Impacts of changes in groundwater recharge on the isotopic composition and geochemistry of seasonally ice-covered lakes: insights for sustainable management

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Keyword: lakes; climate change; recharge; groundwater-surface water interaction; hydrological balance; water stable isotopes

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ABSTRACT

Lakes are under increasing pressure due to widespread anthropogenic impacts related to rapid development and population growth. Accordingly, many lakes are currently undergoing a systematic decline in water quality. Recent studies have highlighted that global warming and the subsequent change in water use may further exasperate eutrophication in lakes. Lake evolution depends strongly on hydrologic balance, and therefore on groundwater connectivity. Groundwater also influences the sensitivity of lacustrine ecosystems to climate and environmental changes, and governs their resilience. Improved characterization of groundwater exchange with lakes is needed today for lake preservation, lake restoration, and for sustainable management of lake water quality into the future. In this context, the aim of the present paper is to determine if the future evolution of the climate, the population and the recharge could modify the geochemistry of lakes (mainly isotopic signature and quality via phosphorous load) and if the isotopic monitoring in lakes could be an efficient tool to highlights the variability of water budget and quality.

Small groundwater-connected lakes were chosen to simulate changes in water balance and water quality expected under future climate change scenarios, namely Representative Concentration Pathways (RCP) 4.5 and 8.5. Contemporary baseline conditions, including isotope mass balance and geochemical characteristics, were determined through an intensive field-based research program prior to the simulations. Results highlight that future lake geochemistry and isotopic composition trends will depend on four main parameters: location (therefore climate conditions), lake catchment size (which impacts the intensity of the flux change), lake volume (which impacts the range of variation), and lake G-index (i.e., the percentage of groundwater that makes up total lake inflows), the latter being the dominant control on water balance conditions, as revealed by the sensitivity of lake isotopic composition. Based on these model simulations, stable isotopes appear to be especially useful for detecting changes in recharge to lakes with a G-index of between 50% and 80%, but response is non-linear. Simulated monthly trends reveal that evolution of annual lake isotopic composition can be dampened by opposing monthly recharge fluctuations. It is also shown that changes in water quality in groundwater-connected lakes depend significantly on lake location and on the intensity of recharge change.

1. INTRODUCTION

For decades, climate change, combined with rapidly expanding urban, industrial, and agricultural water needs, has placed increasing stress on water resources and on groundwater resources in particular. Future pressure on these resources is likely to be even more pronounced, as groundwater is likely to be increasingly exploited to enhance water supply and to alleviate the worsening drought situation in some arid regions (Dragoni and Sukhija, 2008). Many studies have suggested that sustainable groundwater use has to be based on, among other things, a reliable assessment of recharge, which largely controls its evolution. Aquifer recharge refers to the quantity of water reaching the saturated zone of an aquifer, and therefore replenishing the water table. Unfortunately, in many parts of the world, recharge rates are often not well-known at the regional scale (Rivard et al., 2013). While aquifer recharge is crucial to supporting sustainable management of regional groundwater resources, it is difficult to accurately estimate, owing mainly to limited data availability, as well as limitations inherent to estimation methods and field measurements (Rivard et al., 2013). Recharge rates are controlled by geology, soil characteristics, topography, land cover, land use and climate (Rivard et al., 2014). Thorough literature reviews of the various techniques that exist to quantify groundwater recharge are provided in Scanlon et al. (2002) and Healy (2011). Many methods can be used to estimate groundwater recharge, such as water budget methods, modelling methods, tracer methods, and methods based on surface water interaction studies. The latter is based on the estimation of groundwater discharge to surface water, mainly by streambed seepage determination, stream flow duration curves, or stream flow hydrograph separation (Scanlon et al., 2002). The recharge amount (in $mm.yr^{-1}$) is then typically obtained by dividing measured or estimated discharge flow by the surface drainage area at the measurement site. This procedure assumes that aquifer boundaries coincide with watershed boundaries, and consequently that the area of the aquifer that contributes to groundwater discharge is equal to the surface drainage area (Kuniansky, 1989; Rutledge, 1998, 2007). However, this assumption must be considered carefully, as groundwater basins and watershed boundaries can differ drastically (Tiedeman et al., 1997). Miscalculation of the aquifer contributing area will lead to a proportional error in recharge estimate.

Although the groundwater inflow to streams is often taking into account in water budgets, it is less commonly considered for surface water bodies, probably due to the greater difficulty of quantifying groundwater discharge in these settings. However, in recent years some studies have proven that groundwater flow into lakes can be reliably quantified. Interactions between lakes and groundwater depend on geology, soil and sediment properties, and also on hydraulic gradient, which is strongly

95   dependent on climatic conditions and recharge (Winter, 1999). Therefore, variation in groundwater
96   fluxes may indicate a change in recharge in the lake catchment (Meinikmann et al., 2013).

97   In Quebec (Canada), more than ten percent of the surface is covered by freshwater, with more
98   than one million lakes known to exist. In many cases, these are connected to underlying aquifers.
99   However, lake-groundwater interactions are highly dynamic throughout the year, and, even if it now
100   possible to quantify groundwater inflow with a reasonable degree of confidence, it is difficult to
101   determine how and to what extent lakes can be sensitive to changes in groundwater recharge. The lake
102   water isotopic composition has been proven to be particularly useful for determining water balance
103   parameter controls under changing conditions. For example, as shown in Turner et al. (2010), lake
104   isotopic composition can highlight that (i) reduced winter precipitation could cause snowmelt-dominated
105   lakes to become rainfall-dominated lakes, or that (ii) during longer ice-free seasons, mainly rainfall-
106   dominated, but also potentially snowmelt-dominated lakes, may turn into evaporation-dominated lakes.
107   Moreover, among all the methods used to quantify groundwater inflow to lakes, isotopic balances
108   appear to be especially well-adapted for quantifying groundwater flux variations on seasonal and yearly
109   time scales (Arnoux et al. 2017a). Water stable isotopes are therefore expected to be very useful for
110   monitoring seasonal and inter-annual variations in the water budget under changing recharge
111   conditions.

112   The impact of climate change on groundwater recharge is not easy to determine, because of
113   the complexity of interactions and processes evolved, and can varies vastly depending on regions
114   (Rivard et al. 2014; Crosbie et al., 2013). In addition, it is predicted to shift differentially under various
115   climate scenarios and models (Jyrkama and Sykes, 2007; Levison et al., 2014). In Canada, highly
116   variable recharge rates have been proposed in previous studies; for example, for the 2050 horizon
117   (mainly the period 2041-2070) relative to modern (2000-2015) or past recharge rates (1950-2010),
118   depending on study site, scenario, and model: +10 to +53% in the Grand River watershed, Ontario
119   (Jyrkama and Sykes, 2007), -41 to +15% in the Chateauguay River watershed, Quebec (Croteau et al.,
120   2010), –6 to +58% in the Otter Brook watershed, New Brunswick (Kurylyk and MacQuarrie, 2013), -4 to
121   +15% at Covey Hill, Quebec (Levison et al., 2014), +14 to +45% in the Annapolis Valley, Nova Scotia
122   (Rivard et al., 2014), and -28 to +18% for the Magdalen Islands, Quebec (Lemieux et al., 2015).

123   Recharge fluctuations can also impact lake water quality by changing groundwater fluxes, which
124   are closely linked to phosphorous (P) loading to lakes. It is known that lake water quality is mainly driven
125   by variations in P load, since this plays a critical role in limiting lake primary productivity and algal
126   biomass, which in turn regulate lake trophic status. Increasing P concentration in the water column is
127   the primary factor responsible for accelerated eutrophication and associated algae blooms (Schindler,
128   1977; Wang et al., 2008). At sites without urban drainage or point P sources, such as sewage treatment

129 plants, domestic waste from septic systems may represent the largest anthropogenic source of P to
130 lakes on the Canadian Shield (Dillon and Evans, 1993). Increases in shoreline development and
131 population, combined with groundwater fluxes variations, can clearly impact lake quality, but still remain
132 to be quantified.

133   For the present study, ten lakes in southern Quebec were sampled to quantify their yearly
134 groundwater inflows (see Arnoux et al., 2017a for more details), and one of these lakes was sampled
135 over the course of a year to quantify its monthly groundwater inflows (see Arnoux et al., 2017b for more
136 details). Small kettle lakes without surface inlets set in fluvioglacial deposits, and that are most likely
137 well connected to shallow unconfined aquifers, are specifically targeted.The main objectives of this
138 study were (i) to determine how future groundwater recharge changes might affect lake water balance
139 and geochemistry, and (ii) to assess whether stable isotopes might be an effective tool for identifying
140 lakes that are susceptible to change or are undergoing changes in water balance and water quality. To
141 address these objectives, seasonal models of water and isotopic budgets were established for several
142 lakes, and the models were then forced with future yearly and monthly time scale climate data from
143 predictive global models to simulate anticipated conditions. Climate outputs of the Canadian Regional
144 Climate Model were used, based on scenarios RCP 4.5 and RCP 8.5 (Moss et al., 2010; IPCC, 2014). It
145 is assumed that recharge fluctuation is the main parameter influencing groundwater fluxes into lakes,
146 and thus a percentage of recharge change will lead to the same percentage of change of groundwater
147 fluxes to lakes. Different recharge scenarios, which translate into changes in groundwater inflow, were
148 then tested to determine changes in water budget and isotopic evolution of the lakes. Predicted changes
149 in recharge were then compared to predicted population growth in the study areas to discuss lake
150 quality evolution. After determining the evolution of the lake geochemical signature, how lakes
151 connected to groundwater can be used to identify changes in groundwater recharge can be determined,
152 as can whether or not the isotopic composition of lakes can serve as an effective indicator of change or
153 variability.
154

2. METHOD

2.1. Study sites

The ten lakes chosen are located in four regions of southern Quebec characterized by contrasting climatic conditions: Laurentides (LAU), Outaouais (OUT), Abitibi-Témiscamingue (AT), and Saguenay-Lac –Saint-Jean (SAG). These kettle lakes, set in coarse-grained (sand/gravel) fluvioglacial deposits, are specifically targeted in this study, because they (i) are small enough to be sensitive to environmental changes on a short time scale, (ii) do not have permanent surface inflow streams, and so are largely groundwater dependent, (iii) are generally characterized by predictable and uniform geomorphological features, and (iv) are likely connected to shallow, unconfined aquifers (Arnoux et al. 2017a; Isokangas et al., 2015). Kettle lakes originate as depressions in the landscape formed following the melting of ice blocks buried in the ground after glacial retreat of the Late Glacial to Holocene transition period (from -12 to -7 kyr). These kettle holes, becoming kettle lakes when they are filled with water, are mainly found in fluvioglacial deposits, such as outwash plains, deltas, eskers, and kame terraces (Benn and Evans, 2011). Figure 1 shows the locations of the ten lakes analyzed here. Their main characteristics are described in Table 1.

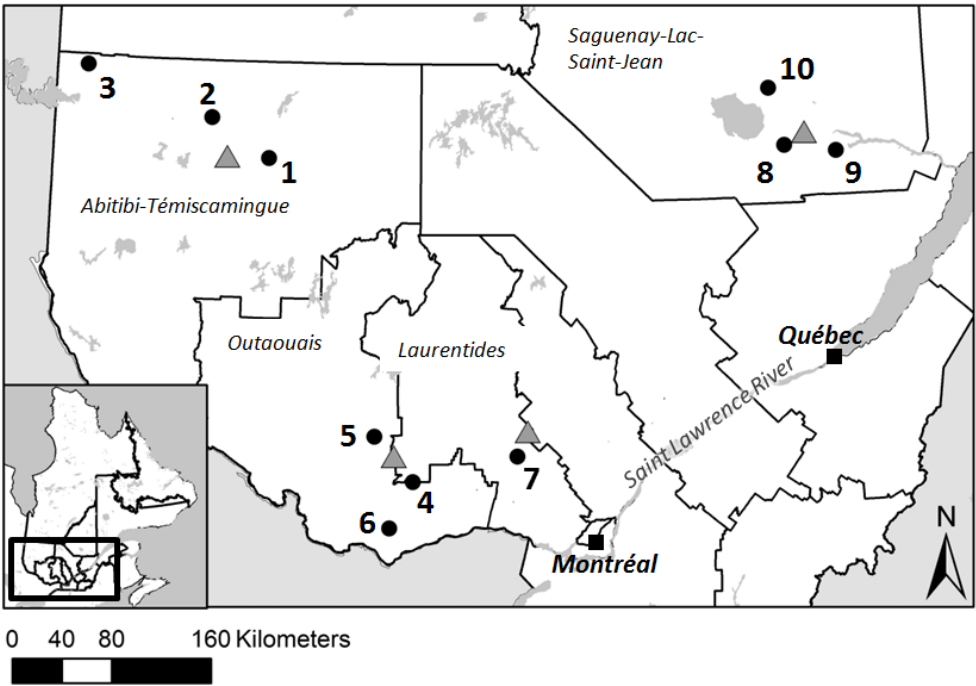



Fig. 1. Locations of the study lakes (circles) and sources of climate data (triangles)

2.2. Lake isotopic composition

2.2.1. Sampling

Water samples from each lake were retrieved during two field campaigns, in June-July and October-November 2014. When physicochemical parameters, measured *in situ* along the water column, revealed a well-mixed lake, the lake was considered to be homogeneous, and only one sample was collected, from close to the lake bottom, at its greatest depth. Otherwise, for stratified periods, two samples were collected: one from the top of the epilimnion and one from the base of the hypolimnion, in order to obtain the complete range of isotopic composition variation. Whenever possible, groundwater was sampled from private wells located in the vicinity of the studied lakes. Untreated groundwater samples were collected from residential wells from the tap after purging approximately three times the well volume.

Samples were transported in a cooler, and subsequently stored at 5°C until analyses were performed. Water stable isotopic compositions were measured with a Laser Water Isotope Analyser (OA ICOS DLT, Los Gatos Research, now ABB) at the GEOPS Laboratory (University of Paris-Sud/Paris-Saclay, France). The measurement accuracy is ± 1 ‰ vs VSMOW for δ^2H and ± 0.2 ‰ vs VSMOW for δ^{18}O. Results are reported in δ values, representing deviations in per mil (‰) from the isotopic composition of the international standard (Vienna Standard Mean Ocean Water, VSMOW), such that δ^2H or δ^{18}O$=((R_{sample}/R_{VSMOW})-1)\times1000$, where R refers to ^{2}H/H or ^{18}O/^{16}O ratios.

One of the lakes, Lake Lacasse, was sampled in more detail throughout 2015-2016. Water samples were collected from the lake at two weeks to one month intervals, mainly from the deepest part of the lake, and at 1 to 2 meter depth intervals in order to monitor the vertical heterogeneity of the water column. Groundwater was sampled twice from eight private wells in the vicinity of the lake (see Arnoux et al, 2017b for more detail).

2.2.2. Water mass balance

The lake water budget is defined as:

$$\frac{dV}{dt} = I - E - Q \quad \text{Eq. (1)}$$

where V is the volume of the lake (m^3); t is time (days); E is evaporation (m^3.day^{-1}); I is the instantaneous inflow (m^3.day^{-1}), corresponding to the sum of upstream surface inflow (I_S; zero for the studied lakes because they do not have surface inlets), runoff (I_R; considered negligible because of the permeable nature of the sandy soils of kettle lakes), groundwater inflow (I_G), and precipitation on the lake surface (P); Q is the outflow (m^3.day^{-1}), which is the sum of surface (Q_S) and groundwater (Q_G)

207   outflows. Under constant atmospheric and hydrologic conditions, steady state is assumed (Gibson et al.,

208   2016), implying that dV/dt=0. Therefore $I_G = Q_S+Q_G+E-P$ for the entire lake.

209   2.2.3.Stable isotopic mass balance

210   Considering water stable isotopes, the lake isotopic mass balance is:

211
$$V \frac{d\delta_L}{dt} + \delta_L \frac{dV}{dt} = I\delta_I - E\delta_E - Q\delta_Q \quad \text{Eq. (2)}$$

212   where δ is isotopic composition of: the lake (δ_L; equals to the mean if the lake is stratified - see Arnoux

213   et al. 2017a and b for more details about lake isotopic compositions used in the model), total inflow (δ_I),

214   which include runoff (δ_R), precipitation (δ_P), surface inflow (δ_S) and groundwater inflow (δ_G), and total

215   outflow (δ_Q), which include surface (δ_{QS}) and groundwater (δ_{QG}) outflows. The isotopic composition of

216   evaporating water (δ_E) was estimated using the Craig and Gordon (1965) model, expressed by

217   Gonfiantini (1986) as:

218
$$\delta_E = \frac{(\delta_L - \varepsilon^+)/\alpha^+ - h\delta_A - \varepsilon_K}{1 - h + 10^{-3}\varepsilon_K} \quad \text{Eq. (3)}$$

219   where h is the relative humidity at the lake surface; δ_A is the local isotopic composition of the

220   atmospheric moisture (‰);α^+ is the equilibrium isotopic fractionation;

221      $\varepsilon^+ = (\alpha^+ - 1)*1000$ is the equilibrium isotopic separation (‰);

222      $\varepsilon_K = C_K(1-h)$ is the kinetic isotopic separation (‰), with C_K being the ratio of molecular diffusivities

223   between heavy and light molecules (Gibson et al., 2016).

224   In this study, C_K values were considered to be representative of fully turbulent wind conditions

225   and a rough surface for both oxygen (C_K =14.2‰) and hydrogen (C_K =12.5‰), based on experimental

226   data (Horita et al., 2008). For calculating equilibrium fractionation factors, experimental values of Horita

227   and Wesolowski (1994) were used:

228      $\alpha^+(^{18}O) = \exp(-7.685/10^3 + 6.7123/T - 1666.4/T^2 + 350410/T^3)$ Eq. (4)

229      $\alpha^+(^2H) = \exp(1158.8 \times T^3/10^{12} - 1620.1 \times T^2/10^9 + 794.84 \times T/10^6 - 161.04/10^3 + 2999200/T^3)$ Eq. (5)

230   where T is temperature (K). The isotopic composition of atmospheric moisture (δ_A, ‰) was calculated

231   assuming equilibrium isotopic exchange between precipitation and vapor:

232
$$\delta_A = \frac{\delta_P - \varepsilon^+}{1 + 10^{-3}\varepsilon^+} \quad \text{Eq. (6)}$$

233   where δ_P (‰) is the mean annual isotopic composition of precipitation. Assuming well-mixed conditions

234   in the lake, the combination of Eq. (3) and Eq. (2) yields:

235
$$V \frac{d\delta_L}{dt} + \delta_L \frac{dV}{dt} = P\delta_P + I_G\delta_G - Q\delta_L - \frac{E}{1-h+10^{-3}\varepsilon_K}\left(\frac{\delta_L - \varepsilon^+}{\alpha^+} - h\delta_A - \varepsilon_K\right)$$ Eq. (7)

236 A steady state was assumed, such that dV/dt=0. Equation (7) can therefore be simplified to:

237
$$V \frac{d\delta_L}{dt} = P\delta_P + I_G\delta_G - (P+I_G-E)\delta_L - \frac{E}{1-h+10^{-3}\varepsilon_K}\left(\frac{\delta_L - \varepsilon^+}{\alpha^+} - h\delta_A - \varepsilon_K\right)$$ Eq. (8)

238 Resolving this calculation therefore allows isotopic composition of the lake water at time t+dt to be

239 determined, expressed as a function of its value at the previous time step, t, and two established

240 parameters, A (‰.m^3/yr) and B (m^3/yr):

241
$$\delta_L^{t+dt} = \frac{A}{B} + (\delta_L^t - \frac{A}{B})\exp(-\frac{B}{V}dt)$$ Eq. (9)

242 with

243
$$A = P\delta_P + I_G\delta_G - \frac{E}{1-h+10^{-3}\varepsilon_K}\left(-h\delta_A - \varepsilon_K - \varepsilon^+/\alpha^+\right)$$ Eq. (10)

244
$$B = P + I_G - E\left(1 - \frac{1}{\alpha^+(1-h+10^{-3}\varepsilon_K)}\right)$$ Eq. (11)

245   The monthly mean isotopic composition of precipitation (δ_P) was assessed in the four regions

246 from the Global Network of Isotopes in Precipitation (GNIP) and Program for Groundwater Knowledge

247 Acquisition (PACES) datasets. Future δ_P trends are uncertain; however, they have been shown to be

248 mainly dependent on temperature evolution and local factors (Stumpp et al., 2014), and a recent study

249 in Siberia showed that a long term increase in precipitation $\delta^{18}O$ is close to the detection limit of the

250 tracers (<1‰ per 50 years) (Butzin et al., 2014). Monthly current means were therefore used in the

251 current simulations. The mean value of groundwater isotopic composition (δ_{Gi}) was determined from the

252 mean groundwater isotopic composition measured in wells, located in the same region and presenting

253 no enrichment due to evaporation. The mean isotopic values used for groundwater are presented in

254 Table 2.

255   The uncertainties associated with the Craig and Gordon (1965) model in the estimated isotopic

256 composition of evaporating moisture (δ_E) can be substantial, especially if relative humidity is greater

257 than 0.8 (Kumar and Nachiappan, 1999). Moreover, a sensitivity analysis of ^{18}O isotopic balance of a

258 small lake in Austria (Yehdegho et al., 1997) indicates that for flow-though, groundwater-dominated

259 systems with limited evaporation, the isotopic composition of the lake water and the inflow water are the

260 parameters critical to the overall uncertainty. Horita et al. (2008) recommended using time-averaged

261 values of the parameters in the calculation of δ_E for the given period of interest. Moreover atmospheric

262 parameters should be preferably evaporation-flux weighted whereas liquid fluxes to a lake should be

263 amount-weighted (Gibson, 2002; Gibson et al., 2016). Therefore, on an annual time step, δ_P is monthly

264   precipitation-flux weighted, except when it is used to estimate δ_A; in this case, δ_P is monthly

265   evaporation-flux weighted. At a monthly time scale, monthly values are used for each parameter of the

266   model, and evaporation is considered to be null during the ice-covered period. Moreover, in winter,

267   when monthly mean temperature is below zero, precipitation is assumed to be zero in the model. Then,

268   when monthly temperature becomes equal to or higher than zero, accumulated precipitation and

269   amount-weighted δ_P are added to the calculation during the melt period. Moreover, sensitivity tests on

270   this model have performed in Arnoux et al. 2017a and b and show that it is mostly sensitive to E, h and

271   δ_G.

272

273   2.3. Evolution scenarios

274   2.3.1. Climate models

275   Climatic parameters used in this study (evaportation, humidity, temperature and precipitation)

276   come from climate models. RCMs allow the downscaling of large-scale information from GCMS to scale

277   closer to watershed scale, leading to a better representation of surface forcings. In the present study,

278   the fifth version of the Canadian RCM (CRCM5) was chosen, which has a 0.44° horizontal grid

279   resolution (approx. 50 km; Sushama et al., 2010; Martynov et al., 2013; Šeparović et al., 2013). The

280   CRCM5 is a grid-point model, based on a two time-level, semi-Lagrangian, (quasi) fully implicit time

281   discretization scheme (Alexandru and Sushama, 2015). The model includes a terrain-following vertical

282   coordinate based on hydrostatic pressure (Laprise, 1991; Alexandru and Sushama, 2015), and an

283   horizontal discretization on a rotated latitude-longitude, Arakawa C grid (Arakawa and Lamb, 1977;

284   Alexandru and Sushama, 2015). Following CRCM4, changes that have been introduced into CRCM5

285   include, for example, evolution in the planetary boundary layer parameterization to suppress both

286   turbulent vertical fluxes under very stable conditions and the interactively coupled one-dimensional lake

287   model (Flake; Mironov et al., 2010; Martynov et al., 2012; Šeparović et al., 2013). CRCM5 uses the

288   Canadian Land-Surface Scheme (CLASS, version 3.5; Verseghy, 1991; Alexandru and Sushama,

289   2015). This model is described in detail in Martynov et al. (2013) and Šeparović et al. (2013).

290   The CRCMs were driven by the second-generation Canadian Earth System Model (CanESM2,

291   improved from CanESM1; Arora et al., 2011), developed by the Canadian Center for Climatic Modeling

292   and Analysis (CCCma). As explained in Šeparović et al. (2013), it consists of a fourth-generation

293   atmospheric general circulation model CanAM4, coupled with (i) the physical ocean component OGCM4

294   developed from the NCAR CSM Ocean Model (NCOM; Gent et al., 1998), (ii) the Canadian Model of

295   Ocean Carbon (CMOC; Christian et al., 2010), and (iii) Canadian Terrestrial Ecosystem Model (CTEM;

296   Arora and Boer, 2010). The CanAM4 is a spectral model employing T63 triangular truncation with

297 physical tendencies calculated on a 2.81 linear grid and 35 vertical levels (Arora et al., 2011; Šeparović

298 et al., 2013).

299 ### 2.3.2. Climate data

300   Four greenhouse gas concentration scenarios (Representative Concentration Pathways, RCP)

301 have been adopted by the IPCC in its fifth Assessment Report (AR5) in 2014: RCP 2.6, RCP 4.5, RCP

302 6.0, and RCP 8.5. The scenarios selected for the present study are RCP 4.5 and RCP 8.5, for which

303 predicted climate data are available until 2100 for the study regions. The RCP 4.5 scenario considers

304 that long-term global emissions of greenhouse gases and land-use-land-cover stabilize radiative forcing

305 at 4.5 $W.m^{-2}$ (approximately 650 ppm CO_2-equivalent) by the year 2100, without ever exceeding that

306 value. The RCP 8.5 scenario corresponds to the highest greenhouse gas emissions pathway scenario,

307 with gas emissions and CO_2 concentrations increasing considerably over time, and thus leading to a

308 radiative forcing of 8.5 $W.m^{-2}$ by the end of the century (approximately 1370 ppm CO_2 equivalent). The

309 defining characteristics of these scenarios are enumerated in Moss et al. (2010).

310   In order to connect these RCP forecasts to our study and to visualize trends, yearly mean data

311 are presented in Fig. 2. Based on previous literature on recharge changes (see part 2.2.3.), a reference

312 period (2010-2040) is compared to a future period (2041-2071). It is noted that both evaporation and

313 temperature display increases between the reference and future periods for both scenarios, although it

314 is more pronounced for RCP 8.5. Moreover, precipitation and relative humidity do not show clear trends.

315 However, it seems that precipitation variability will increase overall for both scenarios, although this is

316 more pronounced for RCP 8.5. Moreover, the southern regions (i.e., OUT and LAU) have higher

317 temperatures than the northern regions (i.e., AT and SAG), and precipitation is higher in LAU than in the

318 other three regions. On a monthly time scale, surface temperatures in LAU show an increasing monthly

319 trend, whereas evaporation increases mainly during summer and stays relatively constant the rest of the

320 year (data not shown). Meanwhile, precipitation does not show any clear trend. However, as

321 temperatures increases in winter, melt periods likely will shift more frequently occur earlier in the year.

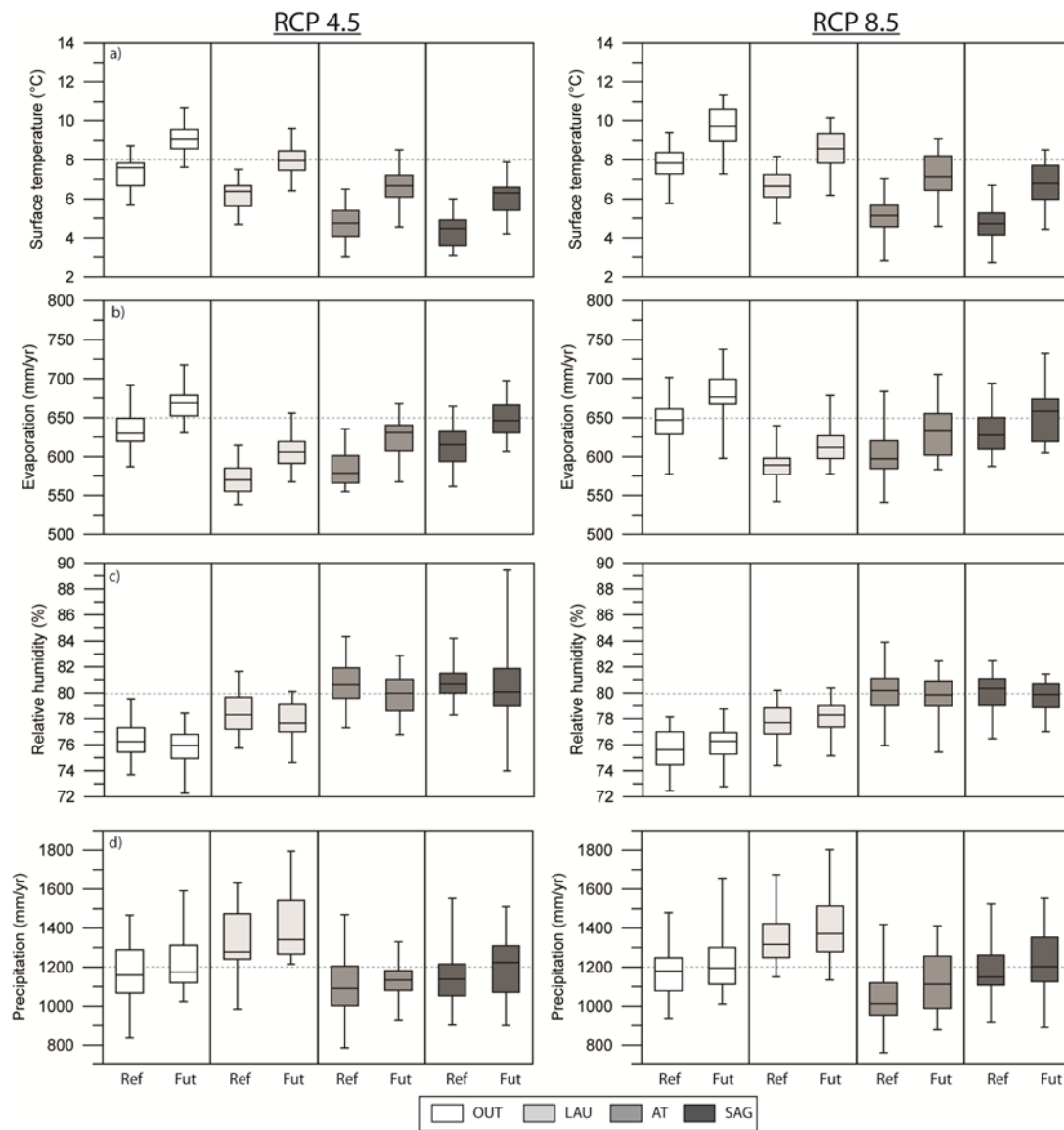



Fig. 2. Climate data for the reference (Ref; 2010-2040) and future (Fut; 2041-2071) periods, obtained from CRCM5 –CanESM2, with RCP 4.5 (left) and RCP 8.5 (right) scenarios for the four different study areas. The variables are: a) surface air temperature, b) surface water evaporation (obtained from surface heat flux), c) surface relative humidity (obtained from surface specific humidity), and d) precipitation (Martynov et al., 2013; Šeparović et al., 2013); bow-whiskers describe median, first and third quartiles and maximum and minimum values.

2.3.3. Recharge evolution

327

328   The mean annual recharge for each lake basin was obtained by dividing the lake drainage area

329   by the calculated mean annual groundwater inflow to the lake (Meinikmann et al., 2013). In this study,

330   recharge evolution is thus expressed in terms of changes in groundwater inflow to the lakes.

331   In the first step, recharge is assumed to be constant for the 2006-2014 period. Over this period,

332   recharge is adjusted to fit the calculated lake isotopic compositions to those measured. In the second

333   step, the results of Rivard et al. (2014) was chosen for the simulation of recharge scenarios, since this

334   study focusses on the Annapolis Valley (Nova Scotia, Canada), not far from southern Quebec and with

335   a similar latitude, geology, and climate. Therefore, the future recharge dynamics determined for the

336   Annapolis valley are assumed to be similar to those of the present study sites. Rivard et al. (2014) found

337   that all scenarios predict an annual recharge to the aquifer within the range of +14 to +45% higher than

338   at present by 2041-2071. They also predict, on a seasonal basis, that recharge will undergo (i) a marked

339   decrease in summer (from 4 to 33%), and (ii) a spectacular increase in winter (more than 200%), due to

340   an earlier melt period starting date.

341   The following section focussed firstly on monthly lake isotopic composition evolution (Part 3.1.)

342   and secondly on yearly lake isotopic composition evolution (Part 3.2.). Monthly and yearly values are

343   compared for the two standard periods (i.e., for reference (2010-2040) and future (2041-2071) periods).

344   For the first part of the study, Lake Lacasse, located in the LAU region, has been chosen, since

345   it was subject to continuous monitoring (Arnoux et al., 2017b). Its groundwater inflow and variability has

346   therefore already been well-constrained throughout the year 2015-2016 (Fig. 3 b). For this lake, the

347   model was run from 2006 to 2071, and four different recharge evolution scenarios were applied to the

348   2041-2071 period, following the predictions of Rivard et al. (2014) for scenarios S1 and S2, as

349   described below.

350   -   NC: no change in recharge (groundwater inflow follows the pattern described in Fig. 3,

351   obtained from Arnoux et al., 2017b);

352   -   S0: a recharge decrease of 33% during the summer period (from June to October);

353   -   S1: a 200 % increase in recharge during the melt period (from January to March), and a 4%

354   decrease in the summer period;

355   -   S2: a 200 % increase in recharge during the melt period, and a 33% decrease during the

356   summer period.

357   For the second part, three annual recharge evolution scenarios were tested, following the

358   predictions of Rivard et al. (2014): no change (NC), a 14% increase (Low), and a 45% increase (High) in

359   mean annual recharge.

2.4. Population growth

Variations in the quantity and/or quality of groundwater feeding lakes can obviously impact the geochemistry, and thus the water quality of lakes, especially for lakes displaying a high G-index (the percentage of groundwater comprising the total lake inflow; Arnoux et al., 2017a). Moreover, in rural areas of Quebec, lake and groundwater quality is likely to be influenced by changes in population density. The population of Quebec is aging, and many seasonal residences (e.g., cottages) around lakes in rural areas are expected to become year-round residences. Furthermore, these residences are not connected to waste water treatment plants; rather, owners have their own private wells for drinking water and private septic tanks with subsurface seepage beds for waste water. The predicted population changes are summarized in Table 3. Population is mainly expected to increase in the southern regions (OUT and LAU), with a mean increase of 24 and 28% respectively (ISQ, 2014; Table 3). Scenarios of population growth are compared with scenarios of recharge evolution for each lake to assess their future quality evolution.

3. RESULTS AND DISCUSSION

3.1. Monthly evolution of lake isotopic composition

Figure 3 shows the measured (see Arnoux et al. 2017b for more details about measured values) and modelled isotopic compositions of Lake Lacasse. It can be observed that the modelled values are more variable than the measured ones, undoubtedly due to the higher evaporation rate in the climatic model (459 mm) than that measured during the field monitoring period (204 mm). It is also shown that the model attributes greater weight to the contribution of the depleted snow value than in reality. This is probably due to the snow column (which is close to 0°C during the snow melt) being less dense than the lake surface water (which has a mean temperature of close to 4°C), and therefore bypasses the lake, flowing rapidly out of the lake outlet. In such a case, the snow does not influence the lake isotopic composition as much as the model predicts. Since similar results are obtained for δ^2H values, only the $\delta^{18}O$ results from the model will be presented in the following sections.

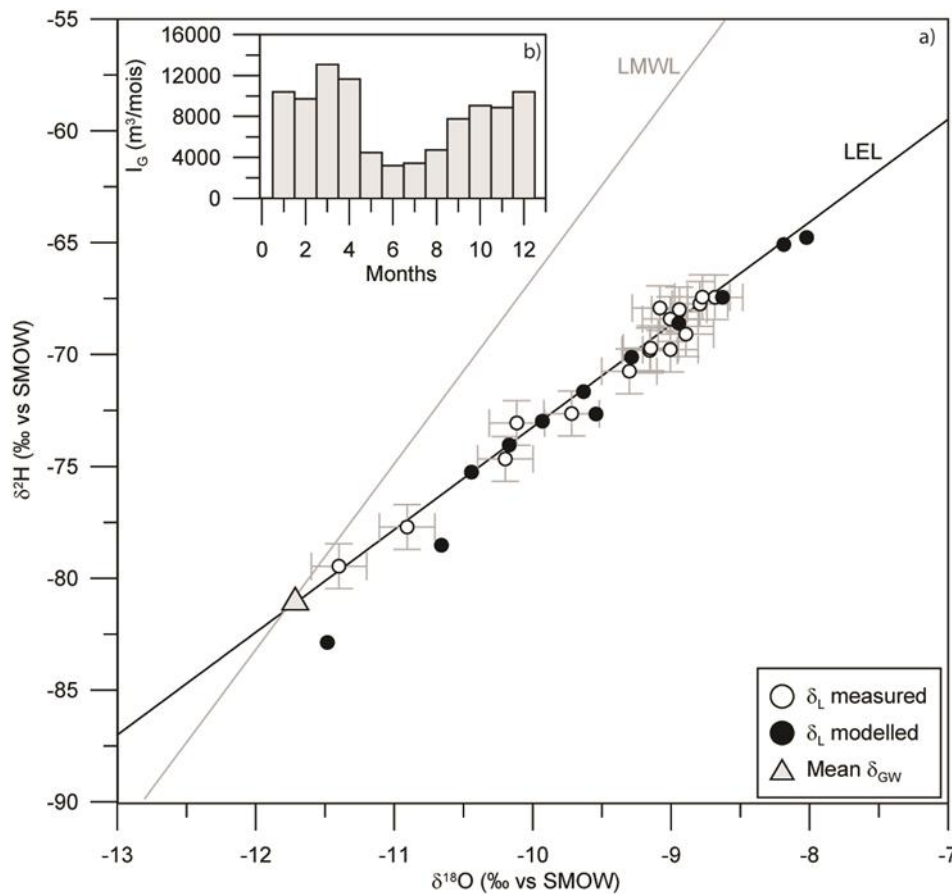



Fig. 3. (a) Isotopic composition of Lake Lacasse between June 2015 and May 2016, measured and modelled from stable isotopic mass balance model using climate data from climate model CRCM5 –CanESM2 and scenario RCP 4.5 ; (b) the pattern of groundwater inflow (I_G) to Lake Lacasse (Arnoux et al., 2017b).

Lake Lacasse has a mean G-index (i.e. the percentage of groundwater in total lake inflows) of 69% during the reference period. Results for monthly simulations, with RCP 4.5 climate data, are illustrated in Fig. 4. Lake isotopic compositions are not significantly different between the reference and future periods if no change is applied to the recharge pattern (Fig. 4). Under scenarios S1 and S2, it can be observed that future $\delta^{18}O$ is nearly 100% different from reference conditions during the two first months of the year (Fig. 4). It is at least 75% different for the month of March, but this month shows important variation during the future period. Throughout the rest of the year, ranges of variation are not completely different, but increasing or decreasing trends can be observed, depending on the season.

Indeed, Fig. 5 shows the monthly differences between mean lake $\delta^{18}O$ in the reference period (which is the same for all scenarios) and mean lake $\delta^{18}O$ in the future period, for the four recharge evolution scenarios.

On the year:

- regarding the reference period, the highest variation is observed in March for S1 (-1 ‰), S2 (-1 ‰), and NC (-0.4 ‰), after the melt period. For S0, the greatest change regarding the

403   reference period is observed in September and October (+0.4 ‰), after the evaporation
404   period;

405   -   regarding the NC future period, the greatest difference between winter recharge is in
406   February (-0.6 and -0.5 ‰ for S1 and S2 respectively). This suggests that future changes in
407   lake isotopic composition associated with recharge may be highest in February.

408   During the summer:

409   -   regarding the reference period, the highest variation will be in August for NC (+0.2 ‰), while
410   it will be in September and October for S0 (+0.4% for both months) and S2 (+0.2 and +0.3
411   ‰ in September and October respectively). S1 do not show any variation;

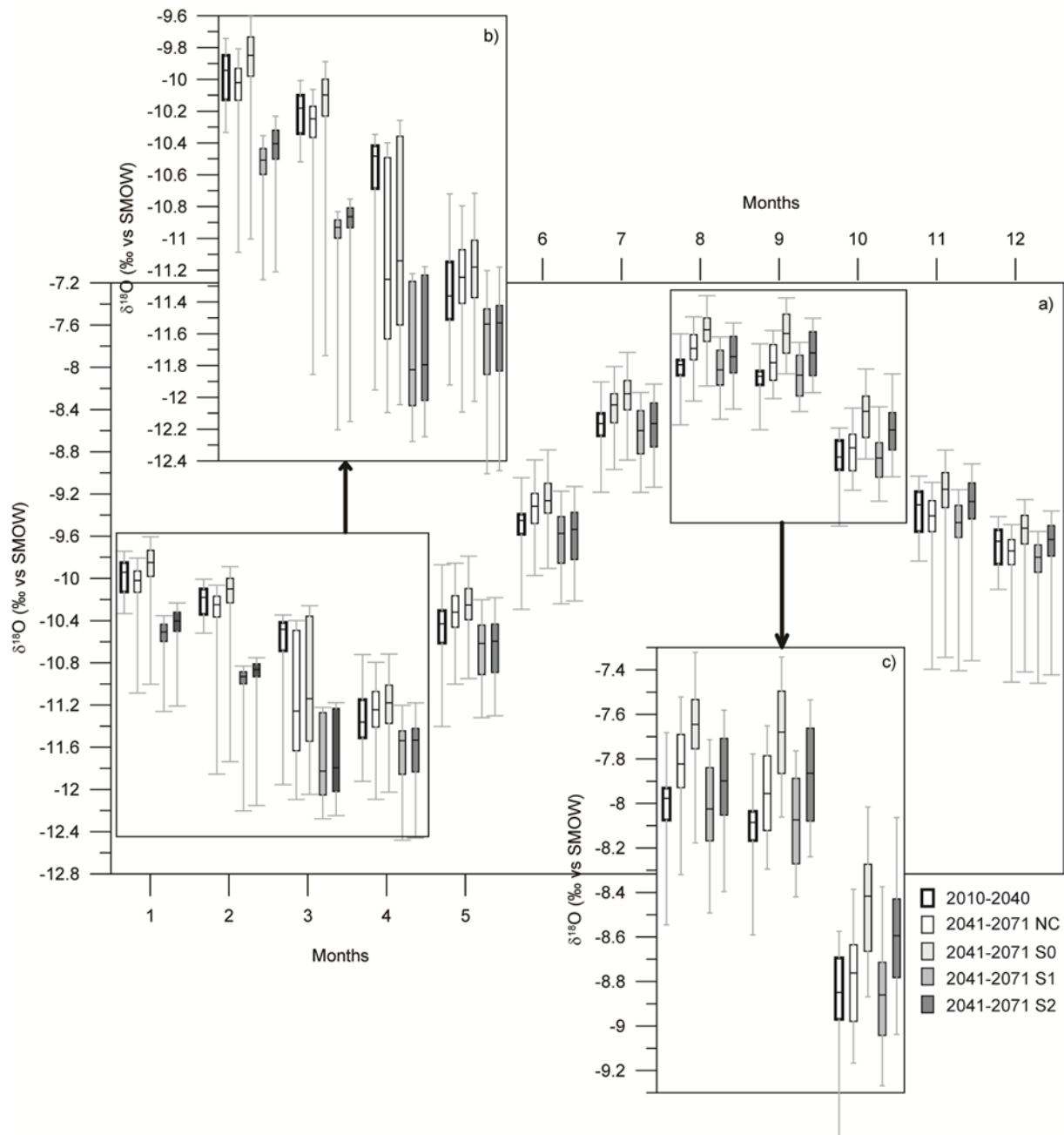
412   -   regarding the NC future period, the greatest change will be in October for S0 (+0.3 ‰) and
413   S2 (+0.2 ‰), and in September for S1 (-0.1 ‰).

414

415   Results of scenario S2, characterized by the greatest changes in recharge, in both summer and
416   winter, highlights that the impact of decreased recharge during summer attenuates the substantial
417   impact of increased recharge during winter. Indeed, during winter, S1 shows more depleted values than
418   S2 (-0.5 versus -0.4 ‰ in January, and -0.8 and -0.7 ‰ with respect to the reference period for S1 and
419   S2 respectively). Therefore, the more recharge decreases in the summer, the more lake isotopic
420   composition increases in the summer, due to increased future evaporation. Meanwhile, the more
421   recharge increases in the winter, the more lake isotopic composition is depleted in the winter. If both
422   phenomena occur in a given year, the mean annual lake isotopic composition evolution will therefore not
423   be expected to shift much, since their opposing impacts on lake isotopic composition will cancel each
424   other out. As such, S1 is the scenario showing the highest variation in annual mean, of -3 ‰, compared
425   with -2 ‰ for S2 and +2‰ for S0.

426   Based on these observations, it appears that isotopic signatures measured at the end of
427   February and in September or October will provide information on the greatest changes during the
428   winter and summer periods respectively. The greatest changes in lake isotopic composition are likely to
429   be at the end of the melt period.

430

431

432 Fig. 4. (a) Monthly Lake Lacasse isotopic composition, calculated using RCP 4.5 climatic data, for different periods and various recharge
433 patterns: no change (NC), -33% in the summer (from June to October; S0), +200 % during the melt period (from January to March) and -
434 4% in the summer (S1), and +200 % during the melt period and -33% in the summer (S2); (b) close-up of the winter months; c) close-up of
435 the summer months; bow-whiskers describe median, first and third quartiles and maximum and minimum values.

436

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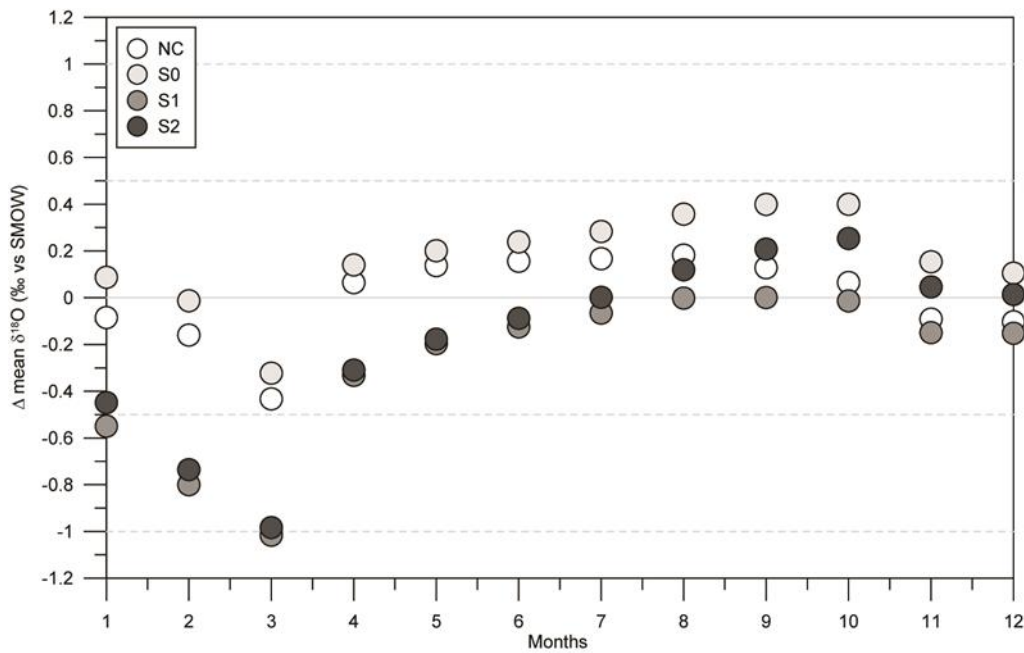
438
439 Fig. 5. Differences between mean Lake Lacasse δ18O in the reference period and mean Lake Lacasse δ18O in the future period, for the
440 RCP 4.5 climate scenario and four scenarios of recharge evolution: no change (NC), -33% in the summer (from June to October; S0), +200
441 % during the melt period (from January to March) and -4% in the summer (S1), and +200 % during the melt period and -33% in the
442 summer (S2).

443

444   Moreover, simulation results show that RCP 4.5 and 8.5 models provide similar results for Lake

445 Lacasse isotopic composition evolution. Figure 6 shows the comparison of lake δ18O composition for

446 both RCP climate scenarios, from 2010 to 2071, assuming the NC recharge scenario. In Fig. 6, it can be

447 observed that there is a small trend toward δ18O enrichment due to a higher evaporation rate, which is

448 more pronounced for the RCP 8.5 than for the RCP 4.5 scenario. However, on a yearly time scale, the

449 impact of evaporation increase in the summer seems to be attenuated by a precipitation increase

450 throughout the rest of the year, likely implying that these climate changes result in a nearly non-

451 measurable impact on lake isotopic composition evolution.

452

453   Finally, all these results show that extreme caution is required when interpreting trends in lake

454 isotopic composition, and that their interpretation requires (i) a minimum background knowledge – at

455 least one year of data – of lake isotopic composition evolution in relation to its hydrological balance, and

456 (ii) an accurate evaluation of weather data variability in the year of monitoring, with respect to their

457 annual means for the study lake. A long term change in recharge will definitely impact lake isotopic

458 composition, but the lake is also sensitive to changes in other water budget parameters. It may therefore

459 still be difficult to definitively isolate the effect of recharge over long time periods. As such, it is also

460 important to consider evolution in the yearly mean lake isotopic composition.

461
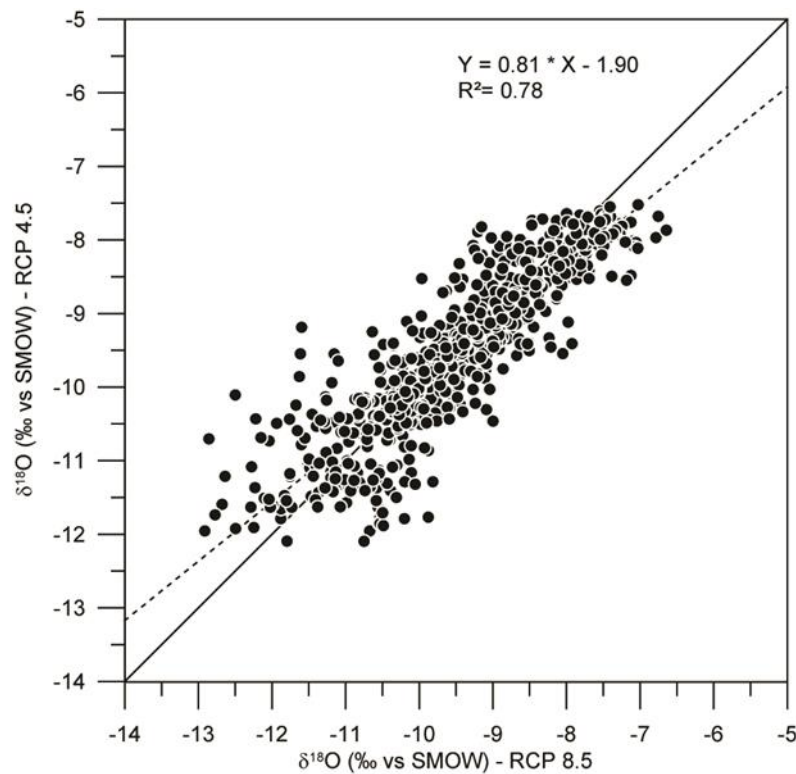
Fig. 6. Comparison between monthly results in δ^{18}O for both scenarios RCP 4.5 and 8.5 for the 2010-2071 period.

3.2. Annual evolution of lake geochemistry

3.2.1. Isotopic signature evolution

The model was run for the ten study lakes, including Lake Lacasse (Table 1 for main lake characteristics). Figure 7 illustrates differences in δ^{18}O in the reference period compared to the future period for lakes which have a range of G-indices (see Arnoux et al. 2017a for more details about lakes measured values). It can be observed that, if the recharge is set as constant from 2010 to 2071 (NC recharge scenario), there is no significant difference between the reference and future period (Fig. 7), although evaporation shows a significant increase with time. The lack of a trend is probably mitigated by concurrent shifts in precipitation (Fig. 2). Without considering changes in groundwater inflow, it appears that lake isotopic composition will be at least as much impacted by changes in precipitation as by changes in evaporation.

Fig. 7 illustrates that the range of lake isotopic composition variation depends significantly on climate conditions, lake volumes, and their associated G-indices. It can be observed that lakes with a low G-index and a small volume have higher potential variability in isotopic composition regarding climatic variations than those with a high G-index and high volume. For example, for two lakes with a similar mean G-index, such as Lake Ludovic (SAG; G-index=51%) and Lake Lacroix (OUT; G-

481   index=53%), the former is expected to have a greater spread in isotopic compositions than the latter,

482   even though the SAG region will likely undergo less evaporation increase compared with the OUT

483   region (Fig. 2). This difference is due to the lower volume of Lake Ludovic (V=400000 m^3), compared

484   with Lake Lacroix (V=1080000 m^3; Table 1). In addition, when lakes have a high G-index, the

485   groundwater flux tends to buffer lake isotopic variations, and so they tend to be less sensitive to

486   changes in climate data. The dominant control on lake isotopic variability therefore appears to be the G-

487   index. Another example is Lake Lanthier, which has a smaller volume (V=125000 m^3) and a higher G-

488   index (G-index=94%), and therefore shows a limited range of isotopic variation compared with Lake

489   Lacroix, although both are located in the OUT region (Fig. 7).

490   If a changing recharge scenario is applied, a decreasing trend in lake isotopic composition is

491   clearly observed (Fig. 7). However, it is also shown that lakes are sensitive to large changes in annual

492   recharge (+45%), but the differences are not significant if a smaller change (+14%) occurs. Moreover,

493   as the percentage of recharge change applied in the model is the same for all lakes, it can be observed

494   that the trend intensity will depend on four main parameters: lake catchment size (which controls the

495   intensity of the flux change), the region (which underlies climate condition), lake volume (which impacts

496   the range of variation), and the G-index. However, a relationship is only found with the latter.

497   Figure 8 illustrates variations in mean lake δ^{18}O versus G-index in both reference and future

498   periods. As shown, lake isotopic composition is more sensitive to changes in recharge for G-indices

499   ranging from 50 to 80%, with a maximum of sensitivity observed for a G-index of around 65 %. It can

500   also be observed that RCP 8.5 predicts a more depleted isotopic composition than does RCP 4.5. This

501   implies that for the same recharge scenario, variations in precipitation and melt period (duration and

502   time in the year) may impact the lake isotopic evolution more than precipitation. Finally, the polynomial

503   relationship between the two variables in Fig. 8 highlights that the G-index drives the response of lake

504   isotopic composition to changes in recharge.

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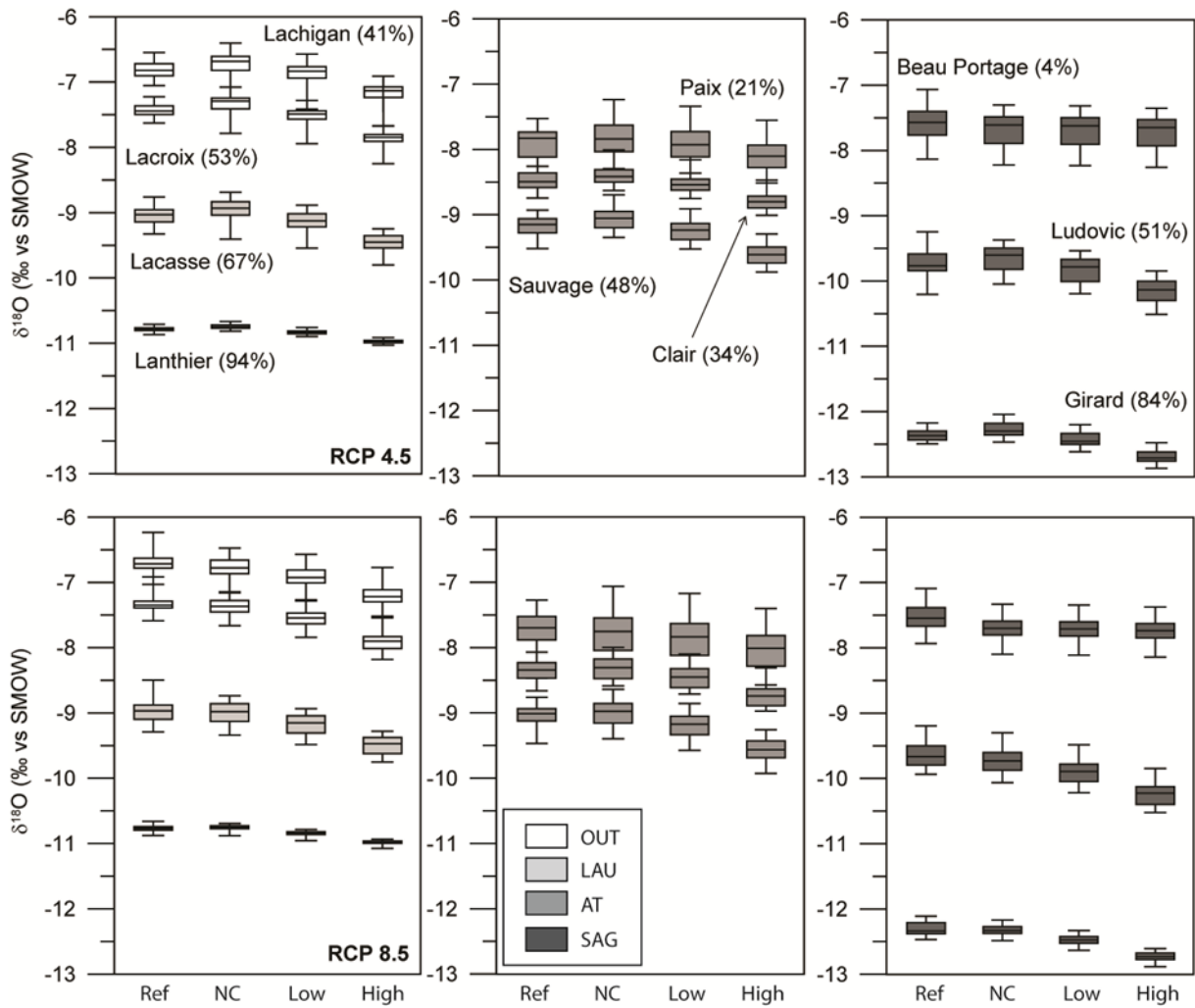
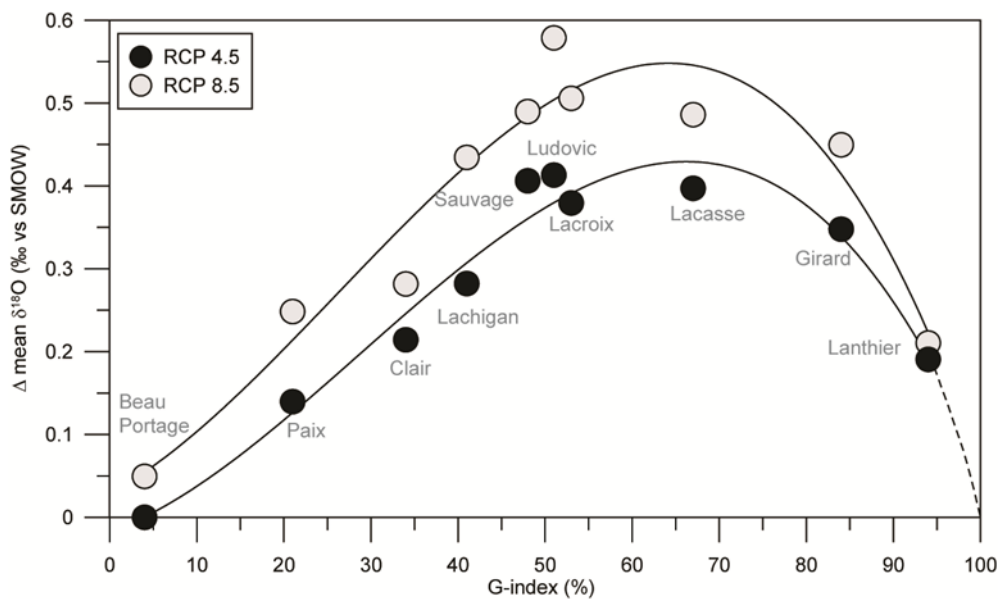

508
509 Fig. 7. Reference period (Ref; 2010-2040) lake δ18O composition and that corresponding to three different future period (2041-2071)
510 recharge scenarios: no change (NC), +14% (Low), and +45% (High), for RCP 4.5 (top) and RCP 8.5 (bottom) scenarios. The values in
511 brackets correspond to the mean G-index (percentage of groundwater flow in the total inflow) for each lake calculated for the reference
512 period; left panels show OUT and LAU regions, middle panels AT and rights panels SAG; bow-whiskers describe median, first and third
513 quartiles and maximum and minimum values.

514
515 Fig. 8. Differences between mean lake δ18O in the reference period (2010-2040) and future period (2041-2071), for the higher recharge
516 change scenario, versus lake G-indices. RCP 4.5 (black dots) and 8.5 (grey dots) scenarios are represented.

517   3.2.2.Lake quality evolution

518   As it has been shown previously, isotopic composition can be sensitive to future change in

519 recharge. This part is now a discussion about how lake water quality could be impacted by future

520 changes in recharge depending on lake location. In the study regions, one of the principal concerns

521 about lake water quality, today and in future, is to prevent blue-green algae blooms in limiting P loads to

522 lakes. This study does not take into account several parameters that can impact blue-green algae

523 blooms in lakes, such as the lake water biogeochemistry, chemical threshold processes, thermal/oxygen

524 stratification and the warming of the water column. The purpose here is to show in which case, lakes

525 could be under risk of too high P loading, and therefore at risk of a decrease in their quality, depending

526 on their catchment evolution as a function of recharge and population evolution. In such cases it will be

527 important to prevent P loads and therefore changes on the lake catchment.

528   Turning to the predictions of population growth summarized in Table 3, population is predicted

529 to increase mainly in the southern regions, OUT and LAU, with a mean increase of 24 and 28% by 2036

530 respectively (ISQ, 2014). Assuming an identical per capita P load, total P load in groundwater

531 originating from waste water should increase by the same percentage.

532   Domestic sewage is the main contribution of anthropogenic sources to the total P load for most

533 of Canadian lakes (Dillon and Evans, 1993; Paterson et al., 2006). The total P load from sewage

534 systems is a function of (i) the population and (ii) the annual P consumption per capita (Paterson et al.,

535 2006). As done by Paterson et al. (2006), assuming an effluent concentration of 9 mg.L^{-1} (considering

536 reductions in the phosphate content of detergents) and a daily water usage of 200 L.capita^{-1}.day^{-1}, the P

537 contribution is estimated to be 0.66 kg.capita^{-1}.yr^{-1}. Investigated lakes in the OUT and LAU regions

538 collect sewage from 4 (Lake Lachigan), 53 (Lake Lanthier), 117 (Lake Lacroix), and 17 houses (Lake

539 Lacasse) within their catchments respectively. If two habitants per house are assumed, P loading to

540 groundwater will be increased from 1 to 39 kg.yr^{-1} in the studied lakes in these areas.

541   The impact of this P load increase on lakes can then roughly be estimated based on the ratio of

542 change in annual P load versus change in annual recharge, as illustrated in Fig. 9. For an increase in

543 recharge, if $\Delta_P/\Delta_R<1$, the change in recharge over the catchment, and thus the evolution of the

544 groundwater inflow to the lakes, will greater than the P variation. In such a case, the lake water quality

545 may not be impacted by this P variation. On the other hand, if $\Delta_P/\Delta_R>1$, the lake water quality will be

546 impacted, and precaution should be taken to minimize the risk of blue-green algae blooms and

547 consequent eutrophication. For the study regions (Fig. 9), if recharge increases 14% by 2036, as

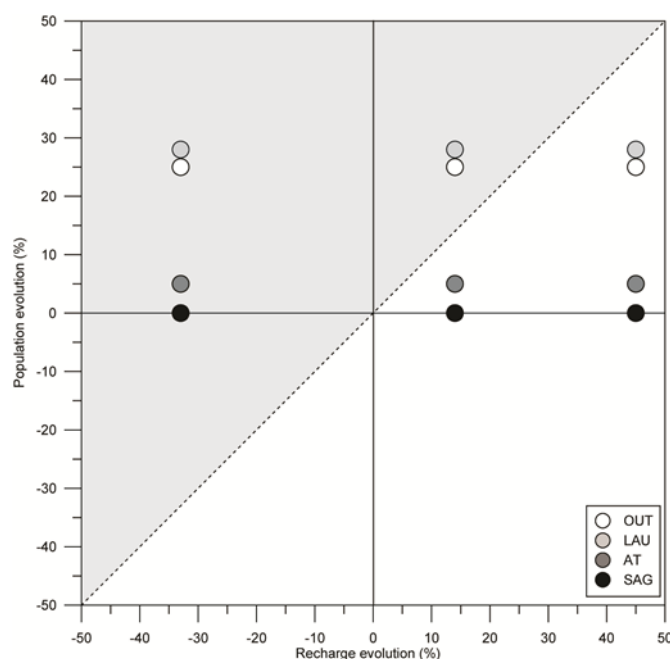
548 estimated by Rivard et al., 2014, lakes in the LAU and OUT areas will experience a decrease in their

549 water quality. However, if the recharge change is closer to +45% (Rivard et al., 2014), lake water quality

550 should not be worse than today, providing all other things remain equal and assuming the population

551 growth forecasts are accurate.

552

553

554 Fig. 9. Population growth predictions versus changes in recharge. The shaded area represents the scenarios for which lakes may be under
555 risk of too high P loading, and therefore at risk of a decrease in water quality. Dots represent lakes in the four study areas for three
556 recharge scenarios.

557 ## 4. CONCLUSION

558   The main objectives of this study were to determine how future trends groundwater recharge

559 can affect lake geochemistry, and to assess whether stable isotopes might be an effective tool for

560 identifying lakes that are susceptible to change, or are undergoing changes, in their water budget and

561 quality.

562   Firstly, climate predictions from both RCPs 4.5 and 8.5 scenarios and their impacts on future

563 lake isotopic composition have been considered. By 2050, temperature and evaporation are expected to

564 increase, and precipitation to exhibit a slightly increasing trend, all trends being more intense under the

565 RCP 8.5 scenario. On a monthly time step, it has been highlighted that future lake isotopic signatures

566 will be more depleted with respect to the reference period, mainly in March and February, because of an

567 earlier melt period. In the summer, lake isotopic composition will be more enriched, mainly in August,

568 due to the higher evaporation rate expected. However, future variations with respect to the reference

569 period are smaller in the summer than in the winter. Scenario RCP 8.5 induces more intense monthly

570 variations, but no significant difference in future lake isotopic signatures is observed on a yearly time

571 step between the two scenarios. This means that enrichment caused by increased evaporation

572 compensates for depletion induced by precipitation variation. It is therefore unclear whether lakes will be

573 impacted more by increased evaporation or precipitation changes. Caution is therefore recommended in

574 the interpretation of isotopic trends in lakes where background knowledge – for at least one year – of

575 their isotopic composition evolution with respect to weather data and their hydrologic balance is lacking.

576   It has then been demonstrated that future lake isotopic composition will also depend on

577 recharge fluctuations, in addition to climate conditions. On a monthly basis, the highest impact of

578 recharge evolution on future lake isotopic composition will be in February. Moreover, if recharge

579 decreases during the summer, the main difference will be observed at the end of the summer, after the

580 evaporation period and before recharge stops decreasing, in September or October. Therefore, to

581 clearly identify future changes in recharge through the lake isotopic signature evolution, sampling only at

582 the end of February and in September or October will provide information on the greatest changes for

583 the winter and summer periods respectively.

584   On an annual time step, modelled evolutions of lake isotopic composition can clearly be

585 sensitive to both +45% and +14% changes in recharge, less so, nevertheless, to the latter. The intensity

586 of the future trend of lake isotopic composition will depend on four main parameters: lake catchment

587 (which controls the intensity of the flux change), the region (which drives climate conditions), lake

588 volume (which impacts the range of variation), and the G-index (which is the dominant control on water

589 balance conditions). Based on these model simulations, stable isotopes appear to be especially useful

590 for detecting changes in recharge to lakes with a G-index of between 50% and 80%.

591   It is important to keep in mind that if both a winter increase and summer decrease in recharge

592 occur during the same year, the trend in mean annual lake isotopic composition will be nullified,

593 because seasonal variation is impacted it in opposing directions, cancelling out the signal at the yearly

594 time step. Consequently, if no clear annual trend is observed, it does not mean that recharge is not

595 changing. Nevertheless, mean annual lake isotopic compositions will be observed to be impacted by

596 recharge evolution only if it evolves in the same way throughout the year for the most part (i.e.,

597 consistently decreasing or increasing). In light of these results, it is a monthly time step is strongly

598 suggested in such investigations, since seasonal recharge fluctuations can be cancelled out in the

599 yearly signal. Moreover, it is important to note that runoff has been considered negligible for our studied

600 lakes but can be important for other lakes and, in these cases, this model could underestimated the

601 effect of spring melt on future lake isotopic composition.

602   It is also shown that changes in water quality in groundwater-connected lakes depend

603 substantially on lake location and on the intensity of recharge change. For the studied lakes, in the case

604 of a +14% recharge increase by 2036, lakes in LAU and OUT regions may experience altered water

605 quality (driven by phosphorous loading), but no change is expected in the case of a +45% recharge

606 intensification. If the percentage of recharge increase is at least equal to the percentage of population

607 growth around the lake, lake quality should not become degraded, but if not, recharge evolution should
608 be considered in lake management. Lakes water quality in the SAG and AT areas may not decrease
609 when considering population growth predictions. However, this study does not take into account several
610 parameters that can impact blue-green algae blooms in lakes, such as the lake water residence time,
611 chemical threshold processes, and the warming of the water column (Planas and Paquet, 2016).

612   Finally, even if small groundwater-fed lakes will be sensitive to climate, and especially to
613 recharge and anthropogenic changes, it is still difficult to predict how their geochemistry will be
614 impacted, as it is very reactive to each slight variation in water balance parameters. However, more
615 indicators are now available to predict lake geochemistry evolution, mainly depending on their location
616 and their G-index. To go further, a recharge model adapted to lake catchments and coupled with melt
617 dynamics, closely dependent on climate forecasts, could provide more details on lake geochemical
618 evolution, for more sustainable lake management.

619 ## 5. ACKNOWLEDGMENTS

620   We thank all participants of this project which is part of a P.h.D. project founded by University
621 Paris-Saclay/Paris-Sud and Florent Barbecot's research founding (CRSNG and FQRNT). We thank all
622 participants of the field campaigns, Viorel Horoi and students for their help on the field, the GRIL team
623 for their logistical support and people living around the study lakes for their welcoming and support. We
624 thank the team of Laxmi Sushama for their help with climate data. Comments of the editor and two
625 anonymous referees have helped to improve this review and we gratefully acknowledge them.

626

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782   Table 1. Main lake characteristics

Region	ID	Lake name	Lake surface area	Lake volume	Catchment Area
			10^3 m²	10^3 m³	10^3 m²
AT	1	Clair	115	695	2646
AT	2	Paix	41	97	796
AT	3	Sauvage	44	142	89
OUT	4	Lachigan	33	142	336
OUT	5	Lacroix	236	1080	772
OUT	6	Lanthier	25	125	1134
LAU	7	Lacasse	27	67	148
SAG	8	Beau Portage	42	271	364
SAG	9	Girard	67	679	211
SAG	10	Ludovic	94	400	1829

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785   Table 2. Mean isotopic composition of groundwater obtained for the four regions; in ‰ vs VSMOW.

Region	$\delta^{18}O$	δ^2H
AT	-14.00	-101.3
OUT	-11.56	-81.6
LAU	-11.71	-80.9
SAG	-14.06	-103.1

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788 Table 3. Predicted population growth in the different study regions in 2036 relative to 2011 numbers, according to three different scenarios
789 (ISQ, 2014)

Region	Scenarios		
	Reference (%)	Low (%)	High (%)
OUT	24	13	36
AT	5	0	10
LAU	28	21	34
SAG	0	-4	4

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