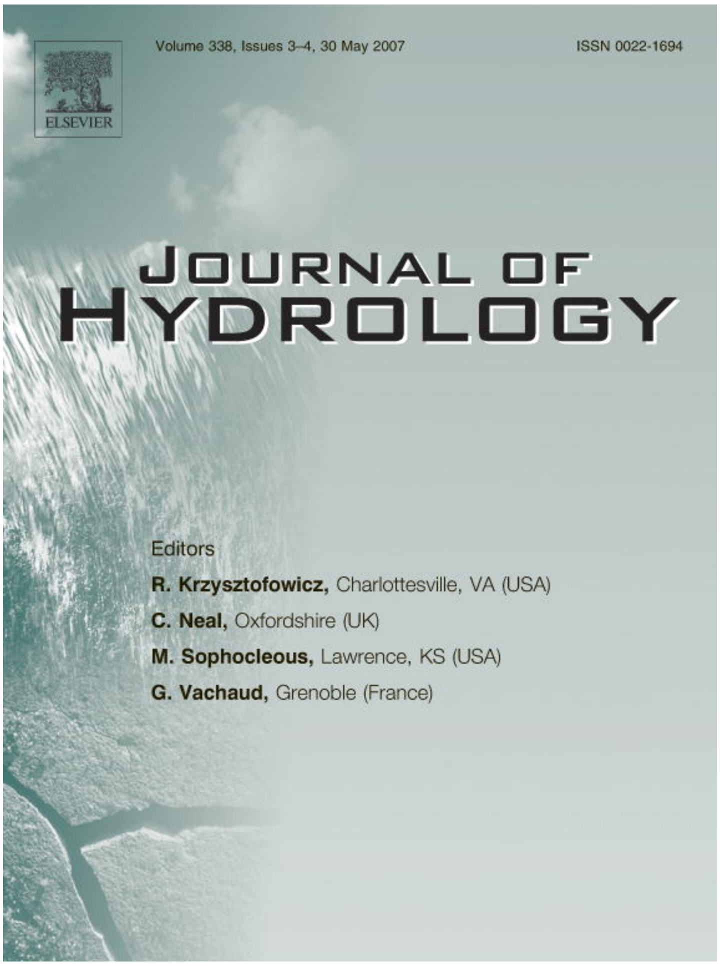
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The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario)

Mikko I. Jyrkama *, Jon F. Sykes

Department of Civil Engineering, University of Waterloo, Waterloo, Ont., Canada N2L 3G1

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Summary Understanding the process of groundwater recharge is fundamental to the management of groundwater resources. Quantifying the future evolution of recharge over time requires not only the reliable forecasting of changes in key climatic variables, but also modelling their impact on the spatially varying recharge process.

This paper presents a physically based methodology that can be used to characterize both the temporal and spatial effect of climate change on groundwater recharge. The method, based on the hydrologic model HELP3, can be used to estimate potential groundwater recharge at the regional scale with high spatial and temporal resolution. In this study, the method is used to simulate the past conditions, with 40 years of actual weather data, and future changes in the hydrologic cycle of the Grand River watershed. The impact of climate change is modelled by perturbing the model input parameters using predicted changes in the regions climate.

The results of the study indicate that the overall rate of groundwater recharge is predicted to increase as a result of climate change. The higher intensity and frequency of precipitation will also contribute significantly to surface runoff, while global warming may result in increased evapotranspiration rates. Warmer winter temperatures will reduce the extent of ground frost and shift the spring melt from spring toward winter, allowing more water to infiltrate into the ground. While many previous climate change impact studies have focused on the temporal changes in groundwater recharge, our results suggest that the impacts can also have high spatial variability.

* Corresponding author. Tel.: +1 519 888 4567x38222; fax: +1 519 725 4834.
E-mail address: mjyrkama@uwaterloo.ca (M.I. Jyrkama).

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Introduction

Changes in future climate will alter regional hydrologic cycles and subsequently impact the quantity and quality of regional water resources (Gleick, 1989). While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and difficult to quantify. Groundwater resources are related to climate change through the direct interaction with surface water resources, such as lakes and rivers, and indirectly through the recharge process. Therefore, quantifying the impact of climate change on groundwater resources requires not only reliable forecasting of changes in the major climatic variables, but also accurate estimation of groundwater recharge.

Accurate spatial and temporal characterization of groundwater recharge can be difficult, however, due to its dependence on a multitude of physical factors such as land use and hydrogeological heterogeneity (Lerner et al., 1990). Groundwater recharge can also be significantly impacted by snowmelt and frozen soil conditions in northern climates, and furthermore be complicated by the issue of scale.

Quantifying the input (i.e., recharge) to the groundwater system is critical for developing an effective watershed management strategy that will ensure the protection of groundwater resources not only from climate change, but also from other stresses such as urbanization (Robins, 1998). Understanding recharge is also necessary to properly assess aquifer vulnerability to contamination, since the transport of most groundwater contaminants, with the exception of density driven contaminants such as DNAPLs, to saturated aquifers occurs in the aqueous phase as part of the recharge process (Foster, 1998). This is especially important in areas where the underlying aquifers are exploited extensively for drinking water purposes.

Assessing the impact of climate change on groundwater resources requires a physically based approach for estimating groundwater recharge. The method must not only account for temporal variations in the climatic variables and their impact on the hydrologic cycle, but also consider the spatial variation of surface and subsurface properties across the study area.

Many climate change studies have focused on modelling the temporal change in the hydrologic processes and ignored or relied on average spatial characteristics due to model limitations or coarse discretization schemes. The objective of this paper is to present a physically based methodology that can be used to characterize not only the temporal impact, but also the spatial effect of climate change on groundwater recharge. The method is based on the hydrologic software package HELP3 coupled with a geographic information system (GIS). The method is used in an example application to simulate the past conditions and possible future changes in the hydrologic cycle of the Grand River watershed in Ontario, Canada.

Background

Groundwater recharge

Groundwater recharge is part of the vadose zone soil water budget, which is driven by precipitation. Depending on the rainfall intensity, temperature, and ground surface cover, the precipitated water is subjected to various processes such as interception, evaporation, and surface runoff. A portion of the water may also infiltrate into the soil, where it may be taken up by the plant roots and subsequently transpired through the vegetation canopy. The remaining water will continue percolating deeper into the soil column, eventually becoming groundwater recharge when crossing the water table into the saturated groundwater zone.

Groundwater recharge is affected by many complex parameters and processes, which themselves are influenced by many factors. Precipitation is affected by climatic factors such as wind and temperature, resulting in a very complex and dynamic distribution. Vegetation influences recharge through the processes of interception and transpiration, and other less commonly characterized, yet potentially significant processes such as stemflow and throughfall (Le Maitre et al., 1999; Taniguchi et al., 1996). Arguably, these processes are very difficult to quantify since they are dependent on a multitude of climatic parameters, such as intensity and duration of rainfall, temperature, and wind speed, as well as the physical characteristics of the individual plants (Larcher, 1983). Plant roots also play an important role in the recharge process not only by enabling plants to draw water from deep in the vadose zone (and even from the saturated zone) thereby reducing the amount of percolating water that reaches the water table, but also be creating preferential flow paths and channels that aid water flow through the soil profile (Le Maitre et al., 1999).

The process of percolation is controlled by the hydraulic properties of the soils which are very sensitive to the moisture content and pressure head distributions. A small change in the volumetric water content can often change the hydraulic conductivity by several orders of magnitude. In addition, the soils in the unsaturated zone rarely exhibit homogeneous properties, often consisting of layered sands, silts, and clays, resulting in non-uniform moisture distributions. Instability in the wetting front and subtle changes in the permeability structure can also lead to flow fingering (Kung, 1990; Selker et al., 1992). Even in relatively homogeneous materials, the unpredictable occurrence of preferred pathways due to plant roots, cracks and fissures, complicates the hydraulic characterization of soils in the unsaturated zone (Simmers, 1990). Large variations in recharge can also occur, even across uniform soils, due to topography, resulting in depression-focused recharge (e.g. Freeze and Banner, 1970; Schuh et al., 1993). Shallow groundwater levels also influence the recharge process by limiting the amount of water entering the ground.

The presence of a snowpack and/or a frozen soil layer will also have a significant impact on the recharge process. Similar to rainfall, the spatial and temporal distribution of snow accumulation is very complex, and even further complicated by its high sensitivity to temperature and wind velocities (i.e., drifting) (Deng et al., 1994). The presence and extent of a frost layer influences the rate and distribution of the infiltrating snowmelt (Johnsson and Lundin, 1991; Kane and Stein, 1983; Granger et al., 1984; Engelmark, 1988; Black and Miller, 1990). Predicting the evolution of the frozen soil layer is very difficult because of its dependence on several factors such as temperature, the duration of freezing temperatures, snow depth at the ground surface, and initial soil water content (Daniel and Staricka, 2000). Modelling unsaturated zone flow in a seasonally (or permanently) frozen environment is clearly very challenging.

Finally, recharge rates can be extensively impacted by human activities such as urbanization, which influence the rates through increased impervious cover; leakage from water distribution systems, sewers, and septic tanks; and over-irrigation of parks and lawns (Lerner, 2002).

Estimation of groundwater recharge requires modelling of the interaction between all of the important processes in the hydrologic cycle, such as infiltration, surface runoff, evapotranspiration, snowmelt, and groundwater level variations. The quantitative description of the hydrologic processes may become very complicated, however, due to the high uncertainty and complexity in the underlying physical parameters. Modelling of natural systems is complicated further by the issue of scale. Addressing the scale problem not only requires appropriate model discretization for the representation of the underlying hydrologic processes, but it also demands conformity between the scale of the input parameters and the modelling framework.

Modelling the impact of climate change on groundwater recharge

Various hydrologic models have been used to study the impact of climate change on surface and groundwater resources (e.g., Vaccaro, 1992; Wilkinson and Cooper, 1993; Gureghian et al., 1994; Cooper et al., 1995; Bobba et al., 1997; Bouraoui et al., 1999; Rosenberg et al., 1999; Kirshen, 2002; Croley and Luukkonen, 2003; Loáiciga, 2003; Eckhardt and Ulbrich, 2003; Allen et al., 2004; Brouyere et al., 2004; Hanson and Dettinger, 2005; Krysanova et al., 2005; Scibek and Allen, 2006). The hydrological effects of climate change are commonly evaluated by estimating the sensitivity of model outputs, such as streamflow hydrographs or soil moisture contents, to hypothetical changes in the magnitude and temporal distribution of model inputs such as precipitation and temperature. In addition to discrete perturbations, however, the results inferred from general circulation models (GCMs) have also been used to predict the effects of climate change on regional hydrology.

In one of the early studies, Vaccaro (1992) investigated the degree of variability in climate and its impact on future recharge predictions in a basin in the northwestern United States. In addition to historical records, climate predictions from the synthetic weather generator WGEN (Richardson and Wright, 1984) and three GCMs were considered along with two different land use conditions. The results of the study indicated that the variability in annual recharge was less under the GCM conditions than using the historic data.

Bouraoui et al. (1999) developed a methodology to disaggregate the outputs of large scale GCMs for use in hydrologic models and investigated the impact of doubling atmospheric CO_2 on groundwater recharge in a watershed in France. The results of the study indicated that recharge would decrease in the basin due to an increase in atmospheric CO_2.

Rosenberg et al. (1999) studied the impact of climate change on the water yield and groundwater recharge of the Ogallala aquifer in the central United States. Three different GCMs were used to predict changes in the future climate due to anticipated changes in temperature and CO_2 concentrations. The study found that recharge was reduced under all scenarios, ranging up to 77%, depending on the simulation conditions.

Kirshen (2002) used the groundwater model MODFLOW to study the impact of global warming on a highly permeable aquifer in the northeastern United States. Groundwater recharge was estimated using a separate model based on precipitation and potential evapotranspiration. Both hypothetical and GCM-predicted changes to the input parameters were used, resulting in higher, no different, and significantly lower recharge rates and groundwater elevations, depending on the climate scenario used.

In another MODFLOW study, Croley and Luukkonen (2003) investigated the impact of climate change on groundwater levels in Lansing, Michigan. The groundwater recharge rates were based on an empirical streamflow model which was calibrated using the results from two GCMs. The results of the study indicated that the simulated steady-state groundwater levels were generally predicted to increase or decrease due to climate change, depending on the GCM used.

Eckhardt and Ulbrich (2003) investigated the impact of climate change on groundwater recharge and streamflow in a small catchment in Germany. The input parameters in their hydrologic model were adjusted based on simulations from five different GCMs. The results of the study indicated that more precipitation will fall as rain in winter due to increased temperatures, resulting in higher recharge and streamflow in January and February. They also found that the increase in recharge from the snowmelt in March disappears, while recharge and streamflow were shown to be potentially reduced in the summer months.

Loáiciga (2003) studied a karst aquifer in south-central Texas and considered the impact of climate change not only on streambed recharge, but also on pumping rates (i.e. groundwater use). The impact of climate change on the streambed recharge was estimated using runoff scaling factors based on the ratio of historical and future streamflows predicted from linked general and regional climate models. The study concluded that the rise in groundwater use associated with predicted population growth would pose a higher threat to the aquifer than climate change.

Allen et al. (2004) and Scibek and Allen (2006) used Visual MODFLOW to study the impact of climate change on two small aquifers in western Canada and the United States. Results from a GCM were downscaled and used to construct three climate scenarios. The recharge boundary conditions for the groundwater models were estimated using Visual HELP. The temporal impact of climate change was modelled by changing the inputs to a stochastic weather generator based on each climate scenario. Recharge was estimated spatially using a rasterized approach resulting in 64 unique recharge zones. Further adjustments to the spatial recharge estimates were also made for one of the aquifers based on an interpolated precipitation gradient. The results of the study indicated only a minor impact from climate change on recharge and groundwater levels at both study areas.

Brouyere et al. (2004) investigated the impact of climate change on a chalky groundwater basin in Belgium using the results from three GCMs with an integrated hydrological model. Two scenarios showed decreases in groundwater levels, while one of the models showed no significant change.

Understanding the impact of climate change is most crucial for studies concerned with the storage and containment of high-level nuclear waste. Due to the slow decay of many transuranic waste products, modelling efforts must be concerned with changes in boundary conditions over very long periods of time. However, predictions of climate change are highly uncertain even for shorter periods such as the next century, making the predictions for the next ten- to hundred-thousand years extremely uncertain.

Yucca Mountain in Nevada is being evaluated as a potential site for high-level nuclear waste disposal in the United States. Because the proposed repository is to be located within the deep unsaturated zone, estimating rates of groundwater recharge at the site is critically important (Flint et al., 2002). Gureghian et al. (1994) studied the impact of climate change on the groundwater recharge rate at Yucca Mountain using a quasi-linear form of Richards' equation. They used two different climatic variation models for temperature and precipitation over the next ten thousand years based on recommendations by a panel of experts. The results of the study indicate minimal differences between the two climate models on the overall movement of the wetting front.

In summary, climate change is likely to have an impact on future recharge rates and hence on the underlying groundwater resources. The impact may not necessarily be a negative one, as evidenced by some of the investigations. Quantifying the impact is difficult, however, and is subject to uncertainties present in the future climate predictions. Simulations based on general circulation models (GCMs) have yielded mixed and conflicting results, raising questions about their reliability in predicting future hydrologic conditions.

Groundwater recharge is influenced not only by hydrologic processes, but also by the physical characteristics of the land surface and soil profile. Many climate change studies have focused on modelling the temporal changes in the hydrologic processes and ignored the spatial variability of physical properties across the study area. While knowing the average change in recharge and groundwater levels over time is important, these changes will not occur equally over a regional catchment or watershed. Long-term water resource planning requires both spatial and temporal information on groundwater recharge in order to properly manage not only water use and exploitation, but also land use allocation and development. Studies concerned with climate change should therefore also consider the spatial change in groundwater recharge rates.

Methodology

In this study, the physically based hydrologic model HELP3 (Schroeder et al., 1994) is used to estimate the changes in the hydrologic cycle of the Grand River watershed in Ontario, Canada. Because numerical modelling at the regional watershed scale, such as the Grand River, involves the handling of large amounts of input and output data, the model is linked with ArcView GIS and the database management system MS-Access. Details of the methodology can be found in Jyrkama et al. (2002).

HELP3 is a quasi-two-dimensional, deterministic water routing model for computing water balances. It simulates the daily movement of water into the ground, and accounts for precipitation in any form, surface storage, runoff, evapotranspiration, snowmelt, vegetative interception and growth, unsaturated flow, and temperature effects (Schroeder et al., 1994). HELP3 was chosen mainly because it is readily available and easy to use. Furthermore, HELP3 simulates all of the important processes in the hydrologic cycle, including the effects of snowmelt and freezing temperatures, which are relevant in the study area. Fig. 1 illustrates a schematic diagram of the methodology. For a detailed description of the HELP model, see Schroeder et al. (1994).

The HELP model has been extensively tested by its developers (Peyton and Schroeder, 1988; Schroeder et al., 1994) and also been compared with Richards' equation based approaches as well as field results under various conditions (Fleenor and King, 1995; Woyshner and Yanful, 1995; Benson and Pliska, 1996; Khire et al., 1997; Chammas et al., 1999; Berger, 2000; Gogolev, 2002; Risser et al., 2005).

Risser et al. (2005) used the HELP3 model to estimate recharge rates in a small watershed in the eastern United States. They compared the results to other modelling approaches and found that the HELP3 recharge estimates were

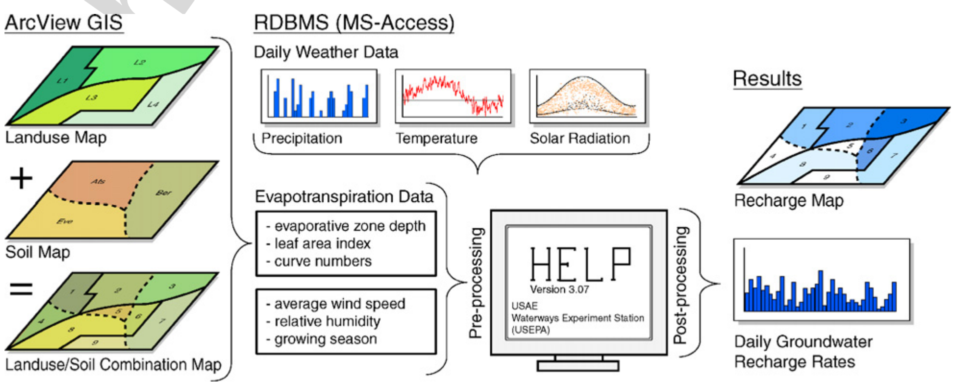

Figure 1 Methodology for estimating groundwater recharge (after Jyrkama et al., 2002).

in closest agreement with direct recharge measurements, even without any calibration of input parameters.

Allen et al. (2004) and Scibek and Allen (2006) adopted an approach similar to Jyrkama et al. (2002) for estimating the recharge boundary condition for groundwater modelling, and used the HELP model to study the response of recharge to potential climate change. Their study involved two small catchments (less than 150 km^2). While their study found only a minor change in the recharge rates due to climate change, they noted that the spatial variation in recharge is directly controlled by the soil and other subsurface properties. This latter point is important, as it highlights the fact that the impact of climate change is non-uniform across a heterogeneous basin.

The main goal of this paper is to present a methodology to quantify the spatial effect of potential climate change on groundwater recharge. The approach is based on the method by Jyrkama et al. (2002) and similar to Scibek and Allen (2006), however, this work demonstrates how the method can be readily extended to the analysis of large, regional scale watersheds. Another important difference with the work by Scibek and Allen (2006) is the concept of zoning or averaging. In their study, Scibek and Allen (2006) defined representative recharge zones for a 50-m raster grid, hence aggregating all input data over an artificial geometric shape.

The concept of zoning is commonly used in the context of model calibration in order to reduce the total number of calibration parameters. Methods such as hydrological response units (HRU) and hydrologically similar units (HSU) have been utilized in many surface water studies to define areas with similar hydrologic responses (e.g., Seyfried and Wilcox, 1995; Bormann et al., 1999; Karvonen et al., 1999). This aggregation of input data is often driven by the rasterization requirements of a particular GIS platform or hydrologic modelling approach. These averaging or lumping approaches, however, lose important information possibly resulting in erroneous analysis, i.e., under- or over-prediction, of the system behaviour.

Although aggregation of the input data may provide significant computational savings in other models, it is not required for the successful implementation of the HELP3 recharge methodology. Because of the one-dimensional nature and relative simplicity of the HELP3 model, as compared to some of the more mathematically rigorous hydrologic models, all available spatially and temporally distributed input parameters can be included in the analysis.

The HELP3 program interface can generally be used to conduct simulations for very small and simple systems, where the total number of different input parameters is small. However, for larger areas, the generation and analysis of HELP3 output files may become awkward resulting in a considerable increase in pre- and post-processing times. Because the actual HELP3 program uses simple input and output text files to define the simulation parameters and report the results, the pre- and post-processing can easily be streamlined using simple programming, for example, using Visual Basic.

Study area

The Grand River watershed is located in south-western Ontario, draining an area of nearly 7000 km^2 into Lake Erie.

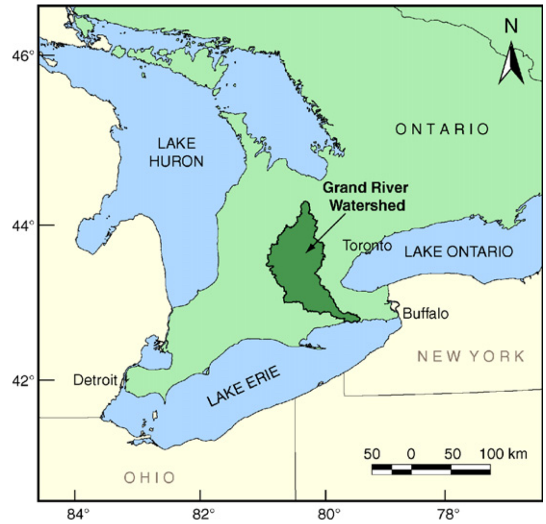

Figure 2 Location of the Grand River Watershed.

The location of the watershed is shown in Fig. 2. The main tributary is approximately 290 km in length with an elevation differential of about 362 m from its source to the mouth. The landscape of the watershed has mainly been shaped by the last period of glaciation, resulting in highly variable soils and topography. The southern part of the watershed consists of low permeability lacustrine clay deposits and low topographic relief. The central part is formed mostly of higher permeability sand and gravel kame moraines with moderately high relief, while the northern portion of the watershed is comprised of lower permeability till plains with varying surface relief (Holysh et al., 2000).

Although 90% of the watershed is classified as rural, the watershed contains some of the fastest-growing urban areas in Ontario, such as the cities of Kitchener, Waterloo, Cambridge, and Guelph. Not only is increasing urbanization stressing the existing water supply, but it is also placing the supply at a greater risk of contamination. There is growing concern about the environmental impact of such rapid urbanization and the ability of the river and groundwater systems to meet the rising demand for water. The recent and continuing dry conditions in southern Ontario have also placed an additional stress on the hydrology and water resources of the watershed.

Input data

HELP3 requires various climatic, soil, and design data to generate daily estimates of water movement through a soil column. The required input parameters for the model are shown in Table 1. The specific data obtained for the Grand River watershed are described in the following sections.

Land use/land cover data

Digital land use and land cover (LULC) data for the Grand River watershed were obtained from the Grand River Conservation Authority (GRCA). The mapping was based on 1999 satellite imagery from the Landsat 7 thematic mapper. As shown in Fig. 3, the raster LULC coverage is based on a 25-m grid with 15 unique land cover categories.

Table 1 Summary of required HELP3 input data

Parameter	Units[a]	Constraints
Daily precipitation	mm/day	$\geqslant 0$
Daily mean temperature	°C	
Daily incoming solar radiation	kJ/m^2	$\geqslant 0$
Average annual wind speed	km/h	$\geqslant 0$
1st quarter relative humidity	%	$\geqslant 0$ and $\leqslant 100$
2nd quarter relative humidity	%	$\geqslant 0$ and $\leqslant 100$
3rd quarter relative humidity	%	$\geqslant 0$ and $\leqslant 100$
4th quarter relative humidity	%	$\geqslant 0$ and $\leqslant 100$
Growing season start day	Julian date	$\geqslant 0$ and $\leqslant 365$
Growing season end day	Julian date	$\geqslant 0$ and $\leqslant 365$
Evaporative zone depth	cm	>0 and $\leqslant$ total column depth
Leaf area index (LAI)	–	$\geqslant 0$ (insensitive to values >5.0)
Curve number (CN)	–	$\geqslant 0$ and $\leqslant 100$
Soil layer depth	cm	$\leqslant$ total column depth
Soil texture	–	
Total porosity (ϕ)	vol/vol	>FC and $\leqslant 1$
Field capacity (FC)	vol/vol	>WP and $<\phi$
Wilting point (WP)	vol/vol	>0 and <FC
Saturated hydraulic conductivity (K_S)	cm/s	>0
Initial volumetric soil water content (θ)	vol/vol	$\geqslant 0$ and $\leqslant 1$
Optional parameters		
Mean monthly precipitation[b]	mm/month	$\geqslant 0$
Normal mean monthly temperature[b]	°C	
Latitude[b]	degrees	$\geqslant -90$ and $\leqslant 90$
Surface slope[c]	%	$\geqslant 0$
Slope length[c]	m	$\geqslant 0$

[a] All units can also be specified in imperial units.
[b] Required for synthetic weather generation.
[c] Required for automatic CN estimation.

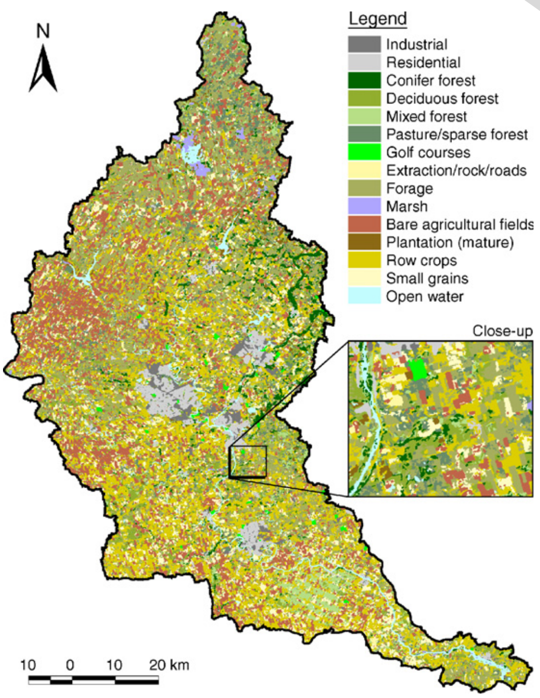

Figure 3 Land use map.

Soil data

The surface soil information, illustrated in Fig. 4, was assembled from various regional soil surveys conducted in the watershed. All the information was obtained from the Canadian Soil Information System (CANSIS) website in digital form. However, several difficulties were encountered during the construction of the soil map and the associated database for the watershed.

The Grand River watershed spans a number of different counties and municipalities, each with its own soil survey and database, as shown in Table 2 and Fig. 4. Due to differences in scales and mapping methods, relatively minor to severe discontinuities and overlaps existed between adjacent soil map sheets. Therefore, in order to generate a continuous soil map for the entire watershed, these gaps and overlaps needed to be corrected. It was assumed that newer maps and maps with finer scales were more accurate and therefore were used to fill gaps (by extending edge polygons), and to trim the surrounding map sheets.

There were a total of 723 unique soil types identified in the watershed. In addition to physical and chemical details, the associated soil database also contains information on soil type, number of layers, layer depths, and soil texture classifications. The subsurface data was then combined with the surface cover information to estimate the SCS curve numbers for the model.

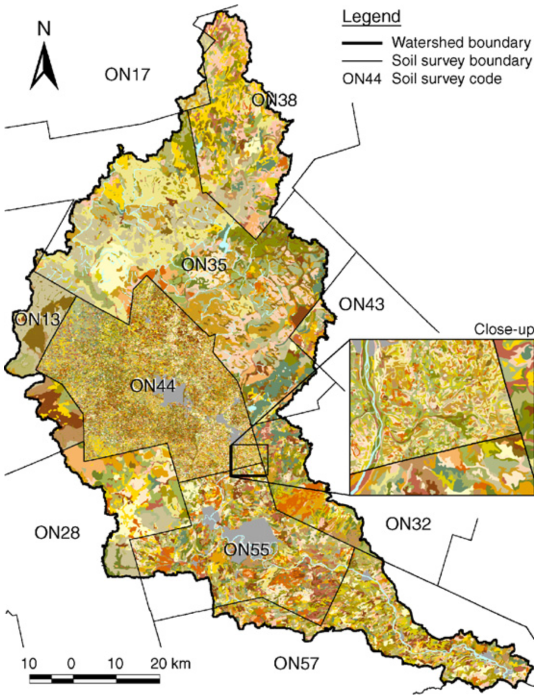

Figure 4 Soil surveys and soil map.

Vegetation data

Plant roots can have a significant impact on recharge as they remove infiltrated water from the soil. However, the determination of plant root penetration and subsequently the evaporative zone depth in the model (i.e., the maximum depth from which water may be removed by evapotranspiration) are very difficult tasks. In this study, the average evaporative zone depths (based on the combination of soils and land cover types) were estimated using the guidelines found in the recharge methodology developed by Charles et al. (1993).

HELP3 also requires a value for the maximum leaf area index (LAI) to calculate transpiration rates for the vegetative cover. Following the guidelines in HELP3, where the LAI ranges from 0 for bare ground to 5.0 for maximum leaf coverage, the values for LAI were assigned based on the LULC data. For example, the maximum LAI for bare agricultural fields was assumed to be 0, and for golf courses 2.0.

Weather data

Due to its large size, the weather varies significantly across the Grand River watershed. Actual daily precipitation and temperature records from January 1960 to December 1999 were obtained from the GRCA. The data were based on point observations at various locations within (as well as outside) the watershed which were then used to represent the weather patterns within 13 sub-regions, or zones of uniform meteorology (ZUM) shown in Fig. 5. The built-in weather generator in HELP3 was then used to generate daily synthetic solar radiation values for each ZUM as a function of latitude, precipitation, and temperature. A preliminary study revealed, however, that the 13 sub-regions were still quite large, resulting in discontinuities in recharge along their boundaries. Therefore, a new method based on an interpolation algorithm was developed.

The Grand River watershed was divided into 293 smaller sub-basins, also shown in Fig. 5, each with its distinct values of daily precipitation, temperature, and solar radiation. The values were interpolated using the inverse distance squared (IDS) algorithm as

$$P^{SUB} = \frac{\sum_{i=1}^{13} \frac{P_i^{ZUM}}{d_i^2}}{\sum_{i=1}^{13} \frac{1}{d_i^2}} \qquad (1)$$

where P is the daily precipitation, temperature, or solar radiation, and d is the distance from the centroid of each ZUM to the centroid of each sub-basin. This provided a much smoother transition of weather data across the entire watershed, while still honouring the original observations.

The average quarterly relative humidities and average annual wind speeds were obtained from Environment Canada as well as the University of Waterloo weather station for various locations in and around the watershed, as shown in Fig. 5. Similar to before, the inverse distance squared weighting scheme was then used to estimate values for each of the 293 sub-basins.

The dates for the start and end of growing season were estimated using guidelines provided in HELP3 (Schroeder

Table 2 Soil surveys of the Grand River watershed

Soil survey	County	Mapping scale	Year	Percent of watershed area
ON13	Perth	63,360	1975	4.5
ON17	Grey	63,360	1981	0.6
ON28	Oxford	63,360	1961	6.4
ON32	Wentworth	63,360	1965	4.7
ON35	Wellington	63,360	1963	29.0
ON38	Dufferin	63,360	1963	10.2
ON43	Halton	63,360	1971	1.0
ON44	Waterloo[a]	20,000	1971	19.9
ON55	Brant	25,000	1989	14.4
ON57	Haldimand-Norfolk	25,000	1984	9.4

[a] Digital GIS map obtained from the University of Waterloo Map and Design Library (all other maps obtained from CANSIS web-site http://sis.agr.gc.ca/cansis/).

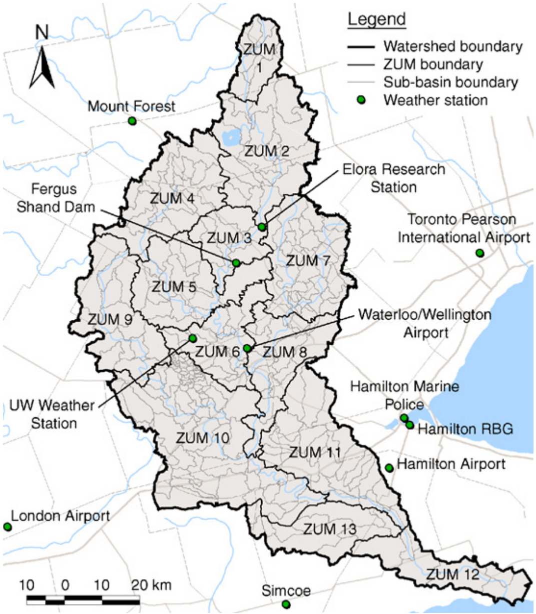

Figure 5 Zones of uniform meteorology (ZUM), sub-basins, and location of relative humidity and average wind speed observations.

et al., 1994). The values were estimated for each ZUM, therefore, constant growing season dates were assumed for each sub-basin within each of the ZUM areas. Growing season starting dates varied from May 2nd to May 6th, while the ending dates ranged from October 7th to October 12th.

Model application and results

Merging of all the relevant meteorological and hydrogeologic information resulted in a total of over 47,000 unique combinations of HELP3 input data. For the Base Case climate scenario, the HELP3 model was run daily over the 40 year study period from January 1960 to December 1999 for each of the unique combinations. Areas classified as open water were ignored in the recharge analysis (approximately 3.4% of the total watershed area). The total computing time was approximately 37 h on a P4 1.8 MHz computer with 2GB of RAM. Because each combination of input parameters is run independently, the approach is ideally suited for distributed computing, which will significantly reduce the total simulation time.

Climate change scenarios

The impact of climate change in this study was modelled by perturbing the HELP3 model input parameters using potential changes in the climate of the Grand River watershed as predicted by the IPCC Third Assessment Report (IPCC, 2001). The IPCC reported the following general predictions for the regional climate around the Grand River watershed over the next 100 years (IPCC, 2001):

- precipitation is projected to increase with an average change between 5% and 20% in the winter,
- precipitation extremes are projected to increase more than the mean with higher intensities and higher frequency of extreme events,
- greater than average warming in both summer and winter temperatures, and
- a possible reduction in incoming solar radiation due to increases in greenhouse gases.

Using the 40 years of actual historical weather data as a reference, several scenarios were constructed to simulate the impact of climate change over a period of 40 years, corresponding to the general predictions made by the IPCC. Details of these scenarios are shown in Table 3. All of the simulation parameters were scaled over the 40-year study period. That is, they were assumed to increase linearly over time. For example, the temperature change of +0.016 °C/year corresponds to a predicted increase of 1.6 °C in 100 years, or to a daily increase of approximately 4.38×10^{-5} °C.

As evidenced by the studies involving results from various GCMs, predicting the actual change in climate variables in the future with even a reasonable level of confidence is very difficult and involves high uncertainty. Downscaling the predicted results from a GCM to the scale of a hydrologic or hydrogeologic model introduces additional error and uncertainty into the analysis. The objective of this study is not to determine with any degree of confidence what specifically would or will happen in the future as a result of climate change, but only to simulate and observe general system behaviour due to changes in the model input parameters based on generally accepted predictions.

Table 3 Climate change simulation scenarios

Scenario	Description
Base case	Actual historical daily temperature, precipitation, and simulated solar radiation for the past 40 years
1	Precipitation +5% for December, January, and February
2	Precipitation +20% for December, January, and February
3	Precipitation +20% for all months
4	Temperature +0.016 °C/year
5	Temperature +0.070 °C/year
6	Solar radiation 2% for all months
7	Combination of Scenarios 1, 5, and 6
8	Combination of Scenarios 3, 5, and 6

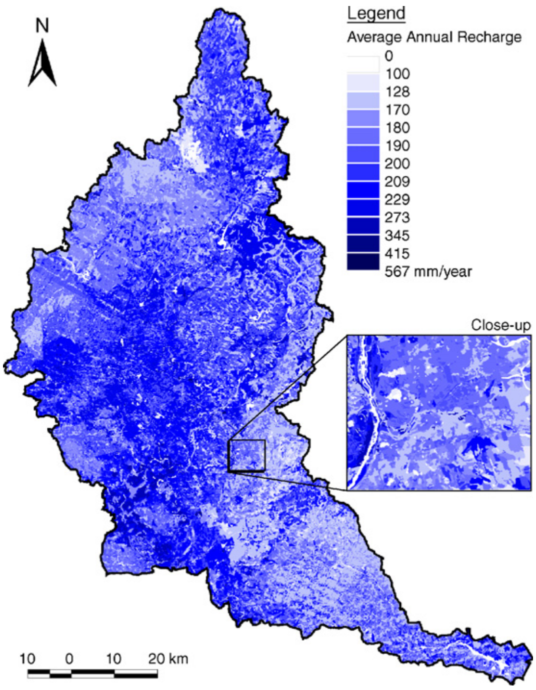

Figure 6 Average annual recharge for the Grand River watershed.

Base case results

Fig. 6 shows the average annual recharge rates obtained from the HELP3 analysis for the Grand River watershed. The average annual groundwater recharge in the watershed is estimated to be approximately 200 mm/year, which is approximately one-fifth of the average annual precipitation (950 mm/year). As shown in Fig. 6, recharge varies considerably across the watershed, responding directly to variations in land use and the hydraulic characteristics of the underlying soils. Because of the one-dimensional nature of the HELP3 model, the spatial variation is not constrained by the modelling approach, i.e., no aggregation of input data is required, but is only limited by the scale of the input data.

Areas of high recharge (as shown by Fig. 6) may also indicate regions where the underlying aquifers are subjected to increased vulnerability from contamination. This may have significant implications on land use planning near the urban areas, where existing lands are rapidly being converted into residential subdivisions and industrial areas.

Climate change simulation results

Temporal impact

Fig. 7 presents the cumulative differences in surface runoff, evapotranspiration, and recharge between all the scenarios and the Base Case scenario, averaged spatially over the entire watershed. As shown, changing the precipitation has the highest influence on the hydrologic cycle, while solar radiation has a minimal impact under the proposed climate change simulation scenarios. Groundwater recharge is predicted to increase under all scenarios, while evapotranspiration increases in all cases, except when incoming solar radiation is reduced (Scenario 6).

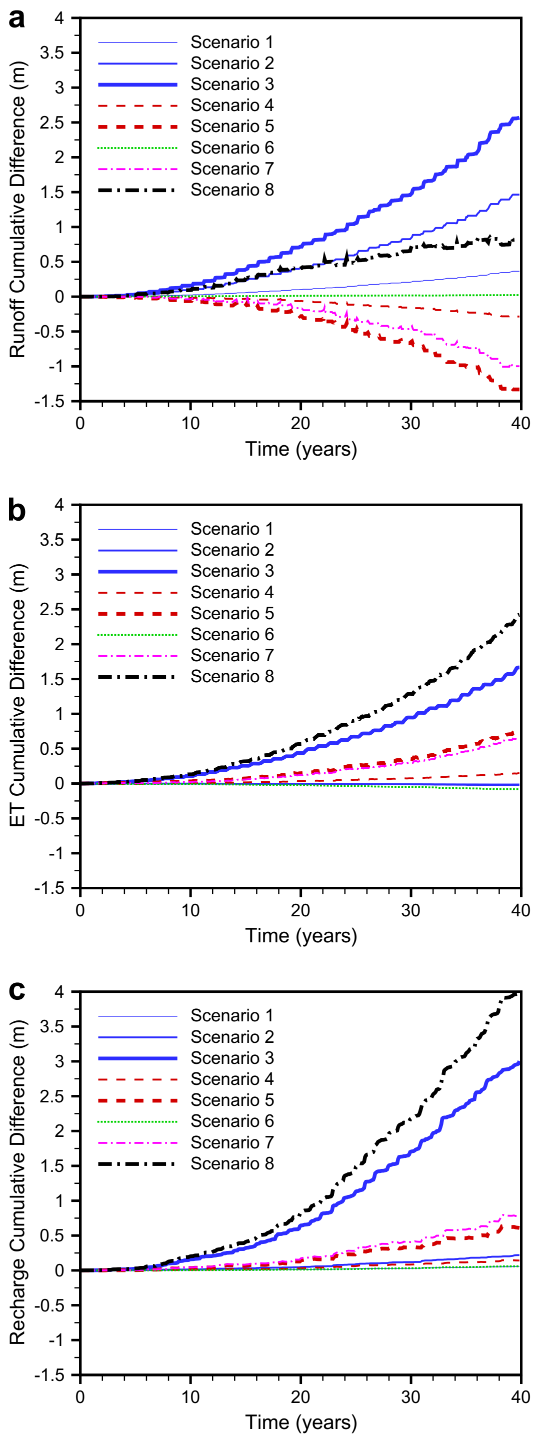

Figure 7 Cumulative differences between the climate change scenarios and the Base Case for (a) surface runoff, (b) evapotranspiration, and (c) groundwater recharge.

Fig. 7 also illustrates that, as expected, surface runoff increases with increasing precipitation. Furthermore, increasing the precipitation rate will generally increase all three hydrologic parameters as there is more water available in the system. Increasing temperature, however, has both a negative and positive impact on the hydrologic processes.

As demonstrated by Scenarios 4 and 5 in Fig. 7a, temperature has a significant influence on the runoff process. The cumulative surface runoff decreases with increasing temperature mainly due to a reduced period of ground frost. Similar to the results by Eckhardt and Ulbrich (2003), warmer winter temperatures allow precipitation to fall as rain rather than snow, thereby reducing runoff by decreasing the amount of water stored in the snowpack, and increasing groundwater recharge through increased infiltration. As expected, evapotranspiration rates are also increased over time by warmer temperatures (see Fig. 7b).

The overall cumulative watershed water budget for the Base Case over the 40-year study period amounts to approximately 36.5 m of precipitation, 8.4 m of surface runoff, 20.4 m of evapotranspiration, and 7.5 m of potential recharge. Therefore, comparing the results of Scenarios 7 and 8, the relative overall impact of climate change ranges from −12% to +10% for surface runoff, +3% to +12% for evapotranspiration, and +10% to +53% for groundwater recharge, depending on the scenario used.

The temporal variabilities in the hydrologic processes are further demonstrated using the results from Scenario 8. Fig. 8 shows the spatially averaged monthly differences for Scenario 8 over a selected time period, while Fig. 9 illustrates the average differences for each month. It is evident that there is a significant reduction in the average runoff in the spring (e.g., April) as the spring melt is shifted earlier (toward the winter months) due to warmer temperatures.

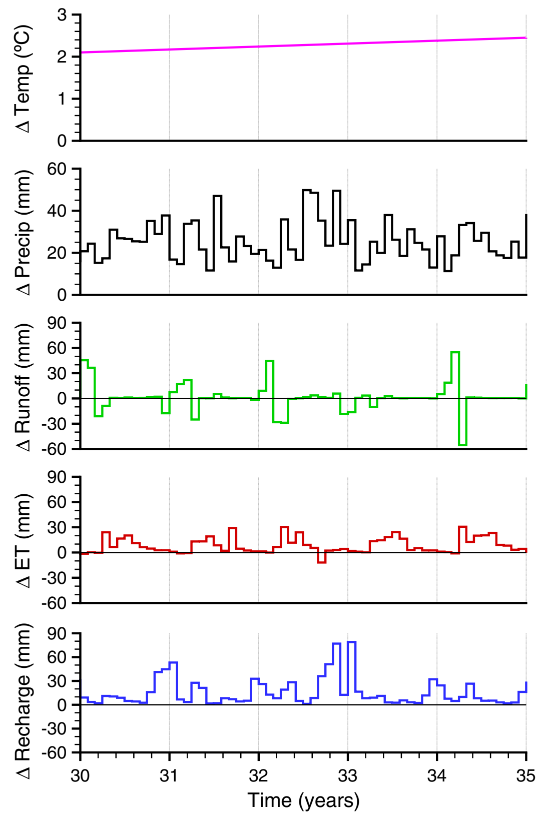

Figure 8 Monthly differences in precipitation, surface runoff, evapotranspiration, and groundwater recharge between Scenario 8 and the Base Case for a selected time period.

The amount of runoff is consequently increased during January, February and March as moisture is released from the snowpack (as opposed to being stored or accumulated). Groundwater recharge also increases significantly during the winter months as more water is able to infiltrate into the ground. Evaporation rates are increased during the summer months due to higher temperatures and increased amount of available water.

Spatial impact

Fig. 10 shows the average annual change in groundwater recharge rates for the entire watershed between the Base Case and Scenario 8. Although recharge rates may be reduced over short periods at specific times, Fig. 10 shows how there is an overall increase in recharge rates across the watershed due to potential climate change. The average rate is predicted to increase by approximately 100 mm/year from 189 mm/year to 289 mm/year over the 40-year study period.

Fig. 10 also clearly illustrates the non-uniform impact of potential climate change across the watershed. Some areas will be subjected to greater changes in recharge rates, while others will experience lesser change. The degree of impact is directly controlled by groundwater levels, characteristics of the ground surface, and the nature of the underlying soils. While quantifying the temporal impact of climate change is important for long-term water resource planning and management, delineating the spatial impact is valuable not only for the protection of the underlying aquifers, but also in the context of land use allocation and development.

Discussion

Verification of results

In the hydrologic context, the terms validation and verification have been generally used to indicate that model predictions match observational data for the range of conditions under consideration (e.g., Anderson and Woessner, 1992; Konikow and Bredehoeft, 1992). Model results can only be evaluated in relative terms, however, by confirming them against observations or other models. The complete verification and validation of numerical models of natural systems is impossible; therefore, one can only increase confidence in the results (Oreskes et al., 1994).

The direct calibration or comparison of the HELP3 estimated recharge rates to field measurements are exceedingly difficult and costly. Therefore, due to the limitations of the field estimation methods, the only reasonable way of adding confidence in the results would be by verifying them indirectly with or within the context of other models. Comparing the results to other models may be difficult, however, because of differences inherent in the methods (Risser et al., 2005).

The estimated recharge rates from the analysis could be incorporated into either a fully saturated groundwater model as the top boundary condition following the method by Jyrkama et al. (2002), while the estimated runoff rates from the model could be used in a surface water routing model. Both approaches, however, have their own limitations with

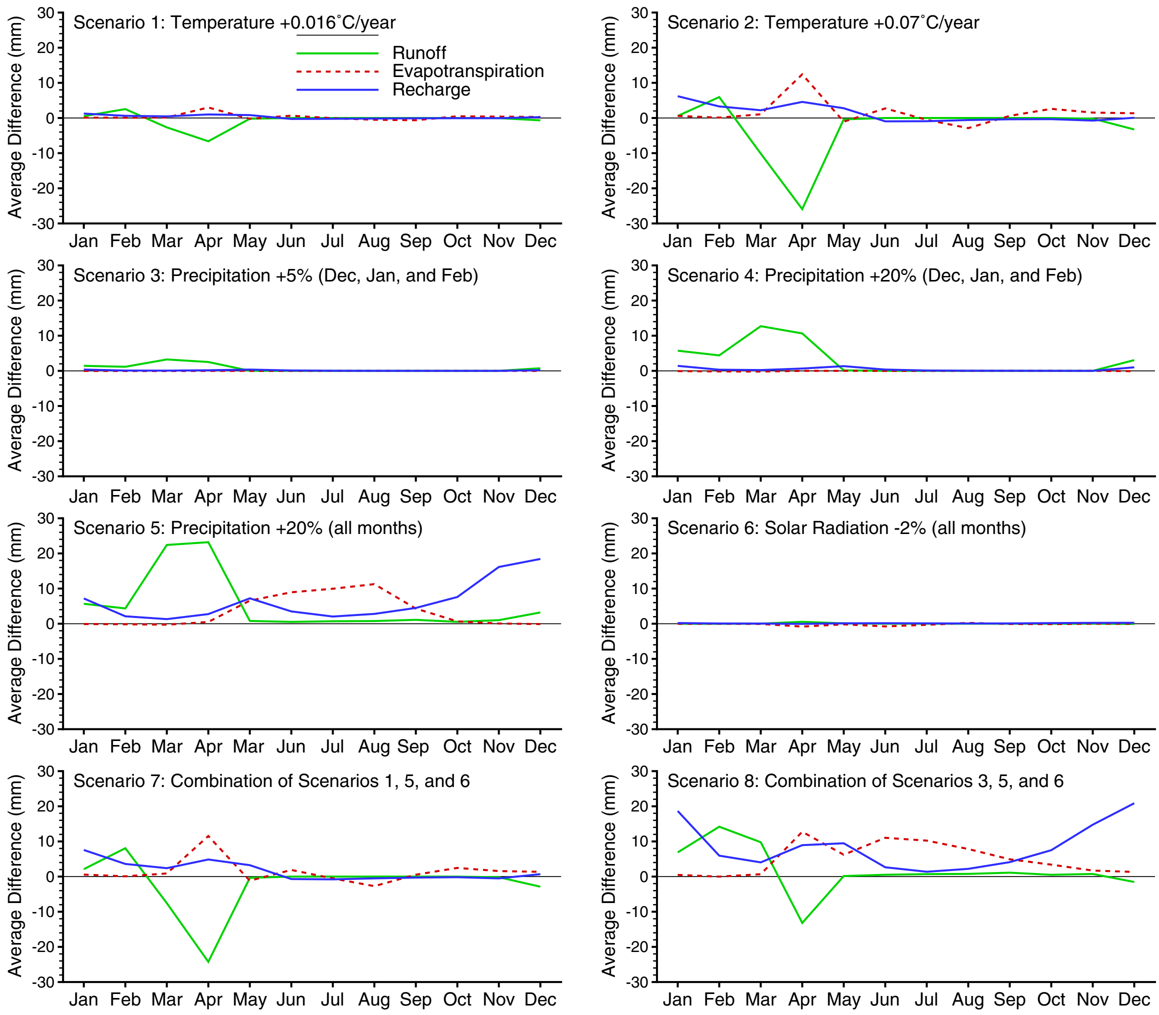

Figure 9 Average differences for each month between the climate change scenarios and the Base Case.

respect to parameterization and scale. While the groundwater model is calibrated against readily available head measurements, the surface routing model relies on baseflow separation of streamflow measurements, which may be subject to potentially large errors.

HELP3 limitations

HELP3 uses empirical relationships in certain instances which may be unreasonable in some applications (Schroeder et al., 1994). In addition, the models representing the various hydrologic processes within the program are subject to their own assumptions and limitations. While lateral discretization is not an issue, since HELP3 is a one-dimensional model, the assumption of purely vertical flow may not be true when there are significant heterogeneities present in the unsaturated zone. Since the unique input parameter combinations are analyzed independently, overland flow between adjacent areas is ignored. This assumption is reasonable since adjacent areas generally experience surface runoff concurrently during a storm event, therefore, water from one area is unlikely to infiltrate in another because both areas are saturated. Furthermore, overland flow typically moves considerably faster than groundwater flow, and is generally rare in humid climates due to less intensive rainfall, well-developed vegetation, and sufficient infiltration capacity of most soils (Knutssen, 1988). Areas with high topographic relief, however, may have significant lateral flow components which may not be captured by the recharge methodology.

HELP3 may have difficulty in estimating water balances in arid climates where upward fluxes can be high. However, it has been shown to work well in humid areas. Compared to other numerical hydrologic models, HELP3 is easy to use, uses data that is readily available, and is highly efficient computationally. Models based on Richards' equation may be preferred by many researchers, however, they are also subject to many assumptions and limitations. They are often limited by the boundary conditions, and are computationally expensive due to the discretization requirements by the highly non-linear equations. The simpler water balance approaches, such as HELP3, can easily be applied to heterogeneous soil columns with physically based boundary conditions and run over long time periods with comparable accuracy to the Richards' equation based approaches. As demonstrated by the results of this study, HELP3 is a valuable tool for assessing not only the temporal response, but

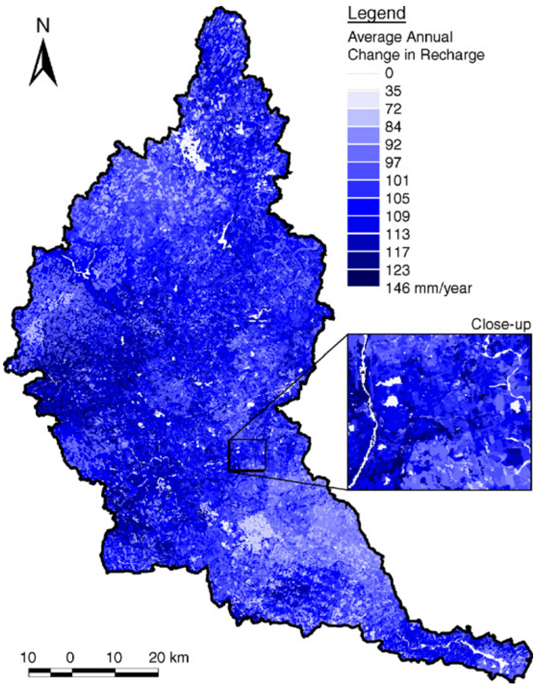

Figure 10 Average annual change in recharge between Scenario 8 and the Base Case.

also the spatial impact of climate change on groundwater resources.

Summary and conclusions

Understanding the impact of potential changes in the hydrologic cycle in response to climate change is essential for ensuring the quality and sustainability of our water resources in the future. While the temporal aspects of climate change influence long-term water resource planning and management, quantifying the spatial impact is critical not only for the protection of the underlying groundwater resources, but also in the context of land use allocation and development.

Groundwater resources are related to climate change indirectly through the process of recharge, and directly through the interaction with surface water bodies such as rivers and lakes. The process of groundwater recharge is not only influenced by the spatial and temporal variability in the major climate variables, but is also dependent on the spatial distribution of land-surface properties and the depth and hydraulic properties of the underlying soils. Quantifying the impact of climate change on groundwater resources requires a physically based approach for estimating groundwater recharge that includes all of the important processes in the hydrologic cycle, such as infiltration, surface runoff, evapotranspiration, and snowmelt.

In this study, the hydrologic model HELP3 (Schroeder et al., 1994) was used to estimate the response of groundwater recharge to potential climate change in the Grand River watershed in Ontario, Canada. The impact of climate change was modelled by perturbing the HELP3 model input parameters using potential changes in the climate of the Grand River watershed as predicted by the IPCC (2001). Various climate change scenarios were constructed to simulate future impact in the hydrologic cycle using 40 years of actual historical weather data as a reference.

Based on the results of this study, climate change may potentially have both positive and negative impacts on the hydrology of the Grand River watershed. The HELP3 simulation results indicated that increasing precipitation will generally lead to increases in surface runoff, evapotranspiration and groundwater recharge. Increasing temperature due to global warming, on the other hand, allowed precipitation to fall as rain rather than snow, thereby reducing the amount the water stored in the snowpack and decreasing surface runoff in the spring. Warmer winter temperatures reduced the amount of ground frost and allowed more water to infiltrate into the ground, resulting in increased groundwater recharge. On average, the potential recharge rate for the watershed was estimated to increase by approximately 100 mm/year, from 189 mm/year to 289 mm/year, over 40 years (under Climate Scenario 8).

In addition to the temporal impacts, the results of the study also demonstrated how the spatial impact of climate change can be quantified effectively using the developed methodology, even for large regional scale watersheds. The results showed how groundwater recharge varied considerably across the Grand River watershed, responding directly to variations in land use and the hydraulic characteristics of the underlying soils. Certain areas of the watershed will be subjected to greater changes in recharge rates, while others will experience lesser change. Delineating the spatial impact is valuable not only in the context of groundwater resource protection, but also for general land use management in the watershed.

The HELP model itself has been extensively tested under various conditions and successfully compared to other hydrologic models. As demonstrated by this study, the main advantage of the model is that it can be easily applied to heterogeneous soil columns with physically based boundary conditions, to quantify in detail the influence of climate change on groundwater recourses.

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