

The lateral extents of the Alder Creek Watershed were identified using a 25-metre Digital Elevation Model (DEM) provided by the Grand River Conservation Authority (GRCA). The resulting watershed boundary was then used to define a two-dimensional triangular-element mesh representing the top of the model domain (ground surface). A watercourse overlay (also provided by the GRCA) was then used to generate control points within the mesh in order to locate nodes along the stream channels in the two-dimensional mesh. The mesh was designed such that regions near the streams have finite element sizes on the order of 25 metres (in plan view), while finite elements further away from the drainage network are approximately 200 metres in size. This design strategy was employed to better capture surface water – groundwater interactions at the land surface interface (for the HGS model). Additional mesh refinement was also carried out in the regions surrounding the pumping wells and observation wells to improve the accuracy of the flow and solute transport solutions in these critical areas. After the generation and subsequent refinements to the mesh were completed, the topography of the watershed was mapped onto the mesh using data from the DEM.

A digital land usage map provided by the Ministry of the Environment of Ontario (MOE) was interpolated onto the surface mesh, and six distinct land-use categories were identified. This interpolation process was then further refined by using a watercourse overlay to incorporate the finer details of the watershed's drainage network (i.e. 2nd- and 3rd-order streams) which were not part of the digital map. The land usage distribution in Alder Creek is very diverse with significant regions of agricultural, urban, forested and grasslands.

The value of the Manning's surface roughness coefficient assigned to each land-use category was determined from tables provided in McCuen (1989). Stream discharge exits the watershed through three surface nodes in the two-dimensional surface mesh, which coincide with the segment of the surficial domain where Alder Creek discharges into the Nith River. A nonlinear critical-depth boundary condition is applied at these outflow nodes which constrains neither the flow rate nor the surface water depth. Instead, discharge leaving the domain is allowed to vary naturally throughout a given simulation period depending on the calculated depth of water at the outlet (only applicable to the HGS model).

In HGS, the two-dimensional surface flow mesh is draped over the three-dimensional triangular prism mesh used to simulate subsurface flow. The top of the three-dimensional mesh is coincident with the two-dimensional mesh such that dual surface-subsurface interaction nodes exist at the land surface. Eighty-seven layers separate the surface and the base of the three-dimensional subsurface mesh, which is defined by the bedrock surface. The vertical distribution of these layers is as follows: a) Ten 10 cm layers in the 1st meter bgs, b) fifty-seven 33 cm layers over the next 19 meters bgs and c) 20 layers evenly distributed 20 meters bgs to the bedrock surface. The sixty-seven uppermost layers of the mesh span across the vadose zone of the system, and provide each model the vertical discretization necessary to calculate meaningful unsaturated flow and solute transport solutions. The hydrostratigraphy of the Alder Creek Watershed as interpreted by Martin and Frind (1998) for the Waterloo Moraine was interpolated onto the mesh during the hydraulic conductivity field mapping procedure described below. The bottom of the model is assumed to be impermeable, while the saturated headwater and discharge regions of the subsurface mesh were assigned constant head values of 372.3 and 296.5 metres, respectively. These constant-head values were determined during calibration of HGS and subsequently applied to the FEFLOW model as well.

The hydraulic conductivity field of the Alder Creek Watershed was mapped onto the subsurface mesh using results of previous saturated-zone modelling studies conducted in the Waterloo Moraine (Martin 1994; Martin and Frind 1998; Radcliffe 2000). These studies employed a borehole log database maintained by the MOE to construct over 300 vertical cross-sections of the Waterloo Moraine, which were then used to build the 3D hydraulic conductivity field within the 3D conceptual model of the

Waterloo Moraine. The resulting K-field for this work contains twelve distinct lithologic categories and exhibits complex spatial interconnectivity between the shallow and deep flow regimes of the system. The hydraulic conductivity values assigned to each lithologic category in the Alder Creek watershed were based on the values used by Radcliffe (2000) and the corresponding porosity and specific storage values were estimated from tables in Freeze and Cherry (1979) and Mercer et al. (1982). The wetting and drying characteristics of the watershed's coarse sands were drawn from Mace et al. (1998), while the wetting and drying characteristics of the other sediments were estimated using pedo-transfer functions (Schaap et al., 1999).

Both the HGS and FEFLOW models were populated using the procedures described above. However, the FEFLOW model did not require the Manning's surface roughness coefficient data for surface water flow. Moreover, the wetting and drying characteristics of the sediments in the vadose zone (along with the corresponding unsaturated hydraulic conductivity values) were implemented in the HGS model using the standard van Genuchten formulation (van Genuchten, 1980). Conversely, these wetting and drying relationships were implemented in FEFLOW using a modified van Genuchten formulation option available in the FEFLOW model. This modified formulation makes the flow solution less nonlinear by restricting the range over which unsaturated hydraulic conductivity values can vary for each sediment type.

2.2 Steady State Flow Results

For calibration of the HGS model, a uniform net rainfall rate of 20 cm/year was applied to the surface of the initially saturated system. The model was run until steady-state flow conditions were achieved. As the system equilibrated, HGS computed the position of the water table, the steady-state head distribution throughout the system, the moisture content distribution in the vadose zone, and the distribution of water infiltrating or exfiltrating across the land surface (termed exchange fluxes – See Figure 2).

The subsurface hydraulic head distribution was then compared to long-term average heads calculated from a network of 28 observation wells distributed across the watershed. A number of manual adjustments were made to hydraulic conductivity values, followed by running the model to steady state conditions, until a satisfactory fit between the simulated and observed subsurface heads was achieved.

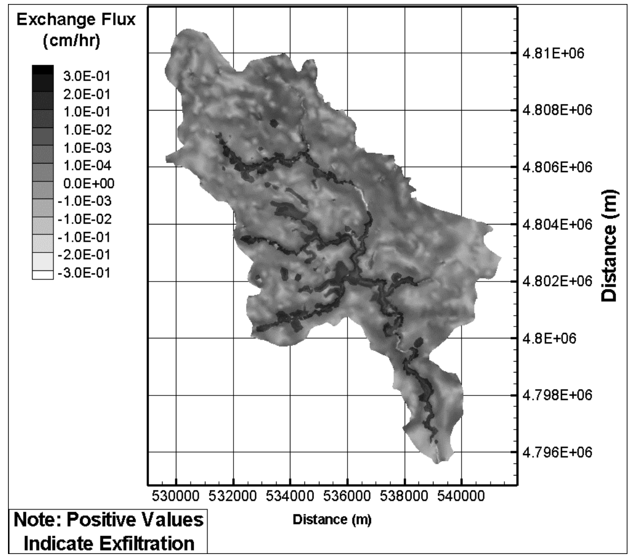

Figure 2. HGS steady state exchange fluxes at the land surface interface.

After completing the calibration of HGS, the steady state exchange fluxes were mapped onto the surface of the FEFLOW mesh as a recharge boundary condition and the FEFLOW model was run to steady state. As can be seen in Figure 3, the steady state head distributions for both models are in good agreement with the observed long-term values and with each other.

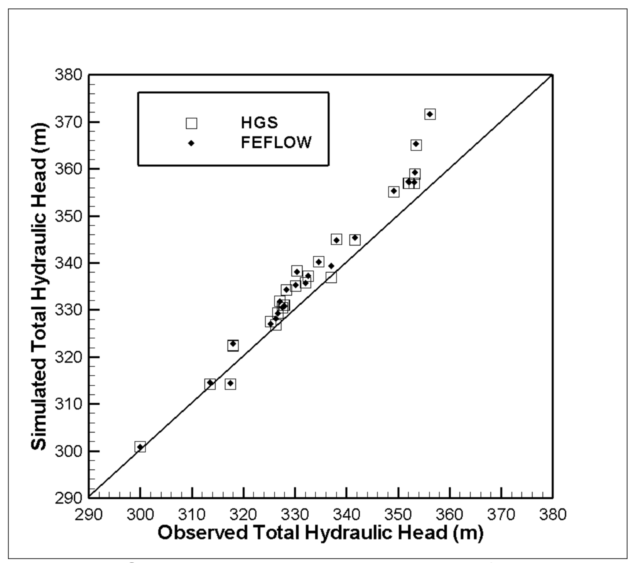

Figure 3. Steady state calibration results for the head distribution below the water table in the HGS and FEFLOW models.

However, the level of agreement between the two models shown in Figure 3 is somewhat misleading in that those results only compare each model's respective flow solution below the water table. A comparison of the differences in each model's head distribution across the entire subsurface domain (including the vadose zone) is shown in Figure 4.

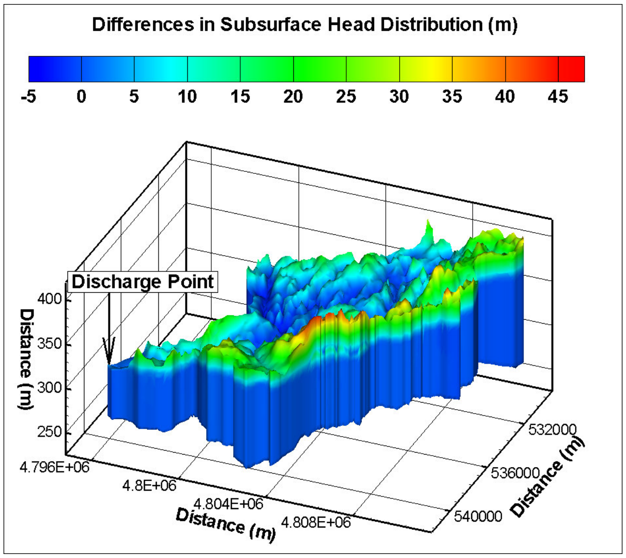

Figure 4. Differences in the hydraulic head distribution across the entire subsurface flow domain for the steady state HGS and FEFLOW results.

The difference in the head solutions shown in Figure 4 remains relatively small below the water table (errors range from -4 to 1.5 meters). However, the head differences in the vadose zone range from approximately 0 in regions where the water table intersects the land surface, to slightly over 45 meters in the thickest vadose zone regions. This discrepancy in the vadose zone head solutions can be explained by recalling that, while both models have identical recharge boundary conditions (i.e. the exchange flux values calculated by HGS), the corresponding unsaturated hydraulic conductivity values in FEFLOW will be considerably larger due to the modified van Genuchten formulation it uses. In turn, these larger unsaturated conductivity values in FEFLOW need to be offset by decreasing pressure head and saturation values to maintain the imposed flux rates. Therefore, the hydraulic head values in the vadose zone calculated by FEFLOW must be lower than the corresponding heads in HGS. Moreover, the divergence in the head calculations made by the two models will magnify as the thickness of the unsaturated zone increases (this is consistent with the pattern shown in Figure 4). The modified van Genuchten formulation also causes the FEFLOW model to store less water in the vadose zone because of the decreased saturations required to maintain the imposed flux. Similarly, the transit time of a 'packet' of water from the land surface to the water table will faster in FEFLOW's vadose zone due to the decreased saturations (recall: velocity = flux / [porosity * saturation]) and this transit time error will grow as a function of vadose zone thickness.

2.3 Discussion and Future Work

The work shown in this paper represents a portion of a larger model evaluation effort being undertaken by the authors. The implications of the saturation, hydraulic gradient, pressure head and especially velocity errors introduced into models employing modified van Genuchten approaches are multi-fold. For example, in the context of source water protection work, considerable errors could be introduced in the calculated extent of time dependent capture zones, depending on the thickness of the unsaturated zone in the system being analyzed.

In the near future, we will extend this work to investigate how a given model's representation of unsaturated and surface flow processes affect well vulnerability calculations. There are also plans to incorporate more models into the study.

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