SENSITIVITY ASSESSMENT OF SIMULATED GROUNDWATER RECHARGE AND EVAPOTRANSPIRATION ACROSS A SHALLOW WATER REGION FOR VARIOUS SOIL AND LAND COVER PROPERTIES

A. Simic (1), R. Fernandes (2) and S. Wang (2)
(1) Noetix Research Inc.(under contract to CCRS), 588 Booth Street, Ottawa, On., Canada. e-mail: Anita.Simic@CCRS.NRCan.qc.ca
(2) Environmental Monitoring Section, Canada Centre for Remote Sensing, Ottawa, On., Canada. e-mail: Richard.Fernandes@CCRS.NRCan.gc.ca; Shusen.Wang@CCRS.NRCan.gc.ca

ABSTRACT
Climate and land cover changes impact groundwater resources primarily through changes in net surface recharge. Actual evapotranspiration (ET) and the partitioning between runoff and infiltration govern the change in drainage to the aquifer (recharge supply). We discuss a comprehensive program of in-situ and model based measurement to quantify current and projected changes in recharge within the Oak Ridges Moraine (ORM), in the Greater Toronto Area. Major findings indicate that land use changes may have a considerable effect on the water balance of ORM and that the sensitivity of recharge to vegetation depends on soils. Substantial differences in average annual ET estimates are noted between modelled results and those based on average annual potential evapotranspiration (PET) formulations. Further work will include the change in recharge to be compared to calibrated recharge values from existing groundwater modelling efforts in the region. Future plans to measure soil water budgets and to extend the modelling effort to include lateral flow processes are discussed.

RÉSUMÉ
Les changements climatiques et de type de couvertures des terres ont un impacte sur les ressources d'eau souterraine, principalement due à la recharge de surface nette. L'évapotranspiration (ET) et la division entre l'écoulement et l'infiltration gouvernent le changement du drainage de l'aquifère (approvisionnement de la recharge). Nous discutons ici d'un programme compréhensif de mesures in-situ et modélisés pour quantifier le changement courant et projeté de la recharge à l'intérieur de l'Oak Ridges Moraine (ORM), dans la grande région de Toronto. Les principaux résultats indiquent que le changement de l'utilisation des terres pourrait avoir un effet considérable sur la balance de l'eau de l'ORM et que la sensibilité de la recharge à la végétation dépend du sol. Des différences substantielles de la moyenne annuelle de l'estimation de l'ET entre les résultats modelisés et ceux basés sur une moyenne du potentiel d'évapotranspiration (PET) annuel ont été remarquées. Les travaux futurs vont inclure le changement de la recharge qui sera comparé à des valeurs calibrées de recharges provenant d'efforts de modélisation des eaux souterraines dans la région. Les plans futurs de mesures du budget de l'eau du sol et une extension de l'effort de la modélisation pour inclure les procédés d'écoulement latéral sont discutés.

1. INTRODUCTION

The growing problem of water availability is being increasingly related to a subsurface component of the water cycle – groundwater. Groundwater is becoming a crucial source of water supply and its quantity and quality has tremendous impact on people and surface water ecosystems. Groundwater use in Canada, for instance, has recently increased 3-fold (Riviera 2002). This increased demand requires the long term protection of groundwater from reduced groundwater recharge and storage (Riviera 2002). Groundwater recharge is available water at the water table surface that entries into the saturated zone together with the associated flow within the saturated zone (Freeze and Cherry 1979). Groundwater and climate are linked, and, changes in precipitation, evapotranspiration and temperature directly affect groundwater recharge (Rivard 2003; Eckhardt and Ulbrich 2003). A correct estimate of ET is fundamental for accurate recharge estimates. ET can account for over 90% of the precipitation in some arid areas (Flerchinger et al. 1996). Besides energy availability, precipitation and meteorology to soil moisture, plant water requirements and responses are major controlling factors of ET. As summarized by Mahmood and Hubbard (2003), both soil characteristics and land use can considerably alter soil water content and evapotranspiration. Thus, the understanding the link between the vegetation cover and evapotranspiration, and an accurate estimate of evaporation is critical. To address the relationship among the land surface energy, water and carbon related processes, and interaction of these processes with climate, the Ecological Assimilation of Climate and Land Observations (EALCO) model (Wang et al. 2002) is applied in this study. The model utilizes carbon-coupled energy and water balances within a plant and soil into soil-vegetation-atmosphere-transfer (SVAT) scheme.

The purpose of this paper is to demonstrate a land-surface based modelling approach to recharge and evapotranspiration estimation for a shallow water region – Oak Ridges Moraine (ORM), Toronto, Canada, and to assess the impact of soil physical properties and land cover/land use on recharge and ET prediction. Sensitivity assessment of ET and recharge for different land uses and soil types, demonstrates the possible consequences of deforestation and urban development within ORM. A preliminary estimate of total recharge is calculated for the Duffins Creek drainage basin situated within the southern part of the ORM region. Due to hummocky terrain of sand and gravel deposits, the moraine operates as the primary recharge area in the region. Up to 60% of the groundwater discharges to almost 30 regional streams that flows into Lake Ontario. The aquifers supply water to most of residents of the Greater Toronto Area through direct withdrawal or using water from Lake Ontario. This study is a part of a collaborative effort of Federal, Provincial and Municipal agencies to produce valid estimated of groundwater recharge across Oak Ridges Moraine (http://www.ess.nrcan.gc.ca/programs/). As the project has identified the lack of in-situ evaporation data, a field campaign has been conducted within the area which will result in monitoring spatial pattern in climate and evaporation across the region.

2. STUDY SITE AND DATA SETS

The Oak Ridges Moraine is a major physiographic feature in south-central Ontario (Figure 1). It is 160-km long and 20-km wide landform that rises more than 300 m above the level of Lake Ontario. Annual groundwater recharge was estimated based on catchment scale baseflow analysis to vary widely between 25 mm and 400 mm (Gerber and Howard 2000). According to the regional geologic model (Sharpe et al. 2003), the ORM region consists of five major stratigraphic units: bedrock, lower sediment, Newmarket Till, channel sediments and ORM sediments, and Halton Till. Paleozoic bedrock underlines the region beneath up to 200m of glacial sediments. Lower sediments consist of uppermost sandy aquifers and silty aquitard sediments, and lower sediments, which are often connected to the surface aquifers. Newmarket forms a regional bed and aquitard. It is 10-40m thick layer, composed of stony sandy silt. A network of channels eroded into the till allows recharge of the underneath sediments. Channel sediments are composed of sand, gravel, and silt and are placed in the surface and buried channels or valleys, commonly found within the ORM region. ORM sediments represent the upper ORM aquifer consists of stratified sand, silt, gravel, and minor clay. Halton Till consists of local aquifers and disconnected aquitards, overlies the southern part of the ORM. Duffins Creek basin is a part of the Lake Ontario catchment area and it is one of the

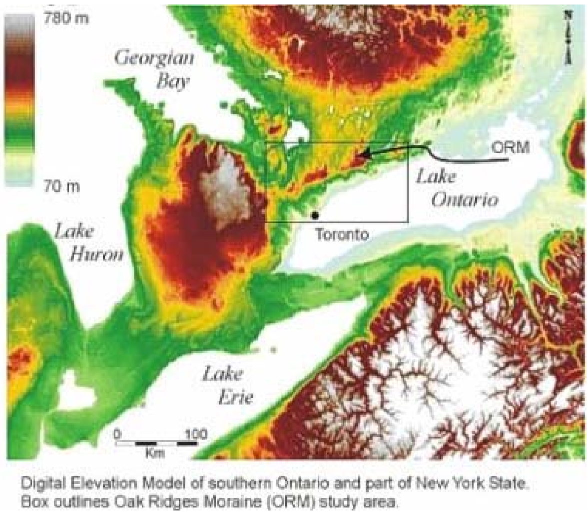


Figure 1 – Location of the Oak Ridges Moraine region (from Geological Survey of Canada 2003)

healthiest watersheds along the north shore of the lake. The headwaters of the basin originate on the ORM. Over 50% of the direct recharge of the basin occurs within ORM and hummocky Halton Till deposits which cover approximately 23% of the basin. The Upper aquifer is located in the northern part and it consists of surficial sand. This aquifer becomes confined toward the south, where, together with two other confined aquifers (The Middle and Lower aquifers) is overlain by the Halton Till, which consists of silty/sandy till interbedded with sand and gravel (Gerber and Howard 2002). The southern part of the basin, where most of urban areas are located, consists of clay and silt.

2.1 Meteorological Data and Surface Parameters

Meteorological data sets were obtained from Environment Canada and they were used for the period 1992-2002. The information on climate is based on point climate forcings. As current in-situ measurements across the region show little climate variability, Toronto Buttonville station measurements (Latitude: 43º 52' N; longitude: 79º 22' W; Station ID: 615HMAK) are chosen to represent the ORM region in this study. The climate data set represents direct hourly records of temperature, surface pressure, solar radiation, relative humidity, wind speed and estimated hourly precipitation. Since most hourly rainfall data were missing within the data set, hourly estimates of rainfall are interpolated based on relative humidity and daily rainfall measurements. Some gap filling was applied to the raw data to estimate missing values based on adjacent hourly stations. Average annual precipitation for the station ranges between 730-1070 mm.

Surface parameters data sets used in the model consists of leaf area index (LAI) (Fernandes et al. 2003) and land cover derived from a Landsat classification of remotely sensed data (Latifovic, R. personal communication). Additional surface parameter data set consists of topography, hydrography, surficial geology and soil texture provided by the Conservation Authorities Moraine Coalition and Earthfx Incorporated, Toronto. A map of the spatial distribution of annual recharge, generated by Eearthfx Incorporated and based on surficial geology, is used as comparison.

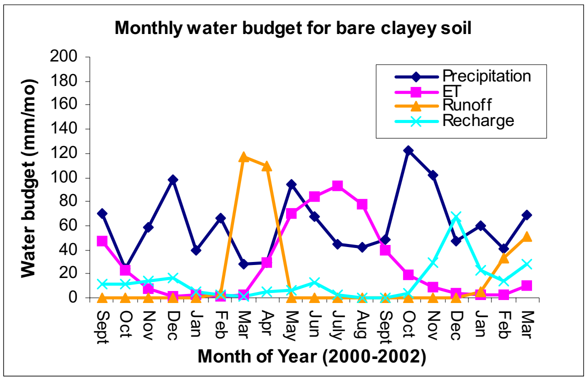
2.2 Model and Methodology

EALCO was developed at Canada Centre for Remote Sensing to study the ecosystem-climate interactions by assimilating Earth Observation datasets (both in situ and satellite). In EALCO, ecosystem processes of various land cover types are simulated by five main modules including radiation, energy, water, carbon, and nitrogen. Radiation calculation uses multi-canopy layer ray-tracing algorithms based on gap probability approach (Wang et al. 2002a; Wang 2004). Energy and water exchanges are simulated by solving the coupled canopy energy and water balance equations, in which canopy temperature and water potential are used as the prognostic variables (Wang et al. 2002b). Carbon and nitrogen dynamics of the ecosystem are simulated to reflect the ecosystem impact on water dynamics (Wang et al. 2001; Wang et al. 2002c). In the model, evapotranspiration is closely related to the ecosystem energy and carbon dynamics through which the climatic and plant physiological control on ET are simulated. Climate change, including the increase of atmosphere CO_2 concentration which affects the stomatal conductance of plant leaves, affects evapotranspiration through changing the ecosystem energy and water balances.

Simulations were performed for the period 1992-2002 and based on different combinations of soil texture, LAI and ponding depth for different land cover classes. Growing season maximum LAI values were chosen within the range from 0 (0.1) to 10 depending on the land cover class used in a given simulation. The temporal profile for LAI was specified using satellite observations over the region. The same Buttonville Airport meteorological data set was used for each simulation. The sensitivity assessment is based on the dominant land cover classes in the ORM region: deciduous forest, grassland/pastures, shrubs/agricultural areas, and bare/urban areas. Soil texture is based on a subset of 13 classes chosen based on initial sensitive analysis. The soil classes range from very gravely sand to heavy clay (Agriculture and Agri-Food Canada 2000). Ponding depth was calculated for each simulation based on SCS curve number approach (USDA 1986). The preliminary estimates of total recharge for the Duffins Creek basin were based on major land cover types and their mean LAI values. Dominant soil types, based on visual analysis of the land cover and soil maps, were chosen for each land cover category. The total recharge was computed using a simple areal weighted averaging of recharge values simulated by the model for given combinations of LAI values and soils.

3. RESULTS

For brevity, a single typical year (2001) of 732 mm precipitation (101 mm snow and 631 mm rain) has been selected to represent the results. Due to both impermeability of clayey bare soil and spring snowmelt, a relatively high runoff is generated during the spring period (Figure 2) when it reaches its max value of 146 mm/mo for vegetated land. Frozen soil enhances the runoff during spring. Consequently, groundwater recharge exhibits relatively low values during melt periods. ET tends to suppress recharge during summer so that recharge reaches its peak of 68 mm/mo for bare land only after large precipitation events in November and December. A small peak of discharge is seen in late spring after soil moisture became unfrozen. Actual ET has similar trend for all scenarios having its peak in mid-summer. In contrast to clay soils, soils at the sandy extreme exhibit almost no runoff throughout the year irrespective of surface cover (Figure3). High recharge is seen within both non-vegetated and vegetated sandy soil reaching 191 mm/mo for bare sandy soil (Figure 3).



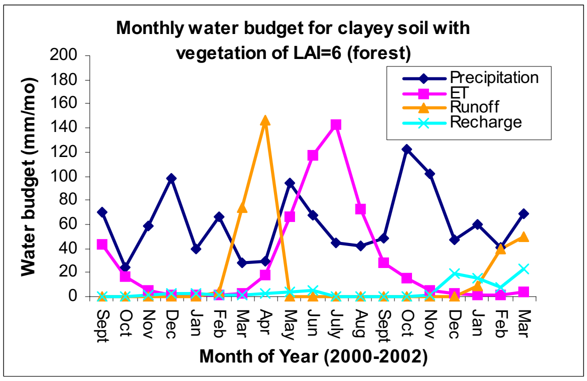
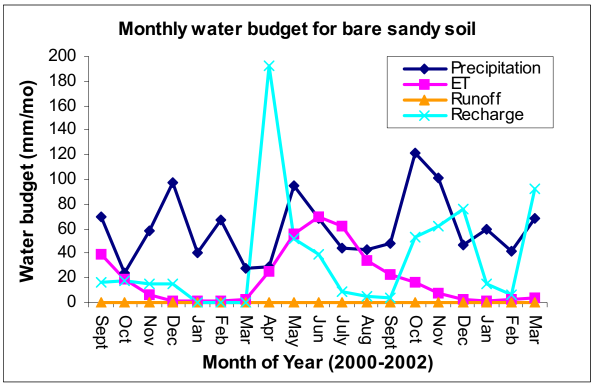


Figure 2 – Impact of vegetation on seasonal surface water budgets for clayey soil for 2001 (Sept 2000-Mar 2002).

Snowmelt directly contributes to groundwater recharge due to the high permeability and lower porosity of sandy soil. Sandy soils exhibit slightly lower ET than clay soils due to higher drainage (Figures 2 and 3). The presence of vegetation considerably increases ET in both clayey and sandy soil (Figure 2 and 3) although the monthly trend of runoff and recharge is similar in timing between vegetated and non-vegetated areas of the same soil type.



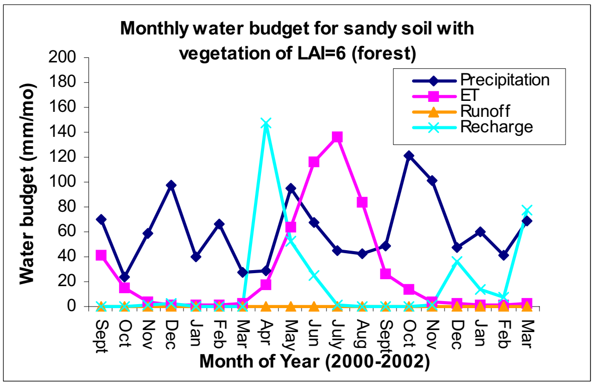


Figure 3 – Impact of vegetation on seasonal surface water budgets for sandy soil for 2001 (Sept 2000-Mar 2002).

Figures 4, 5 and 6 explore the modelled sensitivity of ET and recharge (averaged for the period 1992-2002) in respects to soils, LAI and ponding depths for a flat site covered with seasonal vegetation. Figure 4 indicates that soil type only influences ET at lower LAI values (<4). High LAI represents forest stands where net-precipitation to the soil surface is reduced substantially due to canopy interception. Additionally, the high LAI forests implicitly include a large deep root component that can buffer changes in soil moisture at the near surface. Soils with coarse texture do tend to decrease ET slightly (~25%) at low LAI values due to increased drainage/recharge as shown in Figure 5. The recharge rate decreases for loam, silt and clayey soil in particular. Recharge generally decreases with LAI increase. While average annual recharge rates can vary between ~400mm/year to 0mm/year for a bare surface as a function of soil texture, ponding exhibits a much smaller influence on annual recharge. Figure 6 shows an example of gravely sand soil indicating an abrupt increase in groundwater recharge for lower values of ponding depth, and relative independence of recharge values when ponding depth increases. Ponding depth over naturally vegetated areas is relatively high. Essentially, very low ponding depths likely represent unrealistic conditions for natural landscapes where surface overland flow is unlikely. This phenomenon indicates that, in the ORM region, ponding and hence surface runoff parameterizations may not be critical in vegetated areas if the goal is to model recharge. Although ponding may be a factor in developed areas, the relative change in annual recharge due to ponding variation is also much smaller than that due to soils controls on recharge and vegetation controls on ET.

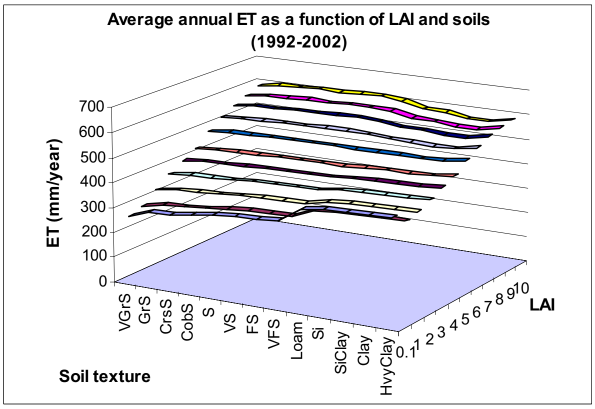


Figure 4 – Impact of vegetation and soil texture on evapotranspiration. ET is averaged for the period 1992-2002.

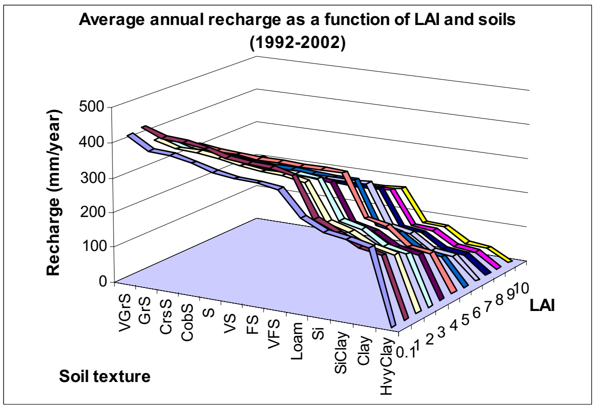


Figure 5 – Impact of vegetation and soil texture on recharge. Recharge is averaged for the period 1992-2002.

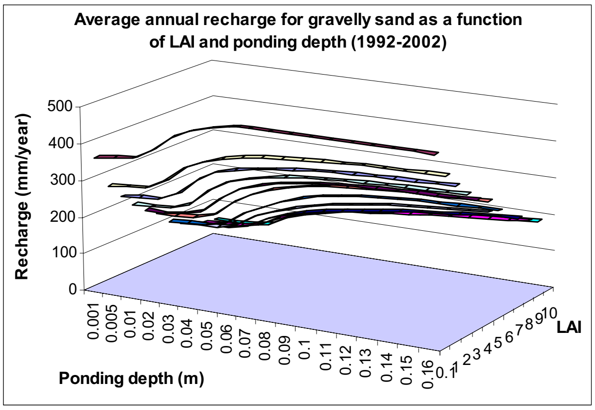


Figure 6 – Impact of vegetation on recharge for gravely sand as a function of ponding depth. Recharge is averaged for the period 1992-2002.

The preliminary results show that the annual recharge for the Duffins Creek basin is ~380 mm/year and ~270 mm/year for the year 2000 and 2001, respectively. However, the results may be biased as a dominant soil type, which is in most cases represented by sand, was chosen for each land cover. Our future work in respect to total groundwater recharge over the area will include Geographic Information System (GIS) to overlay maps of soils, land cover and LAI. This will provide unique categories of soil types and land cover/LAI and the recharge for each category will be area weighted in each (sub)watershed across the ORM region.

The range of recharge estimates in this study is in general accordance with the range of recharge estimates generated by EARTHfx which is based on the surficial geology and ranges from 60mm/year for clayey soil to 420mm/year for sandy/gravely soil. The average annual ET for the period 1992-2002 is found to range between 266-614 mm (Figure 4); it is considerably lower that an average annual PET value (816 mm for Toronto area) which is commonly used in groundwater models as an input data. Most of the difference is seen in late summer when ET of vegetated land (LAI=6) is compared to monthly PET normals.

4. CONCLUSIONS

The variation in land use may considerably affects actual evapotranspiration and, thus, impacts groundwater recharge and drainage. The monthly and yearly actual ET values, estimated with the EALCO model, vary to a large extent depending on land cover/land use and soil texture. Considerably higher ET is seen within vegetated land for both clayey and sandy soil. Sensitivity of recharge to vegetation depends on soils. Sandy soils exhibit considerably higher recharge than impermeable (clayey) soil. Freezing soils during snow melt may have a crucial role in groundwater recharge. This is evident by having high runoff within clayey soils. The preliminary validation of recharge generated by EALCO indicates reasonable values of the results. Due to lack of in situ data, particularly ET, recharge and soil moisture data, the recently set in-situ monitoring system will enhanced further validation especially during snow melt and onset. Surface water budgets derived using EALCO will be assessed using base flow survey and recharge estimates derived using the MODFLOW groundwater model that is calibrated against numerous well records. In addition, the model will be improved for early winter freeze-thaw. Enhancement of EALCO by employing the lateral flow of the soil moisture will further improve the groundwater recharge. Our future work will also include spatial representation of the results, primarily development of sinks and drains digital maps. The results in this study are valuable information for policymakers in bringing decision to further urbanize and develop the ORM. In addition, the results may be used in groundwater models for more accurate predication of groundwater discharge.

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