Assessing the Impact of Leaf Area Index on Evapotranspiration and Groundwater Recharge across a Shallow Water Region for Diverse Land Cover and Soil Properties

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***Abstract*-Climate and land cover changes impact groundwater resources primarily through changes in net surface recharge. Actual evapotranspiration and the partitioning between runoff and groundwater infiltration govern the rate of aquifer recharge. Remote sensing technology opens up new possibilities for groundwater recharge modeling through a rapid method of acquiring up-to-date information at high spatial resolution over a large geographical area. Using the Ecological Assimilation of Climate and Land Observations (EALCO) model, we assess the importance of remote sensing derived land cover, leaf area index (LAI) and soil texture in estimating evapotranspiration and groundwater recharge within the Oak Ridges Moraine (ORM), a complex groundwater recharge area and major aquifer in south-central Ontario, Canada. We explore temporal and spatial dynamics of hydrological variables of the ORM and perform sensitivity analyses based on remote sensing derived inputs to EALCO. The results indicate that LAI is a critical variable of evapotranspiration calculations for the ORM. Soil texture does not have as significant an impact on evapotranspiration as LAI; it is generally found to be a more efficient moderator of recharge and runoff, especially for the soil texture of very fine sand. Based on our results, afforestation of the ORM region would result in the reduction of annual groundwater recharge at the current average precipitation due to increased evapotranspiration. It would also reduce the runoff within the area due to increased evapotranspiration and infiltration.**

Keywords - Evapotranspiration; Recharge; Leaf Area Index; Remote Sensing; Sensitivity Analysis

I. INTRODUCTION

Groundwater is a crucial source of water supply and its quantity and quality have a tremendous impact on people and ecosystems. For example, in Canada water usage increased from 10% in 1970 to 30% in 1998 [1]. This increased demand requires the long term protection of groundwater from reduced groundwater recharge [1]. Climate and land use changes, occurring as a result of natural and anthropogenic processes, are two major external factors affecting the water balance and groundwater recharge. Changes in precipitation and evapotranspiration (ET) directly affect groundwater recharge [2][3]. ET accounts for the loss of as much as half of the precipitation in temperate areas of North America and over 90% of the precipitation in some arid areas [4]. Thus, accurate estimation of ET is fundamental to a good understanding of recharge rates. Aside from energy and moisture availability, vegetation and soil characteristics, such as leaf area index (LAI) and soil texture, are the two major controlling factors of ET [5][6].

Vegetation influences rainfall distribution by means of throughfall and stemflow pathways [7], increases the infiltration capacity of a soil [8] and modifies soil structure [9], which commonly results in a runoff reduction. In addition, vegetation has a considerable effect on ET through both interception losses and stomatal control on transpiration, which is directly related to leaf area [10]. LAI is used as an ecophysiological measure of photosynthetic and transpirational surface and is an important modulator of ET and groundwater recharge [11]. It is defined as half the total leaf area per unit ground surface area [11]. LAI is commonly obtained from the angular distribution of canopy gap fractions, which represents the probability of the light beam penetrating a canopy at an incident angle θ without being intercepted [12][13].

Rapid developments in remote sensing technologies over the last two decades inspired scientists to probe into the relationships between structural variables of a vegetation canopy and remote sensing data. In order to estimate structural vegetation characteristics such as LAI, and map its heterogeneity on a large scale using remote sensing data, two modeling approaches are commonly used: empirical and physically based approach. The former involves statistical correlations between satellite- measured reflectance and field-measured vegetation variables. Vegetation variables for the whole area are estimated based on developed correlation algorithms [14]. The modeling approach, on the other hand, includes radiative transfer (RT) models - physical algorithms that simulate real transfer of radiative energy through a canopy [14][15]. The empirical approach is used in this study.

With the development of surface energy balance analysis, remote sensing has become a spatial quantitative methodology for understanding ET. Assessment of actual ET at regional scale is a challenge to hydrological research requiring the characterization of vast areas to obtain accurate biophysical and meteorological variables. Recent studies have evaluated remote sensing techniques for estimating crop ET on a large scale using different methods and models [16][17][18][19][20]. Commonly vegetation indices from optical remote sensing bands and/or surface temperature from thermal bands are used in different modeling approach to estimate spatial ET. [21] used the ReSET-Raster model in estimating seasonal crop water use for large agricultural areas using Landsat-7 images. A modified version of the Makkink equation based on remote sensed solar radiation and numerical weather forecast of near surface temperature was developed in a study of [22] for a regional scale. The remote-sensing based surface temperature data was used to estimate ET in the study of [23]. The land surface models, for instance ISBA, are based on a physical SVAT (Soil-Vegetation-Atmosphere Transfer) model and they have found their way in estimating ET [24]. The Surface Energy Balance System (SEBS) model was combined with remote sensing NDVI products in the study of [25] implemented for a rotating agricultural cropland monitored during several years. EALCO, a model develop by the Canada Center for Remote Sensing (CCRS), a land surface model, is widely used for study sites in Canada [26].The SVAT models are powerful in a sense that they incorporate calculations of runoff and groundwater recharge in addition to ET and can be used to detect the discharge/recharge zones which are critical in managing groundwater resources. For this reason we will explore a land surface model in this study.

The concept of synergy between remote sensing and groundwater recharge modeling dates back to the late 1980s, when satellite imagery was used to characterize hydrological variables of mapping units [27]. Two decades later, it is still a challenge to employ affordable, physically based, satellite data with a high temporal resolution necessary for monitoring groundwater recharge dynamics. Recent groundwater studies commonly use the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM and LANDSAT images of spatial resolution 30 m. The data are commonly used to construct convergence index maps and groundwater potential zones (GPZ) maps by integrating geological fractures, drainage network, slope and relief [28][29]. Using remote sensing to monitor groundwater dependent variables has received greater attention in recent years [30].

The objective of this case study is to examine temporal and spatial dynamics of evapotranspiration, runoff and groundwater recharge for a complex geological setting at the Oak Ridges Moraine (ORM) region north of Toronto, Ontario, Canada by using remote sensing imagery and the Ecological Assimilation of Climate and Land Observations (EALCO) model. The complex geological setting of the ORM region consists of till and lake deposits overlying the bedrock surface and it is a challenging region for hydrological studies. The impact of urbanization and agriculture on groundwater recharge is adding to the complexity. We propose to use one of the most comprehensive land surface models and recent remote sensing methods to assess the impact of vegetation on groundwater recharge, with the intention to enhance the understanding of groundwater resources management in the region. Trends and relationships between ET, LAI, soil texture, runoff, groundwater recharge and water retention are examined through sensitivity analysis. The spatial analysis is conducted for the Duffins Creek, a partially-urbanized watershed within the ORM region.

II. ECOLOGICAL ASSIMILATION OF CLIMATE AND LAND OBSERVATIONS (EALCO) MODEL

EALCO was developed at the Canada Centre for Remote Sensing (CCRS) to study the ecosystem-climate interactions by assimilating Earth Observation data sets (both *in situ* and satellite). In EALCO, hydrological processes of various land cover types are simulated by five main schemes that include a surface radiation scheme [31][32], snow and water scheme, soil thermal scheme [33], plant and soil carbon and nitrogen bio-geochemical cycle schemes [34][26]. The model applies coupled energy, water, and carbon cycle algorithms for canopy transpiration simulations through which the climatic and plant physiological control on actual ET are simulated [35]. For example, climate change, including an increase of atmosphere CO_2 concentration that affects the stomatal conductance of plant leaves, affects actual ET by changing the dynamics of canopy energy and water balance. The transpiration algorithm is based on solving the governing equation system that represents the coupled canopy energy-water-CO_2 transfer dynamics using the nested convergence approach [36]. Runoff is calculated as the difference between precipitation and infiltration when the difference exceeds the maximum water retention depth. Soil evaporation on the ground surface is simulated by solving the soil/snow surface energy balance equation (Fig. 1). The soil water movement in the soil profile is based on implicit solution of the coupled soil heat and water transfer equations between soil root–canopy–atmosphere [36]. Evaporation (or sublimation) from the soil (or snow) surface and from intercepted precipitation on the canopy is simulated by solving the energy balance equation for ground and canopy surface (Fig. 1). Moisture and thermal profiles for the soil and snowpack are based on 1D vertical energy and water transport and conservation equations solved using a multilayer finite-difference scheme [35]. This includes a predictive dynamic snow-layering scheme and a user-defined soil-layering scheme (six soil layers were used in this study). Water transfer in the soil-root-stem-leaf-atmosphere continuum is based on the hydraulic gradient and resistance in the system. Soil water is linked to groundwater (water table) through diffusive groundwater recharge and discharge [36]. The EALCO model runs at a half-hourly time step, using surface meteorological inputs of air temperature, precipitation as rain or snow, wind speed, surface pressure, specific humidity, down-welling shortwave radiation, and down-welling long-wave radiation [35]. Radiation is partitioned into diffuse and direct components as a function of precipitation amount and solar zenith angle. The radiation scheme simulates the surface albedo and the absorption of radiation by ecosystem elements, such as the leaf-level energy, water, and carbon exchanges. Additional vegetation variables related to canopy interception, transpiration, rooting depths, and photosynthesis are based on the look-up tables related to land cover. The coupled model run enables representation of dynamic ecosystem processes such as snow accumulation, plant phenology, water stress, precipitation interceptions by canopy, and dew and frost presence, in the surface albedo dynamics [37]. EALCO has been found to be reliable while extensively tested with flux tower measurements over Canada and the United States [38][39][31][40][43][37]. Therefore, the model outcome can be expected to be reliable for this study.

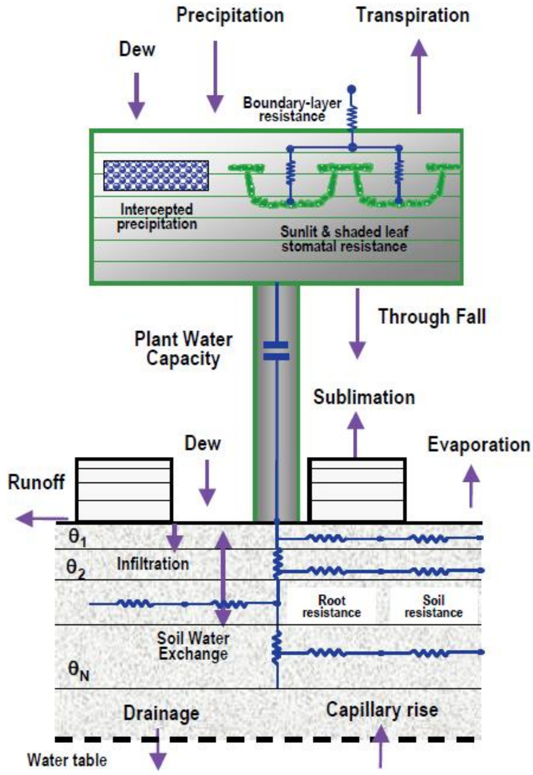

Fig. 1 The EALCO model diagram for the land surface water processes simulated in the model (Source: Wang *et al*. 2013, with permission)

III. DATA AND METHODS

A. Geological setting of the Oak Ridges Moraine

The ORM is a major physiographic feature in south-central Ontario (Fig. 2). It is a 160-km long and 20-km wide landform that rises more than 300 m above the level of Lake Ontario. The aquifer associated with the ORM deposits, named as the Oak Ridges Aquifer Complex (ORAC), feeds the headwaters of major rivers in the Greater Toronto Area [41] (Fig. 2). The ORM is characterized by sandy soils and hummocky topography, with irregular mounds and depressions associated with ice-contact, dead-ice, or glaciofluvial outwash features [45]. The ORM area provides most of the recharge to ORAC and to the underlying aquifers. Annual groundwater recharge has been estimated to vary widely between 25 mm and 400 mm through time and space, based on the watershed-scale base flow analysis [41].

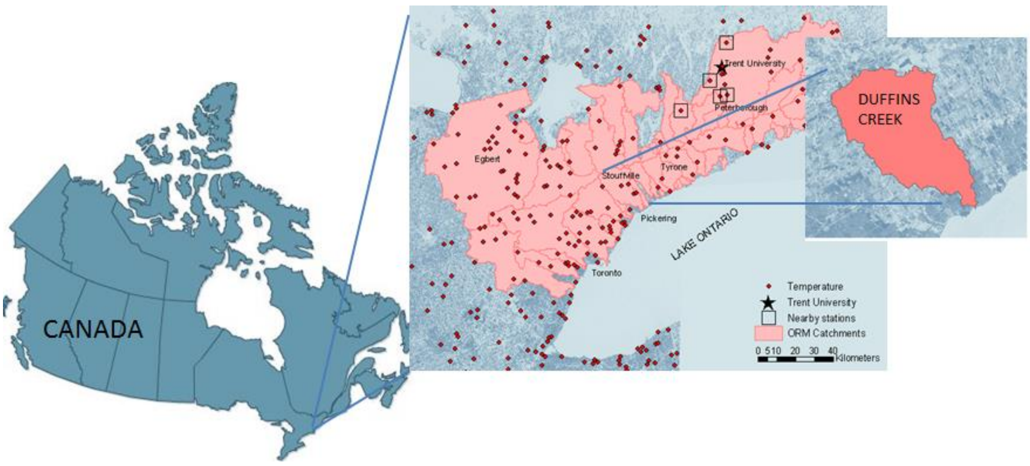

Fig. 2 The Oak Ridges Moraine (ORM) region, located in Ontario, Canada. The Duffins Creek watershed, located in the southern part of the ORM

Three regional aquifer units can be identified within the deposits: a) the lowermost Scarborough aquifer complex (SAC) associated with the sands and silts, found mostly within valleys in the bedrock surface (this unit is confined by the Sunnybrook drift aquitard); b) the middle aquifer, referred to as the Thorncliffe aquifer complex (TAC) associated with the deltaic sand and interbedded lacustrine silt and clay (this unit is confined by the thick, regionally-extensive Newmarket Till aquitard); c) the ORAC overlies the Newmarket Till but becomes thin and discontinuous in the southern area [41][42] (Fig. 3). The geological setting of the Duffins Creek watershed consists of a series of alternating till and lake (silt and clay) or river (sand or gravel) deposits overlying the bedrock surface, ranging in thickness from 0 to 200 m [41][42] (Fig. 3).

B. Meteorological data

Meteorological data sets were obtained from Environment Canada for the period from 1992 to 2002 and used as input data to EALCO. The information on climate was based on point climate forcings. As current in-situ measurements across the region showed little climate spatial variability, Toronto Buttonville station measurements (elevation 198 m, latitude: 43 º 52' N; longitude: 79 º22' W; Station ID: 615HMAK) were chosen to represent conditions in the Duffins Creek watershed. The climate data set represented direct hourly records of temperature, surface pressure, solar radiation, relative humidity, wind speed and estimated hourly precipitation. Gap filling was applied to approximately 5-10% of the raw data to estimate missing values based on adjacent stations (Egbert and Trent University) (Fig. 2). This was performed by using monthly normals developed over the observation periods to adjust the missing data. Hourly estimates of rainfall and snow were temporally interpolated based on hourly relative humidity, daily precipitation and rainfall measurements.

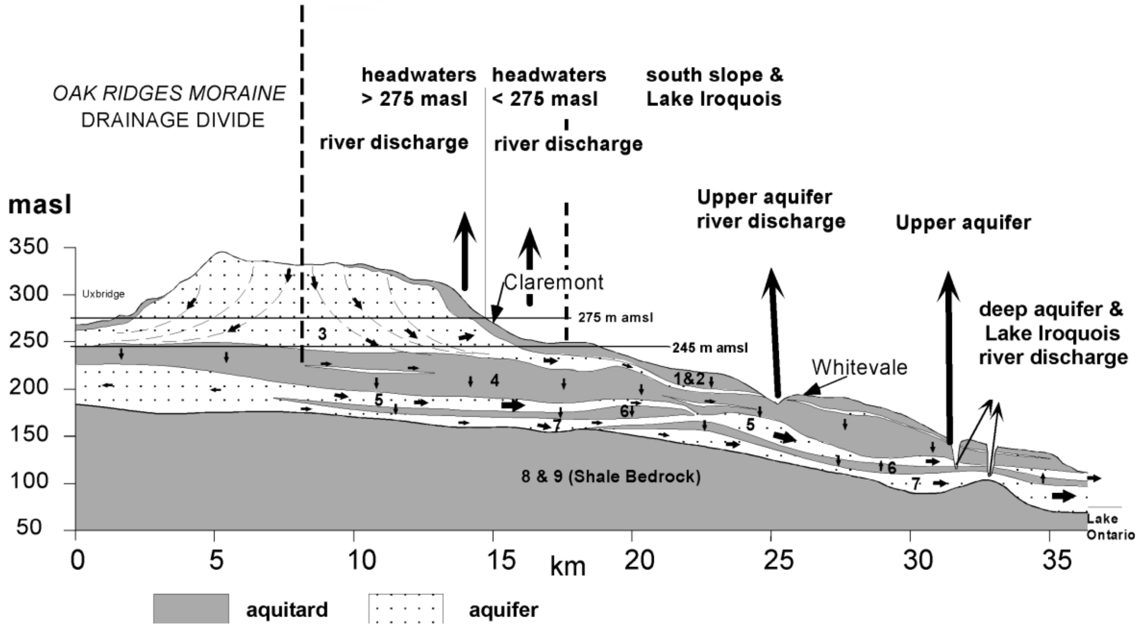

Fig. 3 Geological setting of the Duffins Creek Watershed (*from Geber and Howard, 2000*)

C. Land Surface Variables

Land surface variables used as input data in EALCO included spatial land cover, LAI, soil texture and retention storage. The LAI values were based on four major land cover categories (grassland, shrub land/agricultural, bare land, and forest). The land cover map was derived from three LANDSAT 7 ETM+ scene (Path 18, Row 29 and 30) acquired in growing season of 2002 (Aug 10 2002) using the method developed in [43]. The LAI values were generated using the simple ratio (SR), infrared simple ration (ISR) and normalized difference vegetation index (NDVI) computed from the same remote sensing dataset. Regression models defined for specific land cover type, as explained in [35], were used to estimate actual LAI for each land cover. The LAI prediction equations were based on ISR for forest, SR for grassland and NDVI for agricultural areas. We relied on the validation process conducted in the study of [35]. RMSE for the LAI-IRS relationship for needle and broadleaf stands was reported to be 1.15 and 0.96 based on the Theil-Sen regression [35].

The soil texture classification was based on a subset of 13 classes ranging from very gravely sand to heavy clay [44]. The soil surface retention storage was derived based on the SCS Curve Number (CN) approach [45]. Retention storage is the collection of runoff in an area where it is kept until it can infiltrate into the ground. The method is widely-used, and it calculates the runoff potential for different combinations of soil and land cover. Runoff is related to total precipitation and storage capacity of soil (i.e., potential maximum water retention), as a function of CN. Appropriate CN values were selected based on a look-up table derived by USDA for different soil types (based on infiltration capacity) and land cover. The SCS CN approach was used to calculate how much water infiltrates into a soil surface and then the energy balance was used to calculate how much of this water is lost to ET.

The monthly water balance and sensitivity analyses were generated based on the EALCO model simulations over a 10-year period from 1992 to 2002. The sensitivity analyses of ET, runoff and groundwater recharge were run based on soil texture, LAI and retention storage for different land cover classes representative of those found within the region. We compared the model outputs, recharge and runoff for four sub-catchments of the Duffins Creek with stream flows from four stream flow gauges (Stations 516, 517, 527 and 499) (Fig. 4). A base flow separation technique was applied to separate base flow and surface runoff which were then compared to the simulated recharge and runoff, respectively. The comparison was based on annual averages and the constant-slope method [46], which was in accordance with the previous ORM related studies done by Earth*fx*. The locations of the gauges were representative of the subsurface flow. Several points that could give us misleading results in case of transboundary flow were excluded.

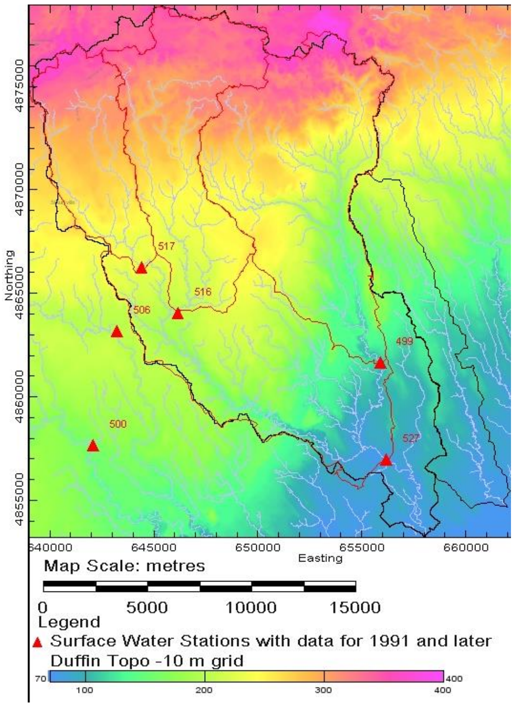

Fig. 4 Topology, sub-catchments and locations of the stream discharge gauges within the Duffins Creek watershed

IV. RESULTS

A. Remote Sensing derived land surface data

The surficial soil consists mainly of Halton Till, a mixture of different particle sizes ranging from clay to boulders (Fig. 5). Sand and gravel deposits are observed in the northern part of the watershed, along the glacial Lake Iroquois shoreline, and within the stream valleys including the large east-central area [44] (Fig. 5a).

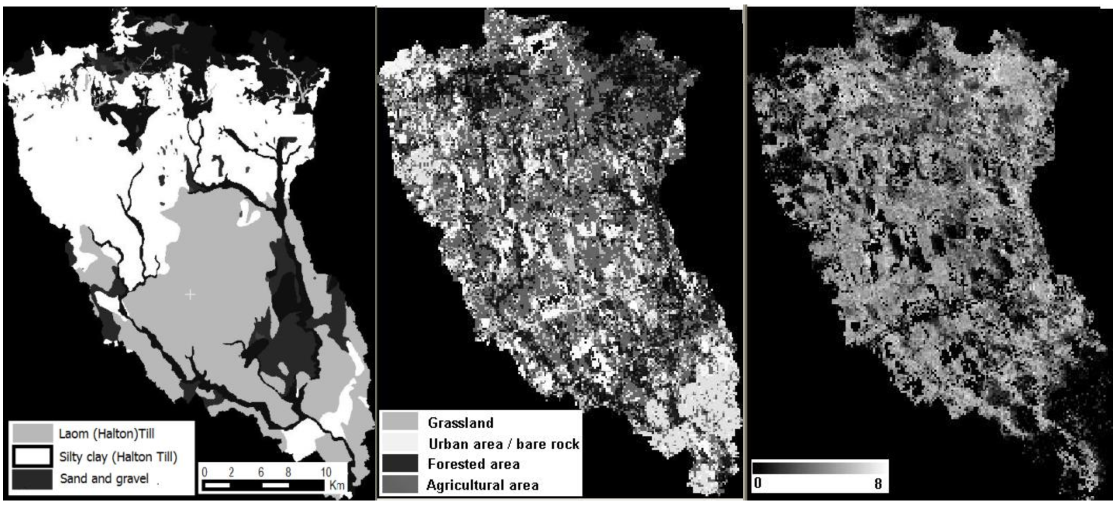

Fig. 5 Spatially distributed land surface variables for the Duffins Creek watershed derived from remote sensing imagery and used in EALCO: a) Soil texture map; b) Land cover map; and c) Leaf Area Index (LAI) map (Centre point coordinates: $43^0$52’26.45’’N, $79^0$8’3.72’’W)

LAI values range from 0 (bare land, ploughed fields, urban areas, and rock) to about 8 (deciduous/mixed forest). The Duffins Creek watershed contains deciduous and mixed forests (30.72%), evergreen forest (4.39%), bare/rock/urban land (10.14%), shrub land/agricultural land (29.6%), grassland (17.54%), and water (7.61%). The agricultural fields, grassland and shrub land, low vegetated areas, and ploughed fields (Fig. 5b) have LAI values around 4 (Fig. 5c) with somewhat increased values in the forested patches. Forested areas commonly correspond with sandy soil and are mainly located within two large areas in the northern and east-central part and along the streams across the watershed. A large urban area with low LAI is situated in the southern part of the watershed (Figs. 5b and 5c).

B. Temporal dynamics of hydrological variables

Average annual precipitation for the Buttonville station, near Toronto, ranges between 730-1070 mm for the period between 1992 and 2002. Monthly water balance for three consecutive years (2000, 2001 and 2002) estimated for the marginal conditions of soil texture and LAI are demonstrated on Fig. 6. Due to both low-permeability of clayey bare soil and spring snowmelt, a relatively high runoff is generated during the spring period (Figs. 6a and 6b). Maximum runoff is seen in spring 2001 on both figures as a result of increased precipitation in winter 2000-2001 [47]. The winter of 2000-2001 had below normal-temperature in this region of Canada, and frozen soil persisted longer than for the two other winter seasons (1999-2000 and 2001-2002) when temperature was generally above normal [47]. Snow and frost remain longer within vegetated areas as they are more protected from solar radiation than open areas. Frost pockets are often located within the root systems of vegetation and temperature within these pockets rises slower than within the soil of the open land. This may cause somewhat delayed runoff peak, as seen in Fig. 6b. The high runoff in spring 2001 results in low groundwater recharge. The opposite trend is seen for 2000 and 2002. During summer, ET tends to suppress recharge (Fig. 6b). In November and December 2001, the recharge reaches its peak of 68 mm month^{-1} for bare land after large precipitation events (Fig. 6b). Since this period exhibits no frozen soil and low ET, the recharge is relatively high for the case of bare land. This event best explains the behaviour of groundwater recharge in typical conditions and adds further support to a number of recent studies [48][49][50] which found that groundwater recharge is reduced with increase in vegetation cover. ET has a similar trend for all scenarios; it peaks in mid-summer (Figs. 6a and 6b).

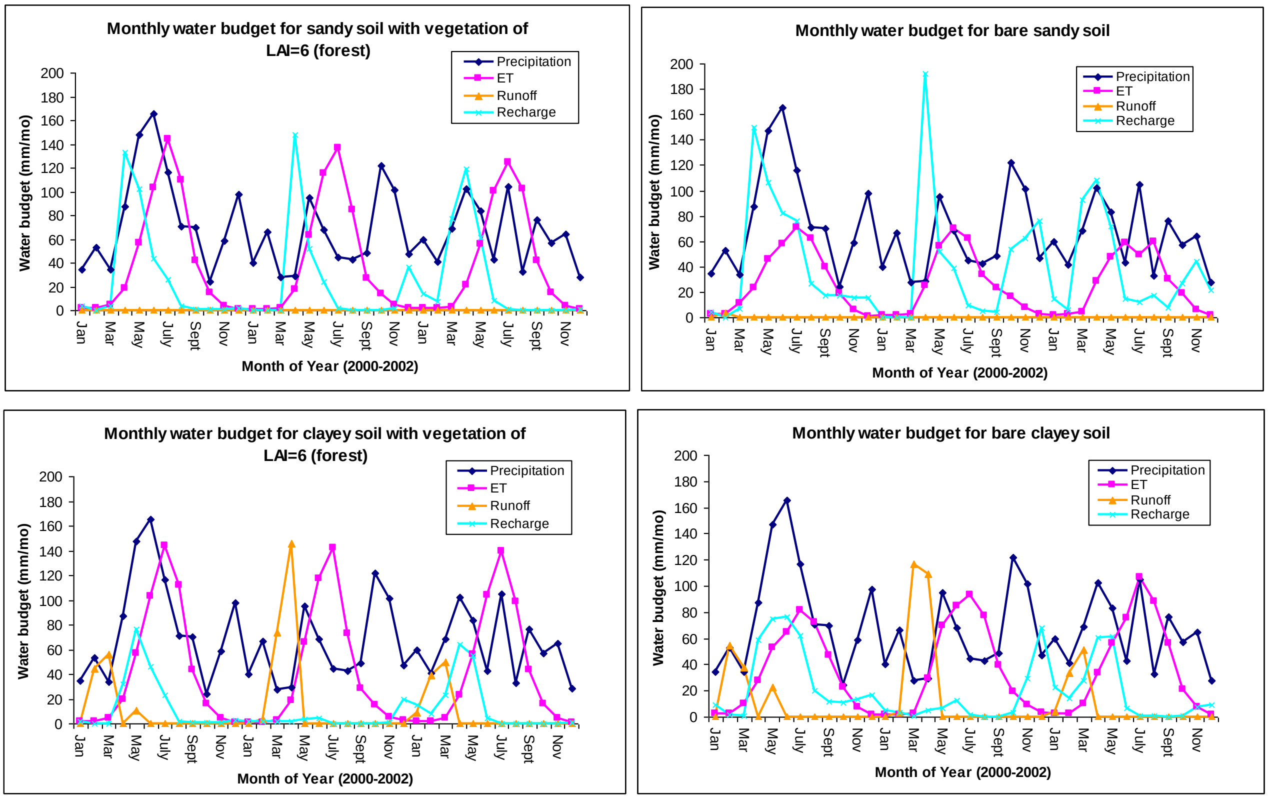

Fig. 6 Monthly water balance components generated by EALCO for the Oak Ridges Moraine (ORM) for different types of soil and high amount of vegetation (a, b), and for different type of bare soil (c, d) using meteorological data from Sept 2000 and Mar 2002

In contrast to clayey soils, which result in high runoff in both LAI extremes, sandy soils exhibit almost no runoff throughout the year irrespective of surface cover (Figs. 6c and 6d). High recharge is seen within both non-vegetated and vegetated sandy soil reaching 191 mm month^{-1} for bare sandy soil (Fig. 6c). This is again in accordance with some recent studies [48][49][50]. Reference [48] found that due to increasing ET, afforestation of old fields results in the reduction of both annual groundwater recharge and runoff. Snowmelt directly contributes to groundwater recharge due to high permeability and low porosity of sandy soil [33]. Sandy soils exhibit slightly lower ET than clay soils due to their higher drainage. The presence of vegetation considerably increases ET in both clayey and sandy soil although the monthly trend of runoff and recharge is similar in timing between vegetated and non-vegetated areas of the same soil type. We also found that during winter months, the transpiration is negligible due to low coverage of evergreen trees in the region and due to closed stomata. Generally, areas with low LAI tend to have higher soil evaporation rates during both winter and summer periods. Reference [50] found that evaporation itself increased and transpiration decreased more than two-fold for low (heath) compared to high (oak) vegetation.

C. Sensitivity analysis of surficial and hydrological variables

The results of the sensitivity analysis indicate that the ET losses generally increase with increasing LAI across the whole soil textural gradient (Fig. 7). References [51] and [52] showed the same trend in their work. Trees maintain their canopies cooler (by higher ET) than grass despite the fact that they intercept higher net energy inputs. The ET values range from about 240 mm year^{-1} in areas of bare land and very gravely sand to close to 600 mm year^{-1} in areas of extreme LAI values and sandy soil. This finding suggests that vegetation canopy structure has a considerable impact on ET within the ORM area.

Soil type, however, has less impact on ET than does LAI. It has almost no impact for high LAI while it has more effect on the vegetation with low LAI (<4). A similar trend is reported by [50] and [50]. Reference [51] found, on the other hand that ET of highly vegetated areas was more strongly affected by soil texture than low vegetated areas such as grass. Our findings partly coincide with the findings of [52]; they demonstrated generally higher ET for silty and clayey soils. Reduced ET is observed for high LAI and fine soil (Fig. 7). High LAI represents forest stands where net precipitation to the soil surface is reduced substantially due to canopy interception. Additionally, forests include a spatially expansive and deeply rooted zone, thereby buffering rapid changes in infiltration into steady amounts of deep percolation. Low vegetated areas, having small LAI and shallow roots, are more sensitive to availability of soil moisture. This process is also determined by the soil properties. Soils with the coarse texture tend to decrease ET slightly (~25%) at low LAI values (Fig. 7) due to increased drainage/recharge as shown in Fig. 8.

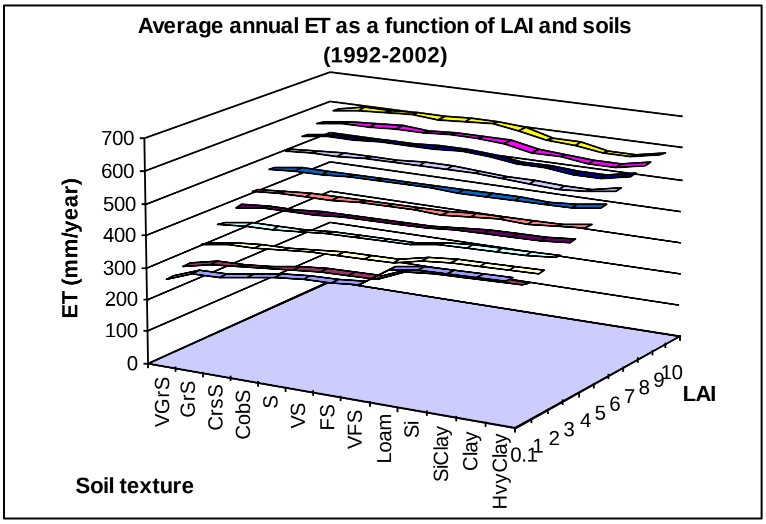

Fig. 7 Sensitivity analysis: Relationship between evapotranspiration (ET), soil texture, and leaf area index (LAI) for the ORM region. ET values were modeled by EALCO and averaged for the period 1992-2002 using local meteorological data (Soil texture: VGrS – Very gravelly sand; GrS – Gravelly sand, CrsS – Coarse Sand, CobS – Cobalt sand, S-Sand, VS-Very sandy, FS-Fine sand, Loam, Si-Silt, SiClay-Silty Clay, Clay, HvyClay – Heavy Clay)

The recharge in the sensitivity analysis ranges from 30 mm year^{-1} for clayey soil (LAI = 10) to about 400 mm year^{-1} in sandy/gravely soil (bare land) (Fig. 8). The values are in general accordance with the range of recharge estimates that Earth*fx* generated based on surficial geology [42]. References [53][54] reported that recharge ranges from about 300 mm year^{-1} to about 400 mm year^{-1} within the ORM area. Dr. Marc Hinton (personal communication, 2008) suggested that the recharge rate in fine textured soil is less than 35 mm year^{-1}. Recharge values in this study agree with the previous findings for areas with high LAI, while recharge for low-vegetated areas exhibits higher values for fine soil. The recharge rate decreases slowly in coarse soils; however, it decreases rapidly in loam, silt clayey soil, and heavy clayey soil in particular. This abrupt recharge decrease coincides with the increase in ET for low LAI (Fig. 7). Although recharge and ET could balance out each other in this case, any water in excess would become runoff in fine textured soils [55].

Overall, the recharge rate is less sensitive to fluctuations in coarse soil. Recharge rates vary considerably with small changes in fine soil suggesting that soil texture plays much bigger role in the recharge. Reference [52] found that soil texture causes slightly larger variations in recharge than land cover, and that the recharge decreases considerably in fine soil for all land cover types. Similarly, we found that the high LAI also exhibits relatively high recharge but it is less sensitive to soil texture than low LAI.

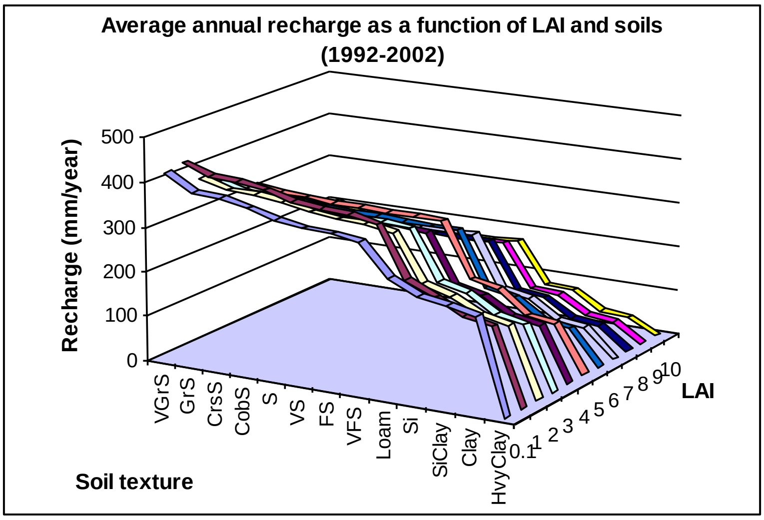

Fig. 8 Sensitivity analysis: Relationship between recharge, soil texture, and leaf area index (LAI) for the ORM region. Recharge values were modeled by EALCO and averaged for the period 1992-2002 using local meteorological data (Soil texture: VGrS – Very gravelly sand; GrS – Gravelly sand, CrsS – Coarse Sand, CobS – Cobalt sand, S-Sand, VS-Very sandy, FS-Fine sand, Loam, Si-Silt, SiClay-Silty Clay, Clay, HvyClay – Heavy Clay)

An increase in LAI from 4 to 10 yields a decrease in recharge from 280 mm year^{-1} to 200 mm year^{-1} for very fine sand (Fig. 8). For their study site with similar soil types, [50] found slightly greater differences in recharge for a mature oak stand (390 mm year^{-1}, and 635 mm year^{-1}, respectively) than did the current study for similar LAI values. In the study of [49], an increase in forested area from 34% to 80% within a watershed with sandy soils resulted in reduced recharge and increased ET on the order of 39 to 41%. Reference [55] also found that afforestation of the catchment by evergreen trees could decrease the water table when compared to arable land. The highest recharge in our results occurs for LAI = 1 suggesting that shallow rooted low vegetation may enhance recharge when compared with bare land. While LAI has an impact on recharge, soil type has overall greater control on the recharge values. Reference [52] similarly found that although recharge was only moderately correlated with land cover and soil texture, soil texture had a higher impact on recharge than land cover. Reference [51] indicated almost no ET changes with different soil texture in grasslands but significant ET changes in tree plantation.

While modelled average annual recharge rates can vary between 0 to about 400 mm year^{-1} for the bare surface as a function of soil texture, retention storage exhibits a much smaller influence on annual recharge. At low retention storage, groundwater recharge increases for all LAI values, whereas for retention storage values over 0.06 m, groundwater recharge generally stays constant (Fig. 9). Retention storage over naturally vegetated areas is relatively high and hence recharge is insensitive to variations in retention storage within this land cover. This suggests the low likelihood of surface overland flow after soil thaw in this region of Canada. The retention storage and hence surface runoff parameterizations in vegetated areas may not be critical if the goal is to model recharge. Although retention storage may be a factor in developed areas, the relative changes in annual recharge due to retention storage variations is much smaller than those due to soils controls on recharge or vegetation controls on ET.

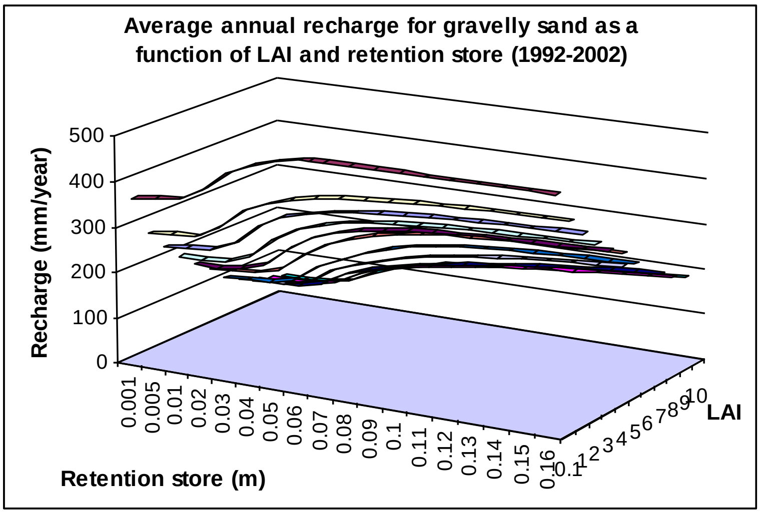

Fig. 9 Sensitivity analysis: Relationship between recharge, retention storage and leaf area index (LAI) for sandy areas of the ORM region. Recharge values were modeled by EALCO and averaged for the period 1992-2002 using local meteorological data (Soil texture: VGrS – Very gravelly sand; GrS – Gravelly sand, CrsS – Coarse Sand, CobS – Cobalt sand, S-Sand, VS-Very sandy, FS-Fine sand, Loam, Si-Silt, SiClay-Silty Clay, Clay, HvyClay – Heavy Clay)

D. Spatial distribution of groundwater recharge in the Duffins Creek Watershed

To summarise, the spatial distribution of remote sensing derived annual ET, runoff and recharge for the Duffins Creek (Fig. 10) demonstrates that ET ranges between 294 to 493 mm year^{-1} (Fig. 10a), runoff ranges between 1 to 523 mm year^{-1} (Fig. 10b), and recharge ranges between 0 to 406 mm year^{-1} (Fig. 10c). When compared with surficial variables (Fig. 5), the pattern of runoff and recharge reflect both the underlying soil texture and land-use distributions; however, soil texture seems to plays a more significant role for runoff and recharge distribution than land-use. The northern and east-central parts, having mostly sandy and gravely soil, are main recharge zones of the watershed (between 300 and 400 mm year^{-1}), with low runoff (generally below 30 mm year^{-1}). These areas are also highly forested where ET reaches the highest values (generally 350-490 mm year^{-1}). This may suggest the importance of the deep tree roots which most likely use groundwater for meeting transpiration demands in dry periods. These results of high recharge and high ET are in accordance with the previous results suggesting that the process of transpiration is a major component of ET in forested areas. In fact, ET and recharge compete, and as earlier estimated in the sensitivity analysis, LAI has more influence than soil texture on both ET and recharge in sandy soils (see Fig. 8). Based on the visual inspection, vegetation has more impact than soil texture on extreme ET values.

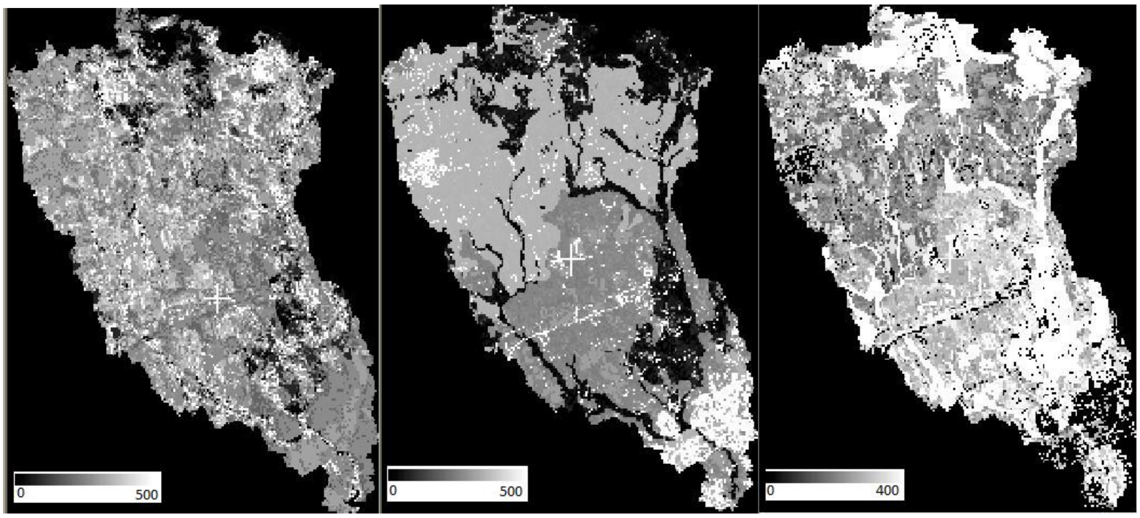

Fig. 10 Remote sensing derived hydrological variables for the Duffins Creek watershed derived by EALCO and averaged over 10 years: a) evapotranspiration (ET), b) runoff and c) recharge. Maximum values: 493 mm/yr for ET, 523 mm/yr for runoff and 406 mm/yr for recharge

Relatively high ET occurs within the vegetated patches on *Halton Till* soils due to higher transpiration from crops, grass and shrubs. Runoff ranges between 130 to 180 mm year^{-1} in this area with higher values in the northern part of the till area due to steeper slopes and the silt and clay veneer. Recharge rates (150 to 260 mm year^{-1}) have the opposite trend for the two till sub-areas (Fig. 10). The southern part of the watershed, which consists mostly of clay and silty clay, has the highest runoff (over 400 mm year^{-1}). Recharge is very low; this part of the watershed is mostly urbanized (Fig. 10) and underlain by Newmarket Till. The ET values are somewhat lower for the urban area and, also, for the less-vegetated areas across the watershed. One should note that the overall ET range is relatively narrow (294 to 493 mm year^{-1}) suggesting that the evaporation component of ET is an important factor in non-vegetated and urban areas for both sandy soil and till areas. Our results agree with the findings of [41]; they found that significant recharge occurs in the ORM area (northern part) of the watershed (400 mm year^{-1}) representing 56% of the direct recharge. Reference [41] estimated recharge on the Halton Till plain to be 150 mm year^{-1}, which accounts for 27 % of the direct recharge. Our estimated ET values are slightly lower than those in the study by [56] which they estimated to be 533 to 559 mm year^{-1}.

In Table 1, we compare the modelled recharge and runoff with the stream flows. The relative errors (defined as the relative difference between recharge/runoff and base flow/surface discharge, respectively) for both recharge and runoff range from 10% to about 35%, being smallest for gauge 527 which collects most of the stream flow within the watershed (Fig. 4). Pumping withdrawals are neglected within the Duffins Creek watershed and do not contribute to the errors.

TABLE 1 COMPARISON OF THE AVERAGE ANNUAL BASE FLOW AND SURFACE DISCHARGE WITH AVERAGE ANNUAL MODELLED RECHARGE AND RUNOFF, RESPECTIVELY, FOR FOUR GAUGES LOCATED WITHIN THE DUFFINS CREEK. NOTE: RELATIVE DIFFERENCE BETWEEN RECHARGE/RUNOFF AND BASE FLOW/SURFACE DISCHARGE VALUES IN THE BRACKETS

	Field data ($m^3 s^{-1}$)			**Modelled data (EALCO) ($m^3 s^{-1}$)**	
	Ave. annual stream flow	**Ave. annual base flow**	**Ave. annual Surface discharge**	**Ave. annual Recharge**	**Ave. annual Runoff**
Gauge 516	0.62	0.39	0.23	0.43 (0.1)	0.28 (0.18)
Gauge 517	0.4	0.22	0.18	0.19 (0.16)	0.22 (0.18)
Gauge 527	2.6	1.54	1.06	1.7 (0.1)	1.18 (0.1)
Gauge 499	1.21	0.81	0.4	0.6 (0.35)	0.35 (0.14)

E. validation of evapotranspiration generated by ealco

Validation of the ET estimates generated by EALCO was a challenge in this study due to lack of the field measurements. The energy balance measurements from 25-31 Aug 1994 collected in South Ontario was the only available dataset to validate modelled ET [57]. Overall, the simulated data fit well with the measured data (Table 2). The correlation is high for the net radiation (Q) (R^2=0.99) and for the latent heat flux (Qe) (R^2=0.83). Somewhat lower agreement is seen for the sensible (Qh) and soil (Qs) heat fluxes (R^2=0.69 and R^2=0.54 respectively). The latent heat flux shows RMSE of 29.83 Wm^{-2}, while both sensible heat and soil heat fluxes show RMSE of 29.83 Wm^{-2} and 30.19 Wm^{-2}, respectively.

TABLE 2 THE COEFFICIENT OF DETERMINATION R^2 AND ROOT MEAN SQUARE ERROR (RMSE) FOR MEASURED AND SIMULATED ENERGY BALANCE COMPONENTS (Q-NET RADIATION, QE-LATENT HEAT FLUX, QH-SENSIBLE HEAT FLUX, QS-SOIL HEAT FLUX)

Energy balance components	R^2	RMSE (Wm^{-2})
Q	0.99	16.81
Qe	0.83	29.83
Qh	0.69	29.24
Qs	0.54	30.19

The simulated latent heat flux (Qe) data aggregated over each hour for the given days (Fig. 11) suggests that generally EALCO has a slight tendency to underestimate Qe (by 14% during midday). One of the reasons for such a trend may be a lack of lateral drainage function, and, therefore, non-representative water table fluctuations [57]. Soil heat flux exhibits an inconsiderable but constant underestimation (Fig. 11). In order to further explore this discrepancy the soil temperature should be explored and validated. Fine resolution of soil layers in EALCO attributes soil moisture and heat simulations. However, attention should be given to initialization of moisture and temperature profile [58]. [59] found that topography has a considerable influence on soil moisture, water table, and saturated water redistribution. In areas of hummocky terrain such is in the region of ORM, topography plays an important role in modeling ET and it should be considered to improve ET and recharge within the region.

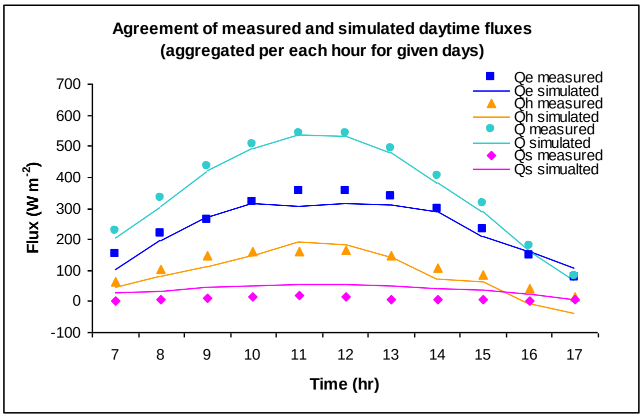

Fig. 11 Agreement of hourly measured and simulated daytime energy balance components for the given days (25-31 Aug 1994) (Q-net radiation, Qe-latent heat flux, Qh-sensible heat flux, Qs-soil heat flux)

V. DISCUSSION

Our findings show that forested areas have lower recharge than low vegetated areas. This trend is emphasised in fine-grained soil where soil types and LAI have considerable impacts on recharge and ET, respectively. Variations in sandy soil, however, do not have considerable impacts on ET nor recharge. Therefore, LAI exerts greater control on both ET and recharge within coarse soil. This study corroborates the findings in [48] and [50]. Afforestation is beneficial for flood and erosion control by reducing runoff; however, it likely has a negative impact on water yield and groundwater recharge [49][51]. Our results suggest that ET is a crucial component of the water balance in the ORM area and should be carefully considered in both land surface and groundwater modelling.

The estimated water balance components for the ORM region (ET, runoff and recharge) demonstrate consistent and stable behaviour. The findings are in accordance with other studies where EALCO was employed for less complex geological settings [38][39][31][40][10][37].

To possibly improve the performance of EALCO for a complex geological setting, additional attention might be given to initialization of moisture and temperature profile [60] and topography. Reference [59] found that the topography has considerable influence on soil moisture, water table, and saturated water redistribution. In areas of hummocky terrain, such as the top of the ORM, topography plays an important role in determining ET. Reference [10] found the strong correlation between modeled ET and measured ET for a boreal aspen forest (R= 0.96). He demonstrated that modeled ET was higher than measured ET by 10% and that an additional modification of the leaf and canopy physiological variables might help improve simulated ET. Incorporating a lateral flow component within the unsaturated zone would affect ET as well. Reference [59] adapted a distributed hydrological model approach to consider the lateral subsurface flow and found that about 10.5 mm of water was lost through saturated subsurface flow during a growing season. This represented almost 6% of the rainfall in the same period in a gently steep terrain area located in Saskatchewan, Canada.

The model may require better partitioning of runoff and recharge within different soil types. The fact that runoff is generated in sandy areas only when there are frozen soil conditions or extreme rainfall may not be realistic in every circumstance, as it may be expected that several areas within the region generate runoff at other times of year as well (Dr. Hinton, personal communication, 2005). The relatively constant ET and recharge for the coarse texture soils for a given LAI (Figs. 7 and 8) may be influenced by the soil water storage calculations (Dr. Hinton, personal communication, 2005); this also deserves further exploration. Spatial groundwater depth and groundwater ET should be incorporated into recharge calculations as well. Reference [52] found that transpiration from shallow water table may account for over 11% of total ET. Therefore, shallow groundwater condition, as often found in the Lake Iroquois beach deposits, would most likely increase ET and decrease recharge. When compared with the stream flow measurements, the model shows relatively good agreement although some groundwater from the sub-catchments may move across the lateral boundaries of the watersheds resulting in water loss. We believe that less agreement in the northern area is due to ‘deep’ groundwater (see the section on Geology of ORM) that bypasses the gauges (for instance, gauge 499). More agreement is observed for the gauges in the southern area where almost all water is captured by the gauges. In his results, [37] also showed satisfactory performance of EALCO where stream discharge measurements were used for model evaluation in the Grand River watershed. Some uncertainties in the results could be also related to the input climate soil, LAI and land cover data.

Our study enhances understanding of ORM and identifies knowledge gaps where increased attention and future research and policy are needed. Using remote sensing derived land surface variables, we have generated the recharge map and concluded that the majority of the Duffins Creek watershed is a recharge area (Fig. 10). To account for the total recharge in the watershed, however, it is important to consider the exchange of water between the aquifers underlying the Duffins Creek watershed as well as underflow into the watershed from external areas [41]. As outlined by [41], 43% of the recharge within the ORM area emerges in the headwaters within the northern part of the watershed. Some of the remaining water moves within the ORAC and is discharged to other headwaters and streams through leakage across the Halton Till. The remainder may leak downward through the Newmarket Till to enter the middle (TAC) and lower (SAC) aquifers. Water from these units discharges to Lake Ontario or to streams where either the aquifers have been exposed or where vertical fractures are present in overlying confining units.

Based on our results, afforestation of the areas could result in the reduction of annual groundwater recharge at the current average precipitation due to increased ET. In addition, afforestation would likely reduce the runoff within the area due to increased ET and infiltration. The uncertainties related to the moraine's complex geology prevent scientists to define the impact of urbanization on groundwater recharge in the ORM. Our results, however, add a critical component related to afforestation/deforestation in the ORM region. In the case that urbanization reduces the amount of precipitation reaching groundwater, both afforestation and urbanization would result in the groundwater reduction, through the effects of ET and runoff alternation. The impact of both LAI and soil types on groundwater recharge is crucial in demonstrating the possible consequences of deforestation/afforestation and urban development [49][50][51][52].

VI. CONCLUSIONS

The rapid technological advancement of remote sensing in recent years has found its role in many fields of earth science. However, not much attention has been paid to use of remote sensing in hydrogeology, where surface hydrological and groundwater variables are analyzed on the large scale and often in near-real time. Groundwater systems are a crucial component of the hydrological cycle and are directly related to population increase, urbanization, industry development, flooding, droughts, climate change, and agriculture/food security. This study focused on generating spatial distribution of hydrological variables, groundwater recharge in particular, using widely available geospatial remote sensing data. The emphasis was to integrate biophysical variables from remotely sensed data into EALCO, a land surface model, and to examine the dynamics of hydrological variables for the geologically complex Oak Region Moraine (ORM) region.

The results justify the rationality and importance of using remote sensing technology in estimating hydrological variables such as actual evapotranspiration (ET), runoff and groundwater recharge at watershed and regional scale. The sensitivity assessments of ET and recharge for different LAI and soil types indicate that LAI is a critical variable in the ORM region. Although the soil texture within the ORM region is an important factor; it does not have as a significant impact on ET as LAI. On the other hand, soil texture is found to be a more efficient moderator of recharge and runoff, especially for the soil texture of very fine sand. The coarse soils are relatively insensitive to recharge and LAI highly modifies both ET and recharge within coarse soils. Thus, up-to-date vegetation information by means of LAI and remote sensing are important for estimating ET and groundwater recharge in the ORM.

The results of this study could provide valuable information to policymakers about the important role that climate change plays in groundwater availability. Interestingly, the results suggest that heavy forestation instead of urbanization would not necessarily increase the amount of groundwater in the ORM region. The land cover within the area should rather be in equilibrium with the process of human land use and current climate conditions. In areas where groundwater is used as potable water, best management should include vegetation species that would inhibit surface runoff and, concurrently, have low evapotranspiration demand. The application of remote sensing technology opens up new possibilities for groundwater recharge modeling through a rapid method of acquiring up-to-date information over a large geographical area. Although, the concept of synergy between remote sensing and groundwater modeling dates back to the late 1980's, it is still a challenge to employ affordable, physically-based satellite data with a high temporal resolution for monitoring groundwater dynamics in near-real time.

This study is part of a collaborative effort of Federal, Provincial and Municipal agencies to produce valid estimates of groundwater recharge across the Oak Ridges Moraine area (ORM).

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