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A review of simulated climate change impacts on groundwater resources in Eastern Canada

Marie Larocque[1*], Jana Levison[2*], Alexandre Martin[1], Diane Chaumont[3]

[1] Département des sciences de la Terre et de l'atmosphère and GEOTOP Research Center, UQAM, C.P. 8888 succ. Centre-ville, Montreal, QC, Canada, H3C 3P8, 514-987-3000 ext. 1515, larocque.marie@uqam.ca

[2] School of Engineering and G360 Institute for Groundwater Research, University of Guelph, 50 Stone Road E., Guelph, ON, N1G 2W1, jlevison@uoguelph.ca

[3] Ouranos Consortium, 550 Sherbrooke West, 19th floor, Montreal, QC, H3A 1B9, Chaumont.Diane@ouranos.ca

Abstract

In Eastern Canada, groundwater is the main water supply for most of the rural regions and in many large urban communities. An understanding of the impacts of climate change on this resource is crucial for sustainable water management in this region. The objectives of this paper are to summarize the state of knowledge about possible climate change impacts on groundwater dynamics in Eastern Canada thus providing a clearer understanding of future conditions. Twenty-two studies are reviewed including Ontario, Québec, New Brunswick, Nova Scotia, and Prince Edward Island, to identify the impacts on groundwater recharge and river baseflows. The studies disagree in their estimates of changes in future recharge conditions, and no trend from West to East was revealed. This could be due to the use of different modelling approaches (model type, climate change scenario, future horizon). Nonetheless, more inter-annual variability during the summer and earlier snowmelt periods causing seasonal shifts in the recharge cycle are expected. This review provided new insights that lead to the following recommendations for future studies: 1) use a variety of climate models and emission scenarios; 2) promote the use of integrated models when possible; 3) study long-term climate change impacts on groundwater resources at different scales; 4) simulate the combined effects of climate change and other pressures; and 5) develop models that cover other regions of Eastern Canada as dictated by stakeholders and water managers.

Key words: Groundwater, Eastern Canada, Model, Climate change

Résumé

Dans l’est du Canada, l’eau souterraine est la principale source d’approvisionnement en eau en région rurale et dans plusieurs grandes villes. La compréhension des impacts des changements climatiques sur cette ressource est cruciale pour la gestion durable de l’eau dans cette région. Les objectifs de cette revue étaient d’établir l’état des connaissances sur les impacts possibles des changements climatiques sur la dynamique des eaux souterraines dans l’est du Canada afin de mieux appréhender les conditions futures. Vingt-deux études portant sur les provinces de l’Ontario, du Québec, du Nouveau-Brunswick, de la Nouvelle-Écosse et de l’Ile-du-Prince-Édouard ont été analysées pour déterminer les impacts sur la recharge des eaux souterraines et les débits de base des cours d’eau. Les études ne s'entendent pas sur une l’évolution future de la recharge et aucune tendance de l’ouest vers l’est n’a été mise en évidence. Ceci pourrait être causé par les différentes approches de modélisation utilisées (type de modèle, scénario climatique, horizon futur). Néanmoins, les résultats montrent généralement une plus grande variabilité interannuelle de la recharge estivale et une recharge printanière plus hâtive. Les études montrent que les débits d’étiage pourraient diminuer, ce qui induirait des conditions critiques pour les approvisionnements en eau et pour les écosystèmes. Cette revue a fourni un nouvel éclairage qui a conduit aux recommandations suivantes pour les études futures: 1) utiliser une variété de modèles climatiques et de scénarios d'émission; 2) utiliser des modèles intégrés lorsque possible; 3) étudier les impacts à long terme des changements climatiques sur les ressources en eaux souterraines à différentes échelles; 4) simuler les effets combinés du changement climatique et d'autres pressions;

et 5) élaborer des modèles qui couvrent d'autres régions de l'est du Canada dictées par les intervenants et les gestionnaires de l'eau.

Most-clés: eau souterraine, est du Canada, modèle, changement climatique

INTRODUCTION

Throughout the world, climate change has become evident from the observations of global mean temperature rise and the higher frequency of extreme weather events (IPCC 2013). These changes could affect groundwater resources in a variety of ways (Taylor et al. 2012). In a warmer climate, increasing demand of water is expected to lead to increased pumping rates for drinking water and irrigation. Conditions of depleting groundwater reservoirs and reduced groundwater flow to rivers, wetlands, and lakes are either already clearly evident or expected around the world in the next decades (Ferguson and Gleeson 2012; Crosbie et al. 2013; Castle et al. 2014; Döll et al. 2014; Kløve et al. 2014; de Graaf et al. 2017).

Canada is amongst the world's richest countries in terms of fresh water resources (FAO 2003). Throughout Canada, groundwater provides approximately 30% of the population with potable water and is often the only source of water in rural areas (ECCC 2017). When investigating the presence of climate change impacts in past time series of baseflows and groundwater levels across the country, Rivard et al. (2009) have identified mixed increasing and decreasing trends country-wide. However, the Atlantic Provinces showed statistically significant decreases of baseflows, while some regions north of 55°N had increasing baseflows. The majority of the longer time series showed negative trends during the summer months. Chen (2015) assessed the impact of climate change on groundwater dynamics at the continental-scale using the integrated HydroGeoSphere model (Therrien et al. 2010) for the entire country and the northern part of the United-States. Confirming some of the trends identified by Rivard et al. (2009), Chen (2015) showed that annual streamflow in most of the northern main rivers could increase under climate change, but results for the southern regions were less clear.

In 2016, more than 68% of the country's population resided in Eastern Canada, notably in Ontario and Québec (Statistics Canada 2016). In Eastern Canada, groundwater is a frequent source of water for many usages like municipal water supply, irrigation for agriculture, and private wells for potable water. In Ontario, Québec, and the Atlantic Provinces respectively, 14, 17, and 12% of irrigation water for farming was taken from groundwater in 2012 (Statistics Canada 2012). A rainfall rate increase is expected, based on a high-resolution regional climate modelling study over the Great Lakes basin (d'Orgeville et al. 2014). Among other effects, climate change is expected to lead to earlier spring flood events and to more severe summer low flows (Ouranos 2015). In the Atlantic Provinces, more storm events and increasing storm intensity, rising sea levels, storm surges, and coastal erosion are expected from climate change (Climate Action Network 2017). The impacts of climate change on groundwater resources are not fully understood and a global picture of possible future conditions is not yet available for water managers.

The simulation of possible groundwater flow conditions provides interesting outlooks for potential conditions in future decades. However, modeling studies are expensive, are often of local application, and can be based on a wide array of future conditions (e.g., stemming from different climate models, groundwater flow models, and emissions scenarios). Holman et al. (2011) made methodological recommendations aimed at improving the assessment of climate change impacts on groundwater. In recent years, the general approach has tended towards implementing these recommendations. As a result, recent studies now commonly used multiple climate change scenarios, including scenarios from global climate models (GCMs), regional climate models (RCMs), different greenhouse gas (GHG) emission scenarios, different downscaling methods and different future horizons (see discussion in Kurylyk and MacQuarrie 2013). Additionally, modeling studies are performed on a wide variety of spatial scales, using models that simulate the dynamics of the entire water cycle or fluxes in some reservoirs only (soil, aquifer, or river). For all these reasons, it is difficult to compare modeling results and to use them in water management decisions that would include adaptation options. The objective of this paper was to summarize the state of knowledge about simulated climate change impacts on groundwater dynamics in Eastern Canada, in order to provide a clearer understanding of possible future conditions and to make recommendations for future studies.

BACKGROUND INFORMATION

Hydrological, hydrogeological, and integrated models

A wide array of models are available to study issues related to groundwater flow. Models such as the spatially distributed HYDROTEL model (Fortin et al. 2001) or the conceptual HBV model (Lindström et al. 2007), can be used to simulate surface flow processes. They usually include a highly simplified representation of the aquifer that empties with a calibrated reservoir coefficient. Nevertheless, surface flow models can be useful to study climate change impacts on groundwater resources if they are used to provide information on future base flow which corresponds to groundwater discharge to the surface in rivers.

Groundwater flow models such as MODFLOW (saturated flow; Harbaugh 2005) and FEFLOW (saturated and unsaturated flow; DHI-WASY 2013) are widely used. This category also includes models dedicated to simulate recharge and which are used with groundwater flow models to provide the upper boundary condition of water that reaches the aquifer through the surface. The most widely used in this category is the HELP model (Schroeder et al. 1994). The SUTRA model (Voss and Provost 2002) allows the simulation of coupled groundwater flow and groundwater temperature and is used to understand the warming effect of climate change on groundwater flow systems. The SEAWAT model (Guo and Langevin 2002) is software based on MODFLOW/MT3DMS (Bedekar et al. 2016). It simulates 3D density-dependent groundwater flow and is frequently used to simulate saltwater intrusion in coastal aquifers.

Integrated models represent the entire land water cycle and usually include evapotranspiration, snow accumulation and melting, runoff, water routing at the surface and in the river channel, infiltration, groundwater flow and groundwater discharge to surface reservoirs. HydroGeoShere (Therrien et al. 2010), MikeSHE (DHI Software 2007), and CATHY (Camporese et al. 2010) are three examples of integrated models that are widely reported in the scientific literature.

Emission scenarios, climate models, and projected horizons

Earlier climate modeling studies were based on GHG emission scenarios. IPCC (2000) recommended the use of different emission scenarios to be used in climate modeling studies (A1, A2, B1 and B2, including sub-scenarios). Representative Concentration Pathways (RCPs) including four GHG concentration trajectories are now used to replace the former emission scenarios in climate modeling and research (van Vuuren et al. 2011). The RCPs describe potential futures of the main drivers of climate change: greenhouse gas and air pollutant emissions. The scenarios are named based on the change in radiative forcing in 2100 compared to pre-industrial values. The RCP4.5 scenario (optimistic) represents an increase in radiative forcing of 4.5 W/m^2 relative to pre-industrial values. It is associated with a capping of emissions which would stabilize the radiative forcing caused by climate change in 2100. The RCP8.5 scenario (pessimistic) represents no change in current human behaviour. Emissions continue to rise beyond 2100 when the radiative forcing is increased by 8.5 W/m^2 relative to pre-industrial values. Most of the recent climate change impact studies use these two RCPs to account for GHG concentration scenarios.

Climate projections are generated either directly from GCMs or from RCMs driven by GCMs. The shift from SRES to RCPs also corresponds to the replacement of the CMIP3 global climate model ensemble (Meehl et al. 2007) with the CMIP5 ensemble (Taylor et al. 2012). There are currently 20 GCMs and 12 pairs of RCM-GCM combinations for North America operated by different research groups around the world for which climate projections are available. Using multiple climate scenarios combining climate models and emission scenarios is the usual approach for climate change impact studies to provide an array of possible futures.

Data from climate models that are readily available for use in hydrological and hydrogeological models are air temperature (daily minimum, maximum or average) and precipitation. These data are generated on grids of various sizes, depending on the climate model used to simulate them. Because the hydrological and hydrogeological models are usually of more local scale than the climate models' resolution, and their outputs usually include statistical bias, the climate model outputs are often adjusted using post-processing methods. When using statistical downscaling (Themeßl et al. 2010; Teutschbein and Seibert, 2012), climatic variables are linked to local meteorological variables using different methods (e.g., quantile mapping, linear regression, analog method). This method takes into consideration changes in climate variability. The delta change method (Diaz-Neto and Wilby 2005) calculates mean deviations in temperature and precipitation between future and past periods. It can be used on monthly or daily data. This method assumes that rainfall frequency is not modified with climate change. Dynamical downscaling (Giorgi and Mearns 1991) corresponds to running a fine scale regional climate model on a sub-domain driven at its boundary by a global climate model. Results from these models sometimes still need to be post-processed.

The earliest studies of climate change impacts on groundwater resources used climate scenarios for 30 to 40 years over which the future conditions were to be considered constant, and compared to simulated recent climate. The more recent climate impact studies use continuous scenarios in which the simulated future conditions evolve through time from past conditions in the 1950s to future 2100 conditions.

STUDIED REGIONS

The surveyed literature concerns studies that simulate future groundwater flow conditions for the provinces of Ontario, Québec, New Brunswick, Nova Scotia, and Prince Edward Island. Newfoundland and Labrador was not included in this overview because no provincial- nor local-scale studies were available. Only peer-reviewed studies in journal papers and theses reporting the use of groundwater flow models, integrated surface-groundwater flow models, recharge models, as well as surface flow models which include at least a simple representation of aquifers and a quantification of baseflows were considered. Surface flow studies with little or no representation of groundwater reservoirs or without any explicit quantification of recharge or groundwater contributions to rivers were excluded. A total of 22 studies have thus been summarized spanning a wide region between southern Ontario and the Magdalen Islands (QC) (Figure 1).

Ontario-based studies

Six studies focusing on groundwater resources and climate change have been reported in the literature for Ontario (see Table 1 and Figure 1b). The studies have been conducted only in southwestern Ontario with no models applied to eastern or northern Ontario. Various hydrological modelling approaches, from strictly recharge models (HELP), to fully-integrated models (e.g., HydroGeoSphere (HGS) and MikeSHE) have been employed. Most of the studies were based on data from multiple climate models. The emission scenarios included A2, B2, and a doubled CO_2 equilibrium (prior to the IPCC (2000) Special Report Emission Scenarios). Projected simulated durations ranged from 20 years (Sultana and Coulibaly 2011) to 60 years (Brouwers 2007). The earliest future horizon starts in 2020 (Brouwers 2007), and the latest ends in 2080. Some studies projected a future time span without using specific years (40 years in Jyrkama and Sykes 2007 and Colautti 2010). McLaren and Sudicky (1993) projected their future steady-state flow conditions in 2050 (no time-span).

One of the most studied aquifer systems in Canada regarding climate change impacts on groundwater at the regional-scale is the Grand River watershed (6,800 km^2) in southern Ontario. As early as the 1990s, researchers were anticipating the potential impacts of the climate change on its groundwater resources. For instance, McLaren and Sudicky (1993) used a 2D, steady-state groundwater flow model for a subregion of the Grand River watershed to examine predicted head and baseflow changes. In the groundwater model, a recharge change of -15 to -35% lead to baseflow changes of -17 to -39%.

Jyrkama and Sykes (2007) presented a physically-based method to evaluate temporal and spatial variability of climate change impacts on the recharge over the Grand River watershed (6,800 km^2). They used a GIS version of the HELP model, a distributed water balance and routing model using a pseudo-2D representation to simulate the recharge. Combining scenarios for temperature, precipitation and solar radiation changes yielded +10% to +53% for future groundwater recharge, -12% to +10% for future surface runoff, +3% to +12% for future evapotranspiration. Among various conclusions for the Grand River watershed, the authors outlined that the increased recharge projected for the future would not be uniformly distributed. Moreover, impacts were controlled by local groundwater elevations, types of soil and land uses.

Brouwers (2007) coupled the HELP model with the HydroSphere model (precursor of the HGS model) for saturated groundwater flow to simulate the projected behaviour of the Alder Creek basin (80 km^2), a subwatershed of the Grand River. The simulations showed a shift in the snowmelt timing, causing a general reduction of the runoff, an increase of the evapotranspiration (mainly during the summer months), and a general increase of the infiltration. Impacts on groundwater were generally lower than on surface water. Changes in average monthly recharge ranged from +0.36 mm (urban land, 2040-

2060) to +4.12 mm (agricultural land, 2060-2080). The author reports that recharge increased the most during the spring, with a shift of the melting season towards earlier dates, although this is not apparent from the average monthly values.

Colautti (2010) applied the integrated HGS model in the Grand River watershed (6,800 km^2) using five climate scenarios. Future scenarios were constructed based on modifying the 1960-1999 historical precipitation record (by -5%, +5%, +10%, +15%, +20%), bounded by GCM-based climate scenario ranges. These scenarios yielded recharge changes of -5% to +22%, and river discharges changes of -15% to +59% with changes in groundwater levels between -0.55 m and +1.25 m. At the local-scale, Colautti (2010) highlighted that simulated depth below ground surface to water table responded differently from one zone to another, suggesting that the local flow patterns may be more sensitive to future climate changes.

Sultana and Coulibaly (2011) used the integrated MikeSHE model for the evaluation of climate change impacts on the Spencer Creek watershed (291 km^2) in southern Ontario The simulations predicted a change of annual groundwater recharge between -6% and -0.5%. This decrease was particularly visible during summer and fall seasons. The authors did not quantify the change in river baseflow, but they note that it is expected to decrease due to the reduction of recharge.

Recently, Motiee and McBean (2017) applied HELP in the Guelph region (unspecified study area) of the Grand River watershed to investigate the impacts of climate change on recharge. The authors predicted increased evaporation and decreased summer recharge, with increased recharge in the winter months due to changing freeze/thaw dynamics. They determined a future recharge change between +7% and +12%.

Quebec-based studies

Ten local to regional-scale climate change and groundwater studies in the province of Québec have been reported in the literature (see Table 2 and Figure 1c). The models used a surface flow (HYDROTEL), a groundwater flow (MODFLOW), or integrated surface-groundwater flow (CATHY, HGS, and MikeSHE). All the studies were based on data from multiple climate models. Simulated future time periods are all similar in lengths, ranging between 24 years (Sulis et al. 2012) and 32 years (Sulis et al. 2011), with projected horizons starting as early as 2010 (2010-2039; Quilbé et al. 2008) and as late as 2071 (2071-2100; Cochand 2014). The latest end for future horizons was 2100 (Cochand 2014). The Québec-based study from Lemieux et al. (2015) in the Magdalen Islands is discussed in the Atlantic studies because of their geographical proximity.

Quilbé et al. (2008) assessed the effect of climate change on the Chaudière River watershed (6,682 km^2), with the HYDROTEL model. The results that are of interest for the current paper concern the critical streamflow sequences over seven days and return periods of two and ten years (Q_{2-7} and Q_{10-7}), as well as critical streamflow sequences over 30 days for five years return periods (Q_{5-30}), which are considered to represent river baseflows during the summer period. Interestingly, the scenarios performed with the Delta method showed changes in the critical low flows of -23% to -5% for the Q_{2-7}, -25% to -7% for the Q_{10-7}, and -29% to -7% for the Q_{5-30}. The simulations performed with statistical downscaling showed no obvious effect of climate change on summer low flows.

Sulis et al. (2011) evaluated the climate change impacts on the Anglais River (690 km^2; Montérégie region) with the integrated CATHY model. The authors identified that the impacts on the river flow at the outlet were greater during winter peaks and summer droughts. In future conditions, the total recharge changed by +16%; however, the changes throughout the year were not constant. The winter recharge was higher (+49%) due to increased rain and snowmelt, the spring recharge remained the same, and the summer recharge was lower (-8%) due to increased evapotranspiration. The fall recharge was higher (+22%) due to increased precipitation. A spatial analysis of recharge patterns shows that the greatest variations in recharge are expected to occur at the highest elevations. The future simulated river flows at the outlet during the June, July, and August summer months (considered as baseflows) were 56% lower than those of the reference period.

In the same des Anglais watershed, Sulis et al. (2012) also investigated the impact of climate change uncertainty in hydrological processes using the CATHY model. Hydrological responses (streamflow, recharge and groundwater storage) reacted differently to the precipitation and temperature variations between the climate models. River discharge changes varied from -18% to +11%. For the future climate, the low flow occurrence frequency increased for all simulations, with a percentage change in low flow occurrence between +12% and 25% for the members (comparison based on the percentage of days with a discharge lower than the first decile of present-day discharges). The change in total recharge varied between a -15% and +4%. The authors underline the impact of changing sequences of rainy days on groundwater recharge.

Bourgault et al. (2014) simulated aquifer-peatland-river interactions under climate change in the Lanoraie peatland complex (364 km^2). The authors used MikeSHE and activated only its groundwater flow component. From three climate scenarios, the recharge was estimated using a simple water budget calculation, based on the hypothesis that there is no runoff on the highly permeable sand aquifer. The resulting recharge variations ranged between 0% and -50%. The authors used average recharge scenarios of -50% and -20% to simulate groundwater flow. It appeared that the storage capacity of the organic deposits contributed to prevent drastic drawdown to the surrounding aquifers and limit river baseflow decreases. However, despite the mitigating role of the peatland, the climate scenarios indicated a change in river baseflows between -41% and -16%.

Cochand (2014) simulated the impact of climate change on the Saint-Charles River watershed (553 km^2) using the integrated HGS model. The summer and fall low flows (June to October) changed between -25% and -10%, mainly due to increased evapotranspiration. Increasing temperatures in winter and early snowmelts triggered recharge increases (+150 to +300%) between December and March and recharge decreased (-50%) in April-May. Recharge decreased also between June and October, but less markedly (-4 to -8%). The winter recharge increase was observed in the higher topography areas.

Levison et al. (2014a) developed a groundwater flow model for the Covey Hill Natural Laboratory in southern Québec (173 km^2; Montérégie region) using a steady-state groundwater flow model (MODFLOW). Similarly to Bourgault et al. (2014), the authors compared the net precipitation from the future horizon to that of the reference period for all the members, with changes in net precipitation ranging between -30% and +10%.

Assuming that recharge variations should be similar to the net precipitation variations, they imposed recharge change scenarios of -30%, -15% and +10%,. The total contribution from the aquifer to the rivers and streams over the study area varied between -44% and +14% for the +10% and -30% recharge scenarios respectively. Near the peatland, the direction of hydraulic gradients also changed in the future conditions, making the peatland feed the aquifer during the summer, the fall and the winter seasons.

In the same location, Levison et al. (2014b) simulated the dynamics of small bedrock springs under climate change conditions using the HGS model representing local scale discrete fractures. Levison et al. (2014b) applied 10 climate change scenarios directly to the HGS model instead of using a sensitivity analysis approach and imposed net precipitation at the soil surface. The simulated spring flow rates changed by +5 to +6% under future conditions, depending on the spring elevation. Results also indicated a significant increase in the number of days of spring flow activity (+1 to +2%) and generally more variability in the duration of the flow for all springs, although these increases varied considerably depending on the spring location. The authors proposed that this location might be resilient enough to face the projected climate changes, but emphasized the importance of improving follow-up programs on ecologically sensitive sites to acquire more information about the ability of natural habitat to face different climate conditions.

With the Hydroclimatic Atlas, the CEHQ (2015) synthesized the impact of climate change on the river regime of 50 medium size basins (500 to 20 000 km^2) in southern Québec. The HYDROTEL model was used to simulate flows. Changes in a series of indicators were quantified to assess the impact of climate change on the watershed hydrology. The indicators of interest here are those for summer low flows which are associated with baseflows. The results showed that summer low flows events will generally be more severe and longer for all scenarios and all watersheds: $Q_{2\text{-}7}$ changed by -54% to -6%, $Q_{10\text{-}7}$ changed by -63% to -9%, and $Q_{5\text{-}30}$ changed by -56% to -8%.

Levison et al. (2016) also investigated long-term trends in groundwater recharge and discharge for the Covey Hill Natural Laboratory using the MODFLOW model. The authors compared the simulated responses of the groundwater system using observed and simulated data from 1900 to 2010 and also used projected climate data for 2041-2070. They used the Levison et al. (2014a) calibrated model, but applied the 10 RCM climate change scenarios from Levison et al. (2014b). It was assumed that recharge variations should be similar to the net precipitation variations (-4% to +15%). For the future scenarios, average baseflows for the three rivers increased (from +10% to +14%), and average spring flow also increased (+18%). These results, in comparison to Levison et al. (2014a; 2014b) illustrate the complexity and uncertainty for making predictions for groundwater and climate change.

Atlantic Canada studies

Thus far in the literature, six climate change related groundwater modelling studies have been reported for New Brunswick, Nova Scotia, and Prince Edward Island. Although it is located in the Province of Québec, the Lemieux et al. (2015) study in the Magdalen Islands is reported here because of its geographical proximity. The models simulate recharge (HELP), groundwater flow and water temperature (SUTRA), unsaturated-saturated groundwater flow (FEFLOW), and salt water intrusion

(SEAWAT). The emission scenarios are A1B, A2, B1, and B2. The future model runs span 27 years (Lemieux et al. 2015) to 90 years (Green and MacQuarrie 2014). The future horizons start as early as 2011 and end as late as 2100 (both from Green and MacQuarrie 2014) (see Table 3 and Figure 1d).

Hansen (2012) used the SEAWAT model to estimate submarine groundwater discharge under climate change conditions on the coastal aquifer of Summerside (PEI). The authors simulated a combination of changes in recharge (assumed to be the same as changes in precipitation), changes in sea water levels and changes in aquifer pumping rates. Their results show that climate change has limited impact coastal groundwater discharge in the study area. Sea-level rise leads to significant saltwater intrusion (between 30 and 60 m) but is mitigated by a +5 to +8% change in recharge. Increasing groundwater pumping appears to be the dominant process for saltwater intrusion.

Kurylyk and MacQuarrie (2013) simulated the impacts of climate scenarios on the recharge with the HELP model at the local-scale watershed, on the Otter Brook watershed (NB) (9.5 km^2). The annual recharge changes varied between -6% and +58%. The authors show that the post-processing method had a large impact on the results, sometimes a larger impact than the emission scenario.

Kurylyk et al. (2014) applied the seven recharge scenarios developed by Kurylyk and MacQuarrie (2013) to simulate groundwater discharge to streams in the unconfined granular aquifer of Otter Brook (NB) under climate change. Groundwater flow, freezing, and thawing were simulated with the SUTRA model, for two aquifer configurations (aquifer discharge to the brook or to lateral seeps). The summer groundwater discharge rates varied between -6% and +39%, with an increase of discharging water temperature up to 3.6°C. The authors conclude that small and shallow aquifers are susceptible to air temperature increases and that thermal refugia could be impacted through warmer groundwater inflows.

In the Richibucto region of New Brunswick, Green and MacQuarrie (2014) used the SEAWAT and HELP models to examine relative impacts of climate change-induced variations in recharge, sea level rise and increased groundwater extraction on saltwater intrusion (2011-2100). Two recharge scenarios were based on a previous study (using the HELP model; Jacobs 2011): one scenario reflected the projected changes developed by Jacobs (2011), and the second doubled the percent change of those projections relative to historic conditions. Recharge changed between -27% and -5%. The impact of decreasing recharge was the most important at depths less than 60 m below sea level. Interestingly, sea-level rise had the least important effect on seawater intrusion in shallow to intermediate aquifers for the future scenarios. Because of the importance of both recharge and pumping on seawater intrusion, the authors suggested that actions to control land use influencing recharge, as well as pumping rates, may help to protect coastal fresh-groundwater supplies.

Rivard et al. (2014) investigated the impacts of climate change on the HELP-simulated recharge for the Annapolis Valley (NS) (546 km^2). The results showed a change in annual recharge from +14 to +45%. Recharge changes during the growing season (May to October) varied between -33% and -4%.

Lemieux et al. (2015) simulated the depth and shape of the groundwater transition zone between freshwater and seawater in the Magdalen Islands (Québec; 200 km^2). The simulation of density-dependent flow was performed with the FEFLOW model along a vertical 2D cross section. The authors calculated recharge values using a surface water budget and the climate scenario variables, and in the model imposed the recharge to evolve linearly from current conditions to the worst-case recharge scenario (-30%). In these conditions, the impact of sea level rise was larger than that of both coastal erosion and reduced recharge on the position of saltwater–freshwater interface which could migrate inland over a distance of 37 m.

Paradis et al. (2016) investigated how nitrate concentrations in groundwater might evolve under climate change conditions and with changes in agricultural practices in Prince Edward Island (PEI) (5,660 km^2). The HELP model was used to simulate recharge with climate scenarios used with a groundwater flow model developed in FEFLOW. Nitrate concentrations resulting from residual soil nitrate for eight scenarios of agricultural changes were simulated with the four recharge scenarios. The results showed changes in annual recharge that ranged between -12% and +7%. The generally increasing nitrate concentrations were primarily attributed to the attainment of steady-state conditions under present-day nitrogen loading, and to an increase in nitrogen loading in some agricultural scenarios. Only 0% to 6% of the increase in nitrate concentrations in groundwater was explained by changes in the recharge scenarios.

DISCUSSION

Changes in recharge

Comparing recharge rates between the different studies is not an easy task since recharge is sometimes reported as mean annual values and sometimes as seasonal values. Some studies simulate infiltration towards deeper soil (aquifer) layers, but do not explicitly quantify recharge (Quilbé et al. 2008; Levison et al. 2014b; CEHQ 2015). The studies based on groundwater flow models (Bourgault et al. 2014; Green and MacQuarrie 2014; Levison et al. 2014; Lemieux et al. 2015) have simulated worst-case recharge scenarios and present the largest recharge decreases (maximum annual recharge decrease of 50%, Bourgault et al. 2014). Although these values are useful to plan for extreme conditions, they do not necessarily reflect the complete array of possible future conditions.

Five out of six studies based on the HELP model show recharge increases (Brouwers 2007; Jyrkama and Sykes 2007; Kurylyk and MacQuarrie 2013; Rivard et al. 2014; Motiee et al. 2017) while four out of six studies with integrated models show at least one scenario with increased recharge (Colautti 2010; Sulis et al 2011; Sulis et al 2012; Cochand 2014), and four out of six studies with integrated models show at least one scenario with decreased recharge (Colautti 2010; Sultana and Coulibaly 2011; Sulis et al. 2012; Cochand 2014). Even though it is generally calibrated on total flow and baseflow separation, HELP simulates water that percolates below the root zone. It is often not clear whether or not this water reaches the aquifer and travel a significant distance with the saturated zone. This could explain why, when these processes are considered in integrated models where lateral and vertical aquifer heterogeneity is included, the changes in recharge are less conclusive.

The reviewed studies do not show any clear trend from West to East. Apart from the type of model used in the simulations, the discrepancies between studies could be due to the climate models, to the post-processing methods, or to the projected horizons. However, no clear causes could be identified with the available studies. The variability introduced by these components of a study have been identified by Quilbé et al. (2008)

and Kurylyk and MacQuarrie (2013). For example, GCMs poorly simulate precipitation but statistical downscaling can improve the projected values and might be superior to the delta change method since it can include changes in rainfall occurrence (Quilbé et al. 2008) which could impact recharge fluxes.

The studies generally agree that a global warming would reduce snow accumulation during the winter. More frequent episodes of warmer temperatures, less snow accumulation, and rain during winter are expected to increase winter recharge and lower spring recharge. In the future projections, recharge is often higher in the winter and lower in the spring season (Brouwers 2007; Colautti 2010; Sulis et al. 2011; Sultana and Coulibaly 2011; Cochand 2014; CEHQ 2015). Sulis et al. (2012) also determined that changes in the duration of the wet season had a large impact on recharge. However, the dynamics of winter recharge still need to be investigated to fully understand how it will be impacted by climate change.

The three studies that focused on coastal groundwater resources in similar geological formations have shown contrasting results. Those of Hansen (2012) and Green and MacQuarrie (2014) indicate that sea level rise would have a limited impact on salt water intrusion, while that of Lemieux et al. (2015) showed that sea level rise would have the largest impact (compared to erosion and change in recharge). Lemieux et al (2015) report that when using a time frame similar to that of Green and MacQuarrie (2014), the impact of sea level rise becomes more important in the Magdelen Island study. It should be acknowledged that sea level rise can be locally variable, so its impacts on seawater intrusion are expected to exhibit more spatial patterns than recharge changes. This underlines an important component of climate change impact studies, i.e. that aquifers can react slowly to changes in recharge and other boundary conditions. Long-term and continuous transient-state simulations are expected to better reflect the slow response of aquifer reservoirs.

The studies also show that more inter-annual variability in recharge should be expected during the summer, due to warmer air temperature and to more intense precipitation generating runoff instead of recharge (not easily captured by models that are based on a daily time step; Allen et al. 2014). This could induce longer drought periods affecting the summer baseflows (Brouwers, 2007; Quilbé et al. 2008; Sulis et al. 2011; Sultana and Coulibaly 2011; Cochand 2014; Levison et al. 2014a; CEHQ 2015). Also, if recharge occurs earlier in the spring, small aquifers and those located in headwater basins may be fully drained by summer months which would induce early low baseflow conditions. Since municipal and agricultural users generally need more groundwater during the summer period than during the winter, these changes could greatly affect economic activities. This underlines the importance of representing soil and hillslope storage variations through time and the importance of changing sequences of rainy days on the simulation of recharge (Sulis et al. 2012). Again, this stresses the importance of using long-term transient-state simulations.

Changes in groundwater discharge to surface water

Only one Ontario-based study (out of the three that reported baseflow values) showed dominating conditions of decreased baseflows (McLaren and Sudicky 1993) while that of Colautti (2010) showed mixed conditions. In Québec, generally decreasing baseflows were reported (Quilbé et al. 2008; Sulis et al. 2011; Sulis et al 2012; Bourgault et al.

2014; Cochand 2014; CEHQ 2015), but mixed conditions were also reported (Levison et al. 2014a; 2014b). The only study in Atlantic Canada that reported baseflows (Kurylyk et al. 2014) shows mainly increasing baseflows for a small granular aquifer.

Sulis et al. (2011) and Levison et al. (2014a) clearly identified that changes in local aquifers near surface water bodies could lead to more frequent reversals of the hydraulic gradient between aquifers and surface water bodies. These reversals lead to reductions in baseflow and adds pressure on ecological habitats and water users in streams and ponds during droughts and low water periods in summer (e.g., Levison et al. 2014b). The absence of significant decreases in baseflows under climate change conditions in New Brunswick can appear counterintuitive since Rivard et al. (2009) have identified decreasing trends in baseflows in past time series for Atlantic Canada. However, the only climate change impact study reported here (Kurylyk et al. 2014) concerns a very small watershed which might not be representative of larger scale conditions.

Although early studies of the impact of climate change on water resources did not include consideration of groundwater flow (e.g., Southam et al. 1999), the most recent studies using surface flow models incorporate at least a simplified representation of aquifer reservoirs (e.g., Quilbé et al. 2008; CEHQ 2015). In these cases, the surface flow model simulates baseflows which can be attributed to a groundwater contribution to the river and changes in these flows under climate change conditions can be studied. Interestingly, four out of five applications of integrated models show at least one scenario with baseflow decrease while two out of five applications show at least one scenario of baseflow increase. It is self-evident that integrated surface water-groundwater models simulate more completely and probably more reliably baseflow conditions. However, in this review, the baseflow results appeared to be independent of the type of model (groundwater flow or integrated surface-groundwater flow model). They also appeared to be independent of the climate model, and of the post-processing method.

Climate change impacts in conjunction with other pressures

Agricultural, urban and potable water pressures on groundwater availability are already of concern in most of the inhabited regions in Eastern Canada. Climate change is expected to influence indirectly groundwater use which can evolve through climate-driven or socio-economically-driven land use change (Taylor et al. 2012). Water quantity stress assignments have been performed on the Grand River watershed and elsewhere to investigate the effect of possible future increases of water use on water availability (e.g., AquaResources 2009a; 2009b) and water use conflicts (e.g., Lavigne et al. 2010a; 2010b). Kurylyk and MacQuarrie (2013) proposed that when studying recharge on a projected horizon longer than a few decades, land use changes and socio-economic factors should be taken in consideration. Nikolic and Simonovic (2015) (not reported in detail herein because the paper did not provide quantified changes in recharge or baseflows) have shown that at the sub-watershed scale, increasing permits to take water for agriculture could have an adverse impact on the groundwater resources. Bourgault et al. (2014) provide similar results and showed that increased groundwater pumping could have a larger impact on groundwater resources than decreased recharge in a St. Lawrence Lowlands granular superficial aquifer. Hansen (2012) and Green and MacQuarrie (2014) have shown that groundwater use through pumping in coastal aquifers can exacerbate saltwater intrusion. Analytical solutions have been developed to better apprehend these conditions and help water managers (e.g., Ferguson and Gleeson 2012).

Changing land use through deforestation, expansion or changes in agricultural activities or urban areas, and drainage of wetlands can have impacts on surface and subsurface hydrology (Mishra et al. 2010). For example, Fossey et al. (2016) have used surface flow modeling to show that isolated wetlands located in the upper part of a watershed have a larger effect on maintaining low flows and damping high flow than wetlands located downstream. If wetland drainage is combined with a dryer or flashier future climate, the impacts of groundwater and surface water resources could be exacerbated. Paradis et al. (2016) have also shown that changes in nitrogen loading that could be a consequence of increased temperatures leading to different crop choices, or that could result from the intensification of agricultural activities, would have a larger impact on groundwater nitrate concentrations than changes in recharge.

Modelling at different scales

The reviewed studies cover a large range of scales. Local scale studies (< 100 km^2) (Brouwer 2007; Hansen 2012; Kurylyk and MacQuarrie 2013), usually need strong collaborative support from specialists familiar with the regional geology and the local characteristics (Frey et al. 2016). Data is often most available at the watershed scale (100 to 1,000 km^2) where watershed organizations contribute to knowledge acquisition and data availability. At that scale, most of the studies of the last decade have been implemented with integrated models (Colautti 2010; Sultana and Coulibaly 2011; Sulis et al. 2011; 2012; Cochand 2014; Levison et al. 2014b). Groundwater flow models are still used (Levison et al. 2014a; Kurylyk et al. 2014; Lemieux et al. 2015; Levison et al. 2016), but they necessitate simplifications in the recharge processes or the coupling of a recharge model to a groundwater flow model (e.g., Kurylyk et al. 2014; Paradis et al.

2016). This has unquantified impacts on the simulated conditions and the surface-unsaturated zone-saturated aquifer feedback processes.

At the regional scale (2,000 to 10,000 km^2) hydrogeological data and detailed descriptions of aquifer properties do not always exist. Major funding has been invested in aquifer characterization in the Province of Québec in the last decade (see MDDELCC 2017a for a full list of reports since 2009). In Ontario, there have been many regional scale hydrogeological studies since the 1980s and 1990s (e.g., Howard and Beck 1986; Novakowski and Lapcevic 1988; Sharpe et al. 1996; Rudolph et al. 1998). These detailed groundwater data over a large region, such as in the Grand River watershed in Ontario, allowed researchers to develop complete groundwater description and integrated models (Jyrkama and Sykes 2007; Colautti 2010). In Atlantic Canada, the Canadian Geological Survey has performed regional hydrological characterization studies in the last decade as part of the Canadian Groundwater Inventory (Paradis et al. 2007; Rivard et al. 2008; Rivard et al. 2012). All these initiatives have led to the development of databases that can support model development for climate change studies.

Climate change impacts on the groundwater dynamics in Eastern Canada have not yet been investigated on a provincial scale. Natural Resources Canada has recently initiated the development of a fully-integrated groundwater-surface water, climate impact model for the southern Ontario Phanerozoic Basin Region (Frey et al. 2016; NRCan 2017). The Québec Ministry of Environment (MDDELCC) has recently initiated the development of an integrated groundwater-surface water model for southern Québec that will be used to better understand the impact of climate change on water resources. These models will facilitate anticipating long-term changes over large areas, including those resulting from climate change. This is clearly a positive development towards integrated water management and adaptation for future conditions. These models could include other cumulative stresses occurring on groundwater resources, such as changes in land use and increasing pumping for drinking water, industrial or irrigation purposes. The combination of studies and models existing at different scales, developed with various purposes in mind, will truly aid decision making for groundwater management.

Uncertainty in future conditions

The large range of possible future recharge conditions in Eastern Canada is not uncommon in climate change studies. It has been reported elsewhere and appears to be intrinsic to the study of climate change effects (e.g., Green et al. 2011). This variability can be due to the use of various climate models, emissions scenarios, data treatment methods (e.g., downscaling), and future time horizons. Although some studies have aimed specifically at better understanding this component and argue that using different downscaling methods and different sources of data is a necessity (Quilbé et al. 2008), the studies reviewed here did not allow to identify which of these methods should be prioritized over others.

Variability in the results also comes from the flow models themselves, notably from over-simplification of the geological conditions stemming from insufficient hydrogeological data used to build the model. The type of modeling approach to be used is also crucial to the array of possible future conditions. The review presented here indicates that coherent results appear between the three regions when similar modeling approaches are used. Among these, and rather intuitively, the integrated surface-groundwater flow models may be more robust to simulate climate change impacts. They allow a more holistic understanding of the entire water cycle and of the feedbacks between reservoirs, within a single mathematical framework, thus alleviating time and spatial scale errors. Going one step further, Sulis et al. (2017) report an application of coupling water flow, vegetation and atmospheric processes in western Germany. This type of integrated approach is expected to become increasingly used as computer capacities continue to increase in the next decade.

Using short time series of heads and flow rate data for model calibration data can also be responsible for model uncertainty because they do not include a wide array of possible meteorological and hydrological conditions (Moeck et al. 2016). A model that has been calibrated based on years of wet conditions is not necessarily robust to simulate dry conditions, or a succession of wet and dry periods. This is certainly a challenge, and although most Canadian provinces have a reasonably well maintained surface water monitoring network, groundwater monitoring has only recently received serious attention. Recent efforts have been invested in Québec since 2000 to install a province-wide groundwater monitoring network (MDDELCC 2017b). Ontario has had the Provincial Groundwater Monitoring Network since 2001, which has 492 monitoring points across the province (MOECC 2017). In Nova Scotia, the Groundwater Observation Well Network was established in 1965 and currently hosts 40 observation wells (Government of Nova Scotia, 2017). In New Brunswick, the groundwater observation well network was established in the early 1970s, was disbanded in 2000 and is currently being re-instrumented with a limited number of stations. In Prince Edward Island, groundwater elevations are available for 14 monitoring wells, with data from as early as the 1967 for some wells available online (Government of Prince Edward Island, 2017).

Recommendations

The first recommendation from this review is that multiple scenarios from an array of climate models and different climate change scenarios should be used. This follows recommendations by Holman et al. (2011), and was observed in most of the reviewed studies. The most recent studies use RCP scenarios and span future horizons that reach 2100. It is now relatively easy for researchers, consultants and water managers who wish to perform climate change impact studies to have access to databases that provide downscaled climate data across Canada. For example, the Pacific Climate Impacts Consortium provides temperature and precipitation data from statistically downscaled climate scenarios (on a grid of approximately 10 km resolution) for the entire country for 1950-2100 (https://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios). The Climate Change Data Portal (http://ccdp.network/) also provides dynamically downscaled climate change scenarios (temperature and precipitation) for Canada and other regions of the world. The Ouranos Consortium provides on demand climate scenarios based on regional or global climate models and is currently developing a web-access platform to make climate scenarios publicly available (*PAVICS – Power Analytics and Visualization for Climate Science*).

The decision of which model to use is often not an easy one since it depends on available data, available time to perform the study and local expertise. Nevertheless, some insights arise from this review. It is clear that surface flow models provide only limited insight to the impact of climate change on groundwater resources because they use highly simplified representations of aquifers and generally not calibrated to fully represent baseflow conditions. They are thus not the preferred tool when studying climate change impacts on groundwater resources. Groundwater flow models are useful to understand conditions in specific areas, but they are tributary to the separate simulation of recharge processes and this adds some level of uncertainty in the simulation of climate change impacts. Integrated surface water-groundwater flow models are a logical approach to understand the impacts of climate change on water resources, and the feedbacks between different water reservoirs. The second recommendation is that these models should be favored when possible in future studies.

This review also highlighted the important spatial variability in simulated changes for recharge and baseflows. This variability can only be taken into account by using models at different scales, depending on the issues under consideration. Local models, watershed models, regional or supra-regional models all contribute to better understanding this variability and to provide managers with decision-making tools. Topographic location, geological conditions have been identified as having a possible influence on how aquifers will respond to climate change. This review also has underlined the importance of performing long term transient-state simulations to assess the impact of temporal variability, as well as the long-term storage potential of aquifers. The third recommendation is that model efforts should represent long-term climate change impacts at different scales.

Other anthropogenic pressures such as land use changes and increased pumping rates are also of crucial importance to assess combined effects and cumulated impacts. The fourth recommendation is that these should be included in future studies to provide a background of information to assess tipping points for groundwater resources and ecosystems. The case of cumulated impacts on coastal groundwater resources has been made in this review. The impact of climate change on groundwater dependent ecosystems subjected to land development pressure and contamination should also be further investigated.

Spatial coverage of the territory of Eastern Canada is another important issue. The studies of climate change impacts on groundwater resources have yet focused only in the southern part of Eastern Canada. The fifth recommendation is that more studies should be performed to assess the impact of climate change in Northern Ontario, North of the St. Lawrence River, and in the Bas-Saint-Laurent and Gaspésie regions, as well as in Newfoundland and Labrador. Additional studies would also be useful to better understand how salt water intrusion will be affected by sea level rise, changes in recharge and pumping in coastal regions of Québec and Atlantic Canada. Locations/regions for future studies should be prioritized based on criteria such as expected increases in water supply demand, ecological flow requirements, resource extraction, and other issues relevant to provincial and municipal governments. This may shift as governmental priorities evolve in each province. Stakeholders who also often provide funding for this type of research (e.g., provincial environment and agricultural ministries, in consultation with other interested parties) can continue to set priorities for critical locations for future investigation based on the above criteria.

CONCLUSION

This paper aimed to review the state of knowledge about simulated climate change impacts on groundwater dynamics in Eastern Canada, including the provinces of Ontario, Québec, New Brunswick, Nova Scotia, and Prince Edward Island. Three major issues have been highlighted from these studies: i) no overall trend in time or space in recharge could be identified from the reviewed studies, but for Eastern Canada, but more inter-annual variability throughout the year is expected due to seasonal shifts in recharge; iii) groundwater discharge to surface water bodies tends to be reduced in future scenarios, and particularly during summer droughts. This exercise has provided a valuable reflection of our current understanding of possible future conditions. The analysis contributed to identifying how to improve climate change impact studies in such a way that they can be more useful for water managers.

There is clearly a need to establish guidelines for performing climate change impact studies on groundwater resources. This review provided new insights that lead to the following five recommendations for future studies: 1) use a variety of climate models and emission scenarios; 2) promote the use of integrated models when possible; 3) study long-term climate change impacts on groundwater resources at different scales; 4) simulate the combined effects of climate change and other pressures; and 5) develop models that cover other regions of Eastern Canada as dictated by stakeholders and water managers. It is clear that a good understanding of aquifer geometry and groundwater flow dynamics, a dense coverage of long-term monitoring stations for piezometric heads and river flow rates, and the development of integrated models that are maintained in the long-term would facilitate water management and planning in a changing climate.

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Figure caption

Figure 1. a) Location of all the available studies reporting climate change impacts on groundwater resources in Eastern Canada (the dotes correspond to the center of the study area), b) Ontario-based studies, c) Québec-based studies, and d) Atlantic Canada studies

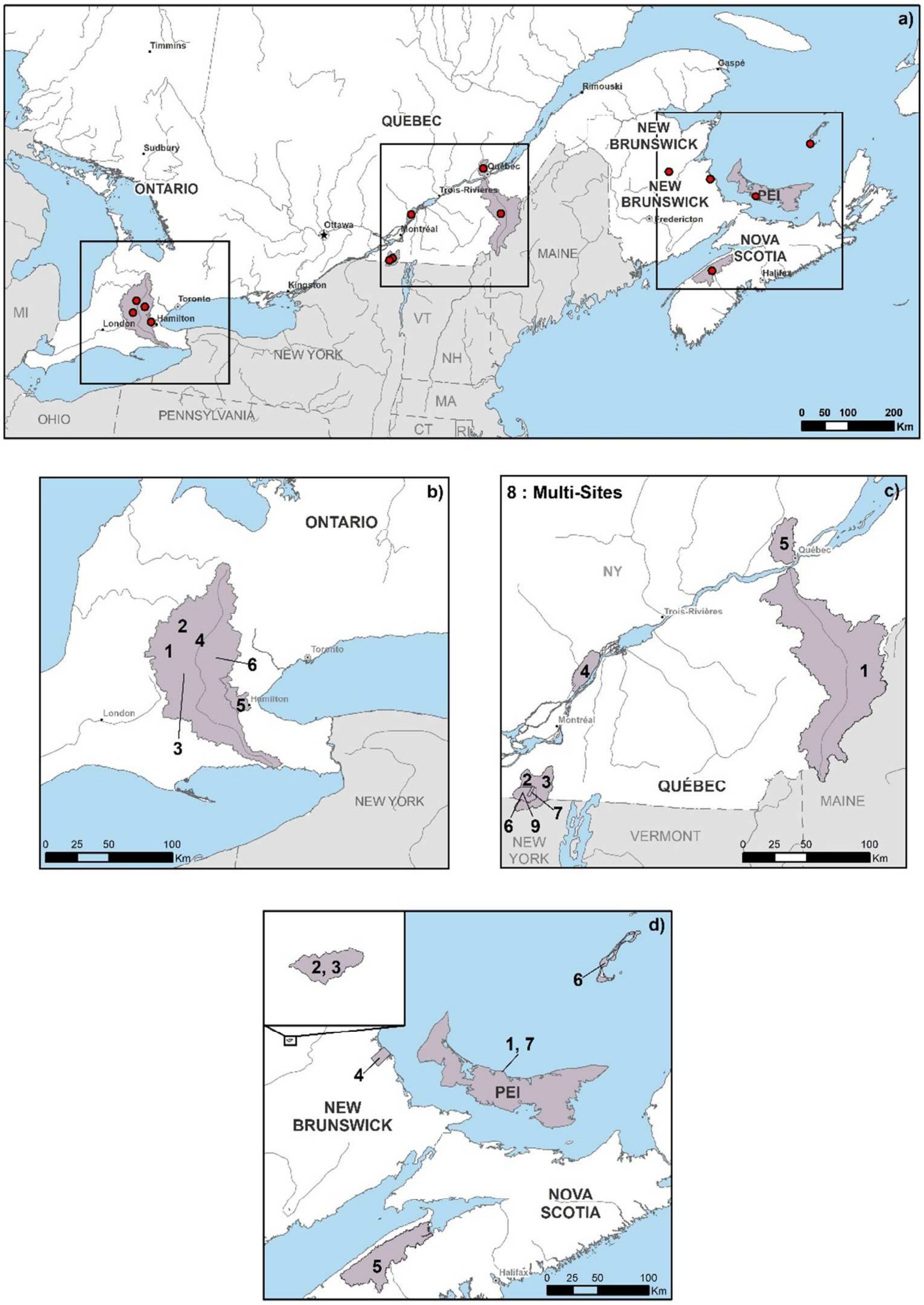

Figure 1
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Table 1. Studies on climate change impacts on groundwater for the Province of Ontario

No.	Study area	Size (km^2)	Model	Post-processing method(s)	Emission scenario(s)	Projected horizon(s)	Simulated change in baseflow	Simulated change in recharge
1.	Subregion of Grand River (ON)	Not stated	2D steady-state groundwater flow model	Delta change method	2 X CO_2	2050	-39% to -17%	-15% to +35%
2.	Grand River (ON)	6,800	HELP	Inverse distance squared	General predictions from IPCC (2000)	40 years	n.a.	+10% to +53%
3.	Alder Creek - Grand River (ON)	80	HELP HydroSphere	Delta change method (monthly)[1]	A2x, B2x	2020-2080	n.a.	+0.36 mm to +4.12 mm
4.	Grand River (ON)	6,800	HydroGeoSphere	Perturbed historical records	n.a.[2]	40 years	-15% to +59%	-5% to 22%
5.	Spencer Creek (ON)	291	MikeSHE	Statistical downscaling Time-lagged-forward neural networks	A2	2046–2065	n.a.	-6% to -0.5%
6.	Guelph region of the Grand River (ON)	Not stated	HELP	Delta change method (monthly)	n.a.	2010-2050	n.a.	+7 to +12%

1. McLaren and Sudicky (1993)
2. Jyrkama and Sykes (2007)
3. Brouwers (2007)
4. Colautti (2010)
5. Sultana and Coulibaly (2011)
6. Motie and McBean (2017)

[1] Scaling factors were available (monthly) for 2020, 2050 and 2080 and linear interpolation was used between the time slices to distribute monthly scaling factors to a daily timestep.

[2] Synthetic scenarios were constructed based on modifying the 1960-1999 precipitation record (-5%, +5%, +10%, +15%, +20%), bounded by GCM-based climate scenarios.

[3] The values are average variations in mm per month (the minimum is for urban land use and the maximum is for agricultural areas) since the reference values were not provided per land use type by the author for the entire study area.

[4] A weather generator algorithm applied changes to a local-climate time series to create future climate conditions.

Table 2. Studies on climate change impacts on groundwater for the Province of Québec

No.	Study area	Size (km^2)	Model	Post-processing method(s)	Emission scenario(s)	Projected horizon(s)	Simulated change in baseflow	Simulated change in recharge
1	Chaudière River (QC)	6,682	HYDROTEL	Delta change method (monthly) based on GCM variables; statistical downscaling; combination of the two methods.	A2, B1, B2	2010-2039	-29% to -5%[1]	n.a.
2	des Anglais River (QC)	690	CATHY	Delta change method (monthly) based on CRCM data	A2	2038-2070	-56%[2]	+16%[3]
3	des Anglais River (QC)	690	CATHY	Dynamic downscaling (for the RCM models) and regridding on a 50 km resolution grid (weighed inverse distance)	A2	2041-2065	Increased low flow occurence	-15% to +4%[5]
4	Lanoraie peatland (QC)	364	MikeSHE (only groundwater flow)	Delta change method	A1B, A2, B1	2040-2069	-41% to -16%	-50% to -20%[6]
5	Saint-Charles River (QC)	553	HydroGeoSphere	Delta change method (monthly)	A1B, A2, B1	2071-2100	-25% to -10%	-50% (spring) +150% to +300% (winter) -8% to -4% (summer)
6	Covey Hill Natural Lab. (QC)	173	MODFLOW	Dynamic downscaling	A1B, A2	2041-2070	-44% to +14%	-30% to +10%[6]
7	Covey Hill Natural Lab. (QC)	173	HydroGeoSphere	Dynamic downscaling	A1B, A2	2041-2070	+5% to +6%[7]	n.a.
8	Multi-sites	500 to 20,000	HYDROTEL	Delta quantile mapping	RCP4.5, RCP8.5	2041-2070	-63% to -6%	n.a.
9	Covey Hill Natural Lab. (QC)	173	MODFLOW	Dynamic downscaling	A1B, A2	2041-2070	+10% to +14%[8] 18%[9]	-4% to +15%[6]

1. Quilbé et al. (2008)
2. Sulis et al. (2011)
3. Sulis et al. (2012)
4. Bourgault et al. (2014)
5. Cochand (2014)
6. Levison et al. (2014a)
7. Levison et al. (2014b)
8. CEHQ (2015)
9. Levison et al. (2016)

[1] : Only the scenarios based on the Delta method showed decreases in baseflows, the scenarios based on statistical downscaling showed no changes in baseflows.

[2]: Reduction in summer (June, July, and August) flows at the outlet (Figure 7 in Sulis et al. 2011).

[3]: Annual variation in total recharge over the watershed (Figure 8 in Sulis et al. 2011).

[5]: 11 out of the 12 simulated futures projected a decreasing annual recharge.

[6]: Recharge scenarios were imposed on the groundwater flow model based on a surface water budget calculated with the climate scenarios.

[7]: Flow rate increase in the springs depending on the altitude, considered here as baseflow.

[8]: Range in average baseflow changes for three rivers.

[9]: Average flow rate increase for the simulated springs, considered here as baseflow.

Table 3. Studies on climate change impacts on groundwater for the Atlantic Provinces

No	Study area	Size (km^2)	Model	Post-processing method(s)	Emission scenario(s)	Projected horizon(s)	Simulated change in baseflow	Simulated change in recharge
1	Summerside (PEI)	4.9	SEAWAT (MODFLOW)	Dynamic downscaling	A1B, A2, B2, multi-ensemble approach	2100	n.a.	+5% to +8%[1]
2	Otter Brook (NB)	9.5	HELP	Delta change method (daily), Hybrid multiple regression, and Dynamical downscaling	A1B, A2, B1	2046-2065	n.a.	-6% to +58%
3	Otter Brook (NB)	9.5	SUTRA	Delta change method (daily), Hybrid multiple regression, and Dynamical downscaling	A1B, A2, B1	2046-2065	-6% to +31%[2]	-6% to +58%[3]
4	Richibucto (NB)	142	HELP SEAWAT (MODFLOW)	Mean deviations from climate indices for 2020s, 2050s and 2080s calculated	A1B, A2	2011-2100	n.a.	-27% to -5%
5	Annapolis Valley (NS)	546	HELP	Dynamic downscaling, and Monthly delta method	A2	2041-2070	n.a.	+14% to +45%[4]
6	Magdalen Islands (QC)	200	FEFLOW	Delta change method (monthly)	A1B, A2, B1	2013-2040	Saltwater-freshwater interface migrates inland by 37 m.	-30% to 0%[5]
7	Prince Edward Island (PEI)	5,660	HELP FEFLOW	Statistical downscaling	A2, B2	2040-2069	n.a.	-12% to +7%

1. Hansen (2012)
2. Kurylyk and MacQuarrie (2013)
3. Kurylyk et al. (2014)
4. Green and MacQuarrie (2014)
5. Rivard et al. (2014)
6. Lemieux et al. (2015)
7. Paradis et al. (2016)

[1]: Assuming that recharge will change with the same percentage as precipitation from the climate change scenarios.
[2]: Values for summer low flows.
[3]: Imposed from Kurylyk and MacQuarrie (2013).
[4]: Mean annual values from the seven simulated scenarios.
[5]: Recharge was made to evolve linearly from current conditions (0% change) to the worst-case scenario recharge obtained from water budget calculations.