UNIVERSITÉ DU QUÉBEC À MONTRÉAL

QUANTIFYING THE GROUNDWATER CONTRIBUTION TO A CANADIAN SHIELD LAKE AND ITS HYDROLOGICAL RESILIENCE UNDER CHANGING CLIMATIC CONDITIONS (QUEBEC, CANADA)

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QUANTIFIER LA CONTRIBUTION EN EAU SOUTERRAINE À UN LAC DU BOUCLIER CANADIEN ET SA RÉSILIENCE HYDROLOGIQUE EN CONDITIONS CLIMATIQUES CHANGEANTES (QUÉBEC, CANADA)

THÈSE

PRÉSENTÉE

COMME EXIGENCE PARTIELLE

DU DOCTORAT EN SCIENCES DE LA TERRE ET DE L'ATMOSPHÈRE

PAR

JAMES HARRIS

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LIST OF SYMBOLS AND ABBREVIATIONS

AET	Actual evapotranspiration
AI	Aridity index
ANN	Artificial neural network
CMIP5	5th phase of the Coupled Model Intercomparison Project
DSWL	Depth to static water level
E	Lake evaporation
EI	Evaporative index
FUT1	Future period 1 (2041-2070)
FUT2	Future period 2 (2071-2100)
GCM	Global climate model
GW_{In}	Groundwater inflow to the lake
GW_{Net}	Net lacustrine groundwater
GW_{Out}	Lake water outflow to the aquifer
HB	HydroBudget
K	Hydraulic conductivity
KGE	Kling-Gupta efficiency
MAE	Mean absolute error
masl	Meters above sea level
ML	Machine learning
NSE	Nash-Sutcliff efficiency
OBS	Observation period (2016-2022)
P	Precipitation
PET	Potential evapotranspiration
PGWR	Potential groundwater recharge
Q	Discharge
Q_{Base}	Baseflow
R	Runoff
RCN	Runoff curve number
RCP	Representative concentration pathway
REF	Reference period (1981-2010)
VI	Vertical inflow
WY	Water year
ΔS	Change in lake storage
ω	Budyko Tixeront-Fu parameter

RÉSUMÉ

Les interactions entre les lacs et les eaux souterraines peuvent être importantes en fonction des contextes hydrogéologiques et climatiques, mais ces interactions n'ont été étudiées que pour un nombre relativement restreint de lacs à travers le monde. L'absence d'observations à long terme entrave les efforts visant à quantifier le rôle des eaux souterraines dans le maintien des bilans hydriques des lacs, ce qui représente un défi majeur pour la gestion de ces ressources sous les pressions croissantes du développement humain et des conditions climatiques futures incertaines. Le but de cette thèse était d'étudier comment des méthodes accessibles peuvent être mises en œuvre pour quantifier la contribution des eaux souterraines à un lac de drainage boréal de taille moyenne dans un contexte de données disponibles limitées. Les objectifs spécifiques de la thèse étaient 1) d'estimer l'écoulement des eaux souterraines dans un lac du Québec méridional où les données sont limitées, en utilisant une approche du bilan hydrique contrainte par le cadre de Budyko, 2) d'évaluer l'impact du changement climatique sur le bilan hydrique des lacs dans les climats froids et humides, et 3) de comprendre les seuils de résilience hydrologique de ces lacs lorsqu'ils sont exposés à des changements climatiques extrêmes. Le lac Papineau de 13 km^2 situé sur le Bouclier canadien, à mi-chemin entre Ottawa et Montréal dans le sud du Québec, a servi d'étude de cas.

La contribution nette à long terme des eaux souterraines lacustres au lac Papineau a été quantifiée dans le deuxième chapitre de cette thèse comme le résidu d'un bilan hydrique classique du lac, dans lequel les apports (ruissellement, débit de base, et précipitations) sont équilibrés par les flux sortants (évaporation et décharge). Les composantes du bilan ont été estimées à l'aide d'un modèle de bilan hydrique du bassin versant, en conjonction avec le cadre de Budyko, afin de limiter la répartition des précipitations disponibles entre la décharge et l'évapotranspiration réelle. En raison du nombre limité d'observations sur la décharge du lac (six ans), l'utilité d'intégrer les conditions hydrométriques passées reconstituées par apprentissage automatique dans la caractérisation des apports d'eau souterraine lacustre à long terme a été étudiée. Ce chapitre a mis en évidence la contribution non négligeable des eaux souterraines lacustres (4-7% des apports totaux) dans le maintien des bilans hydriques des lacs boréaux, tout en reconnaissant les incertitudes liées aux méthodes utilisées.

Les eaux souterraines lacustres entrantes et sortantes ont été quantifiés à l'aide d'un modèle numérique d'écoulement souterrain Modflow plus robuste sur le plan hydrogéologique dans le troisième chapitre. Calibré à partir des observations hydrométriques et piézométriques, le modèle a permis de caractériser les apports saisonniers à long terme des eaux souterraines lacustres, qui étaient autrement très incertains à l'aide de la méthode du bilan hydrique résiduel. Les résultats sont largement conformes à l'estimation annuelle à long terme dérivée de la technique du bilan résiduel et soulignent l'importance des eaux souterraines lacustres dans le maintien des apports estivaux aux lacs lorsque la contribution des eaux souterraines de base diminue et que l'évaporation est plus importante. La simulation des impacts futurs d'un ensemble de 12 scénarios de changement climatique CMIP5, forcés par les scénarios d'émissions RCP4.5 et RCP8.5, a révélé la résilience hydrologique relative du lac Papineau, en l'absence de répartition entre les apports et les écoulements constitutifs. Les résultats montrent que ni les apports des eaux souterraines lacustres ni ceux du débit de base ne seraient modifiés de manière significative dans le futur. La capacité tampon des eaux souterraines lacustres estivales, démontrée dans les conditions observées, semble être maintenue dans les conditions futures testées. Ces résultats soulignent le rôle important des eaux souterraines lacustres dans l'atténuation des effets du changement climatique sur l'hydrologie des lacs dans les climats froids et humides.

Le chapitre quatre de cette thèse a examiné dans quelles conditions climatiques cette résilience pourrait être dépassée. L'hydrologie du lac Papineau a été simulée à l'aide du modèle développé au chapitre deux, cette fois avec des forçages perturbés pour chaque membre de l'ensemble CMIP5 (augmentation de la température et augmentation et diminution des précipitations). La résilience hydrologique du bassin versant et du bilan hydrique du lac a été évaluée à l'aide du cadre Budyko pour décrire les changements à long terme des indices d'évaporation et d'aridité. Les seuils de changement climatique à partir desquels l'hydrologie du lac Papineau pourrait basculer d'un bassin versant où la décharge domine à long terme vers un bassin versant dominé par l'évapotranspiration ont été identifiés. Les eaux souterraines lacustres se sont à nouveau révélées contribuer de manière importante au lac Papineau, compensant ainsi la réduction des autres apports. Avec des conditions climatiques perturbées induisant des transitions vers un régime hydrologique du bassin versant dominé par l'évapotranspiration, les eaux souterraines lacustres permettent d'atténuer la sévérité de ces effets sur le bilan hydrique du lac Papineau. Ces résultats confirment le rôle des eaux souterraines lacustres dans l'atténuation des impacts du changement climatique futur et le maintien de certains aspects de la résilience hydrologique des lacs dans les climats froids et humides.

Cette thèse a permis d’évaluer l'importance des eaux souterraines lacustres dans le bilan hydrique des lacs boréaux, renforçant ainsi l'argument selon lequel cette contribution, souvent considérée comme négligeable, doit être prise en compte dans la caractérisation de l'hydrologie des lacs. Les résultats montrent que les eaux souterraines lacustres compensent la diminution saisonnière des apports d'eau dans les conditions climatiques actuelles et futures, contribuant ainsi à la résilience hydrologique du lac Papineau. Cette composante pourrait en outre atténuer les effets d'un changement climatique encore plus extrême sur l'hydrologie des lacs dans les climats froids et humides. Bien que cette recherche ait démontré l'utilité du cadre de Budyko pour limiter la répartition des flux sortants des bassins versants, des estimations plus fiables de l'évapotranspiration permettraient de mieux définir les seuils régissant la résilience hydrologique des lacs au changement climatique. Ce travail a également démontré l'efficacité de méthodes accessibles pour fournir une estimation du rôle non négligeable et saisonnier des eaux souterraines lacustres dans le bilan hydrique des lacs, qui peuvent être appliquées dans des contextes où les données d'observation sont également limitées. À ce titre, cette thèse souligne la nécessité pour les gestionnaires de l'eau de protéger les caractéristiques du paysage qui contribuent à la recharge des eaux souterraines et de prendre en compte les impacts potentiels du développement humain sur les interactions entre les lacs et les eaux souterraines.

Mots clés : lac; eaux souterraines; bilan hydrique lacustre; modèle numérique ; apprentissage automatique ; Budyko ; changement climatique ; Québec (Canada)

ABSTRACT

Lake-groundwater interactions can be important depending on hydrogeological and climatic contexts, yet these interactions have been investigated for relatively few lakes around the world. The absence of long-term observations hampers efforts to quantify the role of groundwater in sustaining lake water budgets, presenting a major challenge for the management of these resources under the increasing pressures of human development and changing climate conditions. The goal of this Ph.D. was to investigate how accessible methods can be implemented for quantifying the groundwater contribution to a moderate-sized boreal drainage lake where available data are limited. The specific objectives of the thesis were 1) to estimate groundwater flow into a southern boreal lake with limited available monitoring data, using a water budget approach constrained by the Budyko framework, 2) to assess the impact of climate change on the water budget of lakes in cold and humid climates, and 3) to understand the thresholds of hydrological resilience of a southern boreal lake exposed to extreme climatic change. Lake Papineau, a 13 km^2 Canadian Shield lake situated in southern Quebec midway between Ottawa and Montreal, served as a case study.

The long-term net lacustrine groundwater contribution to Lake Papineau was quantified in the second chapter of this thesis as the residual of a classical lake water budget, wherein inflows (runoff, baseflow, and precipitation) are balanced against outflows (evaporation and discharge). Budget components were estimated using a catchment water budget model in conjunction with the Budyko theoretical framework for constraining the apportionment of available precipitation into catchment discharge and actual evapotranspiration. Owing to limited lake discharge observations (six years), the utility of integrating machine learning-reconstituted past hydrometric conditions in the characterization of long-term lacustrine groundwater contributions was investigated. This chapter highlighted the non-negligible contribution of lacustrine groundwater (4-7% of total inflows) in sustaining boreal lake water budgets, while acknowledging uncertainties related to the methods employed.

Lacustrine groundwater inflows and outflows were quantified using a more hydrogeologically-robust Modflow numerical groundwater flow model in the third chapter. Calibrated against observed hydrometric and piezometric head observations, the model allowed for the characterization of long-term seasonal lacustrine groundwater contributions that were otherwise highly uncertain using the residual lake water budget method. Results were largely consistent with the long-term annual estimate derived from the residual budget technique and point to the importance of lacustrine groundwater in sustaining summer lake inflows when the baseflow groundwater contribution is diminished and evaporation is more important. Simulating the future impacts of a 12-member CMIP5 climate change scenario ensemble, forced with RCP4.5 and RCP8.5 emissions scenarios, revealed the relative hydrological resilience of Lake Papineau, with the absence of reapportionment among constituent inflows and outflows. Neither lacustrine groundwater nor baseflow contributions would apparently be significantly modified in the future. The buffering capacity of summer lacustrine groundwater, demonstrated under observed conditions, apparently would be maintained under tested future conditions. These findings underscore the important role of lacustrine groundwater in mitigating the effects of climate change on the hydrology of lakes in cold and humid climates.

Chapter four of this thesis investigated under what climate conditions this resilience might be overcome. Lake Papineau hydrology was simulated with the same model as in chapter 2, this time with perturbed forcings for each CMIP5 ensemble member (increases in temperature and both increases and decreases in precipitation). Catchment and lake water budget hydrological resilience were evaluated using the Budyko framework for describing long-term shifts in evaporative and aridity indices. Climate change thresholds were identified whereby Lake Papineau hydrology could tip from a long-term discharge-dominant catchment release to evapotranspiration-dominant. Lacustrine groundwater was again shown to provide a sustained contribution to Lake Papineau, compensating for reductions in other inflows. With perturbed climate conditions inducing transitions toward a catchment hydrologic regime dominated by evapotranspiration, lacustrine groundwater was shown to mitigate the severity of these effects on the Lake Papineau water budget. These results confirm the role of lacustrine groundwater in lessening the impacts of future climate change and the maintenance of aspects of hydrological resilience for lakes in cold and humid climates.

This thesis provided new evidence for the importance of lacustrine groundwater in the water budgets of boreal lakes, bolstering the argument that this contribution, often assumed negligible, should be considered when characterizing lake hydrology. Lacustrine groundwater was shown to compensate for seasonally diminished inflows under current and future climatic conditions, reinforcing the hydrological resilience of Lake Papineau. This component may additionally attenuate the effects of even more extreme climate change on the hydrology of lakes in cold and humid climates. While this research demonstrated the usefulness of the Budyko framework in constraining the apportionment of catchment outflows, more robust evapotranspiration estimates would assist in better defining thresholds governing lake hydrological resilience to climate change. This work demonstrated the effectiveness of accessible methods in estimating a non-negligible and seasonally important role of lacustrine groundwater in lake water budgets that can be applied in contexts where observation data are similarly limited. As such, this thesis underscores the need for water managers to protect landscape features that contribute to groundwater recharge and to consider the potential impacts of human development on lake-groundwater interactions.

Keywords: lake; groundwater; lake water budget; numerical model; machine learning; Budyko; climate change; Quebec (Canada)

CHAPTER 1

INTRODUCTION

1.1 General context

Lakes abound around the world, collectively representing 87% of available global freshwater storage (Yao et al., 2023). They are used as a water source (de Graaf et al., 2019; Masse-Dufresne et al., 2019), for hydropower (Aminjafari et al., 2024; Hogeboom et al., 2018), irrigation (Kuang et al., 2024; Wine & Laronne, 2020), and recreation (Dupont et al., 2023), and provide crucial habitats for myriad species (Briggs et al., 2018; Saccò et al., 2024). Lakes are a particularly prevalent feature of the Canadian landscape, notably within the context of the post-glacial fractured bedrock of the Canadian Shield (Lehner & Döll, 2004). Canada has the most lakes of any country (nearly 31% of the world total) and the province of Quebec alone, with nearly 200,000 lakes, is home to a fifth of the Canadian total both in number and surface area (Messager et al., 2016). Lake hydrology has been studied widely for many decades (Hayashi & van der Kamp, 2021; Irvine et al., 2024; Sophocleous, 2002; Winter, 1999), though relatively few lakes are monitored, and even fewer on a long-term basis (Huot et al., 2019). Lake hydrology, particularly in response to changing climate and anthropic pressures, is thus not well understood, posing challenges for management and protection.

Groundwater is an important component of the global water cycle (Condon et al., 2021; Gleeson et al., 2020), with baseflow (i.e., groundwater discharging to streams) constituting an estimated 59% of global river discharge (Xie et al., 2024) and sustaining headwater and nonperennial streams (Brinkerhoff et al., 2024; Winter, 2007). As lakes are often connected to their surrounding aquifers, groundwater and surface water interact to such a close degree that they are considered a single resource (Winter et al., 1998). Groundwater sustains groundwater-dependent ecosystems (McLaughlin et al., 2017; Stelzer et al., 2022), particularly in regions with a high density of lakes and wetlands (e.g., the Boreal Shield and Prairie-Pothole Region of Canada) (Hayashi et al., 2016; Smerdon et al., 2012). Elsewhere, groundwater can be an important vector for nutrients, potentially inducing lake eutrophication (Brookfield et al., 2021; Danielescu et al., 2021; Kazmierczak et al., 2020). Despite their close interaction, groundwater exchanges between aquifers and lakes are difficult to quantify due to high spatial and temporal heterogeneity and lakebed inaccessibility for instrumentation (to name but a few challenges). As such, these exchanges are often overlooked in lake studies (Rosenberry et al., 2015). This lack of understanding, however, poses potentially significant risks to the ecological health of lakes (Safaie et al., 2021), their associated ecosystems (Bertrand et al., 2012), and to their role as critical water resources, particularly under the compounding pressures of increased human development (Bierkens & Wada, 2019; Cooley et al., 2021; Döll et al., 2012; Lahens et al., 2024) and climate change (Kløve et al., 2014; Larocque et al., 2019). The concept of hydrological resilience, or the ability to maintain hydrological function while exposed to a perturbation (Lane et al., 2023; Newton & Spence, 2023), is a useful means by which to comprehend the sensitivity of a lake to external pressures and inform efforts to mitigate them. By extension, how groundwater, specifically, can mitigate the impacts of these pressures (i.e. *hydrogeological resilience*) is becoming a topic of increasing interest (Meyers et al., 2021; Santoni et al., 2021).

The direct contribution of groundwater to lakes from their surrounding aquifers, termed lacustrine groundwater, can be quantified by numerous methods (Ma et al., 2024). These methods range from lake water budgets, where groundwater is considered the residual of a balance between more readily estimated inflows and outflows (e.g., discharge, evaporation, precipitation, and runoff) (Trask et al., 2017), to complex numerical modeling of groundwater fluxes (Ntona et al., 2022). These techniques are complemented by observations derived from diverse field-based measurements such as tracers (e.g., chloride, radioactive isotopes, temperature, and stable water isotopes), seepage meters, and Darcy flows (Gibson et al., 2016; Gleeson et al., 2009; Rosenberry et al., 2020; Sukanya et al., 2022; Tecklenburg & Blume, 2017). All methods can present important sources of uncertainty. Furthermore, the temporal and spatial representativeness of field-based measurements and their ability to upscale to whole-lake or long-term conditions are often identified as major limitations to lake-aquifer studies (Petermann et al., 2018).

Owing to the diversity of climatic, hydrological, and hydrogeological contexts of lakes globally, lake-groundwater exchanges are equally varied, making general characterizations about the contributions of groundwater difficult to conclude. Within the context of cold and humid environments, relatively few studies have investigated long-term groundwater contributions to lake water budgets. Arnoux et al. (2017) quantified groundwater contributions to kettle lakes (i.e., small lakes lacking permanent runoff, affluents, and tributaries) in southern Quebec using natural tracers, yet only for one year. Gleeson et al. (2009) similarly used natural tracers to estimate groundwater contributions to several lakes in Ontario, yet only for one summer and assumed results to be representative of steady-state conditions (i.e., mean interannual conditions for a given period). Indeed, most studies quantifying groundwater contributions to lakes in cold and humid climates, including those making use of numerical modeling, only do so under steady-state conditions, failing to account for interannual and intra-annual variability. In climatic contexts where winter exerts an impactful seasonal imprint, leading to humid spring and fall conditions separated by warm and dry summers, this is a severe limitation to better understanding lake-groundwater interactions.

Long-term observations are critical to quantifying lake water budgets, with any type of approach, and to defining the range of variability characteristic of natural conditions. These data are also necessary to understand under what conditions lakes maintain their hydrological resilience. Long-term hydrological observations from experimental watersheds are relatively rare (Tetzlaff et al., 2017), with long-term lake surveillance sites rarer still, despite lakes playing a critical role as sentinels of climate change (Adrian et al., 2009; Williamson et al., 2009). Important examples of hydrological observatories where this type of lake monitoring occurs in cold and humid climates include the Turkey Lakes Watershed (TLW; Webster et al., 2021), Canada's Experimental Lakes Area (IISD-ELA; Higgins et al., 2021), and the North Temperate Lakes Long Term Ecological Research site (NTL-LTER; Jones et al., 2012). These sites include monitoring of lake stages and flowrates of lake affluents and effluents. Elsewhere, these measured data are rarely available. As such, alternative methods, based on machine learning techniques, are increasingly employed to reconstitute long-term past hydrological conditions through regionalization (Lachance-Cloutier et al., 2017), but their use requires regional hydrometric datasets for model training. Hydrogeological monitoring networks, which also provide crucial data to study lake-aquifer interactions, are also rare and sparsely distributed, most often not in conjunction with monitored lakes. In the province of Quebec, for example, the provincial government is now operating a network of approximately 260 observation wells, a relatively small number given the territory covered (MELCCFP, 2020).

Within this context of often limited available data for characterizing long-term conditions, relatively accessible approaches to estimating the groundwater contribution to lakes offer a pragmatic solution. A lake water budget, wherein lacustrine groundwater is solved as the residual of a balance between more readily available inflows and outflows (namely precipitation, runoff, baseflow, evaporation, and discharge), can offer insights into the importance of this contribution, but only if all other components can be estimated to some degree of certainty. As such, the appropriate partitioning of available water at the catchment-scale into discharge and actual evapotranspiration (AET), using a framework such as that developed by Budyko (1974), is of critical importance. Using a catchment water budget model in conjunction with the Budyko framework would allow discharge and its runoff and baseflow constituents to be used in quantifying the groundwater contribution to a lake either with the residual lake water budget technique or a more advanced approach, such as numerical groundwater flow modeling. In the case of the latter, additional observations, particularly of piezometric head, would be required to ensure accurate calibration of aquifer properties.

The impact of possible future climatic conditions on groundwater and surface water resources is generally evaluated using the outputs of global climate models (namely precipitation and temperature), forced with emissions scenarios such as the representative concentration pathways (RCPs) (van Vuuren et al., 2011) of the 5th phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012). These model outputs are further downscaled and bias-corrected against regional observations to ensure proper representation of conditions at the finer scales of surface water catchments. These future conditions are nevertheless highly uncertain, and the ranges of precipitation and temperature may be insufficient to induce a diverse array of possible responses in a hydrological system. As such, perturbing existing future CMIP conditions, through the delta change factor method, is a feasible alternative to provide insights into extreme future conditions.

Beyond assessing changes under a limited set of future climate scenarios, a central challenge in climate change hydrology lies in identifying the conditions under which hydrological systems transition from resilient to altered states. In lake catchments, this challenge is compounded by the interrelated responses of surface water and groundwater to changing precipitation and temperature regimes, including shifts in recharge timing, evapotranspiration demand, and the partitioning of water between runoff, baseflow, and subsurface storage. While ensemble-based climate projections provide valuable insight into likely future conditions, they do not explicitly resolve the sensitivity of lake-groundwater interactions to a broader range of climatic forcings, nor do they readily identify thresholds beyond which groundwater buffering capacity may be exceeded. Addressing these questions requires approaches capable of systematically exploring hydrological responses across a wide spectrum of temperature and precipitation changes. Within this context, evaluating the role of groundwater in sustaining lake hydrology under increasingly extreme climatic conditions is essential for improving understanding of hydrological resilience in cold and humid lake-rich regions.

1.2 Research objectives and hypotheses

The principal aim of this research was to investigate how accessible methods can be implemented to quantify the groundwater contribution to a moderate-sized boreal drainage lake within the context of limited available data. The specific objectives were as follows:

1) To estimate groundwater flow into a southern boreal lake with limited available monitoring data;
2) To assess the impact of climate change on the water budget of lakes in cold and humid climates;
3) To understand the thresholds of hydrological resilience of a southern boreal lake exposed to extreme climatic change.

The hypotheses underlying this research are that:

1) The Budyko theoretical framework can be implemented in the constraining of catchment inflows and outflows and the characterization of long-term hydroclimatic conditions;
2) Future climatic conditions from an ensemble of climate change scenarios will induce significant changes in all water budget components of lakes in cold and humid climates;
3) Certain climatic conditions constitute tipping points by which catchment hydrological character can be fundamentally altered and hydrological resilience overcome.

1.3 Overview of the study area

Lake Papineau is located in southern Quebec (Canada) and served as a case study for this Ph.D. The site is particularly well-suited for investigating lake-groundwater interactions as it is relatively shielded from human activities, within the protected and quasi-pristine Kenauk forest. Observations, consisting of short but high-quality time series, are thus nearly exclusively a reflection of climatic conditions, ideal for studying the impact of climate change on the groundwater contribution to the lake.

The Lake Papineau catchment (93.7 km^2) is located immediately north of the Outaouais (Ottawa) River midway between Ottawa and Montréal. The catchment is comprised almost entirely of forest, with limited human development owing to the administration of the territory by the Kenauk Institute and by the Nature Conservancy of Canada (MFFP, 2018). The remaining land cover consists of smaller lakes (4.8 km^2) and wetlands (8.9 km^2). Lake Papineau (13.1 km^2) is comprised of two elongated lobes, oriented north-south, with a mean depth of 20 m and estimated volume of 258 Mm^3. The lake receives both diffuse runoff and surface flow from a limited number of permanent affluents and is drained from its outlet. It has been instrumented since 2016 to quantify discharge.

The climate of the study area fits within the Köppen-Geiger classification of Dfb, characterized as cold and humid, with warm summers without a dry season (Kottek et al., 2006). Long-term (1981-2010) mean annual total precipitation is 1065 $mm.yr^{-1}$, with 23% occurring as snow between December and March. Mean annual air temperature ranges between 3.2°C and 6.5°C (mean 4.7°C), with mean monthly temperatures ranging from -11.9°C in January to 19.0°C in July. Using the Oudin et al. (2005) formula, mean annual potential evapotranspiration for this same period is 572 $mm.yr^{-1}$.

Geologically, the lake catchment is situated within the Grenville Province of the Canadian Shield, consisting of fractured crystalline bedrock with a mean ground surface slope gradient of 14°. This crystalline bedrock is composed of plutonic igneous and metamorphic rocks, which impart heterogeneous secondary porosity due to weathering and stress-induced fracturing (Rivera, 2014; Sterckx, 2013). Overlaying the bedrock is a layer of heterogeneous Quaternary sediments constituted primarily of glacial till (Daigneault et al., 2012; Montcoudiol et al., 2018).

Groundwater inside the study area circulates within the shallow, unconfined fractured bedrock aquifer, in close connection with the numerous lakes, wetlands, and other groundwater-dependent ecosystems found throughout the Kenauk forest. The Quebec groundwater knowledge acquisition initiative has produced two characterizations of regional hydrogeology (Comeau et al., 2013; Gagné et al., 2022). Furthermore, an investigation specifically into the groundwater contribution to Lake Papineau was previously undertaken by Lavoie Lavallée (2019), of which this research is a continuation, making use of instrumented sites (including the lake outlet, lake affluents, and several wells in proximity to Lake Papineau for monitoring piezometric heads), and elaborating upon key findings.

This research accompanies additional investigations within the Kenauk forest, encompassing subjects such as the role of groundwater in ephemeral pond hydrology (Bizhanimanzar et al., 2024; Roux et al., 2023) and groundwater microbiome connectivity (Villeneuve et al., 2022). Other studies, though not explicitly investigating groundwater, have explored the biodiversity of lake-edge wetlands and their resilience with respect to variations in Lake Papineau stage (Dubois et al., 2020; Loiselle et al., 2021; Loiselle et al., 2023).

1.4 Overview of the methods used

To attain the first specific objective (Chapter 2), a combination of methods was used. Observed (2016-2022) hydrologic conditions (i.e., lake stage and outlet discharge) for the study site were first characterized using rating curves constructed for the Lake Papineau outlet and its main affluents. Using these observations and a machine learning technique (artificial neural networks), making use of surrogate regional hydrometric data, long-term (30-year) lake discharge was reconstituted. A catchment water budget model (HydroBudget; Dubois et al., 2021), calibrated against observed discharge, was used in conjunction with the Budyko framework to constrain the allocation of available water into discharge and AET. HydroBudget outputs (runoff and baseflow) were then used along with all other lake water budget components (i.e., precipitation, evaporation, and discharge) to estimate lacustrine groundwater as the residual of the balance between lake inflows and outflows.

In Chapter 3, a Modflow-NWT groundwater flow model (Niswonger et al., 2011) was developed, making use of the LAK package (Merritt & Konikow, 2000). Calibrated runoff and groundwater recharge from Chapter 2 were used as inputs to simulate the lacustrine groundwater contribution to Lake Papineau under both observed, long-term past, and future climatic conditions. The model was calibrated against observed lake stage and discharge, affluent baseflows, and hydraulic heads from project-instrumented wells and a provincial database. Future temperature and precipitation forcings from an ensemble of CMIP5 scenarios, driven by greenhouse gas emissions scenarios RCP4.5 and RCP8.5, enabled a characterization of the hydrological resilience of the lake and the role played by lacustrine groundwater in buffering the effects of climate change.

Chapter 4 built on the results of the preceding chapters, aiming to better understand the hydrological resilience of the lake under more extreme future climatic conditions. The delta change factor method was implemented, whereby an array of precipitation increases and decreases, and temperature increases were applied directly to the CMIP5 ensemble members from Chapter 3. The catchment water budget model HydroBudget, implemented in Chapter 2, was used to estimate lake water budget variables under these climatic conditions and determine their impact on the lacustrine groundwater contribution. The Budyko framework was revisited to provide insight into how perturbed climatic conditions reallocate available water between discharge and AET and whether these conditions induced long-term shifts in lake hydrological regime.

1.5 Thesis organization

This thesis is organized into five chapters addressing three specific objectives. The present introduction (Chapter 1) is followed by three chapters (Chapters 2, 3, and 4) written in the form of manuscripts intended for submission to peer-reviewed journals, and a final chapter (Chapter 5) presenting the general conclusion.

Chapter 2 presents the article in preparation entitled "*Constraining groundwater flow to a medium-sized southern boreal lake with a lake water budget and the Budyko framework*", wherein the lacustrine groundwater contribution to Lake Papineau is estimated as the residual of a lake water budget. Novel aspects of this work include the constraint of estimated runoff to the lake using the Budyko theoretical framework and the evaluation of the appropriateness of machine-learning-reconstituted hydrological variables in characterizing long-term past conditions.

Chapter 3 presents the article in preparation entitled "*Simulated past and future groundwater flow contribution to lakes in cold and humid climates – The example of a Canadian Shield lake*". Here, a groundwater flow model is calibrated against observed hydrometric and piezometric data and used to evaluate the impact of an ensemble of future climate forcings on the water budget of Lake Papineau, notably its groundwater contribution. Principal insights afforded by this work include the role of lacustrine groundwater in both sustaining summer lake hydrology, under diminished baseflow contributions, and buffering the effects of future climate change.

Chapter 4 presents the article in preparation entitled "*Hydrological sensitivity of a Canadian Shield lake catchment to climate change threshold-mediated processes controlling lake resilience*". The level of hydrological resilience of Lake Papineau to extreme climatic change is evaluated using the catchment water budget model employed in Chapters 2 and 3 and perturbed CMIP5 climate forcings to examine the thresholds that control shifts in lake hydrological regime. Results of primary interest include the capacity of relatively modest conditions beyond those of CMIP5 ensemble members to tip the catchment into an alternate hydrological regime and the ability of lacustrine groundwater to stabilize lake hydrology under future forcings, even those representing extreme departures from observed conditions.

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CHAPTER 2

CONSTRAINING GROUNDWATER FLOW TO A MEDIUM-SIZED SOUTHERN BOREAL LAKE WITH A LAKE WATER BUDGET AND THE BUDYKO FRAMEWORK

2.1 Introduction

Groundwater has been shown to play an important role in lake hydrology in cold and humid climates (Leaf et al., 2020; Rosenberry et al., 2015; Stets et al., 2010), yet relatively few studies within the growing body of research concerning surface water-groundwater interactions have emphasized its contribution (Irvine et al., 2024). With increasing human demand for freshwater resources (Gleeson et al., 2020) and the potential stresses induced by climate change on lakes and their dependent ecosystems (Bertrand et al., 2012), understanding the degree to which groundwater sustains lake hydrology is of critical importance. Canada has the largest combined surface area of lakes of any country (> 30% of the world total), with the nearly 200,000 lakes within the province of Quebec constituting a fifth of the Canadian total, both in number and surface area (Messager et al., 2016). Despite being predominant landscape features, only a limited number of studies have characterized lake-groundwater interactions in southern Canada (e.g., Arnoux et al., 2017; Gleeson et al., 2009), owing primarily to the absence of long-term observations.

Quantifying lake-groundwater exchanges (inflows or outflows) at the lake scale is complicated by important spatial and temporal heterogeneities with which various field-based measurement techniques (e.g., radioactive and stable water isotopes, seepage meters, and Darcy flows) often struggle to contend (Gibson et al., 2016; Rosenberry et al., 2020; Sukanya et al., 2022). Of the many techniques available for quantifying lake-groundwater exchanges, a lake water budget can be implemented relatively easily (Trask et al., 2017; Wiebe et al., 2015). Accurate partitioning of catchment water budget components, notably runoff, actual evapotranspiration (AET), and inter-catchment groundwater exchanges remains challenging, however, due to limited observation data for constraining estimates (Levin et al., 2023).

In absence of local *in situ* measurements of AET at the catchment-scale, from methods such as eddy-covariance, the Bowen ratio energy balance, scintillometry, or weighing lysimetry (Wang & Dickinson, 2012), the Budyko theoretical framework (Budyko, 1974), relating the long-term partitioning of precipitation into the catchment release functions of discharge and AET, can be a useful tool (Gnann et al., 2023). It has been increasingly implemented in water budget modeling to assist in constraining evapotranspiration estimates (Greve et al., 2020; Liu et al., 2022; Nijzink et al., 2018). Integrating this framework into a catchment-scale water budget model would enable the key lake water budget components of runoff and baseflow to be estimated, in keeping with an appropriate separation of precipitation into catchment release functions. A lumped, conceptual water budget model, such as HELP (Schroeder et al., 1994) or HydroBudget (Dubois et al., 2021a) is ideally suited for this purpose, as generally fewer parameters require calibration, in contrast to semi-distributed (e.g., the Soil and Water Assessment Tool, SWAT model; Arnold et al., 2012) or fully-distributed hydrological models (e.g., the Variable Infiltration Capacity model, VIC model; Liang et al., 1994).

When hydrological observations are incomplete or of short duration, regionalization using artificial neural networks (ANN) has been employed extensively in the reconstitution and forecasting of hydrological variables (Beck et al., 2013; Maier et al., 2010; Piasecki et al., 2018; Tan et al., 2023). ANNs are a data-driven machine learning (ML) technique commonly employed for the extension of past discharge time series or for forecasting future discharge (Maier et al., 2010; Ozdemir et al., 2023; Razavi, 2021), lake levels (Li et al., 2024a, b), or groundwater levels (Wunsch et al., 2022), to name but a few variables of interest. ANNs have been implemented within the province of Quebec (Canada) for discharge forecasting (Boucher et al., 2010; Ouarda & Shu, 2009), reservoir inflow forecasting (Coulibaly et al., 2000), and for modeling groundwater dynamics (Adombi et al., 2022).

The objective of this chapter was to quantify the groundwater contribution to a medium-sized southern boreal lake (Lake Papineau in the Outaouais region of Quebec, Canada), using a lake water budget constrained by the Budyko framework. Long-term past lake stage and discharge were reconstituted using an ANN trained on a six-year observation period. A catchment water budget model, HydroBudget (HB; Dubois et al., 2021a), estimated runoff and baseflow to the lake, using the Budyko framework to constrain AET and discharge apportionment. With these variables and direct lake precipitation and evaporation, the net lacustrine groundwater contribution to the lake was estimated as the residual of the lake water budget. This study provides a blueprint for contending with the limitations of short observation time series and demonstrates the capability of accessible methods for quantifying lake-groundwater interactions.

2.2 Study area

2.2.1 Hydrography and land use

The Lake Papineau catchment (93.7 km^2) is located in the Outaouais region of southern Quebec (Canada), midway between Ottawa and Montreal on the north shore of the Outaouais (Ottawa) River (**Figure 2.1**). Situated within the traditional territory of the Omàmìwininìwag (Algonquin) and Anishinabewaki, the study catchment is largely protected (76% of the lake and 66% of its catchment) within the Kenauk forest, a private domain (258 km^2). 13% of the catchment is also protected from any further development through joint stewardship by the Kenauk Institute and the Nature Conservancy of Canada. The Rouge River and Petite Nation River border the study area.

Lake Papineau itself is an oligotrophic lake (i.e., a nutrient-poor, deep, and clear lake), with 13.1 km^2 of open water surface, constituting 14% of the catchment area. The lake is comprised of two elongated lobes oriented north-south, with a perimeter of 77.3 km (excluding the contribution of the numerous small islands which have a combined area of 1 km^2), and an estimated volume of 258 Mm^3 (mean depth 20 m, maximum 80 m; TrakMaps, 2003). Data from IceWatch (2022) shows that Lake Papineau is seasonally ice-covered, with a mean duration of 134 ± 17 days for the 2016-2022 period, beginning in late November to mid-December and lasting until mid-April to early-May. The lake is drained from its outlet located at the southernmost tip of the western lobe, giving rise to the Kinonge (Salmon) River, which flows 26 km before discharging into the Ottawa River.

Of the eleven sub-catchments draining into Lake Papineau having a surface area greater than 1 km^2, the Lake La Croix affluent (22.4 km^2) is the largest. Apart from Lake Papineau, the catchment encompasses numerous lakes (total 4.8 km^2) and wetlands (total 8.9 km^2), disseminated within the study area and along the shore of Lake Papineau. The remaining land cover (66.9 km^2) is comprised almost entirely of forest, dominated by maple (67%), hemlock (9%), birch (3%), and other deciduous species (21%), with only limited human development (MFFP, 2018).

2.2.2 Geology

The study site is situated within the Grenville Province of the Canadian Shield, constituting the exposed portion of the North American Craton or the Precambrian geological core of the continent (Rivera, 2014).

The lake catchment is characterized by an undulating, glacially sculpted topographical relief ranging from 173 to 444 masl (mean 235 masl), composed of plutonic igneous (granites) and metamorphic rocks (gneisses, paragneisses, marbles, and quartzites), with a mean slope of 14°. Overlaying this bedrock is a combination of Quaternary sediments consisting primarily of thin glacial till (0.3 – 1 m), resulting from bedrock abrasion during ice retreat following the last glacial period. Also present are fluvio-glacial and glaciomarine sediments produced by glacial melt and from the transgression and regression of the Champlain Sea (Daigneault et al., 2012; Montcoudiol et al., 2018).

2.2.3 Hydrogeology

Groundwater circulates within the fractured crystalline bedrock of the Canadian Shield, which has negligible primary porosity, yet important secondary porosity imparted by weathering and stress-induced fracturing in the upper 50-60 m (Sterckx, 2013). The low permeability regional bedrock aquifer is characterized by a shallow water table generally closely connected to lakes, wetlands, and streams (Fan et al., 2013; Jasechko et al., 2021). Regional hydrogeology has been characterized through two projects from the long-term Quebec groundwater knowledge acquisition initiative (Comeau et al., 2013; Gagné et al., 2022). From these studies, groundwater recharge estimates ranged between 200 and 300 $mm.yr^{-1}$ in the region of the Lake Papineau watershed. The groundwater contribution to Lake Papineau has previously been estimated to be approximately 19% of all lake budget inflows by Lavoie Lavallée (2019), using a combination of methods (Darcy calculation, seepage meters, and potentiomanometers), but this value was considered highly uncertain.

2.2.4 Meteorological conditions

Daily precipitation (total) and temperature (minimum and maximum) data were available from a provincial spatially interpolated 0.1°-resolution gridded dataset (Bergeron, 2016). An on-site meteorological station (Kenauk station; *Campbell Scientific*) located approximately 5 km south of the Lake Papineau outlet provided hourly data between 2016 and 2022 (hereafter the OBS period). Missing data from the meteorological station were gap-filled with the proximate, provincially-operated weather stations Notre-Dame-de-la-Paix (station ID 7035666; 12 km from the Kenauk station), Chénéville (station ID 7031375; 28 km), and Arundel (station ID 7030310; 29 km), using a multiple linear regression model in the *Ground-Water Hydrograph Analysis Toolbox* (*GWHAT*; Gosselin, 2016).

All hydrometeorological variables were reasoned on a water year (WY) basis, spanning October 1st of a given year to September 30th of the subsequent year (e.g., WY 2016-17). Long-term (1981-2010) climatic conditions (hereafter the REF period) were characterized by mean total precipitation of 1065 $mm.yr^{-1}$ (781 to 1366 $mm.yr^{-1}$). Mean air temperature for the same period was 4.7°C (3.2°C to 6.5°C), with a minimum mean monthly temperature of -11.9°C in January and a maximum of 19.0°C in July (**Figure 2.2**). Mean long-term interannual potential evapotranspiration (PET), estimated using the Oudin et al. (2005) formula, was 572 $mm.yr^{-1}$ (529 to 612 $mm.yr^{-1}$). The OBS period (2016-2022) on-site data show mean precipitation of 1039 $mm.yr^{-1}$ (888 to 1161 $mm.yr^{-1}$), mean temperature of 5.7°C (4.3 to 6.6°C), and mean PET of 595 $mm.yr^{-1}$ (556 to 620 $mm.yr^{-1}$). The observed period and the long-term period total precipitation were not significantly different, but temperature and PET distributions were (Kolmogorov-Smirnov (KS) test, p-value < 0.05). The Lake Papineau catchment is attributed a Köppen-Geiger (K-G) class of Dfb (humid continental climate with warm summers but lacking a dry season; Kottek et al., 2006).

2.3 Methods

2.3.1 Gauging stations and flow rate measurements

Continuous hourly stage recordings at the Lake Papineau outlet began in January 2016 (*Solinst Levelogger* pressure sensor), following the August 2015 replacement of a concrete dam used since 1975 with a progressive weir to facilitate fish migration. Before this period, discharge from Lake Papineau was managed with a wooden dam as early as 1930. A total of 903 manual daily lake stage measurements, recorded sporadically from 2002 to 2014 at a lake marina close to the outlet, approximate recent historical conditions prior to the removal of the concrete dam, with an additional 753 measurements made at this location since January 2016. A gauging station was also installed in May 2017 close to the outlet of the Lake La Croix affluent, flowing into Lake Papineau (*Solinst Levelogger* pressure sensor, hourly measurements; hereafter named La Croix station). This station was displaced approximately 40 m downstream at the end of September 2019 owing to the inability of the probe to capture low flow conditions.

At both stations, discharge was measured regularly with either a *HACH* velocity flow meter (La Croix station) or a *Teledyne StreamPro* acoustic Doppler current profiler (Lake Papineau outlet). A total of 24 and 19 discharge measurements were taken between April 2017 and April 2022 at the Lake Papineau outlet and at the La Croix station, respectively. Rating curves were constructed using the BaRatin (Bayesian Rating curve) method, implemented with the BaRatinAGE v2.2 tool (Horner et al., 2018; Le Coz et al., 2014). The Lake Papineau outlet was configured using a rectangular weir, while the La Croix station was represented using a rectangular channel control. BaRatin rating curve uncertainty is distinguished between parametric (associated with the limited information available for Bayesian model parameters) and structural uncertainty (the inability of the model to account for precise channel hydraulics and temporally-variable stage-discharge relationships), which together constitute the total uncertainty. For the La Croix station, daily baseflow was estimated using the Lyne and Hollick (LH; 1979) recursive digital filter applied to observed discharge. The recession constant (α) was stochastically calibrated using the *baseflows* function of the R package *hydrostats* (Bond, 2022), with the first and last 30 days of observed discharge duplicated and added as padding at the beginning and end of the time series to assist in forward and backward passes of the filter.

2.3.2 Extending observed lake stage and discharge with regionalization

Owing to the limited period of observed stage and discharge at the lake outlet (2016-2022), the multi-layer perceptron (MLP; Rosenblatt, 1957) machine learning (ML) technique, belonging to the family of feedforward neural networks, was used to reconstitute long-term past hydrometric conditions for Lake Papineau using regional meteorological and hydrometric data. Daily Lake Papineau stage was reconstituted with the R package *neuralnet* (Günther et al., 2019) for the 1964-2022 period, i.e., starting at the earliest date when discharge data were available for nearby rivers. The provincially operated hydrometric stations 02LC029 on the Rouge River (9.9 km southeast of the Lake Papineau outlet) and 02LD005 on the Petite Nation River (23 km west of the outlet) (**Figure 2.1**) (DEH, 2023) were used to derive hydrometric conditions at the Lake Papineau outlet. These surrogate stations have long-term (1964-2022; hereafter the ALL period) mean annual discharge of 106.9 m^3s^{-1} (Q_{Rouge}) and 22.6 m^3s^{-1} ($Q_{PNation}$). Daily precipitation and air temperature were taken from the provincial gridded dataset and from the on-site meteorological station.

The artificial neural network (ANN) model was developed using observed daily lake stage at the Lake Papineau outlet between January 2016 and September 2022. Lake stage was chosen for reconstitution to allow for the outlet rating curve to be updated in the future, with the acquisition of new discharge measurements. The first 66% of the measured data served for training and the remaining 33% was used for validation, a data-splitting approach commonly adopted to ensure independent model evaluation. The

Augmented Dickey-Fuller test (ADF; Dickey and Fuller, 1979) and the Kwiatkowski-Phillips-Schmidt-Shin test (KPSS; Kwiatkowski et al., 1992) evaluated the stationarity of the 2016-2022 daily values of Lake Papineau stage and the four dependent variables: the two meteorological variables (precipitation and air temperature) and the two hydrometric variables (Q_{Rouge} and $Q_{PNation}$). ADF (p-value < 0.05) pointed to stationarity for all variables except temperature, while KPSS (p-value > 0.05) indicated all variables to be likely stationary. Cross-correlation analysis (*stats* package; R Core Team, 2024) between observed lake stage and the four dependent variables allowed the latter to be temporally shifted to account for identified lags for Q_{Rouge} and $Q_{PNation}$ (one and five days, respectively) and for identified lags for precipitation and temperature (six and 62 days, respectively). This step allowed the ANN to better identify the relationships between lake stage and the dependent variables. All variables were then normalized between 0 and 1 to ensure they were given equal weight.

The MLP architecture consisted of an input layer, containing the four normalized dependent variables, one hidden layer composed of a variable number of neurons (one to fifteen), and a single output layer for lake stage, following the methodology of Lavoie Lavallee (2019). Depending on the number of neurons in the hidden layer, model parameters ranged from seven (five weights and two biases) to 91 (75 weights and 16 biases), with a maximum of fifteen neurons chosen following Boucher et al. (2020). Model parameters were calibrated through gradient descent via the backpropagation algorithm by minimizing the training period sum of squared errors (SSE), while validation period model performance was evaluated using the Nash-Sutcliff Efficiency (NSE; Nash and Sutcliffe, 1970). 30 repetitions were realized for each model architecture (number of neurons in the hidden layer) and this process was iterated 50 times. The time series associated with the highest validation period NSE from each iteration was compiled and averaged for each daily value to create the optimal reconstituted stage dataset. Lake discharge was then derived from reconstituted lake stage using the rating curve. Comparison against manual measurements from 2002-2014 at the lake outlet marina site (before instrumentation of the Lake Papineau outlet) served as a post-calibration metric of goodness-of-fit, based on the assumption that the current stage-discharge relationship developed following the removal of the concrete dam was a reasonable approximation of conditions prior to 2016.

2.3.3 Catchment hydrological characterization using the Budyko theoretical framework

The Budyko conceptual water balance framework was used for constraining the partitioning of lake catchment available water into discharge (Q) and actual evapotranspiration (AET). The Budyko framework conceptualizes the evaporative index (the ratio of AET to total precipitation; $AET.P^{-1}$) as a function of the aridity index (the ratio of potential evapotranspiration to total precipitation; $PET.P^{-1}$). Here, PET was estimated using the Oudin et al. (2005) formula, with unity between AET and PET (the 1:1 line within Budyko space) constituting the energy supply or atmospheric demand limit, while unity between P and AET constitutes the water supply limit. All variables were reasoned on a water year (WY) basis under the assumption of a closed catchment water budget, wherein both catchment storage and groundwater exchange outside the surface catchment were considered null. AET is inferred from available catchment budget components as follows:

$$AET = P - Q = P - R - Q_{Base} \quad \text{(Equation 2.1)}$$

where inferred AET is the difference between precipitation (P) and discharge at the lake outlet (Q), with the latter consisting of the sum of two constituents – runoff (R) and baseflow (Q_{Base}). All variables were reasoned in mm.

Based on the plotting of long-term conditions for numerous large catchments covering diverse global hydroclimatic conditions, Budyko (1974) derived a non-parametric equation to describe the central tendency of catchments to be situated along a curve (hereafter referred to as the empirical Budyko curve). Subsequent research aimed at extending the use of the Budyko framework led to the definition of several parametric Budyko equations, of which the Tixeront-Fu equation (Fu, 1981; Tixeront, 1964; Zhang et al., 2004) is one:

$$\frac{AET}{P} = 1 + \frac{PET}{P} - (1 + \left(\frac{PET}{P}\right)^{\omega})^{\omega^{-1}} \quad \text{(Equation 2.2)}$$

where $AET.P^{-1}$ is the evaporative index, $PET.P^{-1}$ is the aridity index, and ω is the Tixeront-Fu parameter, governing their relationship. All three variables are unitless. For a given period, a parametric Tixeront-Fu curve was fitted to the point cloud of annual evaporative and aridity indices plotted in Budyko space by minimizing mean absolute error (MAE). A corresponding ω value was obtained for each fitted parametric curve, with higher values indicating greater partitioning of available precipitation into AET. For reference, the global empirical Budyko curve has an equivalent Tixeront-Fu ω of 2.60 (Andréassian & Sari, 2019; Yang et al., 2008). Inferred AET values for the upper and lower bounds of the BaRatin parametric and total discharge uncertainties were similarly plotted in Budyko space, with parametric Tixeront-Fu curves fitted to theses point clouds to define evaporative index uncertainty envelopes.

Curve fitting was realized using the R package *budyko* (Hampton, 2025). Parametric curves were fitted for the OBS and the REF periods, with OBS AET derived from observed discharge and REF AET derived from ANN-reconstituted discharge. A parametric curve was additionally fitted to the entire 1964-2022 (ALL) period, integrating reconstituted and observed conditions. To further test the range of the ω parameter when incorporating periods of varying climatic conditions, parametric curves were fitted to a 30-WY moving window for the ALL period, resulting in 29 ω values.

The parametric Tixeront-Fu equation afforded an additional means of estimating catchment discharge for periods when only precipitation and PET were available. Under the assumption that the ω of a given period was representative of long-term catchment conditions, Equation 2.2 was solved for the evaporative index ($AET.P^{-1}$) of each known aridity index ($PET.P^{-1}$), following the so-called 'catchment trajectory conjecture' (Reaver et al., 2022), whereby changes in aridity translate into predictable shifts in evaporative partitioning along a single Budyko parametric curve. Discharge was then derived from each evaporative index value using Equation 2.1. This method was applied to estimate REF period discharge ($Q_{Tixeront\text{-}Fu}$) using the Tixeront-Fu ω fitted to the OBS period point cluster of inferred $AET_{P\text{-}Q}$.

2.3.4 Simulated catchment water budget components

Lake Papineau catchment water budget components were simulated with the HydroBudget (HB) catchment water budget model (Dubois et al., 2021a, b). These variables included actual evapotranspiration (AET), runoff, and baseflow. The HB model was developed specifically for regional-scale simulations of potential groundwater recharge (PGWR) in cold and humid climates, using a runoff curve number (RCN) approach. In conditions such as those of the study area, PGWR was considered equal to actual recharge due to the absence of confining conditions and thus assumed to equal the baseflow component of discharge for a given catchment. HB was chosen for its parsimony with respect to both the number of parameters to calibrate (eight; **Table 2.1**) and the minimal input variable requirements (daily precipitation and air temperature).

Spatially distributed water budget variables for the Lake Papineau watershed were simulated with a monthly output resolution for 9,485 100 m-resolution grid cells based on land use, pedology, and slope. Soil types, grouped into four categories, were taken from the IRDA (2008) dataset, while the seven land use categories were obtained from Bissonnette et al. (2016), and slope was derived from a 100 m resampling of the 20 m-resolution digital elevation model (CDEM – Natural Resources Canada, 2013).

Automatic calibration of the HB model was realized with the *caRamel* R package (Monteil et al., 2020), with objective function metrics based on measured Lake Papineau discharge (Q_{Outlet}, 2016-2022), La Croix station discharge ($Q_{LaCroix}$, 2017-2022), La Croix station baseflow ($Q_{BaseLaCroix}$), lake catchment AET_{P-Q} (2016-2022), and the Budyko Tixeront-Fu ω fitted against AET_{P-Q}. The inclusion of the Lake Papineau catchment ω in model calibration represented a departure from the otherwise conventional HB calibration procedure of Dubois et al. (2021a). Model performance was assessed with the Kling-Gupta efficiency (KGE; Gupta et al., 2009) and MAE. The time series of Q_{Outlet}, $Q_{LaCroix}$, and $Q_{BaseLaCroix}$ were separated into calibration (first 66%) and validation (last 33%) periods, with the average KGE from these two periods constituting the *caRamel* objective functions. The *caRamel* algorithm explored the parameter space through successive iterations (maximum of 5,000) by optimizing KGEs for Q_{Outlet}, $Q_{LaCroix}$, $Q_{BaseLaCroix}$, and AET_{P-Q}, while minimizing MAE for the Tixeront-Fu ω.

Post-calibration weights were applied to these results, with 60% attributed to $KGE_{QOutlet}$ and 20% each to the $KGE_{QLaCroix}$, and $KGE_{QBaseLaCroix}$, respectively. These percentages ensure that secondary performance metrics remained sufficiently influential in the selection of optimal simulations, particularly for parameters not uniquely constrained by $KGE_{QOutlet}$ alone. To further constrain model output with the Budyko framework, the resulting KGE values from the 5,000 model runs were then filtered to retain only the iterations for which the Lake Papineau catchment Tixeront-Fu ω was within the bounds of the BaRatin parametric uncertainty envelope. As PET_{Oudin} was unaffected by HB calibration, only the evaporative index was constrained by this filtering. The 25 best weighted HydroBudget parameter sets with (*constrained*; HB_C) or without (*unconstrained*; HB_U) filtering were used to evaluate the utility of integrating the Budyko framework into model calibration. The 25 HB_C and HB_U parameter sets were each averaged ($HB_{\bar{C}}$ and $HB_{\bar{U}}$) to obtain respective sets of simulated water budget components for input into the lake water budget.

2.3.5 Lake water budget

A classical lake water budget equation was used to estimate the net lacustrine groundwater contribution to Lake Papineau (GW_{Net}). This technique required that all other components of the lake water budget be quantified, with the residual assumed to be GW_{Net}. As such, only the net lacustrine groundwater contribution could be estimated, potentially masking the simultaneous presence of groundwater inflow to the lake (GW_{In}) and lake water outflow to the aquifer (GW_{Out}). The lake water budget is formulated as:

$$GW_{Net} = GW_{In} - GW_{Out} = VI + R + Q_{Base} - Q - E \pm \Delta S \qquad \text{(Equation 2.3)}$$

where direct vertical inflow (VI; sum of liquid precipitation and melted snow) and direct lake evaporation (E) occur across the Lake Papineau surface area, while runoff (R) and baseflow (Q_{Base}) contributions are associated with the lake catchment surface area (excluding the Lake Papineau extent). VI volumes were calculated using the degree-days snowmelt approach calibrated in HB, with snow and rain separated by a temperature threshold of 0°C. E was estimated with the Oudin et al. (2005) formula, which used only air temperature. Apart from temperature-mediated snowmelt and evaporation, the effects of seasonal ice cover over Lake Papineau were not explicitly accounted for in either the HB simulations or the water budget. Lake catchment R and Q_{Base} were obtained directly from the HydroBudget model. Change in lake storage (ΔS) was calculated from the change in lake stage multiplied by lake area (assumed constant). When direct stage measurements were not available, they were derived from outlet discharge (Q) using the BaRatin rating curve.

The effect on GW_{Net} of integrating the Budyko framework into the HB model calibration was evaluated using results from the constrained ($HB_{\bar{C}}$) and unconstrained ($HB_{\overline{U}}$) calibrated HB model as inputs to the lake water budget. Furthermore, the effect on GW_{Net} of using different lake discharge estimates for both the OBS and REF periods was also evaluated. Observed (Q_{OBS}) and ANN (Q_{ANN}) discharge were compared with HB-simulated discharge (Q_{HB}), and discharge associated with given annual precipitation and PET conditions along the fitted Tixeront-Fu parametric curve ($Q_{Tixeront\text{-}Fu}$). A one-factor-at-a-time sensitivity analysis complemented this evaluation of the impact of different variable estimates on GW_{Net}, by inducing volumetric and percent changes in GW_{Net} through the variation in only one other budget variable, with all others remaining fixed (Pianosi et al., 2016). Changes to each of the water budget components in increments of ±10% (upwards of ±30 %) were chosen to encompass a reasonable range of uncertainty.

As groundwater can be exchanged with Lake Papineau both directly (fluxes across the lake sediments) and indirectly (baseflow discharging to streams that subsequently flow into the lake), the total GW contribution to the lake (GW_{Total}) was considered as the sum of GW_{Net} and the baseflow contribution of total catchment runoff to the lake (Q_{Base}). To facilitate the comparison of both GW_{Net} and GW_{Total} volumetric fluxes to Lake Papineau with estimates from other literature-based studies, all GW values were also transformed into areal groundwater loading, normalized to the Lake Papineau surface area.

2.4 Results

2.4.1 Observed hydrological conditions

The Lake Papineau outlet rating curve was considered satisfactory, despite the absence of discharge measurements for the highest lake stages which introduced uncertainty for the highest flow rates (**Figure 2.3a**). Over the course of the OBS period, the highest daily lake stages generally occurred in April or early May (maximum recorded level April 22, 2019; 173.9 masl), coinciding with the spring freshet, while the lowest stages occurred between July and October (minimum recorded level September 22, 2019; 172.95 masl) (**Figure 2.3b**). The daily flow rates derived from the rating curve followed a similar annual dynamic, varying between a maximum value of 16.9 m^3s^{-1} in April 2019, with the lake outflow running dry for stages below the outlet weir activation threshold of 173.03 masl. Discharges were extremely low from July to October in 2019, 2020, and 2021, with mean monthly values frequently below 0.1 m^3s^{-1} (**Figure 2.3b**).

A BaRatin rating curve was also constructed for the largest affluent, at La Croix station (**Figure 2.3c**). As with the Lake Papineau outlet, the absence of discharge measurements for the highest stages introduced uncertainty for the highest flow rates. Water levels at this station varied with a similar annual cycle as those at the Lake Papineau outlet, with a maximum level of 180.9 masl (April 20, 2019) and a minimum level of 179.8 masl (September 14, 2021) (**Figure 2.3d**). The La Croix station likely never ran dry during the study period, though low flow conditions prior to the displacement of the stream gauge in September 2019 presented some uncertainty. The corresponding maximum discharge was 3.6 m^3s^{-1} and the minimum discharge was 2.0 x 10^{-3} m^3s^{-1}. On average, the contribution of this affluent represented 28% of annual discharge at the Lake Papineau outlet. The calculated LH baseflow for this sub-catchment ranged between 2.0 x 10^{-3} m^3s^{-1} (September 14, 2021) and 0.5 m^3s^{-1} (April 30, 2019), constituting on average 44% of the total annual discharge at the affluent gauging station (**Figure 2.3e**).

2.4.2 ANN-reconstituted past hydrological conditions

The artificial neural network (ANN) satisfactorily reproduced observed Lake Papineau stage (**Figure 2.4a**). On a monthly basis, NSE values of 0.90 and 0.88 and KGE values of 0.91 and 0.80 were obtained for the training and validation periods, respectively, with MAE of 0.03 m for both periods. When transformed to equivalent outlet discharge using the rating curve, mean monthly outlet discharge goodness-of-fit metrics were similar to those obtained for stage (NSE of 0.92 and 0.88, KGE of 0.93 and 0.79, and MAE of 0.45 and 0.38 m^3s^{-1} for training and validation, respectively). Monthly residuals of stage and discharge (observed minus reconstituted) were normally distributed (Shapiro-Wilk test, p-value > 0.05), with spring and fall mean residuals of less than 1 cm and 0.1 m^3s^{-1} (**Figure 2.4c, d**). The ANN overestimated stage and discharge during summer (2 cm and 0.2 m^3s^{-1}), while underestimating them during winter (3 cm and 0.4 m^3s^{-1}). As a post-calibration metric, comparison against manual daily stage measurements for the 2002-2014 period at the marina site confirmed the ability of the ANN to adequately reconstitute past conditions (MAE of 0.08 m and R^2 of 0.47) (**Figure 2.4b**). Here, daily residuals were skewed left for both stage and discharge, with the ANN overestimating to a much greater extent spring conditions (10 cm and 1.6 m^3s^{-1}), while underestimating summer (3 cm and 0.3 m^3s^{-1}) and fall (5 cm and 0.5 m^3s^{-1}) conditions.

On a WY-basis, there was no statistically significant difference (KS test, p-value < 0.05) between the OBS period distributions of observed specific discharge ($mm.yr^{-1}$) at the Lake Papineau outlet (Q_{OBS}) and the specific discharge at the Rouge River (Q_{Rouge}) and Petite Nation River ($Q_{PNation}$) gauging stations used for ANN training (**Figure 2.4e**). The same was true for the REF period, even though the 1981-2010 period was not used for the ANN training. None of the three datasets presented statistically significant differences between the distributions of WY values between the REF and OBS periods (KS test, p-value < 0.05), nor were the means of the three datasets significantly different between the two periods (Tukey honest significant difference (HSD), p-value < 0.05).

2.4.3 Lake Papineau hydroclimatic regime

Lake Papineau discharge for the OBS period (Q_{OBS}), expressed in mm equivalent for the lake catchment, varied from 497 (WY 2020-21) to 804 (WY 2016-17) $mm.yr^{-1}$ (interannual mean 661 $mm.yr^{-1}$). On a mean interannual basis, discharge uncertainty, derived from the rating curve in the form of both parametric and total uncertainty, constituted ±55 $mm.yr^{-1}$ (±8.5%) and ±183 $mm.yr^{-1}$ (±28%), respectively. From here on, only parametric uncertainty was considered in the analysis, to simplify the overall presentation. Annual ANN discharge for the REF period (Q_{ANN}) varied between 299 and 783 $mm.yr^{-1}$ (mean 560 $mm.yr^{-1}$).

Inferred actual evapotranspiration (AET_{P-Q}) was estimated using these discharge estimates and total annual precipitation in Equation 2.1. Contrary to the distributions of both discharge and precipitation, AET_{P-Q} presented significantly different ranges of 319-453 (OBS) and 314-745 (REF) $mm.yr^{-1}$ between the two periods (KS test, p-value < 0.05). Both REF and OBS aridity ($PET.P^{-1}$) index values placed the catchment within an energy-limited hydrological regime, whereby PET never exceeded available precipitation ($PET.P^{-1} < 1$; **Figure 2.5a**). The aridity index ranges of 0.51-0.70 (OBS) and 0.42-0.74 (REF) exhibited statistically similar, limited extents within the Budyko space (KS test, p-value < 0.05). The evaporative index ($AET.P^{-1}$), by contrast, exhibited significantly different ranges of 0.30-0.44 (OBS) and 0.32-0.71 (REF), distinguishing evaporative conditions estimated using observed and ANN-reconstituted AET_{P-Q}.

The evaporative index for a given WY identified whether AET or discharge constituted the dominant catchment release function. All six WY for the OBS period were discharge-dominant (Q constituted 56-70% of P), whereas lower ANN-reconstituted discharge and resulting higher inferred AET_{P-Q} (at most 71% of P) produced much more variable conditions, with AET dominating over a third (11 WY) of the REF period. It should be noted that for the REF period, inferred AET_{P-Q} from ANN results was greater than PET for six of the 30 WY (with AET at most 133 mm greater than PET, representing at most 13% of annual P), thereby violating the atmospheric demand limit of the Budyko framework (**Figure 2.5a**). A further eight REF period WYs had AET_{P-Q} to PET ratios that, while not violating the demand limit, were above 0.95.

Parametric Tixeront-Fu Budyko curves fitted using OBS and REF inferred AET_{P-Q} illustrated the impact of lower REF period ANN-reconstituted discharge. The Tixeront-Fu ω for the 6-WY OBS period was 1.82, while greater AET dominance for the 30-year reconstituted REF period led to a higher ω of 2.33 (**Table 2.2**). The parametric curve fitted to the 1964-2022 ALL period, integrating both ANN and observed discharge conditions, presented a slightly lower ω (2.23). REF period conditions were much closer to the empirical global Budyko curve (2.60), yet since several of the years violated the atmospheric demand limit, this ω value was likely overestimated. The 29 values obtained from the 30-WY moving average for the ALL period exhibited even higher ω values, with a mean of 2.41 ± 0.16 and minimum and maximum values ranging from 2.11 to 2.72 (**Table 2.2**). The BaRatin parametric and total uncertainty envelopes for the OBS period hydroclimatic conditions were defined by ω intervals of [1.61, 2.05] and [1.31, 3.20], respectively (**Figure 2.5a**).

2.4.4 Impact of constraining HydroBudget simulations with the Budyko framework

As part of the 5,000 model runs in the *caRamel* automatic calibration of HydroBudget (HB), the hydroclimatic context of the Lake Papineau catchment, as characterized by fitted Tixeront-Fu Budyko parametric curves, was accounted for both in constraining the exploration of the parameter space during calibration and in post-treatment of the results. Fitted OBS period Tixeront-Fu ω values for all 5,000 calibrated parameter sets ranged from 1.49 to 5.40 (mean 2.15). Applying the constraint of only retaining those model runs with ω values within the range of 1.61 to 2.05, as defined by the BaRatin parametric uncertainty envelope, reduced the number of acceptable parameter sets to 2,792 (mean ω of 1.88).

The 25 parameter sets exhibiting the highest values of the weighted KGE metric (KGE_{Weight}) from both the Budyko-constrained (HB_C) and -unconstrained (HB_U) model runs showed many similarities but also marked differences. The ω values for the 25 best constrained parameter sets for the OBS period presented a narrow distribution of ω values ranging from 1.90 to 2.05 (mean 1.99), clustered near the upper limit of the parametric uncertainty envelope (**Table 2.2**, **Figure 2.5b**), whereas the 25 best unconstrained parameter sets ranged from 2.20 to 3.50 (mean 2.48). All but one of the 25 HB_U ω (3.50) was within the BaRatin total uncertainty envelope (**Figure 2.5b**). The 25 HB_C ω values for both the REF and ALL periods were nearly identical to those obtained using inferred AET_{P-Q}, with all values situated within a range of 2.09 to 2.38. The 25 HB_U ω values for the REF and ALL periods (means of 3.21 and 3.02, respectively), by contrast, were all higher than any of the HB_c ω and reached as high as 5.30 (**Table 2.2**).

Mean calibrated model parameter values were largely consistent between $HB_{\bar{C}}$ and $HB_{\bar{U}}$, with both sets of eight parameters presenting similar means and standard deviations based on their 25 member ensembles (**Table 2.1**). Of the eight calibrated parameters, only the melting coefficient (C_M), runoff factor (f_{runoff}), and infiltration factor (f_{inf}) presented distributions that were significantly different (KS test, p-value < 0.05) between the 25 member HB_C and HB_U parameter sets. The impact of the difference in the C_M parameter between $HB_{\bar{C}}$ and $HB_{\bar{U}}$ on OBS period transformation of monthly total precipitation into vertical inflow (VI) was negligible however (**Figure 2.6a**).

OBS period simulations run with the $HB_{\bar{C}}$ and $HB_{\bar{U}}$ parameter sets yielded ω of 1.97 and 2.40, respectively, with the former closely resembling the ω of 1.82 for the 6-WY inferred AET_{P-Q} (**Table 2.2**). For the long-term REF period, the $HB_{\bar{C}}$ ω (2.26) resembled the 2.33 for reconstituted AET_{P-Q}, whereas $HB_{\bar{C}}$ ω was much higher at 3.00. The ALL period largely followed this dynamic, with 2.22 and 2.85 for constrained and unconstrained conditions, respectively. Whereas the mean ω value for the ALL dataset using inferred AET_{P-Q} was 2.41, the mean ω values for $HB_{\bar{C}}$ and $HB_{\bar{U}}$ were 2.26 and 2.97, respectively, and had smaller uncertainties (**Table 2.2**).

In retaining only those calibrated parameter sets with Tixeront-Fu ω values within the range defined by the BaRatin parametric uncertainty envelope, the calibration objective functions for the 25 best HB_C presented marginally less satisfactory results with respect to the 25 best HB_U (**Table 2.3**). For example, mean KGE_{Weight} was 0.61 for the 25 best HB_c, increasing only modestly to 0.66 for the 25 best HB_U, though the distributions were significantly different (KS test, p-value < 0.05). Similarly, the mean KGEs for the La Croix station discharge ($KGE_{QLaCroix}$) and baseflow ($KGE_{QBaseLaCroix}$) (each contributing 20% to the weighted metric) were both lower for HB_C than for HB_U, with their distributions also significantly different (KS test, p-value < 0.05) (**Figure 2.6c, d**). For both parameter sets, the KGEs for evaluating AET_{HB} against AET_{P-Q} were very poor and proved inadequate in assisting model calibration. The mean Tixeront-Fu ω MAEs for these AET estimates were 0.17 and 0.66 for the 25 best HB_C and HB_U, respectively. This indicated that while including this objective function in the automatic calibration assisted in exploring the parameter space, subsequent filtering of the results was necessary. Objective function values using the mean parameter sets ($HB_{\bar{C}}$ and $HB_{\bar{U}}$) were nearly identical to the mean objective function values of the 25 best HB_C and HB_U (**Table 2.3**).

Of the objective functions used for constraining the model parameter space, only the distributions of KGEs for Lake Papineau discharge were not significantly different between the constrained (mean KGE of 0.74) and unconstrained (mean KGE of 0.75) 25 best parameter sets, owing in large part to this objective function constituting 60% of the weighted KGE metric (**Table 2.3**). Whereas the OBS period catchment discharge KGE exhibited minimal difference when using the mean parameter values from either the 25 best constrained ($HB_{\bar{C}}$) or unconstrained ($HB_{\bar{U}}$) calibrated parameter sets (**Figure 2.6b**), other metrics not explicitly considered in the calibration showed notable improvements when utilizing the Budyko framework. For example, for the combined calibration and validation periods, the percent bias (PBIAS) of simulated monthly Lake Papineau discharge with respect to observed discharge reduced from -12% ($HB_{\bar{U}}$)

to -4% ($HB_{\bar{C}}$), while the mean error reduced similarly from -7 to -2 mm.month^{-1}. Grouped by season, monthly residual errors (observed – simulated) of Lake Papineau discharge indicated that $HB_{\bar{C}}$ was more capable of simulating high spring stages and flows compared to $HB_{\bar{U}}$, while both equally underestimated winter stages and flows (**Figure 2.6e-h**). Similarly, $HB_{\bar{C}}$ overestimated summer and fall conditions to a slightly greater extent compared to $HB_{\bar{U}}$.

2.4.5 Simulated catchment water budget

Given the demonstrated ability of the Budyko framework to improve the estimate of catchment discharge by constraining AET, using $HB_{\bar{C}}$ offered further important modifications to the partitioning of catchment water budget outflows with respect to total precipitation. Comparing the results when using $HB_{\bar{C}}$ rather than $HB_{\bar{U}}$, both the OBS and REF periods saw the contribution of baseflow diminish slightly from 13% (140 mm.yr^{-1}) and 14% (155 mm.yr^{-1}) to 11% (approximately 120 mm.yr^{-1}). The contribution of runoff increased more substantially from 39% (REF) and 41% (OBS) to 47% and 48% (**Table 2.4**). When combined, runoff and baseflow contributions led to increased lake discharge (Q_{HB}) during both periods for $HB_{\bar{C}}$ (58% and 59%) compared to $HB_{\bar{U}}$ (53% and 54%, **Figure 2.7a**). The relative importance of AET_{HB} diminished as a result, from 46% and 47% to 41% and 42% of the total catchment release (**Figure 2.7b**; **Table 2.4**).

In comparing the distributions of simulated annual catchment water budget components for a given period using $HB_{\bar{C}}$ or $HB_{\bar{U}}$, only baseflow and runoff (**Figure 2.7c, d**) during the REF (but not the OBS) period and AET_{HB} (for both REF and OBS periods) presented significant differences (KS test, p-value < 0.05). During winter, when OBS period discharge constituted the overwhelming majority of catchment release (93-94%), baseflow contributed between 26% ($HB_{\bar{C}}$) and 34% ($HB_{\bar{U}}$) of total seasonal catchment outflows (**Table 2.4**). By contrast, for this same period, when summer catchment outflows were dominated by AET (72-79%), baseflow constituted only 1-2% of total seasonal outflows. The REF period showed nearly identical dynamics, albeit with a higher winter baseflow contribution (40-51%) to seasonal total outflows. The seasonal contributions of each catchment water budget component to its annual total presented no apparent differences between $HB_{\bar{C}}$ and $HB_{\bar{U}}$ (**Table 2.4**).

Considering only the magnitudes of annual HB-simulated catchment water budget components using $HB_{\bar{C}}$, AET_{HB} varied from a mean of 432 mm.yr^{-1} for the OBS period (**Table 2.4**, **Figure 2.7b**) to 459 mm.yr^{-1} for the REF period, with the periods presenting significantly different distributions. For the OBS period, the AET_{HB} distribution was not significantly different from that of inferred AET_{P-Q} (mean 378 mm.yr^{-1}), owing to its use in constraining HB calibration results. The AET_{HB} distribution for the REF period, by contrast, was significantly different than that of inferred AET_{P-Q} (mean 505 mm.yr^{-1}), derived from ANN discharge.

As in the case of Q_{OBS} and Q_{ANN}, the distributions of HB-simulated annual discharge (Q_{HB}) for the REF and OBS periods were not significantly different (**Figure 2.8b**). Much like for AET_{HB}, the use of Q_{OBS} in calibrating HB led to an absence of significantly different distributions between Q_{OBS} and Q_{HB} for the OBS period. In the case of the REF period, however, the distributions of Q_{ANN} and Q_{HB} were significantly different. Much like for Q_{HB}, the OBS and REF period distributions of its constituents, runoff and baseflow, exhibited no significant differences (**Figure 2.7c, d**).

2.4.6 Estimated lake water budget under observed and long-term past conditions

Under observed conditions, inflow components to the annual lake water budget (**Table 2.5**) were dominated by surface runoff to the lake (R), which had a mean of 41.9 Mm^3.yr^{-1} for the OBS period (61%). Direct precipitation (VI) contributed to a lesser extent, with a mean of 13.6 Mm^3.yr^{-1} (20%) of inflows. The baseflow component of surface water inflow (Q_{Base}), representing the indirect GW contribution to the lake, contributed slightly less than direct precipitation, with a mean of 9.4 Mm^3.yr^{-1} (14%). Discharge from the outlet (Q) dominated outflows, ranging between a mean of 59.7 to 61.9 Mm^3.yr^{-1} (88% or 89%), when considering all estimates ($Q_{OBS,}$ Q_{ANN}, Q_{HBC}, and $Q_{Tixeront-Fu}$). Lake evaporation (E) constituted the remaining outflows, with a mean of 7.8 Mm^3.yr^{-1} (12%). Annual lake storage, averaged for all discharge estimates, was negligible (-7 x 10^{-3} Mm^3.yr^{-1}, 0.1% of outflows). The GW_{Net} term was of the same order of magnitude for the different methods, with means of 2.5 to 4.7 Mm^3.yr^{-1} (4% to 6% of inflows). More importantly, it was always positive, indicating that more groundwater was feeding the lake than lake water feeding the aquifer (**Figure 2.9b**). When the two groundwater components (Q_{Base} and GW_{Net}) were combined, the OBS period mean total groundwater contribution to Lake Papineau (GW_{Total}) was 12.7 Mm^3.yr^{-1} (19% of lake inflows).

Magnitudes and relative contributions to the lake water budget inflows and outflows were largely the same for the long-term REF period (**Table 2.5**), with some notable exceptions. Despite Q_{OBS} and Q_{ANN} not presenting significant differences between the OBS and REF periods (Welch's t-test, p-value < 0.05 and Wilcoxon rank-sum test (Wilcoxon, 1945), p-value < 0.05), mean Q_{ANN} outflow (52.5 Mm^3.yr^{-1}, 78%) for the REF period was considerably lower than mean observed conditions. Considering that all other lake water budget components were similar for REF vs. OBS conditions, mean GW_{Net} derived from Q_{ANN} consisted of lake budget outflow, with -5.9 $Mm^3.yr^{-1}$ (10% of outflows). Also, although both Q_{HB} ($HB_{\bar{C}}$) and $Q_{Tixeront\text{-}Fu}$ presented REF period lake discharges that were not significantly different from their OBS period conditions (Wilcoxon Rank-Sum Test, p-value < 0.05), mean interannual GW_{Net} derived from $Q_{Tixeront\text{-}Fu}$ (4.6 $Mm^3.yr^{-1}$, 7% of inflows) was nearly double the volume of the OBS period, while the mean estimate derived from Q_{HB} diminished only slightly for the REF period (2.0 $Mm^3.yr^{-1}$, 3% of inflows). The use of the Budyko-constrained HB water budget components ($HB_{\bar{C}}$) rather than $HB_{\bar{U}}$ had the effect of increasing GW_{Net} for both the OBS and REF periods when using Q_{HB}, though only the REF period increase was significant (**Table 2.5**; Wilcoxon Rank-Sum Test, p-value < 0.05).

2.4.7 Lake water budget sensitivity analysis

The sensitivity analysis showed OBS period GW_{Net} to be most sensitive to changes in discharge (**Table 2.6**). Depending on the discharge estimate used (Q_{OBS}, Q_{HB}, or $Q_{Tixeront\text{-}Fu}$), each % increase in discharge induced an increase of 0.60 and 0.62 Mm^3 in GW_{Net} (+13% for Q_{OBS}; +24% for Q_{HB} and $Q_{Tixeront\text{-}Fu}$). Conversely, lake evaporation was found to be the component for which GW_{Net} was least sensitive, as each 1% increase in evaporation increased GW_{Net} by only 0.1 Mm^3 (between 2% and 3%). Increased runoff, baseflow, and direct precipitation induced decreases in GW_{Net}. For example, when using Q_{OBS}, each 1% increase in runoff, baseflow, or direct precipitation induced losses of 9, 2, and 3% in GW_{Net}, respectively. GW_{Net} sensitivities to these components nearly doubled when either the Q_{HB} or $Q_{Tixeront\text{-}Fu}$ estimates were used in the place of Q_{OBS}.

GW_{Net} constituted a positive contribution to Lake Papineau for all six years of the OBS period, regardless of which of the three discharge and associated lake storage estimates were used. Increasing or decreasing individual inflows or outflows by 10%, corresponding to a realistic estimate of the uncertainty of each component, shifted GW_{Net} from a net positive contribution to a net loss to the surrounding aquifer for only the two most sensitive variables, i.e., discharge and surface runoff. Increasing the change to ±30% was sufficient to shift the sign of GW_{Net} when applied to direct precipitation and baseflow for Q_{HB} and $Q_{Tixeront\text{-}Fu}$ but not for Q_{OBS}. A decrease as high as 30% in lake evaporation never induced a shift in GW_{Net} from a net positive to a net loss.

2.5 Discussion

2.5.1 Groundwater inflow to Lake Papineau

Results from this study confirmed that Lake Papineau is a drainage lake (i.e., a lake with an outlet from which discharge is controlled by lake stage), mostly fed by runoff, receiving groundwater through its periphery from the baseflow contribution to its main streams, and from the surrounding aquifer diffused across its lacustrine sediments. The main lake outflow is through discharge at the passive, weir-controlled outlet, while AET is a more minor outflow. There is probably a limited underground outflow towards its lower portion close to the outlet, but this could not be quantified here. Within the Budyko framework, Lake Papineau can be described as energy-limited ($PET.P^{-1} < 1$).

The baseflow GW contribution (Q_{Base}) for the Lake Papineau catchment was largely consistent with estimates for southern Quebec (Delottier et al., 2022; Dubois et al., 2021b; Gagné et al., 2018). Elsewhere in Quebec, in the Canadian Shield of the James Bay area, Nadeau et al. (2022) showed that while runoff constituted approximately 88% of river discharge, GW contributions to rivers were on the order of 12% of the approximately 1000 mm of total annual precipitation, a value nearly identical to the OBS and REF period Q_{Base} contributions for the Lake Papineau catchment (11%). Observed and long-term groundwater recharge of approximately 120 $mm.yr^{-1}$, estimated here using $HB_{\bar{C}}$, contrast somewhat with the regional hydrogeological characterizations of the Quebec groundwater knowledge acquisition initiative. Comeau et al. (2013), for example, estimated recharge of approximately 300 $mm.yr^{-1}$ (30% of precipitation) using the HELP model, while Gagné et al. (2022) estimated approximately 200 $mm.yr^{-1}$ using HydroBudget. Though the HELP model uses a similar RCN architecture as HB, higher observed baseflow estimates against which it was calibrated potentially explain to some degree the greater estimated recharge. The predominance of winter recharge for the Lake Papineau catchment (26% and 40% of annual totals for the OBS and REF periods, respectively) is further consistent with the findings of Jasechko et al. (2014) using long-term stable water isotopes. These authors showed that for temperate forest sites, winter recharge dominates due to reduced evapotranspiration and limited vegetation water uptake during colder conditions.

The lacustrine groundwater contribution to Lake Papineau (GW_{Net}) represented 3% to 7% of total inflows across the OBS and REF periods. When combined with the baseflow groundwater contribution arriving through total flow, the total GW contribution was 18% to 22% of total inflows (**Table 2.5**). These values were coherent but somewhat smaller than 19 ± 18% contribution of GW_{Net} estimated for Lake Papineau by Lavoie Lavallée (2019), who underlined the high uncertainty of estimated GW inflow due to the short duration of available time series data (water year 2017-18) and to the combination of techniques employed. However, given that all estimates of mean interannual GW_{Net} for the OBS period were positive, the total GW contribution to Lake Papineau can be considered a lower limit. The true inflow is potentially higher, considering that there could also be water outflowing from the lake to the surrounding aquifer. Lavoie-Lavallée (2019) identified candidate areas for these flows in the northern portion of the lake, based on analysis of the piezometric map.

Studies quantifying lacustrine groundwater have employed a variety of methods, ranging from seepage meters, water chemistry, natural tracers, the Dupuit formula, numerical groundwater flow modeling, and water budgets estimates, or a combination of them. Of the 51 lakes in cold and humid climates with GW_{Net} quantified in 19 recent publications from the past two decades (**Table A2.1** in Appendix), the majority (39) were drainage lakes, with the remaining 12 being seepage lakes (i.e., lakes without a surface water outlet). These publications generally report only one value per lake, reflecting presumed steady-state conditions, with few studies accounting for interannual and intra-annual variability. In all but three of the seepage lakes compiled here, lacustrine groundwater exchange constituted a net loss from the lake to the surrounding aquifer. When considering only the drainage lakes, the reported mean areal groundwater loading (i.e., normalized with respect to lake surface area) was 1.0 ± 2.2 $m.yr^{-1}$, with only two estimates presenting larger GW_{Out} than GW_{In} (-0.2 and -0.08 $m.yr^{-1}$), and only one study (Stets et al., 2010; based on $\delta^{18}O$) presenting four values greater than 2 $m.yr^{-1}$ (maximum of 13.3 $m.yr^{-1}$). In discounting these latter four values, the mean GW_{Net} of the 35 remaining lakes was 0.4 ± 0.5 $m.yr^{-1}$, consistent with the OBS period findings for Lake Papineau using the three $HB_{\bar{C}}$ discharge estimates (mean annual areal groundwater loading ranging from 0.2 to 0.4 $m.yr^{-1}$). The range of reported literature values is quite large, probably due to different geological conditions, topography, land use, and lake sizes. Studies have shown that these parameters can directly affect lake-groundwater interactions (Genereux & Bandopadhyay, 2001; Hokanson et al., 2022; Kratz et al., 1997; Winter, 1999).

2.5.2 Importance and limitations of models when data are limited

Although the time series data from recent monitoring at the study site were relatively short, this work has shown that available data were sufficient to provide many insights into the water budgets of lakes in cold and humid climates. This was made possible using the HB catchment water budget model and using an ANN to extend existing outflow time series, but each method carries some limitations for the overall analysis. Here, an ANN was chosen for reconstituting past hydroclimatic conditions (discharge and inferred AET) due to its relative simplicity and ease of training. Different machine learning variants, such as recurrent neural networks (RNNs) and long short-term memory models (LSTMs), however, have been shown to better model time series data through the retention of sequential dependencies, albeit with more difficult training and greater use of computational resources (Wai et al., 2022). The MLP technique employed here adequately reconstituted lake stage with roughly the same error with respect to observed stage not included in the training period (MAE of 0.08 m; **Figure 2.4b**) as a suite of ML techniques employed by Wang and Wang (2020) in forecasting the short-term stage (3- to 6-month) of Lake Erie.

Reconstituting past conditions with ML presented several advantages in the context of limited observations, such as not requiring *a priori* knowledge of underlying hydrological processes and being able to use available meteorological and surrogate hydrometric data series, under the assumption that these were sufficiently deterministic to inform reasonable estimates of lake stage and discharge. However, results from this study indicate that even when ANN-derived flowrates reproduced observed conditions with reasonable fidelity, reconstituted conditions deviated from results from the process-based catchment water budget model (HB) and from the Budyko framework. This could be attributed in part to the transition in 2015 from a human-operated concrete dam to a progressive weir at the lake outlet and the inability of the current rating curve to reproduce actual past conditions. Other potential explanations include the limited number of dependent variables used in ANN model construction (most notably the absence of any consideration for evaporative demand) and the limited number of years of lake stage available for ANN training. Bai et al. (2021), for example, included PET as a dependent variable in addition to precipitation and temperature data in an LSTM for the reconstitution of past discharge for 278 USA MOPEX catchments. These authors also found that extending the calibration period from five to ten years enhanced LSTM model performance, while this had little impact on the performance of two conceptual hydrological models (GR4J-Snow and SIMHYD-Snow) used for comparison.

In this work, the parsimonious HydroBudget model provided a means of separating precipitation between AET, runoff, and recharge using readily available study area catchment characteristics and hydrometric data. Whereas hydrological models such as HBV (Bergström, 1992) offer the possibility of more explicitly accounting for a large headwater lake discharging to a stream (in the same manner as a hydroelectric reservoir), such models also present challenges in the context of limited data, such as requiring more extensive parameterization, in addition to greater difficulty in modifying model structure to suit project-specific needs. By contrast, the open-source HB code was easily adjusted to integrate constraints on catchment outflow partitioning, informed by the Budyko framework, into model calibration. Altogether, HydroBudget provided a flexible means of estimating runoff and baseflow to Lake Papineau, allowing for long-term (1964-2022) lake hydrological conditions to be estimated, albeit without consideration for the dam present until 2015.

Catchment PET and direct lake evaporation were estimated with the Oudin et al. (2005) formula (PET_{Oudin}) because of its limited input data requirements. This formula has been demonstrated to adequately characterize evaporative demand for watersheds in cold and humid climates but may be less representative of lake evaporation. At the catchment-scale, Pimentel et al. (2023) used the Budyko framework, MODIS AET estimates, and observed discharge for thousands of global catchments and concluded that temperature-based PET estimates such as that of Jensen and Haise (1963), on which PET_{Oudin} is based, were appropriate for estimating evaporative conditions for energy-limited catchments in cold and humid climates ($0.4 < AET.P^{-1} < 0.8$). Concerning lake evaporation, specifically, Vystavna et al. (2021) found that evaporative loss for lakes in cold climates (K-G of D), expressed as the ratio of evaporation to all inflows ($E.I^{-1}$), was roughly 10%, based on isotope mass-balance modeling. This is consistent with the $E.I^{-1}$ of 11-12% for Lake Papineau, depending on the discharge estimate or the period chosen. Furthermore, in their study of USA reservoir evaporation loss, Zhao and Gao (2019) found evaporated volumes in analogous K-G regions generally of the same order of magnitude as those for Lake Papineau. Lake Papineau also figured among the 1.4M global lakes for which Zhao et al. (2022) estimated lake evaporation, with their REF period volume (6.3 ± 0.5 $Mm^3.yr^{-1}$) closely resembling that estimated with the Oudin et al. (2005) formula (7.5 ± 0.3 $Mm^3.yr^{-1}$). The overall insensitivity of GW_{Net} to changes in direct evaporation from Lake Papineau is also consistent with the findings of Paule-Mercado et al. (2024), who analyzed stable isotope data for 73 European lakes, predominantly in Mediterranean and cold temperate climates. They found that deep lakes in forested catchments were less sensitive to water balance changes, attributing this to the greater aquifer-lake surface area across which groundwater contributions could compensate for evaporation losses.

2.5.3 Including constraints from evaporative demand in catchment water budget modeling

Estimating watershed AET is a challenge in regional studies (Zhang et al., 2023). Relatively few methods exist to reliably quantify AET at the catchment-scale and the large range of possible values brings non-negligible uncertainty in catchment water budget characterization. This study is not the first to use the Budyko framework to better understand evaporative demand and the role of groundwater in cold and humid climates. Liu et al. (2020) used violations of the Budyko atmospheric demand limit ($AET.PET^{-1} = 1$) as evidence of inter-catchment groundwater exchanges in thousands of global catchments. Qiu et al. (2019; Michigan, USA) utilized the Budyko framework, with the fitting of parametric curves, for comparing the impact of different estimations of AET on catchment water balances, while Li and Wang (2021) used it for validating long-term AET estimates across Canada. Fitting the parametric Budyko curve using as few as six annual estimates of inferred AET, as in the case of the present study, can induce imprecisions. Collignan et al. (2023) suggested that a minimum of 11 years was necessary for storage changes in 2,134 European catchments to be considered negligible. However, datasets of shorter durations are reported in the literature, such as the seven years used by Qiu et al. (2019). The use of parametric Budyko equations such as Tixeront-Fu to predict the behavior of a given catchment under climatic forcings has, however, been questioned in other studies (e.g., Reaver et al., 2022), citing the non-uniqueness of the equations. Despite potential limitations of the parametric equations in characterizing the trajectories of a given catchment to changing evaporative and aridity conditions, the resulting Lake Papineau catchment AET estimates making use of constraints imposed by the Budyko framework were broadly consistent with the literature. Pan et al. (2020), for example, compared remote-sensing based physical models, ML algorithms, and land surface model estimates at the global-scale and found AET for 1982-2011 at 45°N to be on the order of 400-500 $mm.yr^{-1}$. Estimates here were also coherent with values obtained from various datasets from similar conditions reported by Wang et al. (2015; southern Quebec) and Vadeboncoeur et al. (2018; northeast USA). Using the Budyko framework to constrain the HB model proved to be an original way of simulating valuable information for the Lake Papineau water budget, especially for AET values which are typically difficult to assess.

In this study, a parametric Budyko framework was implemented, for the first time, as a semi-empirical conceptual tool for constraining model results within an observed range of evaporative index values. It has been particularly useful in generating AET conditions consistent with discharge observations, operating under a closed catchment water budget assumption. Comparison of model calibration results showed that different model parameters controlling snowmelt (C_M), runoff (f_{runoff}), and infiltration (f_{inf}) were obtained when constraining the HB model with the Budyko framework (compared to the unconstrained HB model). This is coherent with results from Dubois et al. (2021b), who found f_{runoff} to be among the most sensitive parameters governing the partitioning of discharge and AET. Furthermore, accounting for the Budyko framework enabled HB parameter sets that would otherwise have led to inadequate simulation results, particularly with respect to AET, to be rejected. For example, among the 25 best unconstrained parameter sets, Tixeront-Fu ω values reached as high as 3.50, corresponding to conditions otherwise associated with catchments found in environments such as the Great Plains of the USA (Li & Quiring, 2021) and not adequate for the study area.

2.5.4 Challenges to the study of lake-groundwater exchanges

Lake-groundwater exchanges in cold and humid climates are rarely considered in water management at the watershed-scale. Although the scientific literature provides some examples of studies that quantify lake-groundwater interactions (see **Table A2.1** in Appendix), these are from lakes set in a wide range of geological contexts, with estimates derived from different methods having been realized over varying durations and non-overlapping periods. This study brings new insights to the extent of the groundwater contribution to one specific lake, while also highlighting the challenges of better understanding the role of groundwater in lake water budgets more generally.

Contending with limited observations for model calibration was not a problem unique to this research. On the contrary, long-term lake monitoring sites are relatively rare in cold and humid climates. The Turkey Lakes Watershed (TLW; Webster et al., 2021), Canada's Experimental Lakes Area (IISD-ELA; Higgins et al., 2021), and the North Temperate Lakes Long Term Ecological Research site (NTL-LTER; Jones et al., 2012) are among the most important sites affording an appreciation of decadal-scale changes in these environments, though some do not systematically monitor groundwater and all are subject to the precariousness of funding availability (as in the case of the IISD-ELA, which underwent temporary defunding in 2012). Moreover, groundwater recharge is directly measured in few energy-limited environments ($PET.P^{-1} < 1$), hampering investigations of groundwater-surface water interactions more generally (Berghuijs et al., 2022; Berghuijs et al., 2024).

The lake water budget presented here complements other investigations which may be hampered by general constraints related to funding or specific limitations such as spatially punctual direct quantifications of lake-groundwater exchanges (e.g., seepage meters) that are difficult to up-scale or field campaigns only capable of characterizing conditions of limited duration (i.e., stable water isotopes). Recent advances in remote sensing, such as the Surface Water and Ocean Topography (SWOT) satellite (Biancamaria et al., 2016), have shown the potential to monitor lake stage and estimate associated discharge (Andreadis et al., 2025; Riggs et al., 2023), though this is currently limited to lakes > 100 km^2, with further limitations relating to elevation accuracy and monitoring frequency (Bergeron et al., 2020). While not explicitly quantifying lake-groundwater exchanges, such data could potentially be useful in inferring conditions over vast areas, when combined with an understanding of these exchanges from long-term lake monitoring sites.

2.6 Conclusion

Lakes interact closely with their surrounding aquifers, yet long-term lacustrine groundwater exchanges are difficult to quantify, and such investigations have been undertaken for very few lakes situated in cold and humid climates. The objective of this chapter was to quantify the lacustrine groundwater contribution to Lake Papineau using a combination of techniques that could be implemented relatively easily, given the constraint of limited available observations. To this end, a machine learning technique (artificial neural networks), trained on surrogate regional hydrometric and meteorological data, was used to reconstitute past long-term (1964-2022) conditions at the lake outlet (stage and discharge). A catchment water budget model (HydroBudget), calibrated against observed lake discharge and affluent discharge and baseflow, provided long-term estimates of runoff and baseflow to the lake. These components, combined with reconstituted discharge, direct lake precipitation, and evaporation, enabled lacustrine groundwater to be quantified as the residual of a lake water budget. Owing to uncertain measurements, particularly lake outlet discharge, the Budyko framework was integrated into the calibration of HydroBudget to constrain the separation of precipitation into discharge and actual evapotranspiration.

This study provided valuable new knowledge for understanding the extent to which groundwater contributes to lakes in cold and humid climates, a topic that remains largely unexplored despite the mounting pressures of human development and changing climate conditions exerted on these environments. This study contributed new insights into the water budget of a medium-sized lake set in the Canadian Shield of southern Quebec. The results confirmed that Lake Papineau is a drainage lake dominated by surface inflows, but where groundwater inflows are non-negligible. Lacustrine groundwater constitutes approximately 4% of total annual inflows to the lake, though this can vary slightly depending on the discharge estimate used. When accounting for the additional groundwater component of baseflow, groundwater contributes roughly 19% of total annual inflows. The water budget components estimated here were largely consistent with ranges found in the literature, generally associated with long-term, steady-state conditions. A lake set in more permeable geological conditions could receive more groundwater inflow from the surrounding aquifer, while a lake located further south might have more evaporation. Nevertheless, the methods used to assess the lake water budget provide a unique understanding of data limitations and resulting uncertainties that will be very useful in the study of northern lakes in general.

This study underlines the feasibility of methods such as artificial neural networks in extending data series, but caution is urged in their application to closed water budgets where discharge and AET are the only outflows considered. Although the observed conditions were reproduced with reasonable fidelity, reconstituted conditions occasionally violated the Budyko atmospheric demand limit. Integrating evapotranspiration into a machine learning approach for hydrometric reconstitution would be constructive, though this was outside the scope of this research. This work also highlighted the relevance of using a catchment water budget model to assess the contribution of lacustrine groundwater to a lake, though an approach such as the implementation of a numerical groundwater flow model would provide a more robust estimate in explicitly accounting for hydrogeological conditions. Despite efforts to minimize the effects of observation uncertainties, the annual groundwater contribution to Lake Papineau estimated here nevertheless remains uncertain. As lacustrine groundwater estimates were found to be most sensitive to discharge estimates, constraining this component with a tool such as the Budyko framework offered a pragmatic solution to reducing uncertainty.

Most of the methods used to attain this understanding have been used before. Their combination and the new framework within which they were implemented, however, including multi-period comparisons and constraining the HydroBudget model with the Budyko framework, have proven to be essential to assessing lake water budgets. These methods were relatively easily implemented and could be used in different geological and climatic settings with minor adjustments. They do not replace other methods such as those using natural tracers, for example, but stand as a complementary and accessible approach.

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2.8 Tables

Table 2.1 Mean of 25 best Budyko-constrained ($HB_{\bar{C}}$) and -unconstrained ($HB_{\bar{U}}$) calibrated HydroBudget parameters, with uncertainties corresponding to one standard deviation

Parameter		Calibration ranges	Budyko-constrained	Budyko-unconstrained
Melting temperature	T_M (°C)	[-2, 2]	1.5 ± 0.4	1.5 ± 0.5
Melting coefficient	C_M (mm °C^{-1} d^{-1})	[2, 12]	2.2 ± 0.3	2.7 ± 0.6
Freezing time	F_T (d)	[5, 30]	10.9 ± 5.4	11.7 ± 5.6
Threshold temperature for soil frost	TT_F (°C)	[-20, 0]	-10.3 ± 4.8	-11.2 ± 3.3
Antecedent precipitation index time	t_{API} (d)	[1, 5]	3.1 ± 0.8	2.8 ± 1
Runoff factor	f_{runoff} (-)	[0.5, 1]	0.7 ± 0.07	0.5 ± 0.03
Infiltration factor	f_{inf} (d^{-1})	[0.01, 1]	0.3 ± 0.2	0.1 ± 0.04
Maximum soil water content	SW_m (mm)	[50, 500]	289 ± 111	294 ± 104

Table 2.2 Tixeront-Fu ω values fitted to different periods and datasets, averaged over a moving window, and derived from Budyko-constrained or -unconstrained calibrated HydroBudget simulations

Dataset	Period	Fitted Tixeront-Fu ω	30-WY moving average*** (n=29)			25 best HB_C and HB_U parameter sets		
			Min ω	**Mean ω ± sd**	**Max ω**	**Min ω**	**Mean ω ± sd**	**Max ω**
Inferred AET_{P-Q}	**OBS 2016-2022**	1.82 (1.61-2.05)*	-			-		
	REF 1981-2010	2.33						
	ALL 1964-2022	2.23	2.11	2.41 ± 0.16	2.72			
AET_{HB} constrained**	**OBS 2016-2022**	1.97	-			1.90	1.99 ± 0.05	2.05
	REF 1981-2010	2.26				2.15	2.30 ± 0.07	2.38
	ALL 1964-2022	2.22	2.22	2.26 ± 0.02	2.30	2.09	2.23 ± 0.07	2.32
AET_{HB} unconstrained**	**OBS 2016-2022**	2.40	-			2.20	2.48 ± 0.30	3.50
	REF 1981-2010	3.00				2.62	3.21 ± 0.61	5.30
	ALL 1964-2022	2.85	2.78	2.97 ± 0.05	3.00	2.29	3.02 ± 0.59	5.10

* Interval resulting from using discharge at the upper and lower bounds of the rating curve parametric uncertainty.
** With AET_{HB} from $HB_{\bar{C}}$ and $HB_{\bar{U}}$
*** Moving average on inferred AET_{P-Q}, and AET_{HB} using $HB_{\bar{C}}$ and $HB_{\bar{U}}$

Table 2.3 HydroBudget calibration objective function (OF) results for the 25 best parameter sets, with and without post-calibration constraint by the Budyko framework. Uncertainty corresponds to one standard deviation.

Dataset	OF_1	OF_2	OF_3	OF_4	OF_5	Weighted
	KGE Lake Papineau discharge (Q_{Outlet})	KGE La Croix discharge ($Q_{Lacroix}$)	KGE La Croix baseflow (Q_{Base})	MAE Tixeront-Fu ω	KGE AET_{P-Q}	KGE_{Weight}
25 best constrained (HB_C)	0.74 ± 0.01	0.44 ± 0.04	0.39 ± 0.05	0.17 ± 0.05	3.8 x 10^{-4} ± 0.04	0.61 ± 0.02
Mean of 25 best constrained ($HB_{\overline{C}}$)	0.75	0.46	0.40	0.15	-0.14	0.62
25 best unconstrained (HB_U)	0.75 ± 0.01	0.55 ± 0.05	0.49 ± 0.05	0.66 ± 0.3	-0.1 ± 0.05	0.66 ± 0.02
Mean of 25 best constrained ($HB_{\overline{U}}$)	0.76	0.60	0.48	0.58	0.04	0.67

Table 2.4 Simulated mean annual lake catchment water budget components for the Budyko-constrained ($HB_{\bar{C}}$) and -unconstrained ($HB_{\bar{U}}$) calibrated HydroBudget parameter sets for the OBS (2016-2022) and the REF (1981-2010) periods, with associated uncertainties corresponding to one standard deviation (annual contribution of variables to catchment outflows given in parenthesis as the mean percentage). Seasonal percentages correspond to the contribution of each variable to total seasonal catchment outputs, and percentages in brackets correspond to the seasonal contribution to the annual total for each variable. Discharge is the sum of runoff and baseflow.

	Runoff (R)		**Baseflow (Q_{Base})**		**AET**		**Discharge (Q_{HB})**	
	$HB_{\bar{C}}$	$HB_{\bar{U}}$	$HB_{\bar{C}}$	$HB_{\bar{U}}$	$HB_{\bar{C}}$	$HB_{\bar{U}}$	$HB_{\bar{C}}$	$HB_{\bar{U}}$
OBS 2016-2021	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**	**mm.yr^{-1}**
Annual	520 ± 23 (48 %)	440 ± 17 (41 %)	117 ± 18 (11 %)	140 ± 11 (13 %)	432 ± 9 (41 %)	489 ± 21 (46 %)	637 ± 9 (59 %)	581 ± 15 (54 %)
Fall (Sept. - Nov.)	50% [23%]	45% [22%]	11% [21%]	9% [14%]	39% [21%]	46% [20%]	61% [22%]	54% [20%]
Winter (Dec. - Feb.)	67% [14%]	59% [15%]	26% [24%]	34% [27%]	7% [2%]	6% [1%]	93% [16%]	94% [18%]
Spring (Mar. - May)	58% [48%]	51% [49%]	14% [52%]	18% [55%]	28% [28%]	31% [27%]	72% [49%]	69% [51%]
Summer (Jun. - Aug.)	27% [15%]	19% [14%]	1% [3%]	2% [4%]	72% [49%]	79% [51%]	28% [13%]	21% [11%]
REF 1981-2010								
Annual	519 ± 23 (47 %)	434 ± 19 (39 %)	124 ± 18 (11 %)	155 ± 12 (14 %)	459 ± 8 (42 %)	513 ± 17 (47 %)	643 ± 8 (58 %)	589 ± 13 (53 %)
Fall (Sept. - Nov.)	52% [26%]	48% [26%]	15% [32%]	14% [23%]	34% [19%]	38% [18%]	66% [27%]	62% [25%]
Winter (Dec. - Feb.)	54% [7%]	42% [7%]	40% [21%]	51% [25%]	8% [1%]	7% [1%]	92% [9%]	93% [12%]
Spring (Mar. - May)	60% [51%]	53% [53%]	12% [42%]	17% [46%]	28% [28%]	31% [26%]	72% [50%]	69% [51%]
Summer (Jun. - Aug.)	25% [16%]	17% [14%]	2% [5%]	3% [6%]	73% [52%]	81% [55%]	27% [14%]	19% [12%]

Table 2.5 Mean annual lake water budget volumetric fluxes ($Mm^3.yr^{-1}$) for the OBS (2016-2022) and the REF (1981-2010) periods, with associated uncertainties corresponding to one standard deviation (contributions to total inflows and outflows given in parenthesis as the mean percentage)

			OBS 2016-2021	REF 1981-2010
Inflows		**Runoff (R)**	41.9 ± 8.5 (61%)	41.8 ± 8.8 (61%)
		Baseflow (Q_{Base})	9.4 ± 1.9 (14%)	10.0 ± 1.9 (15%)
		Precipitation (VI)	13.6 ± 1.4 (20%)	14.0 ± 1.8 (21%)
Outflows	**Discharge**	**Q_{OBS} or Q_{ANN}**	61.9 ± 11.1 (89%)	52.5 ± 12.1 (78%)
		Q_{HB} constrained ($HB_{\bar{C}}$)	59.7 ± 9.2 (88%)	60.3 ± 11.5 (89%)
		Q_{HB} unconstrained ($HB_{\bar{U}}$)	54.5 ± 9.0 (87%)	55.2 ± 11.3 (88%)
		$Q_{Tixeront-Fu}$	59.7 ± 9.0 (88%)	62.9 ± 11.3 (89%)
	Evaporation (E)		7.8 ± 0.3 (12%)	7.5 ± 0.3 (11%)
Lacustrine groundwater (GW_{Net})		**Q_{OBS} or Q_{ANN}**	4.7 ± 4.2 (6% Inflows)	-5.9 ± 7.2 (10% Outflows)
		Q_{HB} constrained ($HB_{\bar{C}}$)	2.5 ± 0.5 (4% Inflows)	2.0 ± 0.7 (3% Inflows)
		Q_{HB} unconstrained ($HB_{\bar{U}}$)	1.8 ± 0.5 (3% Inflows)	1.3 ± 0.8 (2% Inflows)
		$Q_{Tixeront-Fu}$	2.5 ± 1.7 (4% Inflows)	4.6 ± 2.8 (7% Inflows)
Storage (ΔS)		**Q_{OBS} or Q_{ANN}**	7×10^{-2} ± 0.5 (0.3% Inflows)	-3×10^{-2} ± 0.6 (0.4% Outflows)
		Q_{HB} constrained ($HB_{\bar{C}}$)	-5×10^{-2} ± 0.2 (0.1% Outflows)	-1×10^{-3} ± 0.5 (0.4% Outflows)
		Q_{HB} unconstrained ($HB_{\bar{U}}$)	-4×10^{-2} ± 0.2 (0.1% Outflows)	-1×10^{-3} ± 0.5 (0.4% Outflows)
		$Q_{Tixeront-Fu}$	-4×10^{-2} ± 0.2 (0.2% Outflows)	-2×10^{-3} ± 0.5 (0.3% Outflows)

* All budget components use HB constrained values ($HB_{\bar{C}}$) for discharge, GW_{Net}, and storage unless otherwise noted.

Table 2.6 One-factor-at-a-time sensitivity analysis of OBS period net groundwater volumetric flux to Lake Papineau (GW_{Net}) for each percent increase in every other budget component and for each discharge estimate

		Changes in inflows			Changes in outflows	
Discharge estimate	**Baseline GW_{Net} (Mm^3)**	**ΔRunoff**	**ΔBaseflow**	**ΔDirect precipitation**	**ΔDischarge**	**ΔEvaporation**
Q_{OBS}	4.8	-0.42 (-9%)	-0.09 (-2%)	-0.14 (-3%)	+0.62 (+13%)	+0.08 (+2%)
Q_{HB} constrained	2.5	-0.42 (-17%)	-0.09 (-4%)	-0.14 (-6%)	+0.60 (+24%)	+0.08 (+3%)
$Q_{Tixeront-Fu}$	2.5	-0.42 (-17%)	-0.09 (-4%)	-0.14 (-5%)	+0.60 (+24%)	+0.08 (+3%)

2.9 Figures

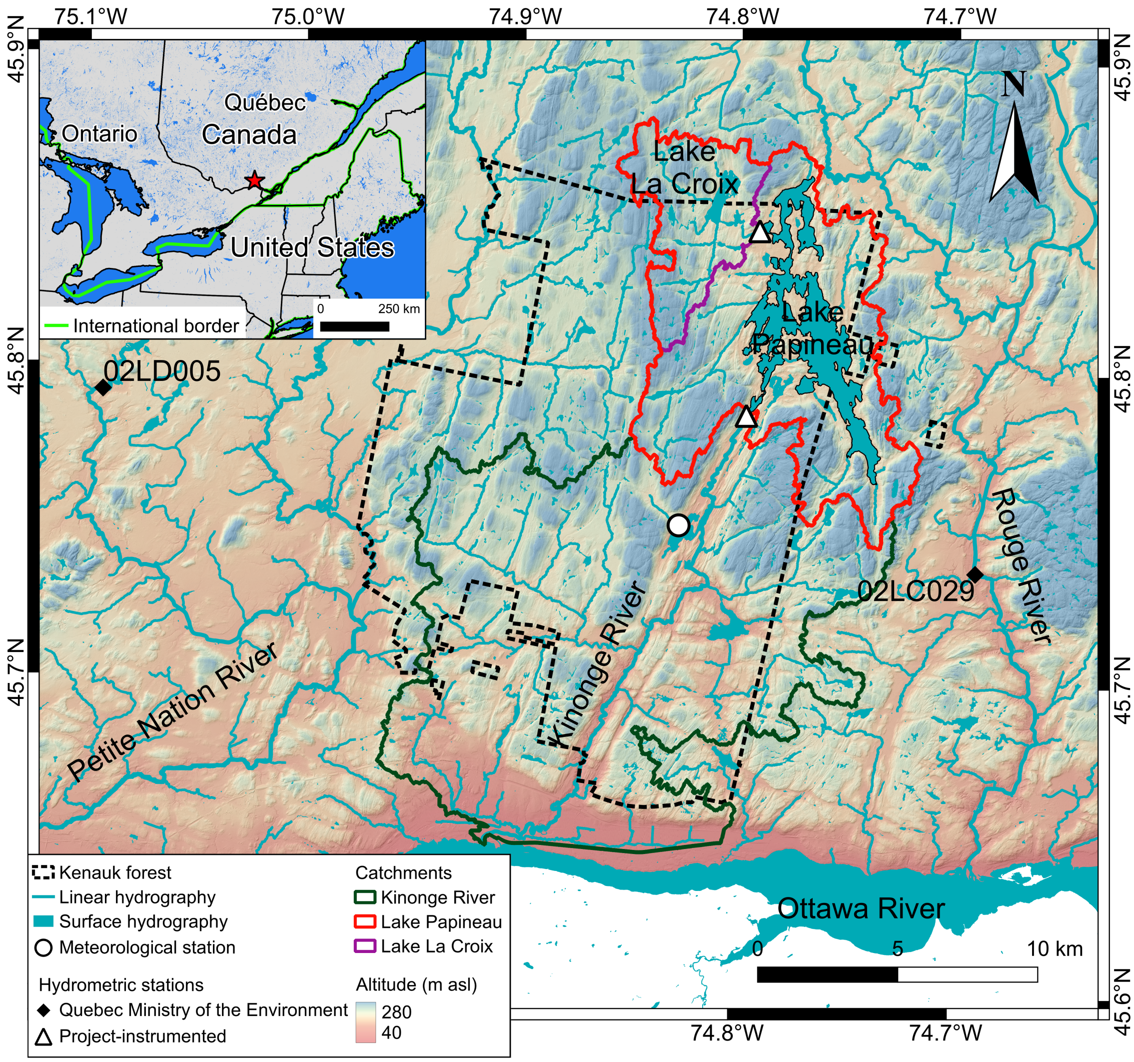

Figure 2.1 Location of the study area and Lake Papineau catchment in the Outaouais region of southern Quebec (Canada), including topography and instrumented sites

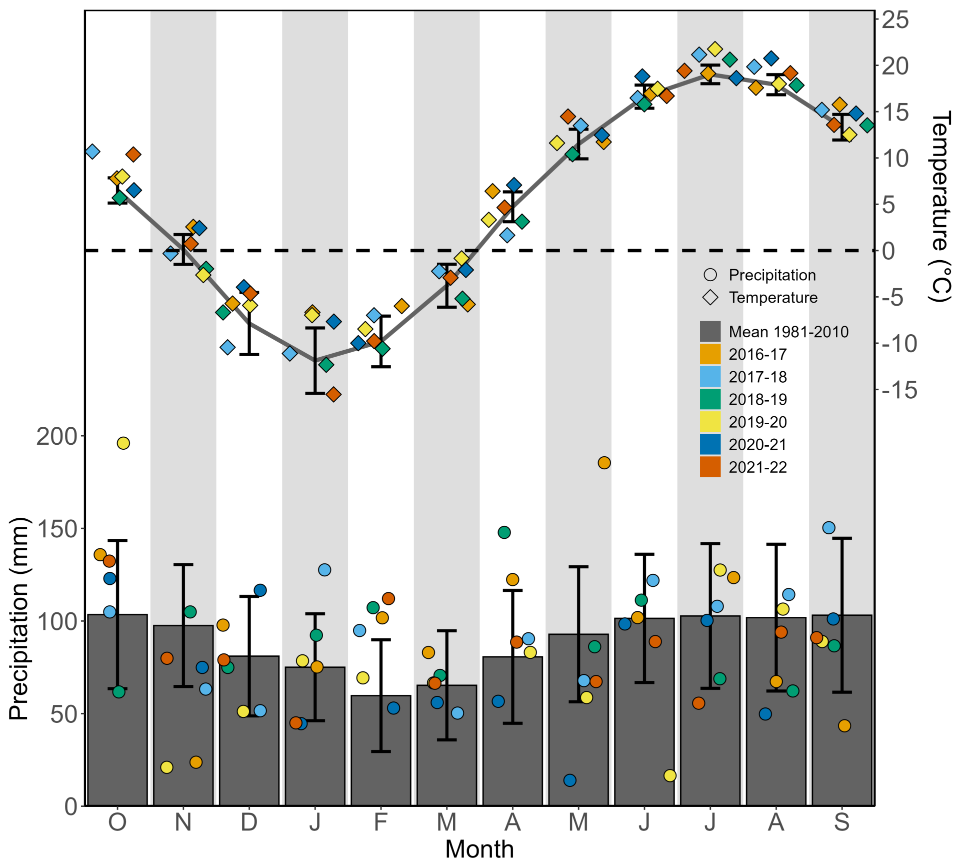

Figure 2.2 Recent (OBS, 2016-2022) and long-term (REF, 1981-2010) air temperature and total precipitation. Error bars indicate one standard deviation of long-term precipitation and temperature data.

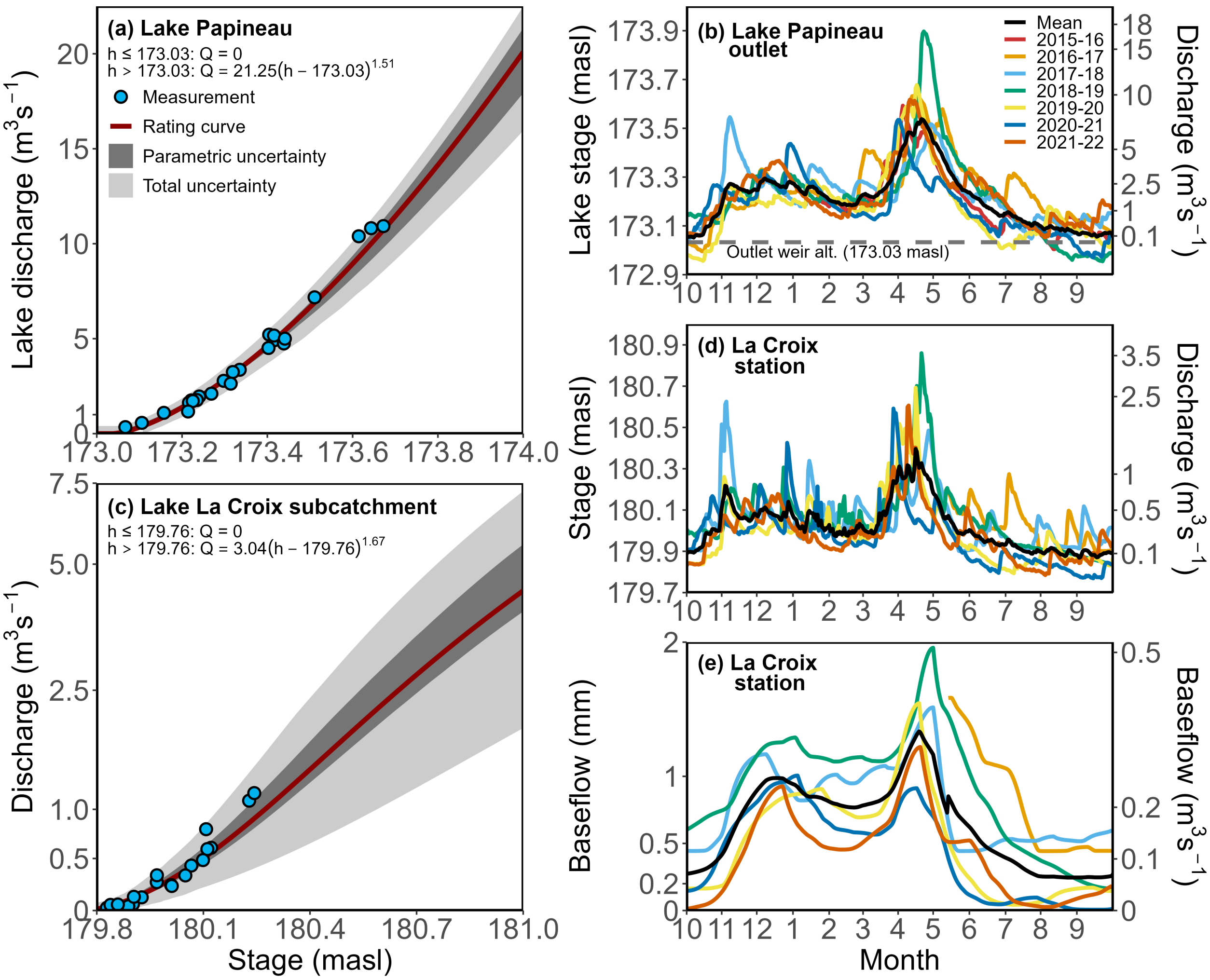

Figure 2.3 Lake Papineau outlet (a) and Lake La Croix sub-catchment (c) rating curves, observed mean daily stages (b, d), and Lake La Croix baseflow (e)

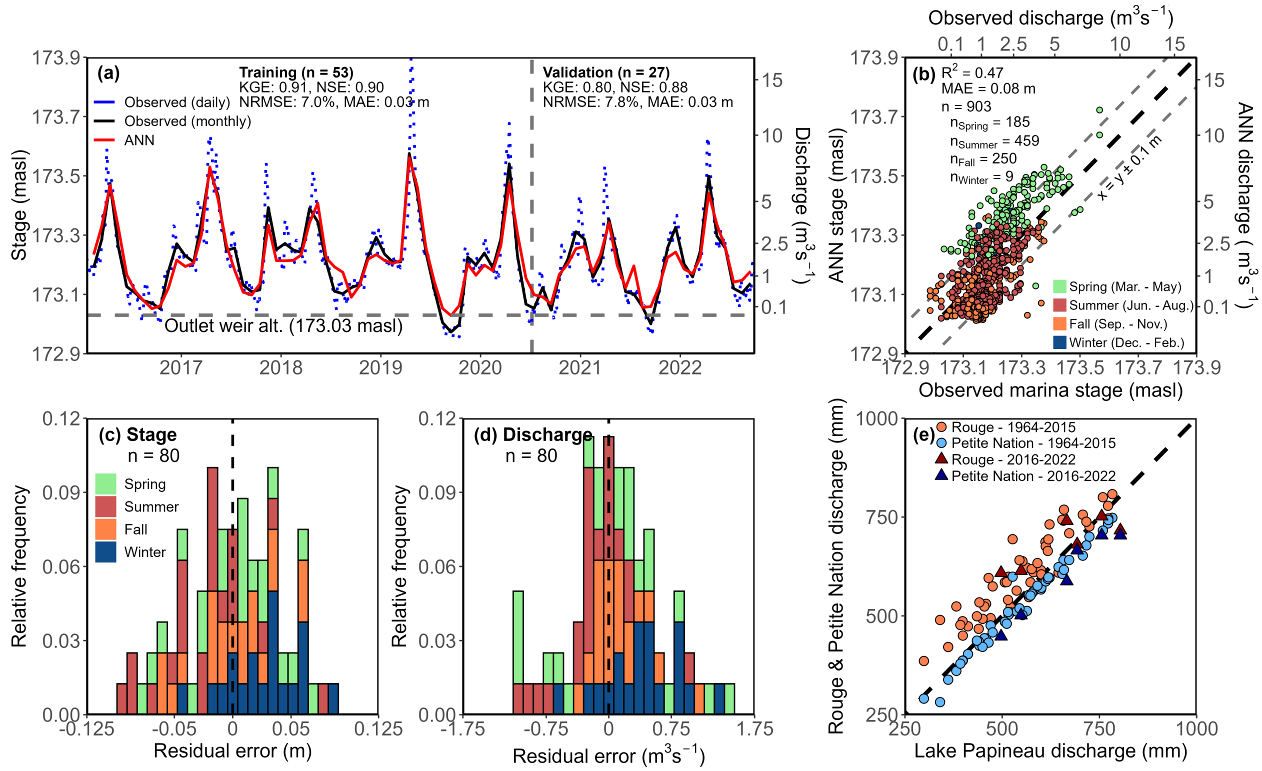

Figure 2.4 Mean monthly ANN and observed (2016-2022) lake stage and discharge for training and validation periods (a), and comparison of daily ANN stage and discharge against observed marina measurements (2002-2014) (b), monthly residual errors (observed – reconstituted) grouped by season for lake stage (c) and discharge (d), and comparison of observed and ANN Lake Papineau discharge with discharge from the Rouge and Petite Nation rivers (e)

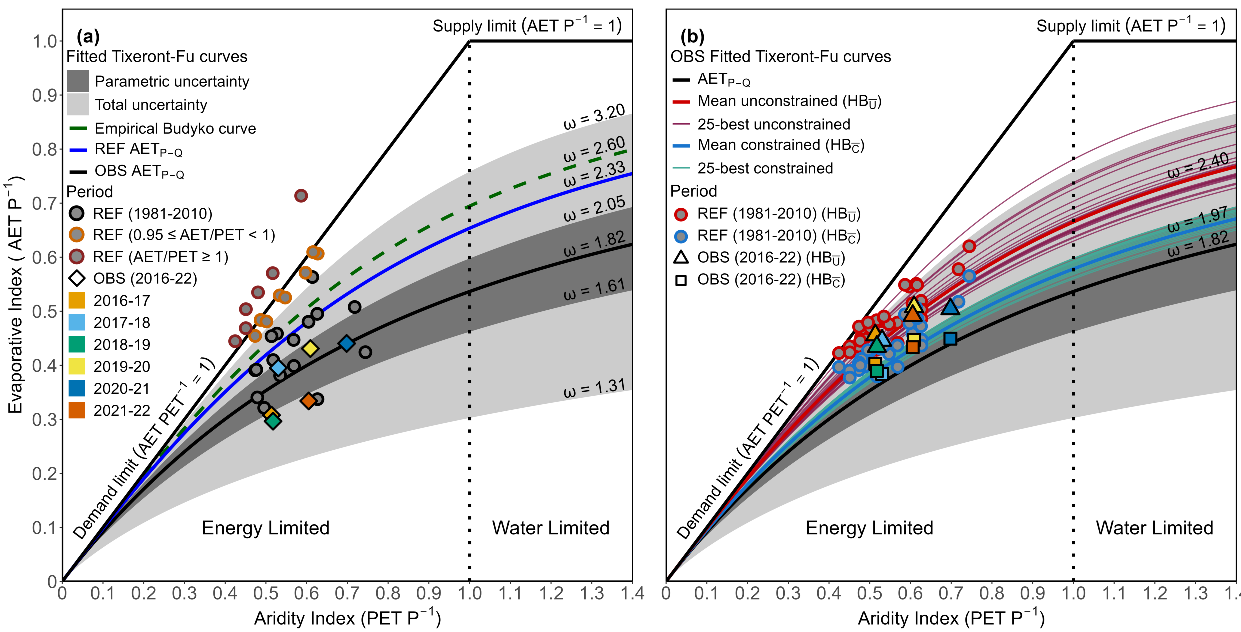

Figure 2.5 Observed and ANN long-term hydroclimatic conditions plotted in Budyko space, with associated Tixeront-Fu parametric curves (a), and parametric curves for the 25 best OBS period calibrated HydroBudget parameter sets either constrained or unconstrained within the BaRatin parametric discharge uncertainty envelope (b)

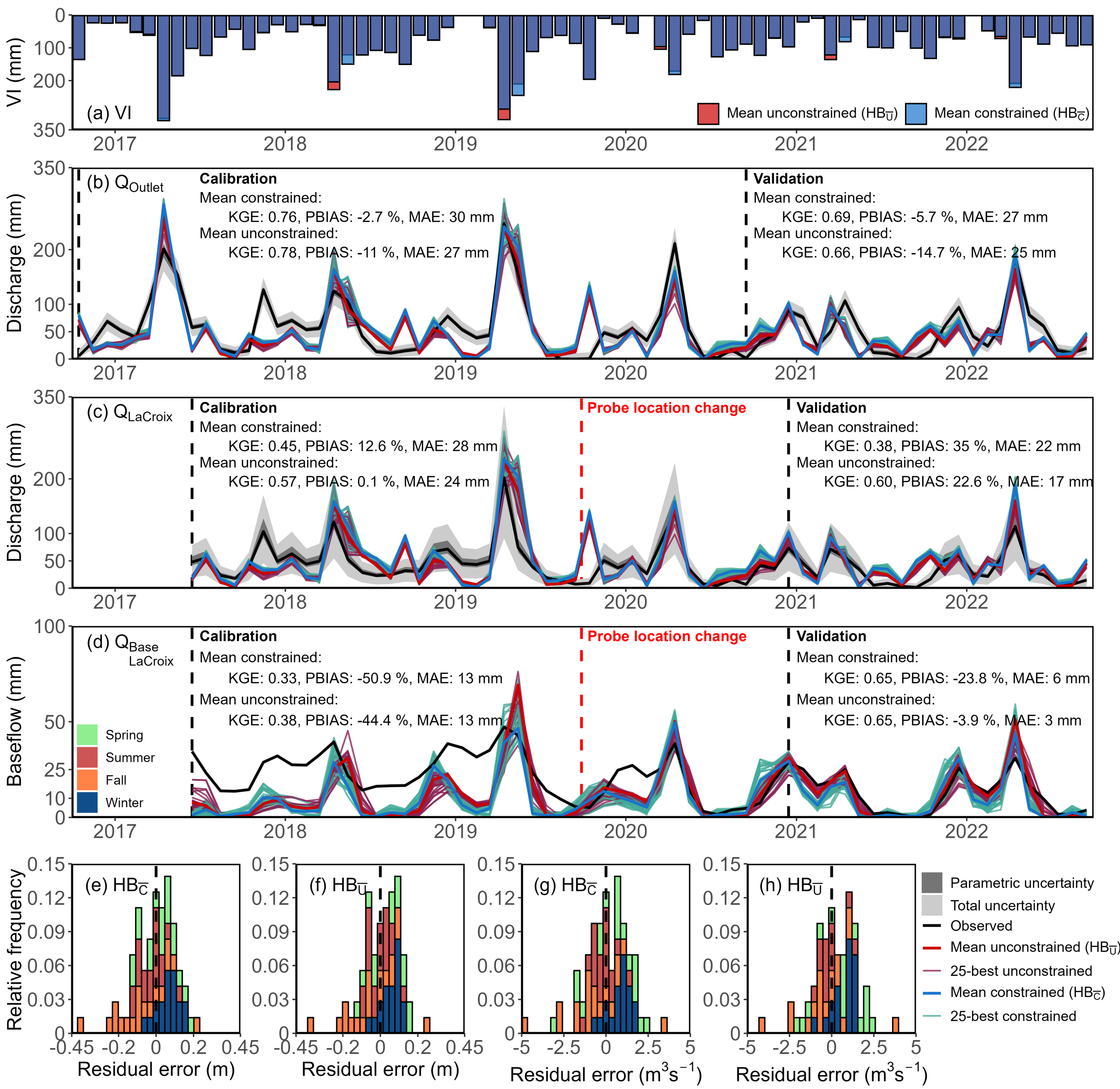

Figure 2.6 Observed and HydroBudget-simulated monthly vertical inflow (a), Lake Papineau discharge (b), Lake La Croix discharge (c), and Lake La Croix baseflow (d), with distinction between HB results having been constrained or unconstained by the Budyko framework. Histograms of Lake Papineau stage (e, f) and discharge (g, h) monthly residual errors (observed – simulated), grouped by season, and obtained using mean Budyko-constrained ($HB_{\bar{C}}$) or -unconstrained ($HB_{\bar{U}}$) calibrated parameters

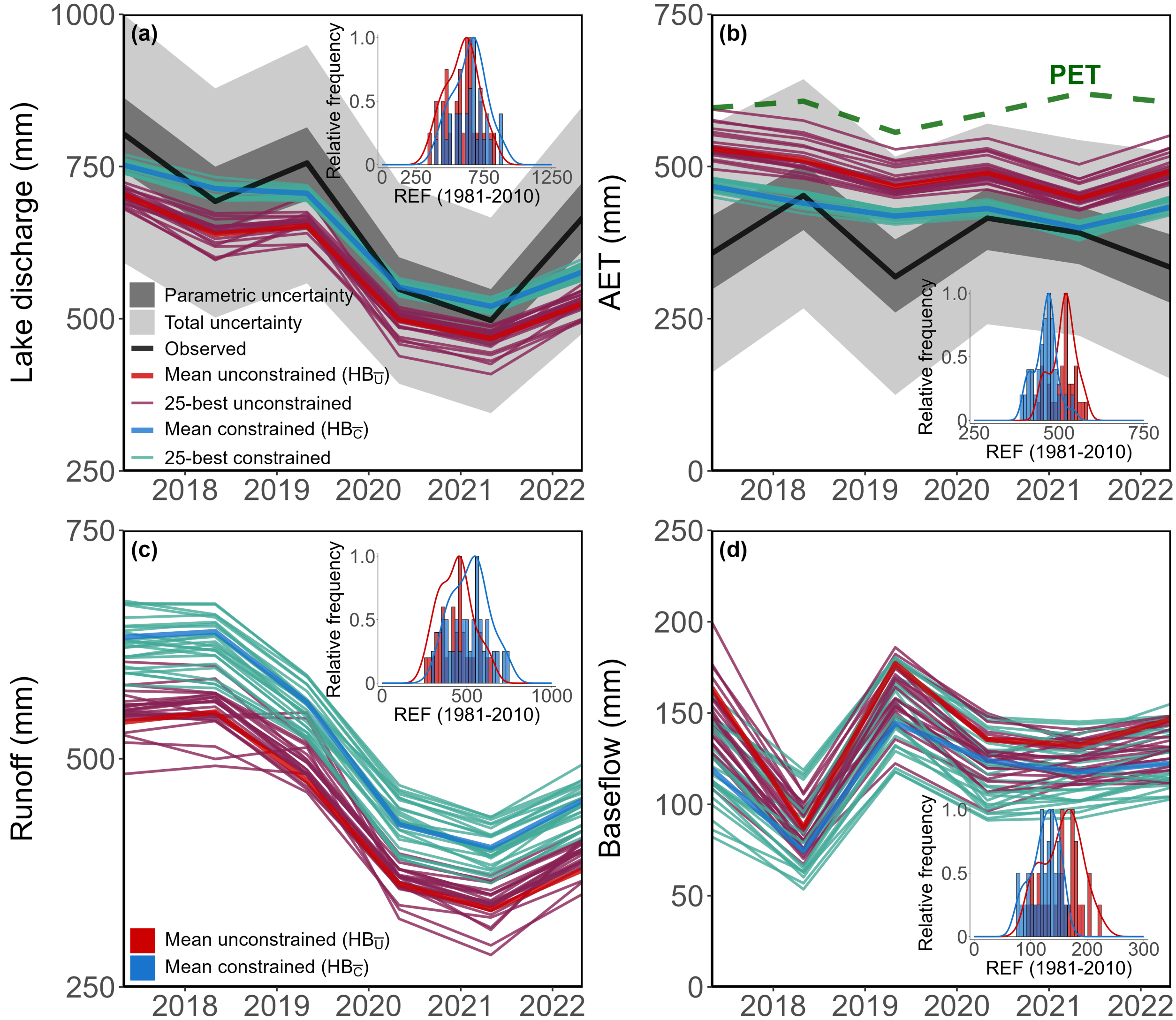

Figure 2.7 OBS period annual observed and HB-simulated Lake Papineau catchment discharge (a), actual evapotranspiration (b), runoff (c), and baseflow (d) under Budyko-constrained (HB_C) and -unconstrained (HB_U) conditions. Inset histograms present long-term REF conditions.

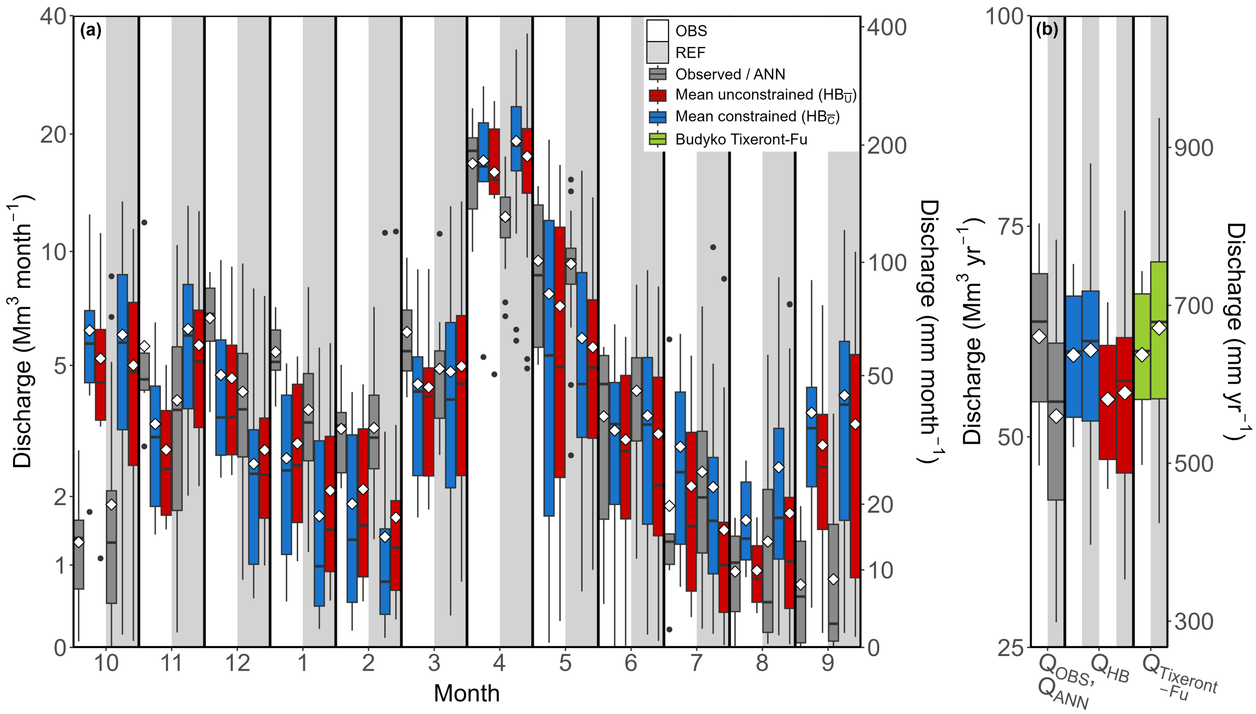

Figure 2.8 OBS and REF period monthly (a) and annual (b) lake outlet discharge estimates. The boxplots show the median, 25th, and 75th percentiles, extremes (whiskers), and outliers (black dots). White diamonds indicate means.

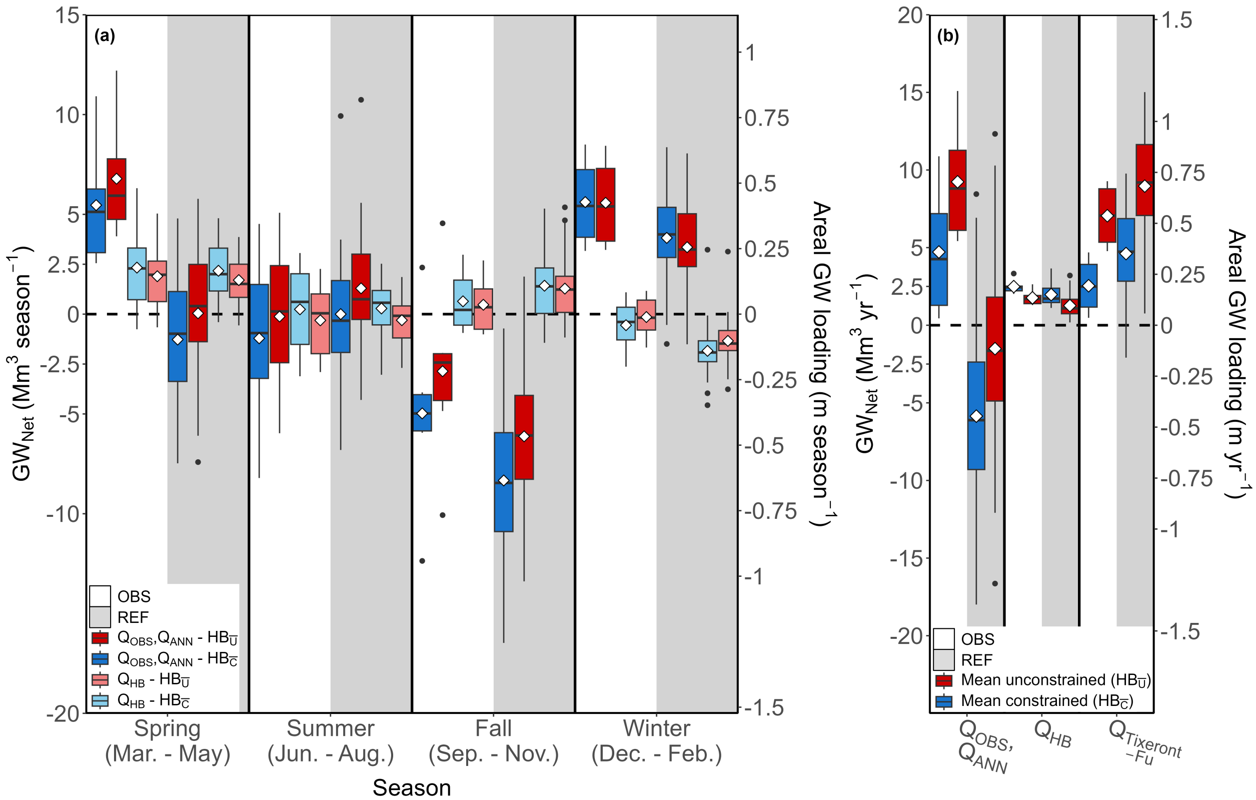

Figure 2.9 OBS and REF period seasonal (a) and annual (b) net lacustrine groundwater contribution to Lake Papineau according to different lake discharge estimates. The boxplots show the median, 25th, and 75th percentiles, extremes (whiskers), and outliers (black dots). White diamonds indicate means.

2.10 Appendix

Table A2.1 Summary of recent publications quantifying lake-groundwater interactions for lakes situated in the Dfb Köppen-Geiger class

No.	Location & Reference	Lake (area, km^2)	Lake type*	Method	Geology	Period	Areal groundwater loading (m.yr^{-1})**
1	IL, USA (Gahala et al., 2024)	Crystal Lake (0.9)	Drainage	Numerical modeling (GFLOW; two-dimensional model)	Shallow glacial deposits	2020 (steady-state)	-0.20
2	ON, Canada (Danielescu et al., 2021)	Poplar Bay, Lake of the Woods (3.4 x 10^{-3})	Drainage	Numerical modeling (FEFLOW)	Shallow glacial till overlaying fractured bedrock	Steady-state	0.76
3	WI, USA (Hanson et al., 2021)	Trout Lake (15.8)	Drainage	Numerical modeling (VIC-GFLOW)	Glacial sand and gravel overlaying bedrock	1979-2013	0.07
		Crystal Lake (0.4)	Seepage				-0.13
4	Canada, USA (Xu et al., 2021)	Lake Superior (8.2 x 10^4)	Drainage	Numerical modeling (HydroGeoSphere)	Quaternary formations overlaying fractured bedrock	1981-2010	0.01
		Lake Huron (6.0 x 10^4)					0.01
		Lake Michigan (5.8 x 10^4)					0.02
		Lake Erie (2.5 x 10^4)					0.01
		Lake Ontario (1.9 x 10^4)					0.02
5	WI, USA (Leaf et al., 2020)	Haskell Lake (0.4)	Drainage	Numerical modeling (SWB-Modflow-LAK)	Glacial sand and gravel	2016-2017 (steady-state)	2.02

* Drainage lakes have a surface water outlet from which discharge is controlled by lake stage. Seepage lakes do not have an outlet.
** GW fluxes were converted to annual areal GW loading (GW_{Net}), normalized to lake surface area.

No.	Location & Reference	Lake (area, km^2)	Lake type*	Method	Geology	Period	Areal groundwater loading ($m.yr^{-1}$)**
6	ON, Canada (Wallace et al., 2020)	Lake Simcoe (722)	Drainage	^{222}Rn	Quaternary formations overlaying fractured bedrock	Summers (May-Sept) 2015-2018	0.10
7	WI, USA (Han et al., 2018)	Big Cedar Lake (3.8)	Drainage	Numerical modeling (SWB-Modflow-LAK)	Quaternary formations overlaying fractured bedrock	2000-2014 (steady-state)	-0.08
		Little Cedar Lake (1.1)	Drainage				1.93
8	WI, USA (Robertson et al., 2018)	Anvil Lake (1.3)	Seepage	Numerical modeling (SWB-Modflow-LAK)	Quaternary formations	1980-2014	-0.16
9	MN, USA (Jones et al., 2017)	Elmo Lake (1.2)	Drainage	Numerical modeling (SWB-Modflow LAK)	Quaternary formations overlaying fractured bedrock	2003-2013 (steady-state)	0.43
		White Bear Lake (9.8)	Seepage				-0.44
		Big Marine Lake (8.3)	Seepage				-0.35
		Snail Lake (0.6)	Seepage				-0.82
10	Canada, USA (Knights et al., 2017)	Lake Superior (8.2×10^4)	Drainage	Water budget	Quaternary formations overlaying fractured bedrock	2015	0.01
		Lake Huron (6.0×10^4)					0.01
		Lake Michigan (5.8×10^4)					0.02
		Lake Erie (2.5×10^4)					0.02
		Lake Ontario (1.9×10^4)					0.01

* Drainage lakes have a surface water outlet from which discharge is controlled by lake stage. Seepage lakes do not have an outlet.
** GW fluxes were converted to annual areal GW loading (GW_{Net}), normalized to lake surface area.

No.	Location & Reference	Lake (area, km^2)	Lake type*	Method	Geology	Period	Areal groundwater loading ($m.yr^{-1}$)**
11	MI, USA (Safaie et al., 2017)	Gull Lake (8.3)	Drainage	Water budget	Glacial outwash (sand and gravel) overlaying shale bedrock	Summers 2014-2015	1.20
12	MT, USA (Shaw et al., 2017)	Georgetown Lake (12.2)	Drainage	Water budget, stable isotopes ($\delta^{18}O$ & δD)	Precambrian metasedimentary rocks	Dec. 2012 to Nov. 2013	0.74
13	WI, USA (Juckem et al., 2014)	Flambeau lakes (combined) (17)	Drainage	Numerical modeling (GFLOW; two-dimensional model)	Glacial outwash (sand and gravel)	Steady-state	0.68
		Fence Lake (14)	Drainage				0.38
		Tippecnoe (0.5)	Seepage				-0.15
		Mindy (3×10^{-2})	Seepage				-0.15
14	WI, USA (Hunt et al., 2013)	Trout Lake (15.8)	Drainage	Numerical modeling (GSFLOW - PRMS-Modflow)	Unconsolidated glacial deposits	1999-2006	0.50
		Allequash Lake (1.6)	Drainage				2.00
		Big Muskellunge (3.6)	Seepage				0.30
15	WI, USA (Juckem & Robertson, 2013)	Shell Lake (10.4)	Seepage	Numerical modeling (Modflow-LAK)	Glacial deposits underlaying sandstone	1949-2011	-0.22

* Drainage lakes have a surface water outlet from which discharge is controlled by lake stage. Seepage lakes do not have an outlet.

** GW fluxes were converted to annual areal GW loading (GW_{Net}), normalized to lake surface area.

No.	Location & Reference	Lake (area, km^2)	Lake type*	Method	Geology	Period	Areal groundwater loading ($m.yr^{-1}$)**
16	MN, USA (Stets et al., 2010)	Shingobee Lake (0.7)	Drainage	Stable water isotope ($\delta^{18}O$)	Unconsolidated glacial deposits	2004-2005	2.70
		Island Lake (0.3)	Drainage				5.40
		Steel Lake (0.3)	Drainage				4.30
		Mary Lake (0.1)	Drainage				13.30
		Crystal Lake (0.8)	Seepage				0.05
		Williams Lake (0.4)	Seepage				0.03
17	ON, Canada (Gleeson et al., 2009)	Bob's Lake (29.5)	Drainage	^{222}Rn	Quaternary formations overlaying fractured bedrock	Summer 2008 (steady-state)	0.60
		Christie Lake (7)	Drainage				0.68
		Otty Lake (6.7)	Drainage				0.28
		Eagle Lake (6.4)	Drainage				0.46
		Crowe Lake (4.4)	Drainage				0.75
		Long Lake (3.4)	Drainage				1.28
		Pike Lake (3.3)	Drainage				0.26
		Big Crosby Lake (2.2)	Drainage				0.37
		Leggat Lake (1.8)	Drainage				0.32
		Farren Lake (1.7)	Drainage				0.26
		Little Crosby Lake (0.6)	Drainage				0.28
		Little Silver Lake (0.6)	Drainage				0.20
		Davern Lake (0.5)	Drainage				0.45
		Miller Lake (0.3)	Drainage				0.54
		Sucker Lake (0.3)	Drainage				0.08
		Abbot Lake (0.1)	Drainage				0.19

* Drainage lakes have a surface water outlet from which discharge is controlled by lake stage. Seepage lakes do not have an outlet.

** GW fluxes were converted to annual areal GW loading (GW_{Net}), normalized to lake surface area.

No.	Location & Reference	Lake (area, km^2)	Lake type*	Method	Geology	Period	Areal groundwater loading ($m.yr^{-1}$)**
18	WI, USA (Robertson et al., 2009)	Whitefish Lake (3.4)	Seepage	Numerical modeling (GFLOW; two-dimensional model)	Sand overlaying fractured crystalline bedrock	2005-6 (steady-state)	-0.25
19	NH, USA (Tiedeman et al., 1998)	Mirror Lake (0.2)	Drainage	Numerical modeling (Modflow)	Shallow glacial till overlaying fractured bedrock	Steady-state	0.85

* Drainage lakes have a surface water outlet from which discharge is controlled by lake stage. Seepage lakes do not have an outlet.

** GW fluxes were converted to annual areal GW loading (GW_{Net}), normalized to lake surface area.

CHAPTER 3

SIMULATED PAST AND FUTURE GROUNDWATER FLOW CONTRIBUTION TO LAKES IN COLD AND HUMID CLIMATES – THE EXAMPLE OF A CANADIAN SHIELD LAKE

3.1 Introduction

Cold and humid regions of the world, such as the Canadian and Fennoscandian Shields and post-glacial landscapes of the northern hemisphere, more generally, are characterized by an abundance of lakes and wetlands (Lehner & Döll, 2004; Messager et al., 2016). These surface water features interact closely with their surrounding aquifers, with groundwater frequently serving as an important component of their water budgets (Harris et al., *in prep*., Thesis Chapter 2; Kidmose et al., 2025; Leaf et al., 2020; Rosenberry et al., 2015) and sustaining groundwater-dependent ecosystems (Kløve et al., 2014; Saccò et al., 2024). With increased warming and changes to global precipitation patterns induced by global climate change (IPCC, 2022), lakes in both these regions and elsewhere risk fundamental alterations to their hydrology (Lane et al., 2023). Investigations of climate change impacts on lakes have focused primarily on issues such as lake water temperature and surface evaporation (Golub et al., 2022; La Fuente et al., 2024), lakes as sources of carbon dioxide (CO_2) release to the atmosphere (Einarsdottir et al., 2017; Kiuru et al., 2018; Tranvik et al., 2009), lake water levels (Kayastha et al., 2022; Ozdemir et al., 2023; Seglenieks & Temgoua, 2022), and lake water quality (Butcher et al., 2017; Messina et al., 2020; Paulsson & Widerlund, 2022), particularly with respect to eutrophication (Meinikmann et al., 2015; Richardson et al., 2019; Suresh et al., 2023) and the health of lentic ecosystems (Brabrand et al., 2002). How climate change will affect lake-groundwater interactions is a topic, however, that remains largely unexplored (Baják et al., 2024; Hanson et al. 2021; Irvine et al., 2024; Pan et al., 2022).

Numerical modeling approaches are not frequently undertaken for quantifying lake-groundwater interactions in cold and humid climates, particularly where direct observations (e.g., flow rates and groundwater levels) are sparse or temporally limited, posing challenges for model calibration. Existing studies demonstrate a large range of groundwater contributions to lakes (Gleeson et al., 2009; Hanson et al. 2021; Harris et al., *in prep*., Thesis Chapter 2; Leaf et al., 2020; Rosenberry et al., 2015), reflecting the strong influence of local hydrogeological settings and climate conditions. While field-based methods provide valuable point-scale information, they often struggle to represent the spatial and temporal heterogeneity inherent in lake-groundwater exchanges and are commonly applied under steady-state assumptions (i.e., mean interannual conditions for a given period) rather than attempt to account for seasonal variability and long-term changes (Ma et al., 2024). In this context, numerical groundwater flow models enable the explicit simulation of groundwater inflow and outflow exchanged between lakes and their surrounding aquifers, rather than inferring net contributions as residuals of classical lake water budgets (Harris et al., *in prep*., Thesis Chapter 2; Trask et al., 2017). A range of modeling strategies has been applied to this problem, from uncoupled surface water-groundwater model combinations (e.g., VIC-GFLOW; Haitjema, 1995; Liang et al., 1994) to fully coupled groundwater-surface water models (e.g., HydroGeoSphere; Therrien et al., 2010), offering increasing capacity to resolve seasonal dynamics and long-term variability in lake-groundwater exchanges.

The impacts of climate change on the hydrology of catchments set in cold and humid climates, such as that of southern Canada, have been the subject of increased investigation (Guay et al., 2015; Larocque et al., 2019; Talbot et al., 2025). Impacts range from the modification of groundwater recharge volumes and timing (Dubois et al., 2022) to more intense and prolonged low flow conditions (Kinnard et al., 2022). How these impacts translate specifically to lake-groundwater interactions in cold and humid climates has been studied to only a limited extent. Arnoux et al. (2017a), for example, studied the impact of climate change on kettle lakes in southern Quebec (i.e., closed basin groundwater-fed lakes without outlets), while Hanson et al. (2021), using the VIC-GFLOW model, investigated changing lacustrine groundwater contributions to Trout Lake (Wisconsin, USA) under the influence of climate change scenarios. Important questions remain concerning the seasonal responses of lake-groundwater interactions, including whether shifts in the timing and magnitude of groundwater recharge alter seasonal lacustrine groundwater exchange, and whether increased lake evaporation or changes in direct precipitation are offset by corresponding adjustments in groundwater contributions.

The objective of this chapter was to assess how climate change alters the hydrological functioning of lakes in cold and humid climates, with particular emphasis on quantifying future seasonal lake-groundwater exchange dynamics. Building on the results of the classical lake water budget estimated for the medium-sized southern boreal lake (Lake Papineau in the Outaouais region of Quebec, Canada) presented in Harris et al. (*in prep*., Thesis Chapter 2), a Modflow groundwater flow model (Niswonger et al., 2011) was implemented for the long-term quantification of all components of the lake water budget, under observed and future climatic conditions based on a 12-member CMIP5 ensemble (forced by RCP4.5 and RCP8.5 emissions scenarios). The results inform how climate change will impact the long-term and seasonal hydrology of lakes set in cold and humid climates and the role of lacustrine groundwater in potentially mitigating these impacts.

3.2 Study area

3.2.1 General description

Lake Papineau (13.1 km^2) is located in the Outaouais region of the province of Quebec (Canada), midway between Montreal and Ottawa (**Figure 3.1**). The 93.7 km^2 lake catchment feeds the Kinonge River, a tributary of the Ottawa River flowing south of the site and ultimately discharging into the St. Lawrence River. To the east and west of the lake catchment, flow the Rouge River and the Petite Nation River, respectively, located at the limits of the studied region. Elevation spans 420 m (mean elevation 212 masl), with the highest point (454 masl) situated in the northeasternmost area, and the Ottawa River to the south constituting the lowest point (35 masl). The Lake Papineau catchment itself ranges from 173 to 444 masl (mean 235 masl), with the lowest point constituting the lake outlet. Lake Papineau contains an estimated 258 Mm^3 of water, with mean and maximum depths of 20 and 80 m, respectively. The lake catchment is comprised almost entirely of forest (71%), consisting of maple and deciduous species, with limited human development owing to the administration of the territory by the Kenauk Institute and the Nature Conservancy of Canada (MFFP, 2018). The remaining land cover consists of smaller lakes (total 4.8 km^2) and wetlands (total 8.9 km^2).

3.2.2 Geology and hydrogeology

Situated in the Precambrian Canadian Shield, groundwater in the study area circulates within a fractured crystalline bedrock composed of plutonic igneous (granites) and metamorphic rocks (gneiss, paragneiss, marble, and quartzite) (Rivera, 2014). Quaternary geological features overlaying the bedrock were grouped into five classes following the methodology of Comeau et al. (2013) (**Figure 3.2**). Silty sand and gravel, characteristic of the thin glacial till overburden (class 3), is the most prevalent Quaternary feature across both the entire model domain and the Lake Papineau catchment (76.3% and 84.0% of the surface areas, respectively). Clays and silts associated with the Champlain Sea incursion of the Late Wisconsinan deglaciation (class 1) are found primarily in the lower topographical regions of the model along the floodplain of the Ottawa River (less prevalent within the lake catchment). When taken together, marine and lacustrine sediments (class 2), coarse sand and gravel (class 4), and sedimentary rocks of the Saint-

Lawrence platform (class 5), occupy a small portion of the study area (7.7%) and of the Lake Papineau catchment (9.4%). The fractured crystalline bedrock (class 6) is present at the surface on 2.6% and 1.3% of the study area and of the Lake Papineau catchment, respectively.

Hydrogeological observations consist primarily of eight project-instrumented wells (hereafter referred to as Kenauk wells) equipped in 2016 with *Solinst Levelogger*s, providing hourly heads in the unconfined fractured bedrock aquifer (**Figure 3.2**). Of these, six wells are near Lake Papineau (mean distance of 67 m from the shore). As most of these wells were actively pumped (except for wells Cedar, Poisson Blanc, and Maholey), hourly heads varied frequently, with a mean head range of 6.8 m across all wells. After applying an interquartile range filter to lessen the effects of pumping, the monthly interannual depth to static water level (DSWL) for all eight wells was 2.8 ± 2.3 m, pointing to a relatively shallow aquifer in proximity to Lake Papineau. Additional heads and DSWL were available from the Quebec provincial well database (MELCCFP, 2020). Following the methodology of Tremblay et al. (2015), outliers from this more uncertain dataset were excluded using a combination of geospatial and statistical analyses (e.g., exclusion of wells for which DSWL deviated by more than 5 m from the regional mean). The initial 662 provincial wells located within the study domain were reduced to 435 by retaining only those in the regional fractured crystalline bedrock aquifer. These wells presented a larger and more uncertain DSWL of 6.6 ± 5.7 m, compared to the project-instrumented wells.

3.2.3 Hydrography

Since its instrumentation in 2016 with a *Solinst Levelogger*, following the replacement in 2015 of a concrete, human-operated dam used since 1975 with a progressive weir, the Lake Papineau outlet has exhibited relatively limited water level variation (0.95 m), with hourly stage recordings ranging from 172.95 to 173.90 masl. A rating curve at the lake outlet has been progressively constructed since 2016, showing that the mean annual discharge varied from 1.5 to 2.4 m^3s^{-1} between 2016 and 2022 (OBS period). Water level highs coincided with the spring freshet (April, 173.5 masl), with lows maintained over the course of the summer months (July to October, 173.1 masl). As lake discharge was controlled by a human-operated dam prior to 2015, past conditions were not available prior to instrumentation, but long-term discharge conditions have been reconstituted with an artificial neural network approach (Harris et al., *in prep*., Thesis Chapter 2).

Surface water inflows into Lake Papineau from a selection of its numerous sub-catchments have been measured since 2016. Rating curves have been developed for both the largest of these, the Lake La Croix affluent (22.4 km^2, 24% of the total lake catchment area), and from two smaller sub-catchments (Jackson and 041 – 3.3 km^2 and 1 km^2, respectively) (Harris et al., *in prep*., Thesis Chapter 2). These data allowed for estimations of the baseflow contribution of runoff to the lake, using the Lyne and Hollick (1979) recursive digital filter. On a mean annual basis for the OBS period, the Lake La Croix sub-catchment discharge (0.38 m^3s^{-1}) constituted an estimated 28% of the discharge measured at the Lake Papineau outlet, with baseflow (0.17 m^3s^{-1}) constituting 44% of sub-catchment discharge. Sub-catchments Jackson and 041, in turn, with mean annual discharges of 0.04 and 0.02 m^3s^{-1}, respectively, together constituted 4% of observed Lake Papineau outlet discharge.

Simulations of the mean long-term lake catchment water budget, using the HydroBudget (HB) catchment water budget model (Dubois et al., 2021a, b) have shown that during the 1981-2010 reference period (hereafter the REF period), lake discharge, expressed in mm of the lake catchment surface area, (643 $mm.yr^{-1}$, 58% of annual precipitation) was of a similar order of magnitude to the other catchment release function, actual evapotranspiration (AET – 459 $mm.yr^{-1}$, 42% of annual precipitation) (Harris et al., *in prep*., Thesis Chapter 2). Potential evapotranspiration (PET) for this period, estimated using the Oudin et al. (2005) formula and constituting the theoretical limit for AET, was 572 $mm.yr^{-1}$. Potential groundwater recharge, representing the maximum recharge that can reach the saturated zone, was estimated to vary between 76 and 162 $mm.yr^{-1}$ (mean 124 $mm.yr^{-1}$) for the REF period (i.e., 19% of the long-term mean interannual discharge at the lake outlet).

3.2.4 Meteorological conditions

The study area is characterized by a humid continental climate with warm summers and no dry season (Köppen-Geiger class of Dfb; Kottek et al., 2006). Daily precipitation and air temperature data for the study site were taken from gridded data (1961-2017) (Bergeron, 2016), and a project-specific meteorological station (2016-present) located approximately 5 km south of the Lake Papineau outlet. During the 1981-2010 REF period, long-term mean annual temperature was 4.7°C, while average annual precipitation was 1065 $mm.yr^{-1}$, of which 23% fell as snow. Precipitation conditions were similar during the 2016-2022 period of measured data, with 1039 $mm.yr^{-1}$ of precipitation, albeit accompanied by higher temperatures (mean 5.7°C) and less snow (20% of annual precipitation). Owing to this increase in temperature, both OBS period temperature and PET (mean 595 mm.yr^{-1}) presented significantly different distributions from that of the REF period (mean 572 mm.yr^{-1}) (Kolmogorov-Smirnov (KS) test, p-value < 0.05).

3.3 Methods

3.3.1 Groundwater flow model

3.3.1.1 Spatial and temporal discretization

The United States Geological Survey (USGS) groundwater flow model, Modflow-NWT (Niswonger et al., 2011) was implemented to simulate the water budget of Lake Papineau, specifically the exchange of groundwater between the lake and its surrounding fractured bedrock aquifer. The Newton-Raphson model formulation (Modflow-NWT), making use of the Upstream Weighing (UPW) inter-cell conductance package, was selected specifically to better account for the difficulties of model convergence resulting from drying and rewetting nonlinearities within the context of unconfined fractured bedrock aquifers.

The model domain was roughly 39 km N-S by 23 km E-W, covering a total area of 884 km^2, with the Lake Papineau catchment situated at the center (**Figure 3.2**). The uniform 100 m-resolution model consisted of 88,407 active square grid cells which were repeated over the six model layers, giving a total of 530,442 cells. The five topmost layers had uniform thicknesses of 10, 20, 30, 60, and 80 m (from the top down), with the bottom layer having a variable thickness defined by a bottom elevation set to -300 m, ensuring sufficient minimum thickness throughout the model domain. The topmost layer was divided into zones based on Quaternary geological features and sedimentary and crystalline bedrock exposed at the surface, while subsequent layers were characterized by varying degrees of fracturing for the Grenville Province bedrock.

Transient-state simulations were undertaken with monthly stress periods (i.e., a time interval during which boundary conditions are held constant), each one using ten time-steps. A 16-year period from 1964 to 1980 was used as an initial spin-up, driven by monthly transient potential groundwater recharge and lake boundary conditions. Following this, stabilization of simulated heads in eight Kenauk wells confirmed that the spin-up period was of sufficient duration to remove initialization artifacts that could have impacted model simulations for the periods of interest, beginning with the REF period.

3.3.1.2 Boundary conditions

The southern model limit corresponded to the Ottawa (Outaouais) River and was represented using a constant head (Dirichlet) boundary condition within the first two layers of the model (from the surface to a depth of 30 m) (**Figure 3.2**). This was presumed consistent with the influence imposed by a river of such regional importance, with long-term mean discharge of 1980 m^3s^{-1} (Hudon, 2000). The northern boundary of the model domain was positioned at a sufficient distance from the Lake Papineau catchment to limit artificial boundary influences and was represented as a no-flow (Neumann) boundary, consistent with the regional surface water divides. The Rouge and Petite Nation rivers (long-term mean interannual discharges of 106 and 23 m^3s^{-1}, respectively) constituted the eastern and western limits of the model and were represented using the Modflow River package (RIV) in the upper layer of the model. The Maskinongé River, flowing north of the Lake Papineau catchment, but for which long-term discharge was not known, was also represented with the RIV package.

Small rivers and streams were represented with the Modflow Drain (DRN) package, with DRN features assigned exclusively to mapped perennial watercourses having a minimum upstream flow accumulation area of 1 km^2 (100 cells). This criterion aligns with the threshold proposed by Gagné et al. (2018) (1.9 km^2) for groundwater travel-time simulations in fractured bedrock aquifers in southern Quebec. Smaller lakes within the model domain were simulated using a constant head boundary condition in the topmost layer, with elevation corresponding to the DEM surface. For the few lakes for which project-specific stage time-series data was available (lakes La Croix and Mills), observed annual variations were on the order of 30 cm, thus justifying the use of constant boundary conditions.

Groundwater recharge (GWR) to the unconfined fractured bedrock aquifer was estimated using the HydroBudget (HB) catchment water budget model (Dubois et al., 2021a, b), developed for the simulation of GWR in cold and humid climates. Using the runoff curve number (RCN) method, the parsimonious eight-parameter model was calibrated under the 2016-2022 observed catchment conditions (Harris et al., *in prep*., Thesis Chapter 2). RCN values were attributed to 100 m x 100 m grid cells based on slope, land cover, and pedology. They remained constant for all simulation periods, under the assumption of unchanging future land cover. GWR was applied at the topmost active model layer. Two HB parameters (melting temperature and melting coefficient) governed a degree-day snowmelt model for transforming total precipitation to available liquid water (vertical inflow – VI) in the simulation of GWR.

Groundwater exchange between the aquifer and Lake Papineau was simulated using the Modflow LAK package (Merritt & Konikow, 2000), representing dynamic lake-aquifer exchanges through time-varying lake stage and water balance calculations. HB-simulated VI was used for direct precipitation to the Lake Papineau surface, while direct lake evaporation was estimated using the Oudin et al. (2005) formula for potential evapotranspiration (PET). Whereas this method may not be optimal for estimating lake PET, limited data requirements (air temperature and latitude-based extraterrestrial radiation) made it particularly useful in simulating observed and future evaporative demand. Runoff from the watershed to the lake was also estimated using the HB model. As the DRN package removes the baseflow groundwater contribution to perennial streams from the model rather than routing it to the LAK package, HB-simulated total runoff input to the LAK package consisted of the sum of excess infiltration (Hortonian) runoff, saturation excess (Dunnian) runoff, and groundwater exfiltration (baseflow) to the land surface.

The LAK package was implemented in conjunction with the streamflow routing (SFR2) package (Niswonger & Prudic, 2005), simulating the Kinonge River from the Lake Papineau outlet to its confluence with the Ottawa River. SFR2 allowed Lake Papineau to be discharged using a stage-discharge table, based on the lake outlet rating curve, for increments of 0.05 m above the 173.03 masl activation threshold of the progressive weir. A triangulated irregular network (TIN), constructed using the Lake Papineau bathymetric map (TrakMaps, 2003), allowed for the definition of Modflow cell surfaces across which lake-aquifer groundwater fluxes would occur. A total of 1,331 model cells within the top layer were intersected by the LAK bathymetry, with progressively fewer intersected with increasing depth (409 and 170 in the second and third layers, respectively). All cells intersected by the LAK TIN became inactive and groundwater exchanges (inflow to the lake and outflow to the surrounding aquifer) were recorded directly by the GAGE package at the lake outlet.

3.3.1.3 Hydrogeological parameters

Quaternary and fractured bedrock hydrogeological properties were defined using Modflow material sets to facilitate calibration (**Table 3.1**). Quaternary geological formations were accounted for using the 10 m-thick top layer and were separated into five classes, following Comeau et al. (2013), with a sixth class corresponding to the outcropping of the Grenville Province crystalline bedrock at the surface. Properties of the remaining five layers (2 through 6) distinguished the progressive decrease in fracturing with depth for this 6th bedrock class. Quaternary geology geospatial data was modified from MERN (2018).

Initial material hydraulic conductivity (K) intervals for steady-state calibration were taken from regional studies (Comeau et al., 2013; Daigneault et al., 2012; Sterckx, 2013), while transient simulation parameter targets for specific yield (S_y) and specific storage (S_s) were obtained from the literature (Comeau et al., 2013; Domenico & Mifflin, 1965; Kuang et al., 2020). All hydrogeological properties were applied uniformly by material class and remained constant. Furthermore, all materials were defined as isotropic (K_x=K_y=K_z) to facilitate model convergence. This choice was justified by the regional literature suggesting a rapid decrease in bulk K with depth (Montcoudiol et al., 2018; Snowdon et al., 2020). Parameters governing groundwater-surface water exchanges, including conductance (for RIV and DRN boundary conditions), leakance (LAK boundary condition), and streambed hydraulic conductivity, were initially informed by values reported for southern Quebec (Gagné et al., 2018; Levison et al., 2014) and comparable hydrogeological settings, with final parameter values evaluated based on model performance.

3.3.1.4 Model calibration strategy

Model calibration was performed first in steady-state, reflecting the mean interannual conditions for the 1964-2022 period of all available observed climatic conditions, using the automated parameter estimation software PEST (Doherty, 2018). Calibration was first realized simultaneously for aquifer hydraulic conductivities, conductance, streambed hydraulic conductivity, and leakance, then was refined only on K values due to the limited sensitivity of the model to the other parameters. The PEST objective function minimized differences between simulated and observed hydraulic heads in the 443 Kenauk and provincial observation wells. Owing to computational time constraints, transient-state calibration was performed manually by trial and error, calibrating specific yield (S_y) and specific storage (S_s) to reproduce measured piezometric head time series in the eight Kenauk observation wells during the OBS period (2016-22). Transient-state observed Lake Papineau stage and discharge were also compared to LAK simulation results. Similarly, DRN-simulated baseflows for the three instrumented lake sub-catchments (La Croix station, Jackson, and 041) were compared against observed (Lyne and Hollick-filtered) and HB-simulated baseflows.

3.3.2 Simulation of climate change scenarios

Simulations of possible future hydrological conditions, under two representative concentration pathways (RCPs 4.5 & 8.5) (van Vuuren et al., 2011) of greenhouse gas emissions, were realized using a selection (**Table 3.2**) of 12 global climate model (GCM) daily outputs (air temperature and precipitation) from the 5th phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012). These scenarios were provided by Ouranos, the Montréal-based Consortium on Regional Climatology and Adaptation to Climate Change. From an initial set of 54 GCM-RCP outputs (27 of each of the two RCPs), the k-means clustering technique (Casajus et al., 2016) enabled the identification of 12 clusters, based on both annual and seasonal changes in temperature and precipitation between a reference period (REF, 1981-2010) and a near-future period (FUT1, 2041-2070), from which the simulation closest to the cluster centroid was retained (CE2-4.5, using the CanESM2 GCM, was manually retained from its cluster).

The retained climate change scenarios included eight RCP4.5 (A10, B1M, CE2, CMS, GF3, GIR, INM, and MIE) and four RCP8.5 (A13, BNU, MIC, and MRE). All scenarios were bias corrected against the 1981-2010 period of the Natural Resources Canada gridded observation database (NRCANmet – Hopkinson et al., 2011; Hutchinson et al., 2009; McKenney et al., 2011) and downscaled to a 10 km x 10 km reference grid using the quantile-quantile mapping technique (Maraun, 2016; Mpelasoka & Chiew, 2009). Long-term (30-year) lake water budgets were contrasted between the REF, FUT1, and FUT2 (2071-2100) periods.

The four RCP8.5 scenarios consistently showed both increasing precipitation and temperature over the course of the century, whereas RCP4.5 scenarios generally presented less important increases in temperature and more variable changes in precipitation (**Figure 3.3a, b**). The 12-member GCM-RCP ensemble presented a significant increase (Wilcoxon signed-rank test (Wilcoxon, 1945), $p < 0.001$) in mean ± one standard deviation annual air temperature for the FUT1 (+2.9 ± 1.0°C) and FUT2 (+4.2 ± 1.8°C) periods, with respect to the REF period (mean 4.7°C), with all changes for all ensemble members significant (Student's t-test, p-value < 0.05). Similarly, the ensemble pointed to a significant increase in annual precipitation, albeit with changes for several RCP4.5 members not being significant (B1M, CMS, and INM for FUT1 and B1M, CE2, and INM for FUT2). Ensemble mean annual precipitation presented increases of 125 ± 78 $mm.yr^{-1}$ (+12 ± 7%) for FUT1 and 162 ± 108 $mm.yr^{-1}$ (+15 ± 10%) for FUT2, with respect to the REF period (1065 $mm.yr^{-1}$).

3.4 Results

3.4.1 Calibrated model

Calibrated hydraulic conductivity (K) values were within the standard deviation ranges compiled by Comeau et al. (2013), except for the clays and silts (class 1), for which the calibrated value was above the upper limit (**Table 3.1**). PEST results showed K values to be insensitive to modifications of RIV and DRN conductances, SFR2 streambed K, and LAK leakance parameters. Values for each of these parameters, based on the literature and for the closest associated material set, were therefore selected and applied uniformly throughout the model. RIV conductance was set at 259 $m^2d^{-1}m^{-1}$, under the assumption that rivers occupy the entire cell width and consist of 5 m thick sediments, with K = 1.5 x 10^{-4} ms^{-1}. The Kinonge River was similarly parameterized with SFR2 leakance of 1.1 x 10^{-4} ms^{-1}, closely matching the calibrated K of class 3. A DRN conductance of 432 $m^2d^{-1}m^{-1}$ (K = 1.0 x 10^{-3} ms^{-1}, drain material = 10 m, and width = 2 m) was shown to adequately simulate the annual baseflow contribution for the three instrumented Lake Papineau sub-catchments, and was similar to values used in other numerical modeling investigations in southern Quebec (e.g., Levison et al., 2014). A LAK leakance value of 0.35 day^{-1} (corresponding to K = 2 x 10^{-5} ms^{-1}, with sediment thickness = 5 m) yielded steady-state Lake Papineau discharge (2.2 m^3s^{-1}) and stage (173.3 masl) resembling OBS period observed conditions (2.0 m^3s^{-1} and 173.2 masl, respectively).

The post-calibration manual sensitivity analysis of the LAK leakance parameter, realized by varying the imposed value of 0.35 day^{-1} by ± one order of magnitude, indicated a negligeable impact on mean OBS monthly values of both lake stage (< 1 mm) and discharge (< 0.01 m^3s^{-1}). Decreasing the leakance parameter by one order of magnitude decreased the mean annual net groundwater exchange (GW_{Net}) between the lake and surrounding aquifer by -0.24 $Mm^3.yr^{-1}$ or -5.1% of the OBS period baseline contribution (4.7 $Mm^3.yr^{-1}$). Interestingly, when increasing leakance, the mean annual contribution also decreased slightly (-0.04 $Mm^3.yr^{-1}$ or -0.9% of the baseline), owing to an increase in water outflow from the lake. Considering both the insensitivity of lake stage and discharge and the comparatively small changes in GW_{Net} contribution induced by changes to the parameter, the chosen LAK leakance value was deemed satisfactory.

While calibrated specific storage (S_s) values for most of the Quaternary materials (**Table 3.1**) were higher than those found in the literature, from which manual calibration targets were derived (Kuang et al., 2020), other sources record higher intervals (Domenico & Mifflin, 1965). It should be noted that model geology was greatly simplified and frequently did not correspond precisely to classes found in source material. Calibrated material specific yields (S_y), ranging from 0.01 to 0.20, (with the deepest fractured bedrock materials ascribed as little as 1.0 x 10^{-4}) were, however, consistent with the expected interval of 0.01 to 0.30 for unconfined aquifers more generally (Kuang et al., 2020), and specifically with the regional estimate (6.0 x 10^{-3}) for the Grenville Province (Comeau et al., 2013).

Steady-state simulated heads in the observation wells were equally distributed along the 1:1 line with respect to observed values, with no systematic bias (**Figure 3.4**). All 435 provincial wells presented a 6.1 m mean absolute error (MAE), which is considered reasonable given the uncertainties associated with this database and the representation of the fractured bedrock aquifer with a porous media equivalent. The eight Kenauk wells, by contrast, presented a much lower MAE (2.2 m), with only two wells (Maholey and Poisson Blanc), situated furthest from Lake Papineau, presenting residual simulated head (observed minus simulated) > 1.5 m. A total of 66 out of the 443 observation wells presented simulated residual head values 10 m above or below observed values, of which only 12 had simulated heads between 10 and 20 m above observed values, and only one > 20 m. All 87,076 active top layer cells (excluding the 1,331 LAK cells) presented a simulated steady-state DSWL of 9.2 ± 7.1 m, comparable to the simulated (6.4 ± 5.6 m) and observed (6.6 ± 5.7) DSWL for the 443 observation wells. Of the 5,792 flooded (DSWL ≤ 0 m) layer 1 cells under calibrated steady-state conditions, 62.1% were associated with boundary conditions (constant head, RIV, LAK, and SFR2) for which water above the DEM surface was considered appropriate, with the remaining flooded cells having a mean DSWL of -3.3 ± 3.7 m, primarily situated in the class 1 Quaternary formations of low K clays and silts.

Transient groundwater heads in the eight Kenauk wells were normalized (head minus OBS period mean head), for both observed and simulated data, to facilitate interpretation (**Figure 3.5a**). The mean simulated normalized monthly piezometric head for all eight project wells was generally more constrained (0.07 ± 0.09 m) than for the mean monthly (0.27 ± 0.27 m) or daily (0.29 ± 0.28 m) observed head, owing largely to the residual influence of pumping on observations. Those wells (Cedar and Poisson Blanc) presenting comparable ranges of simulated and observed head were notably not pumped. Monthly residuals (i.e., normalized observed minus normalized simulated) were generally lowest during winter months (December to February) (**Figure 3.5b**), as many of the actively pumped wells were unoccupied during this season. Spring (March to May) and summer (June to August), by contrast, were associated with the highest negative residuals, owing to more active pumping during this period, inducing lower observed head. Increased evapotranspiration (71% of annual AET occurs from June to November) and limited GWR (5% of annual recharge occurs from June to August) during summer and fall (September to November) also likely explained lower observed heads.

3.4.2 Simulated Lake Papineau hydrology and sub-catchment baseflows

For the OBS period, simulated monthly Lake Papineau discharge and stage were consistent with observations. The Kling-Gupta efficiency (KGE; Gupta et al., 2009) was satisfactory for both lake discharge (0.78) and stage (0.67), with MAE of 0.94 m^3s^{-1} and 0.08 m, respectively (**Figure 3.6a**). When compared against long-term (REF period) stage and discharge conditions, reconstituted with an artificial neural network (ANN) (Harris et al., *in prep*., Thesis Chapter 2), MAE only increased marginally for discharge (1.06 m^3s^{-1}) but remained unchanged for stage (**Figure 3.6b**). REF period simulated discharge and stage presented less satisfactory goodness-of-fit metrics (KGE of 0.40 and 0.57, respectively) compared to those obtained against observed conditions, but this could be attributed in part to the uncertainty associated with reconstituted values. OBS period residual (observed minus simulated) discharge (**Figure 3.6c**) and stage (**Figure 3.6d**) showed the greatest discrepancies in the fall, with simulated discharge on average 0.86 m^3s^{-1} higher (corresponding to 0.13 m higher stage). Winter, by contrast, presented average simulated discharge 0.62 m^3s^{-1} lower than observed (corresponding to 0.05 m lower stage). REF period seasonal residual discharge and stage largely followed a similar pattern, with simulated discharge 1.37 m^3s^{-1} higher during fall and 0.52 m^3s^{-1} lower during winter compared to ANN-reconstituted conditions.

Mean annual water budgets for the three instrumented sub-catchments (La Croix station, Jackson, and 041) indicated overall consistency between simulated baseflows (sum of DRN and net constant head fluxes) and baseflows obtained from both HB-simulated GWR (considered equivalent to baseflow) and Lyne and Hollick (LH) filtering of observed and reconstituted discharge (**Figure 3.6e**). For all three stations, residuals with LH values were generally positive (i.e., LH baseflows > simulated values), while residuals with HB values were generally negative (i.e., HB baseflows < simulated values). Similar residuals were obtained for both the OBS and REF periods. The Jackson sub-catchment was particularly well simulated for both periods compared to LH values. For the Lake La Croix sub-catchment, simulated baseflows were very similar to HB values for both periods, but residuals were larger for LH values.

For both the OBS and REF periods, the mean net annual groundwater exchange between the Lake Papineau catchment and the surrounding regional aquifer was consistently negative (on the order of -1.0 $Mm^3.yr^{-1}$). This loss, representing between 7% and 14% (mean 9%) of annual recharge to the Lake Papineau catchment, indicated that the surface water catchment extent was a relatively close approximation of the groundwater catchment extent. The majority of groundwater recharge thus remained within the catchment, capable of furnishing groundwater to Lake Papineau through both baseflow and lacustrine contributions.

3.4.3 Simulated lake water budget under current and past conditions

On a mean annual basis, Lake Papineau water budget inflows and outflows were nearly identical for the OBS and REF periods (**Table 3.3**). During the long-term REF period, discharge at the lake outlet dominated the water budget, with 88.6% of total outflows, while direct evaporation constituted 10.8%, and lacustrine GW_{Out} 0.6%. Lake water budget total inflows were dominated by runoff at 55.8%, followed by the groundwater contribution of baseflow (16.8%), direct precipitation (20.0%), and lacustrine GW_{In} (7.5%). Mean seasonal contributions, however, presented some notable differences between the OBS and REF periods (**Table 3.3**). For example, the winter available liquid precipitation (vertical inflow) contribution to the lake was half as important for the REF period (0.7 $Mm^3.season^{-1}$) as for the OBS period (1.3 $Mm^3.season^{-1}$). Due to less winter precipitation during the REF period, mean winter runoff to the lake (29.8% of total inflows) represented half as much as it did during the OBS period (49.5%). The baseflow contribution, while remaining similar in terms of volume (2.5 to 2.7 $Mm^3.season^{-1}$), took on greater importance in the budget for the REF period (37.8%) compared to the OBS period (25.8%). The REF period summer baseflow contribution was similarly more important, both in terms of volume (0.6 vs. 0.3 $Mm^3.season^{-1}$) and percent of total inflows (4.8 vs. 2.9%), owing to increased summer vertical inflow.

For both periods, seasonal GW_{Out} remained virtually constant at 0.1 $Mm^3.season^{-1}$, while seasonal GW_{In} was systematically greater by an order of magnitude (10 to 14 times larger than that of GW_{Out}). The simulated annual net lacustrine GW contribution (GW_{Net}) to the Lake Papineau water budget was 6.8% (OBS) and 6.9% (REF) of total inflows. When accounting for the additional 16.2% (OBS) and 16.8% (REF) contribution from baseflow through contributing affluents, the total annual groundwater contribution to the lake (GW_{Total}) ranged from 23.0% (OBS) to 23.7% (REF) of total inflows. The seasonal GW_{Net} contribution to the annual total was divided roughly equally among the seasons, with both periods showing the same pattern (values not shown in **Table 3.3**). OBS period spring had the highest contribution (29.2% of the annual total), followed by winter (25.1%), summer (24.1%), and fall (21.5%). This contrasted with the groundwater contribution from baseflow, which was heavily influenced by the spring snowmelt. For the OBS period, spring baseflow constituted 52.2% of the annual baseflow total, followed by winter (23.9%), fall (20.9%), and summer (3.0%). The long-term REF period was similarly dominated by the spring contribution (43.2%) to the annual total, with fall (31.3%) contributing more than winter (20.6%), and summer contributing least (4.9%).

On an annual basis, GW_{Net} constituted the smallest inflow contribution to the lake water budget (6.8% and 6.9% for the OBS and REF periods, respectively). However, during certain seasons it was demonstrated to be more important than components such as vertical inflow during winter (21.9% vs. 8.9% for the REF period) and baseflow during summer (10.3% vs. 4.8% for the REF period). Comparing monthly baseflow and GW_{Net} values for the OBS and REF periods (**Figure 3.7a, b**) showed that GW_{Net} played a critical role in sustaining inflow to the lake water budget throughout the summer and into early fall, when baseflow was lower and evaporation was more important. All summer months (June through August) and all but one of the September months during the OBS period exhibited GW_{Net} greater than baseflow. Of the months presenting this condition, 59% occurred during the summer for both the OBS and REF periods. The value of 0.45 $Mm^3.month^{-1}$ served as the approximate threshold above which baseflow was consistently greater than GW_{Net}. The interval of 0.21 to 0.24 $Mm^3.month^{-1}$ corresponded to the minimum monthly GW_{Net} contribution for the REF and OBS periods, respectively, occurring systematically during September at the conclusion of the hydrological year. On a seasonal basis, total summer GW_{Net} was 0.8 and 0.5 $Mm^3.season^{-1}$ larger than total baseflow for the OBS and REF periods, respectively.

3.4.4 Lake catchment hydrology and lake water budget under future conditions

Under increased precipitation and temperature forcings from the 12-member CMIP5 ensemble, nearly all annual catchment water budget components presented significant future increases with respect to the REF period (Wilcoxon signed-rank test, p-value < 0.05). For both the FUT1 and FUT2 periods, respectively, increases in discharge (+9% and +11%) coincided with increases in actual evapotranspiration (+12% and +17%). Ensemble mean groundwater recharge also increased during FUT1 and FUT2 with respect to REF (+5 $mm.yr^{-1}$ and +10 $mm.yr^{-1}$), though neither change was significant. Of seasonal changes to recharge, only winter significantly increased by +17 and +27 $mm.season^{-1}$ for FUT1 and FUT2 (+53% and +87%, with respect to REF), with all other seasons presenting significant decreases.

On a monthly basis, CMIP5 ensemble members presented positive significant changes in monthly mean catchment AET for all scenarios and for the two future periods with respect to the REF period (**Figure 3.8a**; Student's t-test, p-value < 0.05). The largest increases were simulated during spring with +22 $mm.month^{-1}$ (FUT1) and +32 $mm.month^{-1}$ (FUT2). Discharge presented significant monthly increases, mainly in March, and decreases, mainly in April. This shift in allocation of discharge within the spring season is largely balanced out between months, with FUT2 total spring discharge ultimately decreasing significantly (-27 $mm.season^{-1}$). Total winter discharge significantly increased for both periods (+62 for FUT1 and +98 $mm.season^{-1}$ for FUT2), while all remaining seasonal changes were non-significant. Not surprisingly, Lake Papineau stage followed this exact same seasonal pattern (results not shown), with only ensemble mean winter stage increasing significantly by +55 $mm.season^{-1}$ and +84 $mm.season^{-1}$ for FUT1 and FUT2, respectively (with all other seasonal changes non-significant). Simulated future monthly lake stage was occasionally below the outlet weir activation threshold of 173.03 masl (maximum of 6 cm below), and almost exclusively during summer (2.4% of all summer months for both FUT1 and FUT2 across all ensemble members).

All annual lake water budget components increased under future conditions during the FUT1 and FUT2 periods (**Table 3.4**), though only the two groundwater components (baseflow and GW_{Net}) presented non-significant ensemble mean changes. Even when these components were combined, neither future period presented significant changes in total annual groundwater contribution (GW_{Total}). Despite annual volumetric changes for any given budget component of at most +7.15 $Mm^3.yr^{-1}$ (FUT2 discharge with respect to REF), or annual percent changes relative to the REF period of at most +22.9% (FUT2 lake evaporation), when annual budget component changes were expressed in percent change relative to total annual inflows or outflows, none of the components presented changes surpassing ±1.4%, indicating an absence of fundamental change in the partitioning of lake water budget inflows or outflows under long-term future ensemble mean conditions.

On a seasonal basis, however, volumetric increases or decreases were frequently higher than the net annual changes, particularly in winter. This translated into important shifts in the seasonal percent contributions to the annual total for most budget components (**Table 3.4**). All budget components presented significant volumetric changes during winter and fall (except for changes in fall discharge) for both future periods with respect to the REF period, with all changes being positive except for the groundwater components (baseflow and GW_{Net}) during fall. Winter systematically presented the greatest shifts in the seasonal contributions to the annual total for each component, with, for example, +10.6%

(FUT1) and +16.6% (FUT2) of baseflow shifting to winter at the expense largely of fall (-5.1% and -8.6%) and spring (-3.9% and -6.0%), and to a lesser extent summer (-1.6% and -1.9%).

While nearly all lake budget components (except for the groundwater components) presented positive fall and summer volumetric changes, these gains ultimately translated to small or non-significant losses in their seasonal contributions to annual totals. For example, summer direct lake evaporation increased the most of any seasons for the two future periods (+0.49 and +0.70 $Mm^3.season^{-1}$), yet its contribution to total annual lake evaporation diminished. Lake evaporation and GW_{Net} were the only components for which spring volumetric and seasonal percent contribution increases were significant. Whereas the baseflow groundwater contribution decreased for all seasons except winter, FUT1 and FUT2 GW_{Net} increased during both winter (+1.7% and +2.5%) and spring (+1.3% and +2.0%), with losses only during fall (-1.8% and -2.8%) and summer (-1.2% and -1.7%). Winter saw the largest increases in GW_{Net} for the FUT1 and FUT2 periods with respect to REF (+9.3% and +14.7%), while spring increases were nearly as important (+7.4% and +12.1%). Future losses for GW_{Net} with respect to REF were more modest for fall (-5.9% and -8.1%) and non-significant for summer.

Across all ensemble members and for the two future periods, +0.4 $Mm^3.month^{-1}$ was the threshold value for significant monthly baseflow increases for both winter and spring (**Figure 3.8b**), while significant decreases in spring baseflow began at -0.5 $Mm^3.month^{-1}$. Significant monthly baseflow changes were compared here against significant monthly temperature changes, as only 4% of the latter were non-significant. Total spring baseflow decreased for both FUT1 (-0.36 $Mm^3.season^{-1}$; significant) and FUT2 (-0.52 $Mm^3.season^{-1}$; non-significant), with monthly significant decreases during April and May slightly overcompensating for significant increases during March (at most +1.9 $Mm^3.month^{-1}$). All significant monthly baseflow changes for summer were negative, ranging from -0.05 to -0.22 $Mm^3.month^{-1}$ and ultimately inducing significant total seasonal losses for FUT1 (-0.20 $Mm^3.season^{-1}$) and FUT2 (-0.23 $Mm^3.season^{-1}$), corresponding to seasonal losses of -26.6% and -32.5% with respect to REF conditions.

GW_{Net} largely followed the same distribution of significant monthly changes against significant monthly temperature changes (**Figure 3.8c**), with +0.05 $Mm^3.month^{-1}$ serving as the approximate threshold for significant winter and spring changes. Fall and summer significant monthly losses occupied a nearly identical range of -0.02 to -0.08 $Mm^3.month^{-1}$. Much like the 0.45 $Mm^3.month^{-1}$ threshold seen under observed conditions, ensemble mean future summer GW_{Net} was approximately +0.7 $Mm^3.season^{-1}$ larger than the baseflow groundwater contribution during both future periods, with only marginally larger increases (at most +0.8 $Mm^3.season^{-1}$) when considering only the most extreme FUT2 conditions under RCP8.5. Across all ensemble members and for the two future periods with respect to REF, 29% of monthly changes were significant for both baseflow and GW_{Net} (**Figure 3.8d**). Under none of these conditions did an increase in baseflow coincide with a decrease in GW_{Net}. The reverse to this is true, however, as significant spring increases in GW_{Net} (ranging from +0.07 to +0.16 $Mm^3.month^{-1}$ and all occurring in April) coincided with significant decreases in baseflow.

3.5 Discussion

3.5.1 Relative importance of groundwater contributions to lakes

Modflow results demonstrated that lacustrine groundwater is an important component of the Lake Papineau water budget under observed and long-term past conditions, constituting roughly 5 $Mm^3.yr^{-1}$ or 7% of total inflows. This is consistent with the 2-5 $Mm^3.yr^{-1}$ or 4-7% lacustrine groundwater contribution to total inflows estimated using the residual lake water budget technique (Harris et al., *in prep*., Thesis Chapter 2). Whereas seasonal GW_{Net} estimates derived from the residual of the lake water budget were highly uncertain and sensitive to variations in the other budget components (e.g., +0.6 $Mm^3.yr^{-1}$ for each percent increase in discharge), Modflow simulation results provided insight into the importance of lacustrine groundwater in sustaining the lake water budget seasonally. During summer, for example, when the baseflow contribution to lake inflows is much less important (approximately 3-5%), net lacustrine groundwater acted in a buffering capacity, providing approximately 10% of total seasonal inflow volumes. Furthermore, the total groundwater contribution to the lake (GW_{Net} plus baseflow) was shown to be a non-negligible component of the Lake Papineau water budget both on an annual basis (23-24%) and seasonally, representing between 13% (OBS summer) and 60% (REF winter) of total lake inflows. Transforming annual GW_{Net} to areal groundwater loading (GW volume divided by lake surface area; a metric commonly found in the literature), the OBS and REF period presented sustained mean contributions of 0.35 $m.yr^{-1}$ and 0.36 $m.yr^{-1}$, respectively. When accounting for the additional groundwater contribution of baseflow to the lake, this metric increased to 1.2 $m.yr^{-1}$ and 1.3 $m.yr^{-1}$ for the respective periods.

When considering long-term groundwater quantifications from lakes with similar characteristics as Lake Papineau, results presented here were of the same order of magnitude. For example, Robertson and Berry (1985) used the residual water budget technique to estimate a 15% contribution of lacustrine groundwater to 1969-1980 total inflows of a small Ontario drainage lake (i.e., a lake with a surface water outlet) (Perch Lake, 0.45 km^2; mean depth of 2 m) set within the fractured Canadian Shield bedrock. Using an uncoupled VIC-GFLOW model, Hanson et al. (2021), however, quantified a less important long-term lacustrine groundwater contribution (2% of total annual inflows) to Trout Lake (15.8 km^2, drainage lake) in Wisconsin (USA). Baker et al. (2018) used the Darcy method to estimate areal GW loading of 0.48 $m.yr^{-1}$ for Sylvan Lake (42.8 km^2; AB, Canada), set within a fractured sandstone aquifer (K on of the order of 10^{-4} ms^{-1}), consistent with the findings here. For the same study, chloride and stable isotope mass balances further quantified a long-term GW contribution relative to total inflows of approximately 37%. Although Sylvan Lake is a drainage lake situated in a similar climatic context, permanent inflow through runoff is limited, and direct evaporation is slightly higher than direct precipitation. The authors reported that lake stage was mostly below the weir threshold, leading to intermittent outlet discharge on the order of 2% of lake volume (compared to 25% for Lake Papineau).

Other studies report markedly larger groundwater contributions to lakes. For example, Arnoux et al. (2017b) estimated mean groundwater contribution to total inflows of approximately 50% for 10 small kettle lakes in southern Quebec (mean area of 0.07 km^2). These lakes were characterized by both the absence of surface runoff and aquifers consisting of coarse-grained Quaternary deposits, such that groundwater constitutes the dominant, and in some cases the only, inflow to the lake, a hydrological setting that contrasts strongly with that of Lake Papineau. High groundwater contributions of 75% were also found by Isokangas et al. (2015) for 67 kettle lakes (mean area of 0.10 km^2) in the Rokua esker (Finland). At the other end of the spectrum, Xu et al. (2021) used the HydroGeoSphere model to quantify a mean annual lacustrine GW contribution to the five Great Lakes (Canada/USA) ranging from 0.6% to 1.3% (mean 0.8%) of total inflows for the same REF period used here (1981-2010). Such low contributions are likely attributable to the larger lake surface to catchment area ratio for the Great Lakes (mean 0.44), compared to 0.14 for Lake Papineau, affording direct precipitation a greater contribution to total inflows. In addition to these annual estimates, Roy and Hayashi (2008) found that GW_{Net} contributed approximately 37% of 2005-2006 summer total inflows to Hungabee Lake (0.03 km^2; BC, Canada), compared to the long-term summer GW_{Net} contribution of approximately 10% estimated here.

3.5.2 How climate change will affect watershed and lake hydrology

Although it would be reasonable to assume that significant future increases in temperature and precipitation forcings would induce marked long-term shifts between water budget terms, the simulated results under the climate change scenario ensemble here did not show these changes, with at most only approximately ±1% change in reapportioning among inflows or outflows. Whereas nearly all mean budget components presented significant future volumetric increases, this was interestingly not the case for ensemble mean changes in the groundwater components of baseflow and GW_{Net}, which were not significantly different from zero (though some ensemble members, particularly those run with the more pessimistic RCP8.5, did induce significant GW changes). Groundwater fluxes thus remained relatively unaffected by future climatic forcings, providing Lake Papineau with a sustained lacustrine groundwater inflow. Other authors have noted the buffering capacity of groundwater, more broadly, with baseflow sustaining summer and fall catchment discharge, thus mitigating to some extent increasingly warm future climatic conditions (Mayer & Naman, 2011; Tague et al., 2008; Tague & Grant, 2009).

Hydrogeological investigations quantifying the impact of climate change scenarios on the lacustrine groundwater contribution to lakes are relatively rare. Baják et al. (2024), for example, used Modflow and the LAK package to quantify a 5% lacustrine groundwater contribution to Lake Velence, a 24 km^2 shallow Hungarian soda lake. The future impacts of RCP2.6 and RCP8.5 climatic forcings were also simulated, though only with respect to lake stage and only under mid-21^{st}-century conditions. Results here contrast to some degree with other findings for lakes with similar hydrologic conditions (i.e., drainage lakes) situated in regions with analogous climatic conditions. Under future conditions, Hanson et al. (2021) found that GW_{Net} (representing 2% of observed total annual inflows to Trout Lake) significantly decreased under future CMIP5 forcings (-3.4% for FUT1 and -8.0% for FUT2, with respect to the same REF period used here). The different hydrogeological properties (unconsolidated glacial sediments in the case of Trout Lake) likely explain the contrasting lacustrine groundwater responses to modified future climatic conditions.

The net lacustrine groundwater contribution to Lake Papineau was demonstrated here to play an increasingly important role in sustaining the lake water budget under future summer conditions. This was particularly evident with mean summer baseflow losses reaching -32.5% in FUT2 compared to the REF period, while corresponding GW_{Net} losses were only -3.1% (and non-significant). These results can be interpreted as an indication of the ability of lacustrine groundwater to ensure the hydrological resilience of Lake Papineau under changing climatic conditions. Here, hydrological resilience is defined as the ability of a watershed to maintain hydrological function while exposed to a perturbation, in this case climatic forcings (Lane et al., 2023; Newton & Spence, 2023). This resilience could be explained in part by the inertial capacity of both the fractured crystalline aquifer and the lake sediments in attenuating the impact of climate change on lacustrine GW. Cornett et al. (1989) estimated groundwater advection rates across lake sediments (approximately 10 m of sand and gyttja) of 0.1 to 1.0 $m.yr^{-1}$ for Perch Lake (0.45 km^2) within the Canadian Shield fractured bedrock (Ontario, Canada). Similar lake sediment groundwater fluxes have been estimated for small Shield lakes within Canada's IISD Experimental Lakes Area (Ontario; Schindler et al., 1996). Combining relatively long fractured aquifer residence times with the potentially limited capacity of lake sediments to facilitate groundwater flow, it is likely that the Modflow model results presented here give an incomplete appreciation of the impact of climate forcings on the lacustrine groundwater contribution to the lake, with the full extent of future impacts requiring a simulation horizon beyond the 60-year span of the FUT1 and FUT2 periods.

3.5.3 Simulation challenges

The calibrated Modflow groundwater flow model quantified the lacustrine groundwater component of the Lake Papineau water budget in a hydrogeologically rigorous manner, and at a reasonable temporal resolution for characterizing long-term observed and future seasonal groundwater exchanges under the impact of changing climatic conditions. These results echoed and elaborated upon the key insights from previous investigations into lacustrine groundwater contributions at the study site (Harris et al., *in prep*., Thesis Chapter 2; Lavoie Lavallee, 2019), notably the determination that lacustrine groundwater furnished a non-negligible component of total lake inflows. Nevertheless, important uncertainties are inherent to the different aspects of the modeling process presented here and may mask the true extent of such exchanges.

It was demonstrated here that GW_{Net} was relatively insensitive to variations of ± one order of magnitude of lake leakance. The calibrated LAK leakance parameter (0.35 day^{-1}) was also consistent with values found in the literature. For example, Kidmose et al. (2011) used a calibrated Modflow LAK leakance of 0.26 day^{-1} in their study of an 0.8 km^2 drainage lake situated within unconsolidated Quaternary sediments (Denmark). Other studies report lower leakance values, such as 2.3 x 10^{-4} day^{-1} and 3.9 x 10^{-2} day^{-1} used by Hunt et al. (2013), with the GSFLOW model (coupling the PRMS surface water model with Modflow), for simulating lacustrine groundwater exchange in deep and shallow WI, USA drainage lakes set in unconsolidated glacial deposits. Despite the consistency of the long-term annual lacustrine groundwater contributions simulated here with estimates both from the residual lake water budget (Thesis Chapter 2) and from lakes in similar hydroclimatic contexts, uncertainties associated with this parameter could mask important changes induced by future climatic forcings. For example, Xu et al. (2021), using HydroGeoSphere in their quantification of the GW contribution to the Great Lakes, realized a manual sensitivity analysis of the impact of varying calibrated K values and lake sediments by one order of magnitude and found induced GW contribution changes of ±3 to ±6 times the baseline contribution.

Despite measures taken to calibrate the Modflow model against available observations and the overall consistency of simulation results with the more accessible residual water budget technique, uncertainties stemming from calibrated model parameters, input variables, and model limitations may obscure lake-groundwater interactions, particularly on a seasonal basis. The limited sensitivity of simulated heads and fluxes to RIV and DRN conductances is consistent with these boundaries behaving effectively as specified-head conditions, with RIV cells functioning as distant model limits exerting negligible influence on the Lake Papineau catchment and DRN conductances nevertheless adequately reproducing observed baseflow. Furthermore, simulating groundwater flow within a fractured medium is challenging and although discrete fractures were not considered here, modeling the fractured crystalline bedrock aquifer as an equivalent porous medium was considered appropriate given sufficient permeability (Snowdon et al., 2020). Additional uncertainty arises from the manual calibration of storage parameters, which may dampen short-term aquifer responses to recharge variability but is expected to have limited influence when reasoning at multi-decadal time scales. Conversely, the inability of aquifer storage to adequately reflect changes in future groundwater head might lead to less important lacustrine groundwater contributions to Lake Papineau in line with other investigations (Isokangas et al., 2015; Rossi et al., 2014; Yapiyev et al., 2023). Whether parameters (either Modflow or HydoBudget) calibrated against observed conditions will adequately reflect the hydrological response of the catchment under significantly different future conditions is not a concern unique to this study and largely outside the scope of this investigation.

Not explicitly accounting for the presence of ice during winter, using any number of models simulating lake thermodynamics driving surface evaporation, such as the Freshwater Lake (FLake) model (Golub et al., 2022; Mironov, 2008), is an additional source of uncertainty. Nevertheless, changes in future lake evaporation simulated here (+15.6% and +22.9% for FUT1 and FUT2, respectively) were broadly consistent with changes estimated by other authors such as +16% (Wang et al., 2018) and +27% (La Fuente et al., 2024) under FUT2 conditions, despite these future and reference periods not perfectly coinciding with those used here. La Fuente et al. (2024) further note that future lake evaporation uncertainty in northern latitudes is associated primarily with GCMs rather than the chosen lake model.

3.5.4 Insights for water and land use managers

The apparent hydrological resilience of the Lake Papineau water budget is an encouraging result for watershed managers. This resilience is, however, contingent on the maintenance of underlying assumptions about future catchment conditions. Foremost, the hydrological variables driving hydrogeological simulations (i.e., recharge and runoff) were simulated with current land cover in the belief that future land management and climate-vegetation dynamics will remain unchanged. This is likely the case for the Lake Papineau catchment, with 66% lying within the private Kenauk forest and 13% managed for conservation and long-term protection by the Nature Conservancy of Canada and the Kenauk Institute.

While future development may be limited within the Lake Papineau catchment, this study potentially furnishes insights into the water budgets of lakes situated in regions with wholly different climates and where investigations might focus on issues such as lake water quality and availability of water for human consumption, both highly impacted by development. Using the SWAT model to estimate runoff, Yang et al. (2021), for example, found that lacustrine groundwater (as the residual of a water budget) accounted for 19% of long-term (1975-2004) inflows to Lake Qinghai (China; 4294 km^2). They further concluded that human activities (notably pumping and land use changes) accounted for only 2% of observed lake volume changes, with the remainder attributed to increasing temperature and precipitation. Evidence for the seasonal importance of lacustrine groundwater in maintaining lake hydrology presented here might bolster arguments aimed at the protection of catchments such as that of Lake Qinghai and elsewhere from future development to ensure adequate future groundwater recharge.

From an ecological perspective, future variations in lake stage under the influence of climate change are of concern for the survival of lake-edge wetland ecotones, such as those found along the shores of Lake Papineau. Loiselle et al. (2021) estimated limited impacts of a ±0.5 m level change on lake-edge wetlands in Lake Papineau, while a ±2 m stage change was estimated to trigger changes of -20% to +13% for tree-dominated wetlands. Results under CMIP5 ensemble conditions indicated no significant long-term increase in lake stage and significant seasonal increases only during winter (+55-84 $mm.season^{-1}$).

Furthermore, no future lake stages were consistently below the passive weir activation threshold (only intermittently so during summer months), ensuring that water will continue to discharge to the Kinonge River and sustain that riverine ecosystem. In light of the results shown here, extreme changes in lake-edge wetlands may not be realistic. However, considering the uncertainty of simulated results, the precautionary principle would suggest avoiding major alterations to catchment land cover (e.g., large-scale forest harvesting) and development that modifies hydrological connectivity (e.g., road construction), thus allowing smaller lakes and wetlands to continue storing runoff and attenuating lake stage variations.

3.6 Conclusion

Despite the prevalence of lakes in the post-glacial landscapes of cold and humid climates, few investigations have been undertaken to quantify the degree to which groundwater sustains lake water budgets and few studies have sought to characterize these interactions under the influence of global climate change. This chapter provided new insights into long-term and seasonal lake-groundwater exchanges under both observed and future climatic conditions, informed by a selection of CMIP5 scenarios. A Modflow numerical groundwater flow model was implemented to quantify groundwater fluxes between Lake Papineau and the surrounding fractured crystalline bedrock aquifer of the Canadian Shield (southern Quebec, Canada).

Calibrated against hydrometric and groundwater head observations, results demonstrated that the lacustrine groundwater contribution to Lake Papineau is approximately 7% of total annual lake inflows under long-term (1981-2010) observed conditions. When combined with the groundwater contribution of baseflow, groundwater contributes nearly a quarter (23-24%) of total inflows to the lake. These findings echo the important contribution of groundwater to Lake Papineau quantified using a residual water budget technique, though Modflow simulations here crucially afford more robust seasonal estimates through explicit modeling of groundwater exchanges. Lacustrine groundwater was shown to constitute 20% and 10% of long-term winter and summer contributions to total lake inflows, respectively. In the case of summer, lacustrine groundwater acts in a buffering capacity, sustaining the lake water budget under diminished baseflow contributions and increased evaporation.

Results indicate that Lake Papineau will probably be relatively hydrologically resilient, even under the influence of future increases in temperature and precipitation associated with an ensemble of CMIP5 scenarios. This resilience is manifest in several ways, including the absence of fundamental reapportionment among lake inflows or outflows. Additionally, non-significant ensemble mean changes in future annual lacustrine groundwater inflows point to this contribution being largely unaffected by climate change and capable of dampening the full effects of these changes on Lake Papineau hydrology. On a seasonal basis, future summer lacustrine groundwater contributions are similarly largely unaffected by CMIP5 conditions, in contrast to reductions in the baseflow groundwater contribution of runoff to the lake. This work highlights the ability of lacustrine groundwater to provide a sustained, non-negligible contribution to the lake water budgets of boreal lakes and potentially mitigate the extent of climate change impacts on these environments. These results should provide impetus for both the conservation of catchment areas contributing to groundwater recharge and ensuring lake-groundwater interactions are considered in future investigations of the impact of climate change on environments within which lakes are a prevalent landscape feature.

3.7 References

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3.8 Tables

Table 3.1 Measured and calibrated hydrogeological parameters

Layer	Thickness (m)	Depth interval (m)	Material class	Description	Hydraulic conductivity (K) (ms^{-1})		Specific storage (S_s) (m^{-1})		Calibrated specific yield (S_y) (-)
					Measured* (Min – Max)	Calibrated	Measured** (Min – Max)	Calibrated	
1	10	0 to -10	1	Clay, silt	$3.2 \times 10^{-9} – 7.9 \times 10^{-6}$	3.3×10^{-5}	$1.6 \times 10^{-6} – 5.6 \times 10^{-5}$	4.0×10^{-3}	0.04
			2	Gravely silt	$7.9 \times 10^{-8} – 5.0 \times 10^{-4}$	4.7×10^{-5}	$2.5 \times 10^{-5} – 5.0 \times 10^{-3}$	8.0×10^{-3}	0.08
			3	Silty sand & gravel	$5.0 \times 10^{-6} – 1.3 \times 10^{-3}$	1.7×10^{-4}	$7.6 \times 10^{-5} – 6.0 \times 10^{-3}$	0.01	0.10
			4	Coarse sand & gravel	$5.0 \times 10^{-5} – 2.0 \times 10^{-3}$	6.4×10^{-4}	$2.0 \times 10^{-6} – 4.0 \times 10^{-3}$	0.02	0.20
			5	Sedimentary rock	$1.0 \times 10^{-6} – 1.0 \times 10^{-4}$	7.6×10^{-5}	$1.3 \times 10^{-7} – 6.9 \times 10^{-5}$	5.0×10^{-3}	0.05
			6	Grenville Province	$2.5 \times 10^{-7} – 4.0 \times 10^{-5}$	1.1×10^{-4}	$1.3 \times 10^{-8} – 3.6 \times 10^{-5}$	1.0×10^{-3}	0.01
2	20	-10 to -30				1.1×10^{-7}		5.0×10^{-4}	0.01
3	30	-30 to -60				5.6×10^{-8}		1.7×10^{-4}	5.0×10^{-3}
4	60	-60 to -120				3.8×10^{-8}		1.7×10^{-5}	1.0×10^{-3}
5	80	120 to -200				5.0×10^{-9}		6.3×10^{-6}	5.0×10^{-4}
6	Variable	-200 to surface-300				1.1×10^{-9}		3.3×10^{-7}	1.0×10^{-4}

* Comeau et al. (2013); ** Kuang et al. (2020)

Table 3.2 Selected climate scenarios

GCM-RCP-ensemble member	Institution Name	Name	RCP
ACCESS1-0_rcp45_r1i1p1	Commonwealth Scientific and Industrial Research Organisation, Bureau of Meteorology (Australia) – Bi et al. (2013)	A10	4.5
ACCESS1-3_rcp85_r1i1p1		A13	8.5
bcc-csm1-1-m_rcp45_r1i1p1	Beijing Climate Center, China Meteorological Administration (China) – Wu et al. (2014)	B1M	4.5
BNU-ESM_rcp85_r1i1p1	College of Global Change and Earth System Science, Beijing Normal University (China) – Ji et al. (2014)	BNU	8.5
CanESM2_rcp45_r1i1p1	Canadian Centre for Climate Modelling and Analysis (Canada) – von Salzen et al. (2013)	CE2	4.5
CMCC-CMS_rcp45_r1i1p1	Centro Euro-Mediterraneo per i Cambiamenti Climatici (Italy) – Fogli et al. (2009)	CMS	4.5
GFDL-CM3_rcp45_r1i1p1	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA) – Donner et al. (2011)	GF3	4.5
GISS-E2-R_rcp45_r6i1p3	National Aeronautics and Space Administration, Goddard Institute for Space Studies (USA) – Schmidt et al. (2006)	GIR	4.5
inmcm4_rcp45_r1i1p1	Institute for Numerical Mathematics (Russia) – Volodin et al. (2010)	INM	4.5
MIROC-ESM-CHEM_rcp85_r1i1p1	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology (Japan) – Watanabe et al. (2011)	MIC	8.5
MIROC-ESM_rcp45_r1i1p1		MIE	4.5
MRI-ESM1_rcp85_r1i1p1	Meteorological Research Institute (Japan) – Yukimoto et al. (2011)	MRE	8.5

Table 3.3 Lake Papineau seasonal and annual simulated lake water budget components for the OBS and REF periods

			Season				Annual
			Fall (Sept. - Nov.)	**Winter (Dec. - Feb.)**	**Spring (Mar. - May)**	**Summer (Jun. - Aug.)**	
Outflows	**Discharge (Mm^3)**	**OBS (2016-2022)**	14.5 ± 2.8 (90.3%)	10.6 ± 2.9 (98.2%)	30.3 ± 11.8 (93.2%)	7.4 ± 3.4 (58.7%)	62.8 ± 9.3 (88.1%)
		REF (1981-2010)	17.5 ± 6.1 (91.7%)	7.3 ± 2.8 (97.6%)	30.9 ± 6.6 (94.0%)	8.4 ± 4.1 (61.5%)	64.1 ± 11.9 (88.6%)
	Evaporation (Mm^3)	**OBS (2016-2022)**	1.4 ± 0.1 (9.0%)	0.1 ± 0.03 (1.0%)	1.8 ± 0.2 (6.4%)	4.6 ± 0.1 (40.5%)	7.9 ± 0.3 (11.3%)
		REF (1981-2010)	1.3 ± 0.1 (7.7%)	0.1 ± 0.03 (1.0%)	1.8 ± 0.2 (5.7%)	4.4 ± 0.2 (37.7%)	7.6 ± 0.3 (10.8%)
	GW_{Out} (Mm^3)	**OBS (2016-2022)**	0.1 ± 0.01 (0.7%)	0.1 ± 0.0 (0.9%)	0.1 ± 0.01 (0.4%)	0.1 ± 0.0 (0.8%)	0.4 ± 0.01 (0.6%)
		REF (1981-2010)	0.1 ± 0.01 (0.6%)	0.1 ± 0.01 (1.4%)	0.1 ± 0.01 (0.4%)	0.1 ± 0.0 (0.8%)	0.4 ± 0.01 (0.6%)
Inflows	**Vertical inflow (Mm^3)**	**OBS (2016-2022)**	3.6 ± 0.6 (22.2%)	1.3 ± 0.4 (11.8%)	5.4 ± 1.8 (16.9%)	3.6 ± 0.6 (32.0%)	13.8 ± 1.4 (19.7%)
		REF (1981-2010)	3.8 ± 0.8 (20.4%)	0.7 ± 0.4 (8.9%)	5.6 ± 0.9 (17.2%)	4.1 ± 0.8 (34.3%)	14.1 ± 1.8 (20.0%)
	Runoff (Mm^3)	**OBS (2016-2022)**	9.0 ± 2.7 (55.4%)	5.4 ± 2.0 (49.5%)	19.4 ± 8.9 (59.0%)	6.4 ± 2.8 (53.9%)	40.2 ± 8.6 (56.7%)
		REF (1981-2010)	10.4 ± 4.4 (52.7%)	2.5 ± 2.1 (29.8%)	20.7 ± 5.1 (62.6%)	6.5 ± 3.3 (49.9%)	40.1 ± 8.6 (55.8%)
	Baseflow (Mm^3)	**OBS (2016-2022)**	2.4 ± 1.0 (15.2%)	2.7 ± 1.2 (25.8%)	5.8 ± 2.0 (18.8%)	0.3 ± 0.1 (2.9%)	11.2 ± 2.2 (16.2%)
		REF (1981-2010)	3.8 ± 1.5 (19.9%)	2.5 ± 0.9 (37.8%)	5.1 ± 1.3 (15.7%)	0.6 ± 0.6 (4.8%)	11.9 ± 2.3 (16.8%)
	GW_{In} (Mm^3)	**OBS (2016-2022)**	1.1 ± 0.1 (7.2%)	1.3 ± 0.2 (12.9%)	1.5 ± 0.2 (5.2%)	1.2 ± 0.1 (11.3%)	5.1 ± 0.4 (7.4%)
		REF (1981-2010)	1.2 ± 0.1 (6.9%)	1.3 ± 0.2 (23.5%)	1.4 ± 0.1 (4.5%)	1.2 ± 0.1 (11.1%)	5.2 ± 0.4 (7.5%)
GW_{Net} (Mm^3)		**OBS (2016-2022)**	1.0 ± 0.1 (6.5%)	1.2 ± 0.2 (11.9%)	1.4 ± 0.2 (4.9%)	1.1 ± 0.1 (10.4%)	4.7 ± 0.4 (6.8%)
		REF (1981-2010)	1.1 ± 0.1 (6.3%)	1.3 ± 0.2 (21.9%)	1.3 ± 0.1 (4.2%)	1.1 ± 0.1 (10.3%)	4.8 ± 0.4 (6.9%)
Total groundwater (Mm^3)		**OBS (2016-2022)**	3.4 ± 1.0 (21.7%)	3.9 ± 1.4 (37.8%)	7.2 ± 2.1 (23.7%)	1.4 ± 0.2 (13.3%)	15.9 ± 2.6 (23.0%)
		REF (1981-2010)	4.9 ± 1.6 (26.3%)	3.8 ± 1.1 (59.7%)	6.4 ± 1.4 (19.9%)	1.7 ± 0.6 (15.0%)	16.7 ± 2.7 (23.7%)

All values are means in Mm^3 for the 12-member ensemble, with % in parentheses corresponding to mean ensemble seasonal or annual contribution to total inflows or outflows.
GW_{Net} and total groundwater % are per total inflows.
Uncertainties correspond to ± one standard deviation.

Table 3.4 Future seasonal and annual changes in Lake Papineau lake water budget components under ensemble CMIP5 conditions

			Season				Annual
			Fall (Sept. - Nov.)	**Winter (Dec. - Feb.)**	**Spring (Mar. - May)**	**Summer (Jun. - Aug.)**	
Outflows	**Δ Discharge (Mm^3)**	**FUT1-REF**	n.s.****	+5.93* (+7.1%) [+65.1%]	n.s. (-5.4%)*** [n.s.]	n.s.	+6.20 (-0.5%) [+9.5%]
		FUT2-REF	n.s. (-2.1%) [n.s.]	+9.27 (+11.3%) [+101.5%]	-2.72 (-8.1%) [-8.7%]**	n.s.	+7.15 (-1.0%) [+10.9%]
	Δ Evaporation (Mm^3)	**FUT1-REF**	+0.24 (+0.3%) [+18.0%]	+0.06 (+0.5%) [+79.2%]	+0.40 (+1.4%) [+22.7%]	+0.49 (-2.3%) [+11.0%]	+1.19 (+0.6%) [+15.6%]
		FUT2-REF	+0.35 (+0.5%) [+26.5%]	+0.11 (+0.9%) [+145.1%]	+0.59 (+1.9%) [+33.3%]	+0.70 (-3.3%) [+15.7%]	+1.75 (+1.1%) [+22.9%]
Inflows	**Δ Vertical inflow (Mm^3)**	**FUT1-REF**	+0.41 (n.s.) [+10.7%]	+0.92 (+5.0%) [+94.5%]	n.s. (-3.8%) [n.s.]	+0.29 (-1.1%) [+7.2%]	+1.67 (+0.3%) [+11.6%]
		FUT2-REF	+0.44 (n.s.) [+11.3%]	+1.49 (+7.9%) [+153.3%]	n.s. (-5.8%) [n.s.]	+0.38 (-1.3%) [+9.5%]	+2.15 (+0.5%) [+14.9%]
	Δ Runoff (Mm^3)	**FUT1-REF**	+1.47 (n.s.) [+15.0%]	+3.42 (+6.8%) [+98.6%]	n.s. (-6.9%) [n.s.]	n.s.	+5.14 (n.s.) [+13.0%]
		FUT2-REF	+1.44 (n.s.) [+14.2%]	+5.25 (+10.3%) [+150.1%]	-1.87 (-10.1%) [-9.0%]	n.s.	+5.57 (n.s.) [+14.0%]
	Δ Baseflow (Mm^3)	**FUT1-REF**	-0.57 (-5.1%) [-13.5%]	+1.59 (+10.6%) [+53.2%]	-0.36 (-3.9%) [-6.7%]	-0.20 (-1.6%) [-26.6%]	n.s.
		FUT2-REF	-0.90 (-8.6%) [-21.6%]	+2.61 (+16.6%) [+86.8%]	n.s. (-6.0%) [n.s.]	-0.23 (-1.9%) [-32.5%]	n.s.
	Δ GW_{Net} (Mm^3)	**FUT1-REF**	-0.07 (-1.8%) [-5.9%]	+0.13 (+1.7%) [+9.3%]	+0.10 (+1.3%) [+7.4%]	n.s. (-1.2%) [n.s.]	n.s. (-0.5%) [n.s.]
		FUT2-REF	-0.10 (-2.8%) [-8.1%]	+0.20 (+2.5%) [+14.7%]	+0.17 (+2.0%) [+12.1%]	n.s. (-1.7%) [n.s.]	n.s. (-0.4%) [n.s.]
Δ GW_{Total} (Mm^3)		**FUT1-REF**	-0.64 (-4.2%) [-11.8%]	+1.72 (+8.1%) [+39.5%]	n.s. (-2.4%) [n.s.]	-0.23 (-1.6%) [-12.0%]	n.s. (-1.4%) [n.s.]
		FUT2-REF	-1.00 (-6.9%) [-18.6%]	+2.81 (+12.6%) [+64.4%]	n.s. (-3.7%) [n.s.]	-0.27 (-2.0%) [-14.1%]	n.s.

* All values are mean changes in Mm^3 for the 12-member ensemble with respect to the REF period.

** Values in brackets correspond to percent change relative to seasonal or annual REF period.

*** Seasonal % in parentheses correspond to ensemble change in mean seasonal percent contribution to the annual total of a given variable. Annual percent change given in parentheses is relative to total inflows or outflows.

**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$)

3.9 Figures

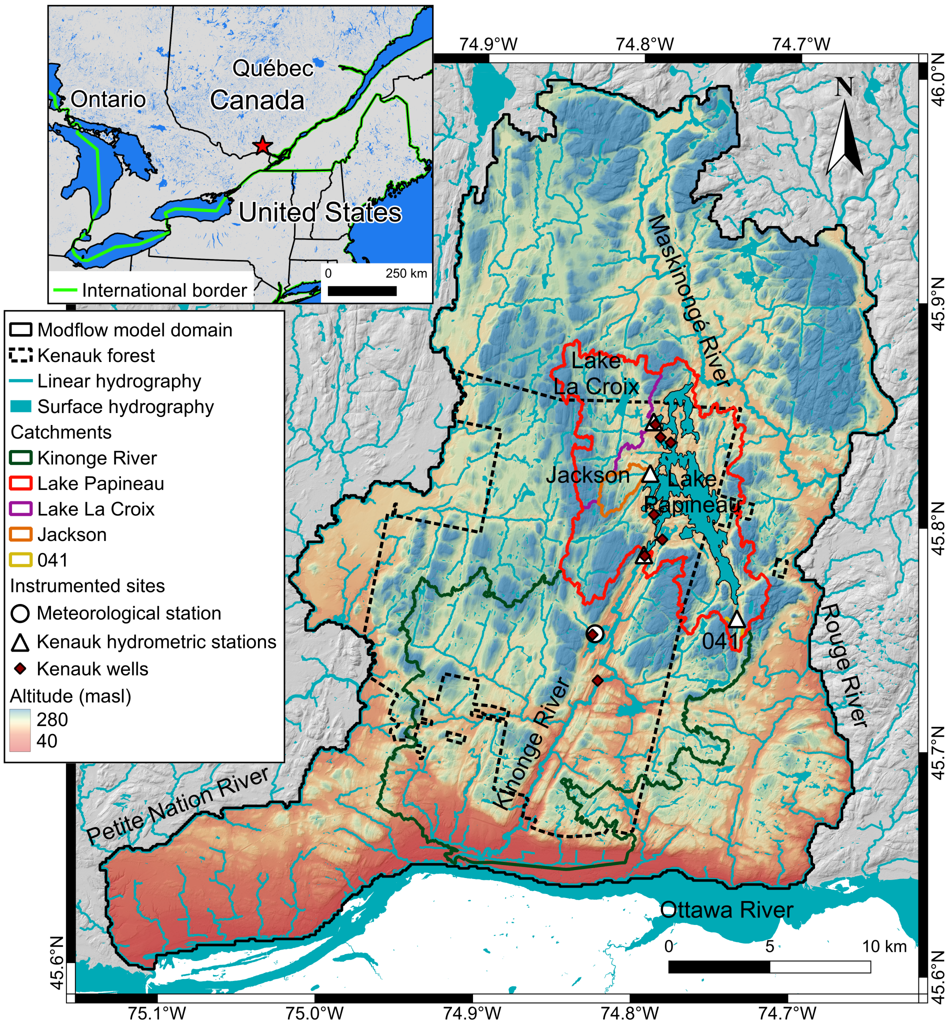

Figure 3.1 Location of the study area and Lake Papineau catchment in the Outaouais region of southern Quebec (Canada), including topography and instrumented sites.

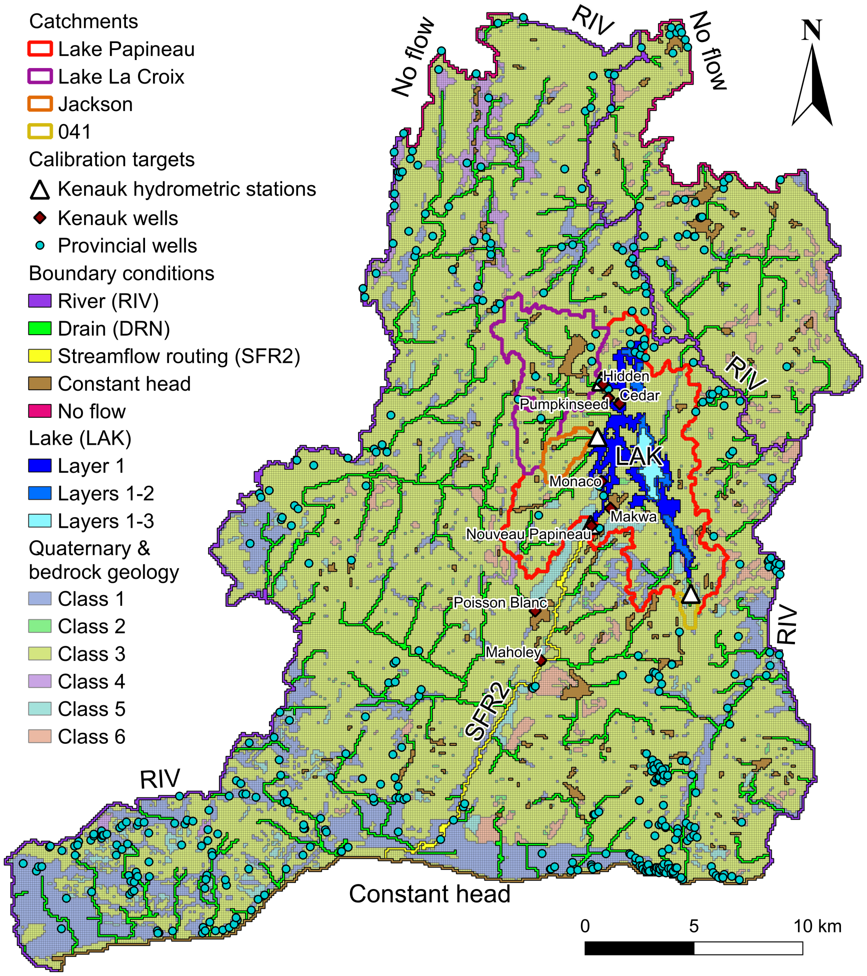

Figure 3.2 The simulated model domain, including boundary conditions, catchment delineations, and location of calibration wells (see Table 2 for description of geological classes)

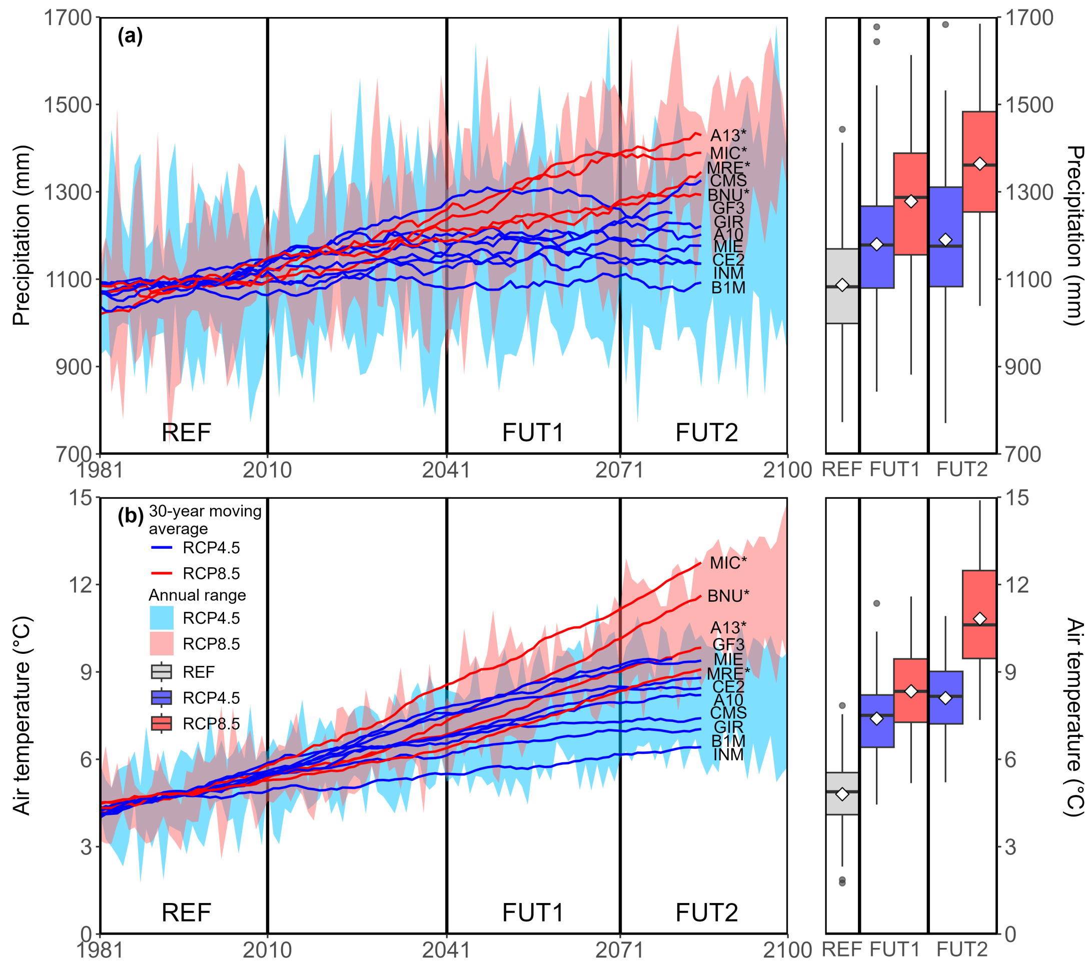

Figure 3.3 CMIP5 ranges and moving averages for precipitation (a) and temperature (b) from all 12 climate scenarios (RCP4.5 and RCP8.5), including the reference period (REF, 1981-2010), the near future (FUT1, 2041-2070), and the far future (FUT2, 2071-2100). RCP8.5 scenarios are identified with asterisks.

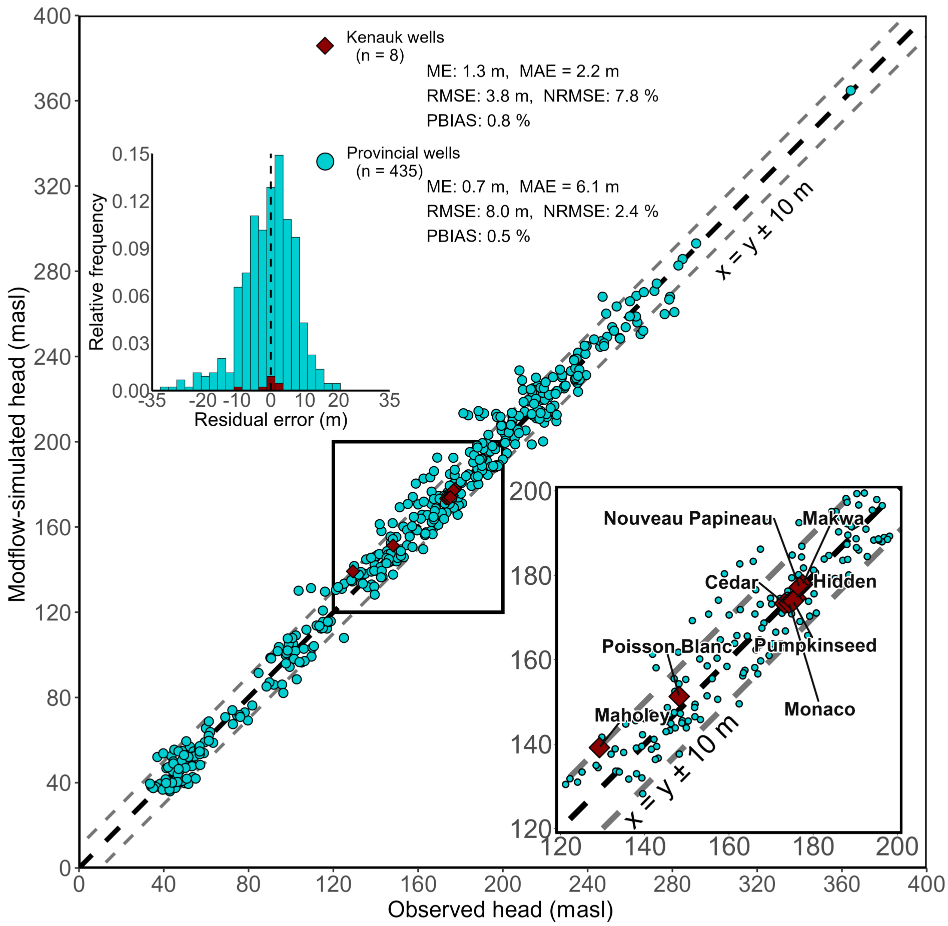

Figure 3.4 Observed and simulated steady-state hydraulic heads in Kenauk wells and provincial wells, including relative frequency of residual errors, and the ±10 m envelope around the x=y line.

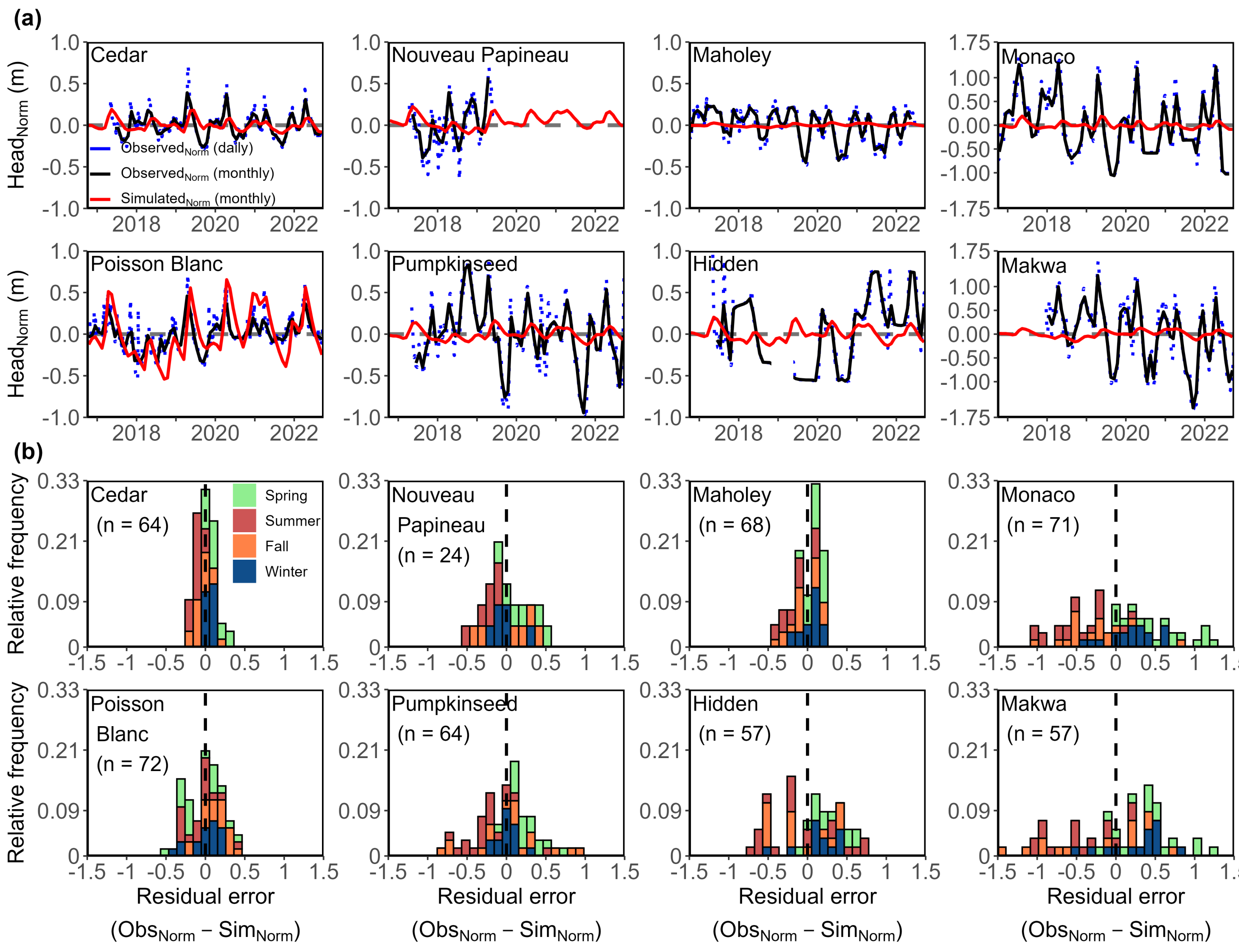

Figure 3.5 Observed and simulated monthly interannual normalized hydraulic head (a) for the Kenauk wells for the OBS period (2016-2022), and monthly residual errors grouped by season (b). Normalization corresponds to head minus OBS period mean for either observed or simulated data. Note that the vertical scale of the Monaco and Makwa wells is larger than that of the other wells.

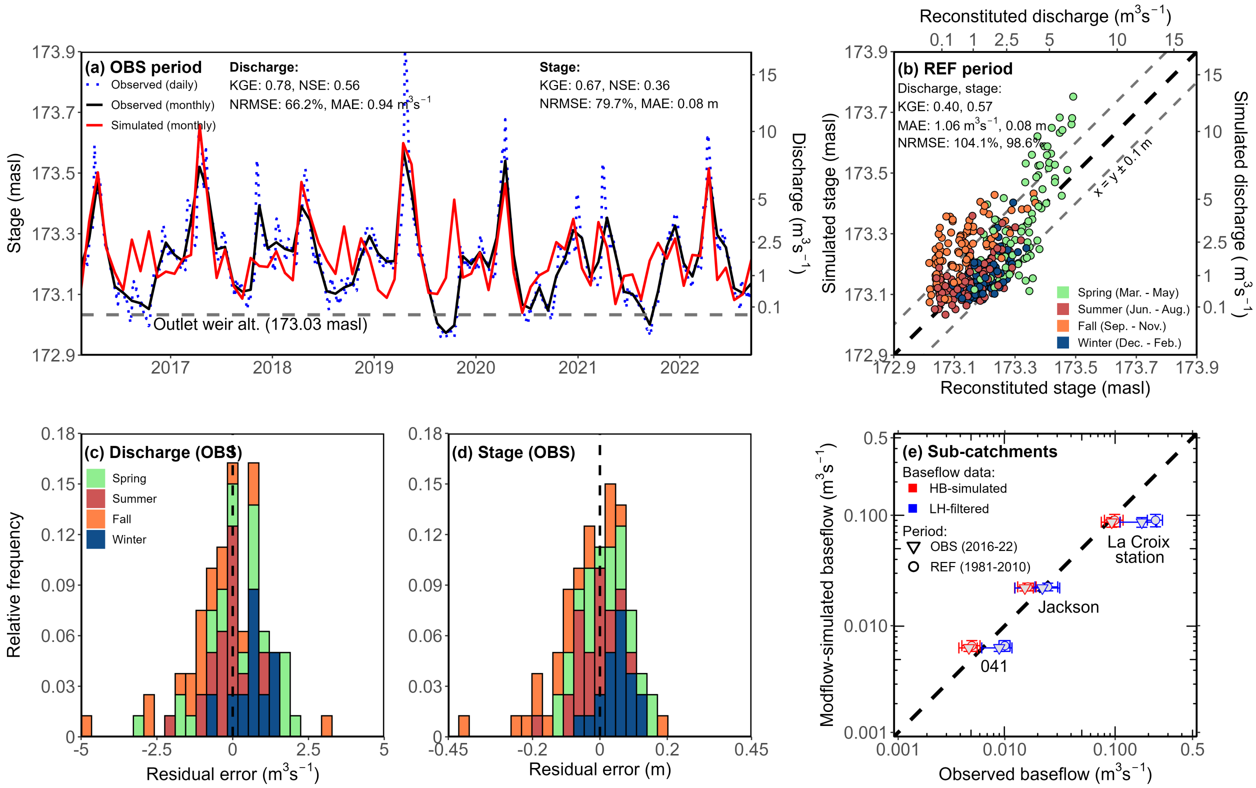

Figure 3.6 Simulated and observed monthly Lake Papineau discharge and stage for the OBS (2016-22) period (a) and REF (1981-2010) period (b), with OBS monthly discharge (c) and stage (d) residual errors (observed minus simulated) grouped by season, and mean annual baseflow for instrumented sub-catchments (e), with baseflow error bars corresponding to ± one standard deviation.

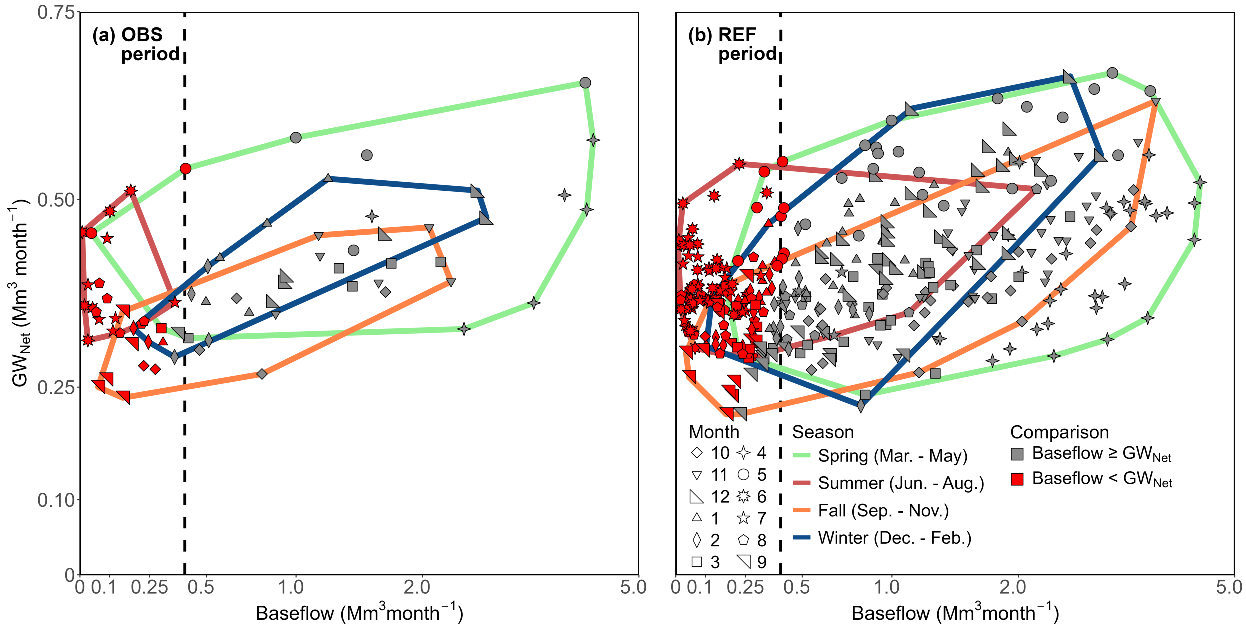

Figure 3.7 OBS (a) and REF (b) period monthly baseflow as a function of monthly net lacustrine groundwater flow (GW_{Net}) to Lake Papineau, with seasonal contours and identification of months during which GW_{Net} is superior to baseflow. The vertical dotted line corresponds to the approximate threshold above which baseflow > GW_{Net}.

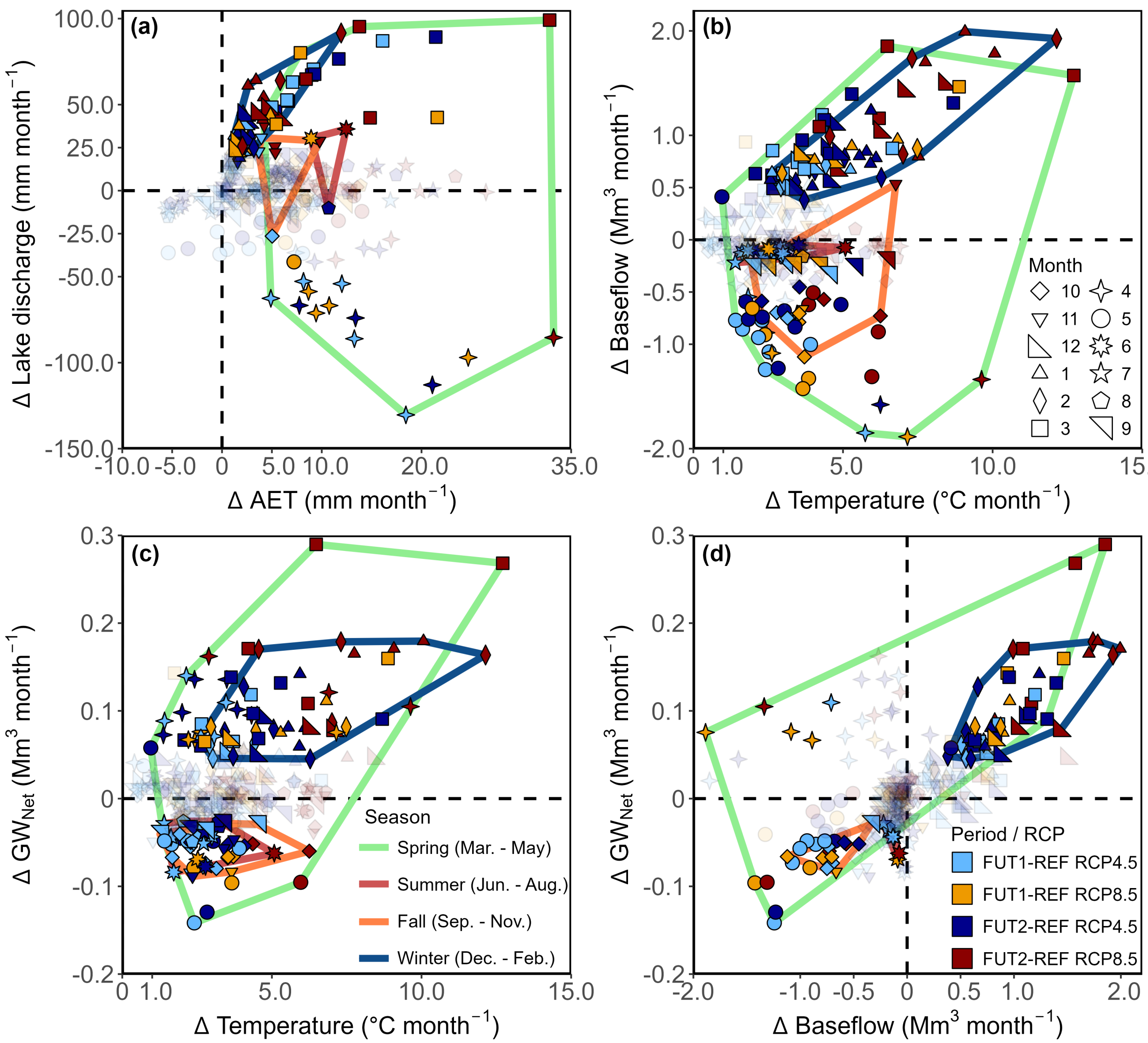

Figure 3.8 Significant mean monthly changes between the reference and future periods grouped by season for lake discharge as a function of actual evapotranspiration (a), baseflow as a function of temperature (b), net groundwater inflow as a function of temperature (c), and net groundwater inflow as a function of baseflow (d). Faded points represent non-significant changes for both variables (Student's t-test, $p < 0.05$).

CHAPTER 4

HYDROLOGICAL SENSITIVITY OF A CANADIAN SHIELD LAKE CATCHMENT TO CLIMATE CHANGE THRESHOLD-MEDIATED PROCESSES CONTROLLING LAKE RESILIENCE

4.1 Introduction

In cold and humid regions, the impacts of climate change on catchment hydrology include changes in the quantity and timing of snowmelt (Aygün et al., 2022), engendering both increased flood frequency (Grenier et al., 2024) and more extreme low flow conditions (Kinnard et al., 2022), and alterations to groundwater recharge (Dubois et al., 2022; Larocque et al., 2019), to name but a few impacts. Lakes found in these regions (such as the Canadian Shield of southeastern Canada) are generally accepted to be closely connected to their surrounding aquifers, either receiving groundwater or discharging water to a superficial aquifer (Rosenberry et al., 2015; Winter et al., 1998). Few studies, however, have characterized these interactions in these environments (e.g., Arnoux et al., 2017; Gleeson et al., 2009; Harris et al., *in prep*., Thesis Chapter 2; Leaf et al., 2020), and even fewer have focused on how these interactions will be impacted by climate change (e.g., Baják et al., 2024; Hanson et al. 2021; Harris et al., *in prep*., Thesis Chapter 3). As such, the hydrological resilience of these environments, defined as their ability to maintain hydrological function while exposed to a perturbation (Lane et al., 2023; Newton & Spence, 2023), and the role of groundwater in maintaining resilience remain topics of ongoing investigation (e.g., Briggs et al., 2025; Devito et al., 2023; Granata & Nunno, 2025). It is generally acknowledged that future land use and climatic conditions of a watershed will influence its hydrological resilience (Harder et al., 2015). However, relatively few studies have investigated under what future climatic forcings (precipitation and temperature) hydrological conditions might be altered beyond the thresholds of resilient conditions (Singh et al., 2014).

Assessments of climate change impacts on catchment hydrology most commonly make use of the outputs from a selection of global circulation models (GCMs) such as those of the CMIP5 project (Taylor et al., 2012), forced by Representative Concentration Pathways (RCPs; van Vuuren et al., 2011), or more recently of CMIP6 (Eyring et al., 2016), forced by Shared Socioeconomic Pathways (SSP; Riahi et al., 2017). While the outputs from a multi-model ensemble give insight into hydrological responses induced by future radiative forcing, they nevertheless represent only a specific array of possible future conditions and are accompanied by a host of uncertainties (Maraun et al., 2017). It is also recognized that model ensembles can sometimes be biased, as is the case for the so-called *warm* models which are overrepresented in the

CMIP6 ensemble (Cannon, 2024; Hausfather et al., 2022; Rahimpour Asenjan et al., 2023). These *warm* models exhibit greater future effective radiative forcing in CMIP6 outputs with respect to those of CMIP5, and future atmospheric CO_2 concentrations which might exceed those assumed under RCP8.5 (Forster et al., 2020; Fredriksen et al. 2023). Expanding beyond available climate change scenarios would be helpful in providing insights into extreme future conditions. For this reason, researchers have sought alternative approaches such as the implementation of pseudo-global warming (PGW) scenarios, whereby GCMs are run with boundary conditions consisting of observed or reanalysis data (generally temperature and precipitation forcings) perturbed to reflect anticipated climate change signals informed by existing GCM outputs (Aubry-Wake & Pomeroy, 2023; He & Pomeroy, 2023; Xue et al., 2023). Given the high computational cost of this approach, the delta change factor or climate perturbation method, which applies perturbations directly to climatic time series (usually observed conditions) without recourse to additional GCM runs, has been shown to be a feasible alternative for quantifying the effects of a larger array of climate forcings (Arsenault et al., 2013; Aygün et al., 2020; He et al., 2023; Poulin et al., 2011; Rasouli et al., 2022; Valencia Giraldo et al., 2023).

The delta change factor method is highly conducive to quantifying sensitivity, broadly defined as the change in one output variable induced by the change in an input variable or parameter. In hydrology, this concept was initially introduced by Schaake (1990) for runoff with respect to precipitation. It has been implemented more specifically in the evaluation of the impact of climate perturbations on the water budgets of lakes by Crowe (1993), with an emphasis on the impact on lake-groundwater interactions. Quantifying the sensitivity of catchment hydrology to climate forcings is an important step in characterizing overall hydrological resilience. Under the assumption of a closed catchment water balance, long-term hydrological behavior can be conceptualized as the partitioning of available water between discharge (Q) and actual evapotranspiration (AET), providing a useful basis for evaluating hydrological sensitivity and resilience within the Budyko framework (Budyko, 1974), relating long-term aridity and evaporative conditions.

The objective of this study was to investigate the thresholds of hydrological resilience of a southern boreal lake exposed to extreme future climatic change. Previous work has shown that Lake Papineau (southern Quebec, Canada) is relatively hydrologically resilient to the impacts of a CMIP5 GCM-RCP ensemble (Harris et al., *in prep*., Thesis Chapter 3). Building on this finding, this chapter examines under what combinations of future temperature and precipitation forcings the hydrological resilience of the Lake Papineau catchment might be overcome, how changes in climatic forcings alter the partitioning between discharge (Q) and actual evapotranspiration (AET) at the catchment scale, and the extent to which lacustrine groundwater contributions can mitigate the impacts of extreme climatic conditions on the lake water balance. To address these questions, the HydroBudget (HB) water budget model (Dubois et al., 2021), was used to estimate catchment AET, runoff, and baseflow (the latter two components constituting Q) under perturbed CMIP5 forcings (increases in temperature and increases and decreases in precipitation). Lacustrine groundwater contributions were subsequently inferred using a residual lake water budget approach. Hydrological resilience was further evaluated using the Budyko framework to interpret changes in long-term catchment water partitioning under extreme climatic forcings. In doing so, this chapter provides a framework for identifying climatic forcing thresholds associated with shifts in catchment water partitioning, thereby diagnosing when hydrological resilience may be exceeded, and for assessing the role of groundwater in moderating lake responses to extreme climatic change in cold and humid environments.

4.2 Study area

4.2.1 General conditions

The study site consists of the 93.7 km^2 Lake Papineau surface water catchment, located in the Outaouais region of southern Quebec (Canada), midway between Ottawa and Montreal on the north shore of the Outaouais (Ottawa) River (**Figure 4.1**). Lake Papineau (13.1 km^2) is a drainage lake (i.e., a lake with a surface water outlet) that is fed by a few streams, runoff, and groundwater. Comprised of two elongated lobes oriented north-south, the lake is drained at the southernmost tip of the western lobe, giving rise to the Kinonge (Salmon) River, which discharges into the Ottawa River 26 km downstream. Lake Papineau has an estimated volume of 258 Mm^3, with mean depth of 20 m (maximum 80 m; TrakMaps, 2003). Apart from the 14% of the catchment area consisting of Lake Papineau, 71% of land cover is comprised almost entirely of forest, dominated by maple (67%), hemlock (9%), birch (3%), and other deciduous species (21%) (MFFP, 2018). Numerous smaller lakes and wetlands constitute the remaining 5% and 10% of the catchment, respectively. Development is largely limited within the catchment, as 66% lies within the private Kenauk forest and 13% is jointly administered by the Kenauk Institute and the Nature Conservancy of Canada.

4.2.2 Geology and hydrogeology

The Lake Papineau catchment is situated within the Grenville Province of the Canadian Shield, characterized by a fractured bedrock composed primarily of granite, gneiss, paragneiss, marble, and quartzite (Rivera, 2014). With a mean surface slope of 14°, the catchment is largely covered by Quaternary sediments consisting primarily of thin glacial till. Groundwater circulates within this shallow, unconfined Precambrian fractured crystalline aquifer, interacting with surface water features (lakes, wetlands, and rivers). Crystalline rocks of the Grenville Province are characterized by low permeability and primary porosity but significant secondary porosity from fracturing (Sterckx, 2013). Regional hydrogeology has previously been characterized as part of the Quebec groundwater knowledge acquisition initiative (Comeau et al., 2013; Gagné et al., 2022), with lake-groundwater exchanges between Lake Papineau and its surrounding aquifer also being quantified by field-based techniques and a classical lake water budget (Lavoie Lavallée, 2019). Results from additional investigations using both a residual water budget technique and a Modflow numerical groundwater flow model estimated lacustrine groundwater to furnish a non-negligible contribution on the order of 7% of total inflows to Lake Papineau (Harris et al., *in prep*., Thesis Chapters 2 & 3).

4.2.3 Hydrological conditions

The Lake Papineau outlet, consisting of a progressive weir, has been instrumented since 2016 with a *Solinst Levelogger*, following the removal in 2015 of a concrete, human-operated dam in place since 1975. Observed mean annual discharge (2016-2022), derived from a rating curve progressively constructed since 2016, varied from 1.5 to 2.4 m^3s^{-1}. Hourly observed lake stage never varied beyond the range of 172.95 to 173.90 masl. These data informed the characterization of long-term catchment hydrology, estimated by Harris et al. (*in prep*, Thesis Chapter 2) using the HydroBudget (HB) catchment water budget model (HB; Dubois et al., 2021). Calibrated against observed discharge at the lake outlet for 2016-2022, HB characterized the long-term (1981-2010; REF period) partitioning of precipitation into the catchment release functions of discharge at the lake outlet (Q; 643 $mm.yr^{-1}$; 58% of total catchment outflows) and actual evapotranspiration (AET; 459 $mm.yr^{-1}$; 42% of catchment outflows). With a long-term evaporative index ($AET.P^{-1}$) that ranged from 0.38 to 0.57 (mean 0.44), and an aridity index ($PET.P^{-1}$) that varied from 0.42 to 0.74 (mean 0.55), the catchment is characterized as both humid and energy-limited.

4.2.4 Current climatic conditions

The site is characterized by a Köppen-Geiger class of Dfb, consisting of a humid continental climate with warm summers and absence of a dry season (Kottek et al., 2006). Observed climatic conditions were available from a daily gridded 0.1°-resolution precipitation and air temperature dataset (Bergeron, 2016), and from a project-specific meteorological station (2016-present), located approximately 5 km south of the Lake Papineau outlet. All hydrometeorological variables presented herein were reasoned on a water year (WY) basis, spanning October 1st of a given year to September 30th of the subsequent year. The long-term observed reference period (REF; 1981-2010) was characterized by a mean annual temperature of 4.7°C and average annual precipitation of 1065 $mm.yr^{-1}$, of which 23% falls as snow. Mean interannual potential evapotranspiration (PET), estimated using the Oudin et al. (2005) formula, was 572 $mm.yr^{-1}$.

4.2.5 Future climatic conditions

The anticipated near-term (FUT1; 2041-2070) and long-term (FUT2; 2071-2100) hydrological impacts of 12 CMIP5 GCM-RCP scenarios (**Table 4.1**) were detailed in Harris et al. (*in prep*, Thesis Chapter 3). These scenarios constituted the baselines for the sensitivity-based approach presented herein. Eight of these scenarios represented conditions under radiative forcing of 4.5 Wm^2 by the end of the century (RCP4.5), while the remaining four represented conditions under radiative forcing of 8.5 Wm^2 (RCP8.5), associated with greater greenhouse gas emissions. All 12 GCM-RCP outputs were statistically downscaled to the 10 km-resolution grid of the Natural Resources Canada reference observed meteorological database (NRCANmet – Hopkinson et al., 2011; Hutchinson et al., 2009; McKenney et al., 2011), against which they were additionally bias corrected for the REF period using the quantile-quantile mapping approach (also called daily scaling) (Maraun, 2016; Mpelasoka & Chiew, 2009).

The 12-member ensemble presented significant (Wilcoxon signed-rank test (Wilcoxon, 1945), $p < 0.001$) increases in mean annual air temperature for the FUT1 (+2.9 ± 1.0°C) and FUT2 (+4.2 ± 1.8°C) periods, with respect to the REF period (**Table 4.2**), with all changes also being significant for all ensemble members (Student's t-test, p-value < 0.05). Similarly, precipitation for the ensemble presented significant increases of +12 ± 7% (+125 ± 78 $mm.yr^{-1}$) for FUT1 and +15 ± 10% (+162 ± 108 $mm.yr^{-1}$) for FUT2, with respect to REF, albeit with three ensemble members not presenting significant changes for each period (though not necessarily the same members). While these constitute important departures from long-term conditions, annual temperature and precipitation anomalies with respect to the REF period mean presented even greater changes, though not sustained over long periods. For example, FUT2 period mean annual temperature anomalies grouped by RCP scenario were +3.4 ± 1.2°C (RCP4.5) and +6.1 ± 1.7°C (RCP8.5), while mean annual precipitation anomalies ranged from +125 ± 156 mm (RCP4.5) to +299 ± 140 mm (RCP8.5).

4.3 Methods

4.3.1 Perturbation of CMIP5 climatic forcings

In a variation of the delta change factor method (Hay et al., 2000; Xu et al., 2005), perturbations were applied to daily precipitation and air temperature for each of the 12 members of the CMIP5 ensemble of GCM-RCP outputs. Climatic forcings remained unaltered for the REF period, with the 30-year period between REF and FUT1 (2011-40) used to gradually ramp-up the perturbations (one third of the perturbation per decade) (**Figure 4.2**). This ramp-up period was done to minimize the creation of artificial discontinuities in the time series and is not considered in subsequent analyses.

For each of the 12-member GCM-RCP outputs, perturbations consisted of six increases in mean air temperature (+0.5, +1.0, +1.5, +2.0, +2.5, and +3.0°C; no temperature decreases were considered) and six modifications to precipitation (±10, ±20, and ±30%). These ranges of temperature and precipitation deltas were determined empirically to reflect the uncertainty surrounding future precipitation, while acknowledging the likelihood of only increases in temperature. The seasonality of temperature and the seasonality and frequency of precipitation were thus unaltered in all the scenarios. As such, mean annual anomalies of temperature reached a maximum of 9.1 ± 1.7°C (RCP8.5; FUT2; +3.0°C) with respect to the REF period mean, while mean annual precipitation anomalies varied from +708 ± 181 mm (RCP8.5; FUT2; +30%) to -239 ± 102 mm (RCP4.5; FUT1; -30%).

All 36 combinations of perturbations to precipitation and temperature were considered, to which were added the 12 combinations in which all perturbations of one variable were realized without perturbing the other variable (noted as either *d*P or *d*T). To these 48 conditions (together noted as *d*P, *d*T) was added the unaltered baseline GCM-RCP scenario, for a total 49 climatic forcing conditions for each of the 12 CMIP5 ensemble members, yielding altogether 588 scenarios. Both the Lake Papineau catchment and lake water budget were evaluated under each of these conditions for both the FUT1 and FUT2 30-year future periods.

4.3.2 Catchment and lake water budget models

Catchment water budget components, notably discharge and AET, were calculated on a monthly basis using the HydroBudget (HB) catchment water budget model calibrated in Harris et al. (*in prep*., Thesis Chapter 2) under observed conditions and used in Harris et al. (*in prep*., Thesis Chapter 3) for the evaluation of the impact of future climatic conditions under the 12-member CMIP5 ensemble. HB was developed for the simulation of potential groundwater recharge in cold and humid climates, using a runoff curve number (RCN) approach. The 100 m-resolution RCNs were attributed based on slope, land cover, and pedology, with these values remaining constant across all simulation periods under the assumption of unchanging land cover through time. Eight model parameters govern the partitioning of available water into runoff and baseflow (the sum of these two components equaling outlet discharge), with the remainder into AET. HB was calibrated in Thesis Chapter 2 under observed conditions (WY 2016-2022), with model parameter values retained for simulating both CMIP5 conditions (Thesis Chapter 3) and the perturbed climatic conditions evaluated here.

In addition to the evaluation of which component (Q or AET) constituted the dominant catchment release function, HB results were used for estimating the groundwater contribution to Lake Papineau, using a classical water budget equation, wherein lacustrine groundwater (GW_{Net}) constitutes the residual:

$$GW_{Net} = GW_{In} - GW_{Out} = VI + R + Q_{Base} - Q - E \pm \Delta S \qquad \text{(Equation 4.1)}$$

where GW_{Net} is the lacustrine groundwater contribution, equal to groundwater inflow to the lake (GW_{In}) minus lake water outflow to the aquifer (GW_{Out}). Direct vertical inflow (VI; sum of liquid precipitation and melted snow) and direct lake evaporation (E) occur across the Lake Papineau surface area, while runoff (R) and baseflow (Q_{Base}) contributions were associated with the lake catchment surface area (excluding the Lake Papineau extent). E was calculated using the Oudin et al. (2005) formula, which uses only air temperature. R, Q_{Base}, and discharge (Q) were obtained directly from HB. Lake storage change (ΔS) from one month to the next was derived from estimated discharge using the lake outlet rating curve. The sum of GW_{Net} and Q_{Base} constituted the total groundwater contribution to Lake Papineau (GW_{Total}). All volumes were reasoned in Mm^3.

The residual lake water budget technique was employed in Harris et al. (*in prep*., Thesis Chapter 2) and resulted in comparable long-term observed GW_{Net} estimates to those obtained using a Modflow model, specifically constructed for the quantification of lacustrine groundwater exchanges (Harris et al., *in prep*., Thesis Chapter 3). As the transient Modflow model (monthly stress periods) required approximately 12 hours of computation time to simulate conditions under each CMIP5 ensemble member, the evaluation of all 588 perturbed climatic forcings here would have been unfeasible. The residual lake water budget technique constituted an acceptable and less computationally demanding alternative for estimating lacustrine GW under as many varying climatic conditions.

4.3.3 Budyko theoretical framework

The Budyko water balance framework (Budyko, 1974) was used to characterize the partitioning of precipitation into the catchment release functions of discharge (Q) at the lake outlet and actual evapotranspiration (AET) over the watershed. Within the framework, the evaporative index ($AET.P^{-1}$) is a function of the aridity index ($PET.P^{-1}$), with unity between AET and PET constituting the atmospheric demand limit, and unity between P and AET constituting the water supply limit. Budyko derived a non-parametric equation to describe the central tendency of numerous large catchments from diverse hydroclimatic conditions to be situated along a curve (hereafter termed the empirical Budyko curve) within the space defined by the two indices. Several parametric Budyko equations have since allowed curves to be calculated for individual catchments, based on evaporative conditions. One of these is the Tixeront-Fu equation (Fu, 1981; Tixeront, 1964; Zhang et al., 2004):

$$\frac{AET}{P} = 1 + \frac{PET}{P} - (1 + \left(\frac{PET}{P}\right)^{\omega})^{\omega^{-1}} \qquad \text{(Equation 4.2)}$$

where AET is the actual evapotranspiration ($mm.yr^{-1}$), P is annual precipitation ($mm.yr^{-1}$), PET is potential evapotranspiration ($mm.yr^{-1}$), and ω is the Tixeront-Fu parameter (dimensionless). The catchment evaporative index ($AET.P^{-1}$) is thus directly related to the aridity index ($PET.P^{-1}$) through ω. PET was estimated using the Oudin et al. (2005) formula, while AET was estimated under the assumption of a closed catchment water budget, where both storage terms and groundwater exchange outside the surface catchment were considered negligible. As such, AET is inferred as the difference between precipitation and discharge (P – Q) and the evaporative index is formulated as $AET.P^{-1}$ or $(1\text{-}Q).P^{-1}$. The ω parameter was fitted to long-term aridity and evaporative conditions using a best-fit metric (for this study, mean absolute error) using the R package *budyko* (Hampton, 2025). Higher ω values indicate a larger partitioning of available precipitation into AET. The global empirical Budyko curve, based on watersheds located worldwide, has a Tixeront-Fu ω of 2.60 (Andréassian & Sari, 2019; Yang et al., 2008). This framework was used in Harris et al. (*in prep*., Thesis Chapter 2) to partition the main water fluxes of the Lake Papineau watershed, with a ω value of 1.97 characterizing the 2016-2022 period. It was used here to understand how this partitioning might change under extreme future climatic conditions.

4.3.4 Evaluation of the long-term shift in catchment release function under perturbed climate change conditions

The Lake Papineau catchment hydrological regime, which is considered here to be characterized by the dominance of either discharge or AET, was evaluated on a long-term basis (30 years) using an empirical cumulative distribution function to determine the non-exceedance probability for an evaporative index ($AET.P^{-1}$) of 0.5 (**Figure 4.3**). The degree to which AET constituted the long-term dominant catchment release function of each of the 588 combinations of climatic forcings was measured in the form of deciles of cumulative probability for an evaporative index above 0.5. Owing to natural climate variability, annual water budgets are occasionally dominated by one release function or the other for a given hydrological year. As such, a shift in hydrological regime was considered for non-exceedance probabilities of at least 0.5. All calculations were performed using R (version 4.2.1), with specific packages noted where necessary (R Core Team, 2024).

4.4 Results

4.4.1 Lake water budget under perturbed climatic conditions

Under long-term (REF period) baseline conditions, the lake water budget outflows were dominated by discharge (89%), with the remaining outflows attributed to direct lake evaporation (11%) (**Table 4.3**). Inflows were dominated by runoff (60%) and, to a lesser extent, by direct precipitation (21%), and the baseflow groundwater contribution (16%). Lacustrine groundwater (GW_{Net}) accounted for the remaining 3% of inflows. When GW_{Net} and baseflow were combined, the total groundwater contribution represented 19% of lake inflows. Mean REF period GW_{Net} volume was 1.8 ± 1.6 $Mm^3.yr^{-1}$, corresponding to 13% of the REF period annual direct precipitation to the lake surface or 16% of the baseflow groundwater contribution.

Under the influence of the baseline CMIP5 GCM-RCP forcings, the contributions of each lake water budget component to total inflows or total outflows remained largely unaltered for both the FUT1 and FUT2 periods (**Table 4.3**). Significant changes in the contributions of discharge and evaporation to total outflows never exceeded ±1% (Wilcoxon signed-rank test, p-value < 0.05), while GW_{Net} was the only inflow to present significant changes in contribution to total inflows, and only to a limited extent (+1% for FUT2). With respect to the REF period, forcings induced significant increases during both future periods in the lake water budget outflows of discharge and evaporation, with increased discharge of +12% and increased evaporation of +23% in FUT2. All lake water budget inflows presented significant increases for both future periods, except for the Q_{Base} contribution of runoff. Among all the budget components, GW_{Net} presented the greatest increases with respect to the REF period of +27% and +39% for FUT1 and FUT2, respectively. Despite non-significant changes in Q_{Base}, when combined with GW_{Net}, changes in GW_{Total} to Lake Papineau with respect to REF were significant (+7% and +12% for FUT1 and FUT2, respectively).

Considering the lake water budget only under perturbed precipitation conditions (i.e., *d*P columns in **Table A4.1** and **Table A4.3** in Appendix, where future temperature changes only corresponded to baseline CMIP5 scenarios), increasing precipitation significantly increased all inflow and outflow values in FUT1 and FUT2, with respect to REF (Wilcoxon signed-rank test, p-value < 0.05). Conversely, only precipitation decreases (-*d*P) of -20% and -30% induced significant changes in nearly all variables (except for GW_{Net} and GW_{Total}). Decreasing precipitation by 10% was insufficient to induce significant changes for direct precipitation, Q_{Base}, and GW_{Total} in both FUT1 and FUT2, and runoff (R) and Q in FUT2. Whereas precipitation increases led to increased volumes for all water budget components, decreased precipitation led to decreased volumes in all components except for evaporation and GW_{Net}.

When also accounting for the effect of increased temperature (i.e., *d*P, *d*T columns), results grouped by precipitation changes exhibited similar magnitudes of volumetric and percent changes relative to the REF period, generally accentuating losses or attenuating gains with respect to *d*P conditions. The only exceptions were the groundwater components (Q_{Base} and GW_{Net}), which presented greater increases for all instances of *d*P, *d*T in comparison to changes seen under *d*P alone. Non-significant changes under *d*P also often became significant under *d*P, *d*T (e.g., in the case of FUT2 conditions for Q, R, and GW_{Total}). For clarity, the 12% increase in direct precipitation to the lake surface in absence of increased precipitation (*d*P, *d*T with P+0%) reflected conditions of the baseline CMIP5 ensemble.

Whereas baseline CMIP5 scenarios induced minimal changes in the contribution of specific budget components to total inflows or outflows, perturbed conditions induced much more important shifts in the allocations of inflows and outflows. For example, under the most extreme decrease in precipitation (-30%), Q contributed approximately 10% less to total outflows, shifting the allocation to E (values not shown). Under the same conditions for total inflows, R contributed 15% less than under REF conditions, with the reallocation separated equally among P, Q_{Base}, and GW_{Net} (values not shown). Under increased precipitation scenarios, this phenomenon reversed, with Q and R contributing more to total outflows and inflows, respectively, albeit with much lower magnitude shifts than under decreased precipitation conditions (approximately one-third).

When mean lake water budget changes were reasoned with respect to temperature perturbations alone, increasing only temperature (i.e., *d*T columns in **Table A4.2** and **Table A4.4** in Appendix) significantly increased discharge and runoff up to +1.5°C in FUT1 and up to +1.0°C in FUT2. As the increased volumes of these components became less important with increasing temperature, *d*T beyond these thresholds failed to induce ensemble increases in Q and R with respect to the REF period that were significantly different from zero (Wilcoxon signed-rank test, p-value < 0.05). Conversely, the volumes of direct lake evaporation (E) and the three groundwater components (Q_{Base}, GW_{Net}, and GW_{Total}) all significantly increased with increasing temperature, though significant increases for Q_{Base} only began at +2.0°C in FUT1 and +1.0°C in FUT2. As *d*T scenarios did not account for increased precipitation, direct lake precipitation only accounted for increases associated with baseline CMIP5 members.

Considering the combined effects of perturbed precipitation and temperature (*d*P, *d*T columns in **Table A4.2** and **Table A4.4**), nearly all budget components presented the same pattern of significant increases in volume with respect to the REF period as seen under *d*T conditions alone, with increases systematically greater than under their associated *d*T condition. The only exceptions were for E and Q_{Base}, with the former remaining unchanged between *d*T and *d*P, *d*T conditions due to the Oudin formula simply not accounting for precipitation. Q_{Base} exhibited the same non-significant changes as seen under *d*T alone for FUT1. Under FUT2, however, changes in Q_{Base} were only significant for the unmodified temperature condition. Despite the prevalence of non-significant Q_{Base} changes, the addition of the consistently significant GW_{Net} changes resulted in significant GW_{Total} changes for all perturbed conditions. Overall, *d*P, *d*T conditions induced volume and percent change (with respect to the REF period) that were only marginally greater than under *d*T conditions alone. Contrary to the more important shifts in the allocations of inflows and outflows seen when grouping conditions by precipitation perturbations, temperature perturbations induced maximum shifts of only approximately -5% in the case of the contribution of Q to total outflows reallocated to E

(+3.0°C) (values not show). With increasing temperatures, GW_{Net} and direct precipitation (and to a lesser degree Q_{Base}) were similarly reallocated.

When taking into account all mean future perturbed CMIP5 conditions grouped by changes to either precipitation or temperature, GW_{Net} presented consistently significant increases on the order of 0.4 to 1.5 $Mm^3.yr^{-1}$, corresponding to percent changes with respect to the REF period, ranging from +24% (FUT1; P+30%; *d*P) to +85% (FUT2; P-30%; *d*P, *d*T). As in the case of the baseline CMIP5 scenarios, GW_{Net} increased with increasing temperature, though increasing precipitation had the effect of stagnating or slightly decreasing volumes. Each successive decrease in precipitation beyond the baseline CMIP5 conditions, however, induced ever greater increases in GW_{Net} with respect to the REF period.

Under the influence of conditions grouped by temperature perturbations, GW_{Net} increases were sufficiently important to ensure GW_{Total} increases were consistently significant (even when the majority of Q_{Base} increases were non-significant). Conversely, when grouped by precipitation perturbations, GW_{Net} increases were insufficient to ensure significant increases in GW_{Total} under decreased precipitation conditions and induced losses in FUT1 GW_{Total} of -9% (*d*P) and -5% (*d*P, *d*T), with respect to the REF period, in the case of the most extreme *d*P (-30%). As lake stage and lake storage were factors influencing the estimation of GW_{Net} as the residual of the lake water budget, it bears mentioning that mean annual lake stage across all perturbed conditions for both future periods was never below 173.0 masl and never exceeded 174.0 masl (roughly corresponding to observed conditions for 2016-2022). Based on these stage conditions, annual lake storage values across all perturbed scenarios had an interquartile range of -1.2 to 1.1 $Mm^3.yr^{-1}$, which was smaller than that of any other water budget component, including GW_{Net}.

4.4.2 Changes in catchment aridity index, evaporative index, and ω

The lake catchment aridity index (AI) and evaporative index (EI) were calculated for each long-term future period and plotted in Budyko space, along with their corresponding fitted Tixeront-Fu curves. 30-year mean conditions for the REF period and future periods (FUT1 and FUT2) for the baseline CMIP5 scenarios and their perturbations were categorized by changes to precipitation (**Figure 4.4a**) and increases to temperature (**Figure 4.4b**). Concerning AI, the baseline ensemble mean was 0.54 for the REF period, 0.56 for FUT1, and 0.57 for FUT2 (**Table 4.4**). Considering all perturbed conditions, the results showed that annual values reached a maximum of 1.40 (T+3.0°C, P-30%) and as low as 0.29 (T+0.0°C, P+30%) for both FUT1 and FUT2 (not shown in **Figure 4.4**). On a mean long-term basis, however, only the most extreme increases in temperature (+3.0°C) and reductions in precipitation (-30%) transitioned the catchment from energy-limited to water-limited conditions ($PET.P^{-1} > 1$; 2.1% for FUT1 and 3.4% for FUT2) (**Figure 4.4a**).

When considering only *d*P, the FUT2 ensemble mean AI steadily decreased from a -30% precipitation perturbation (0.82) to a +30% increase in precipitation (0.44), with similar but slightly higher values when accounting for combined temperature and precipitation perturbations (**Table 4.4**). When considering only *d*T, the FUT2 ensemble AI increased from 0.59 to 0.67 with each successive temperature perturbation, with similar but slightly higher values when considering *d*P, *d*T. AI appeared to be much more sensitive to precipitation changes than to temperature changes, with each incremental change in precipitation producing a larger shift than obtained for each successive increase in temperature. Similar results were obtained for the FUT1 period. Plotting long-term conditions in Budyko space underscored the greater sensitivity of the catchment to changes in precipitation, with FUT1 and FUT2 conditions clearly grouped by precipitation increases and decreases (**Figure 4.4a**), while grouping by temperature perturbation (**Figure 4.4b**) produced no readily discernable pattern.

Concerning the evaporative index, the baseline CMIP5 ensemble mean EI was 0.44 for the REF period, varying little for FUT1 (0.44) and FUT2 (0.45) (**Table 4.4**). All 12 baseline CMIP5 members remained discharge dominant (EI < 0.5) for both future periods, with EI reaching only as high as 0.48 (MIE; RCP4.5; FUT2). As in the case of the aridity index, EI was also more sensitive to changes in precipitation than to increases in temperature, with FUT2 values ranging from 0.36 to 0.57 (for *d*P), and from 0.38 to 0.60 (*d*P, *d*T). As with AI, ensemble mean FUT1 EI values closely followed those of FUT2, with *d*P and *d*T values slightly lower than those of *d*P, *d*T. Relative to AI, EI occupied a much narrower interval, with annual values ranging from 0.26 (T+0.0°C, P+30%) to 0.82 (T+3.0°C, P-30%) (**Figure 4.4**).

When reasoning with respect to precipitation perturbations, a 20% reduction in precipitation was the threshold for shifting mean catchment conditions from discharge dominance to AET dominance (EI > 0.5), under both *d*P and *d*P, *d*T conditions and for both FUT1 and FUT2. Decreasing precipitation by 30% pushed the catchment well into the region of AET dominance for both periods. As the catchment was less sensitive to temperature perturbations, the maximum increase of +3.0°C was required to reach the threshold for AET dominance in FUT2 and only under combined *d*P, *d*T conditions. Ensemble mean EI only reached 0.48

to 0.49 under *d*T conditions alone for FUT2, and for FUT1 under both *d*T and *d*P, *d*T conditions, showing near parity among Q and AET as the dominant catchment release function.

The sensitivities of AI and EI with respect to perturbed climatic forcings were translated to Tixeront-Fu ω values, fitted against the point clouds of long-term AI and EI conditions. The baseline CMIP5 ensemble mean was characterized by an ω of 2.28 for the REF period, 2.20 for FUT1, and 2.19 for FUT2. For both periods, the 12-member ensemble presented ω values that ranged from 2.03 (B1M; RCP4.5; FUT1) to 2.42 (INM; RCP4.5; FUT2). For FUT2, the ω values showed limited sensitivity to precipitation perturbations, decreasing with each successive increase in precipitation from 2.28 to 2.16 (*d*P) and from 2.28 to 2.13 (*d*P, *d*T) (similar results were found for FUT1). When analyzed with respect to temperature perturbations, ω values exhibited even less departure from baseline conditions, with 2.19 to 2.17 between +0.0°C and +3.0°C for *d*T in FUT2, and 2.20 to 2.17 for *d*P, *d*T in FUT2 (similar results were found for FUT1). When considering all perturbed conditions (not simply the ensemble means categorized by *d*P or *d*T), ω values ranged from 1.92 (A10; RCP4.5; all *d*T, P+30%; FUT2) to 2.46 (INM; RCP4.5; all *d*T, P-30%; FUT2) and remained well below the global, empirical ω value of 2.60 (**Figure 4.4**).

4.4.3 Thresholds that control Lake Papineau hydrology

Complementing the analysis using the Budyko framework, shifts in the dominance of discharge or AET as primary catchment release function were identified for each CMIP5 ensemble member under all perturbed conditions by characterizing the distribution of annual evaporative index (EI) values for a given long-term period with respect to the 0.5 threshold (**Figure 4.5a**). According to the empirical cumulative distribution function, all baseline CMIP5 conditions under both FUT1 and FUT2 conditions were dominated by Q, with at most only a 30% probability of AET exceeding the threshold, consistent with a similarly low exceedance probability of 20% during the REF period (**Figure 4.5b**).

This dynamic was further reinforced through increased precipitation, with all instances dominated by Q. Under the most extreme *d*P of +30%, all annual catchment water budgets for a given period (in both FUT1 and FUT2) were dominated mostly or entirely by discharge, irrespective of temperature increases. The other end of the extreme (*d*P of -30%) was sufficient to transition AET to the dominant release function for all or nearly all annual catchment water budgets for all ensemble members and for both periods, with this being nearly the case for *d*P of -20% as well, but only in conjunction with *d*T of at least +1.0°C. Given the anticipated +15 ± 10% baseline FUT2 ensemble mean CMIP5 increase in precipitation (**Table 4.2**), this effectively translates to a possible shift in catchment release function under slightly higher temperatures than the baseline CMIP5 forcings. Discharge dominance was maintained by all ensemble members for all other increases in precipitation, and all (FUT1) and nearly all (FUT2) members for P+0%. Even with a reduction of 10% precipitation during FUT1, all members retained discharge dominance even with a *d*T of +0.5°C. Reducing precipitation by 20%, however, induced AET dominance in all ensemble members during FUT1 (except for A13 for *d*T of +0.0°C). This dominance was generally maintained in FUT2, but only when accompanied by *d*T of at least +1.0°C.

Although EI was generally more sensitive to changes in precipitation than to changes in temperature, applying *d*T of +1.5°C in absence of any *d*P was sufficient to transition the first ensemble member (MIE) from discharge- to AET-dominated during FUT2, while three additional members were capable of transitioning for the same period with +3.0°C. No changes to T in the absence of changes in P could induce similar shifts during FUT1. A reduction of 10% precipitation accompanying +3.0°C allowed all ensemble members to become AET-dominant during FUT1, but this was not maintained during FUT2.

With respect to the long-term mean REF precipitation of 1065 $mm.yr^{-1}$, the most extreme mean long-term future conditions associated with precipitation increases (+30%) and decreases (-30%) for the FUT2 period represented, respectively, 757 $mm.yr^{-1}$ (B1M; RCP4.5) and 1859 $mm.yr^{-1}$ (A13; RCP8.5). As only increases in temperature beyond CMIP5 conditions were considered, mean long-term FUT2 conditions were at most 15.8°C (MIC; RCP8.5; T+3.0°C), compared to 4.7°C for the REF period. Within this combined range of climatic forcings, there did not appear to be a clear tipping point for transitioning the catchment water balance from a discharge- to AET-dominated regime (**Figure 4.6**). Certain perturbed ensemble members pointed to AET dominance under future conditions that other members indicated to be discharge-dominant and vice-versa. A transition zone appears to exist, wherein relatively small changes to baseline CMIP5 conditions could potentially tip the balance from discharge to AET dominance.

This transition in dominant catchment release function would induce contrasting changes to the volumes and relative importance of lake water budget components, specifically the groundwater contributions (Q_{Base} and GW_{Net}). Whereas Q_{Base} volumes decreased as the importance of AET as dominant catchment release increased (to the detriment of Q), their contribution to total inflows actually increased (**Figure 4.7a, c**). The relative contribution of lacustrine groundwater to total lake inflows would similarly increase with AET dominance, yet contrary to Q_{Base}, so too would inflow volumes (**Figure 4.7b, d**). While GW_{Net} volumes would increase as compensation for other inflow losses, the range of increases would remain relatively constrained, underscoring the buffering capacity of GW_{Net} in providing a sustained contribution with minimal regard to the degree of climatic perturbation.

Changes in lake hydrological regime and lake water budget components are generally best characterized over long-term periods, consisting of conditions quantified on an annual basis. An appreciation of sub-annual dynamics, however, was instructive in understanding how these changes were propagated. The mean interannual seasonal contributions of lake water budget components to total inflows and total outflows pointed to the relative stability of FUT2 conditions under the baseline CMIP5 ensemble with respect to the REF period (**Figure 4.8a, b**). Only FUT2 results were considered here, as the baseline CMIP5 and their perturbed conditions presented largely the same seasonal dynamics during both future periods. Much like the water budget characterized on an annual basis, discharge and runoff dominated outflows and inflows, respectively, with only summer (Jun. – Aug.) direct evaporation accounting for nearly half of outflows (42%). Baseflow was most important during winter (Dec. – Feb.) (34% during REF and 27% during FUT2), while GW_{Net} contributed 17% of summer inflows and between 16% (REF) and 12% (FUT2) of winter inflows. GW_{Net} constituted a budget outflow in only a minority of instances, contributing at most 5% to outflows during spring (Mar. – May) of FUT2. Considering only the FUT2 period under *d*P, *d*T conditions categorized by precipitation perturbations, lake outflows were insensitive to *d*P during winter, with fall (Sep. – Nov.) and spring characterized by the increased importance of evaporation with decreasing *d*P (**Figure 4.8c**). Seasonal outflows largely followed the same dynamic under combined perturbations reasoned with respect to temperature perturbations (**Figure 4.8d**). The lacustrine groundwater contribution to summer inflows increased with successive decreases in *d*P when reasoning with respect to precipitation perturbations, whereas changes in *d*T had negligible effect for the same season when reasoning with respect to temperature perturbations. In both cases, the baseflow groundwater contribution was virtually absent for summer.

4.5 Discussion

4.5.1 Resilience of the Lake Papineau watershed

The results indicate that the Lake Papineau catchment could be relatively hydrologically resilient to diverse future climatic conditions beyond those anticipated under a 12-member CMIP5 ensemble forced with two RCPs (RCP4.5 and RCP8.5). In the specific conditions of this study area, potential explanations include the roles of land cover, the relative importance of the lake to catchment area ratio, and the attenuated response of groundwater resources, arising from subsurface storage and long residence times that dampen and delay the transmission of climatic signals. This resilience was apparent in the hydrological response of the catchment, translated through the Budyko framework. Under the impact of future climate forcings (both CMIP5 scenarios and their perturbations), annual conditions largely remained within the energy-limited domain, with only occasional excursions into water-limited conditions ($PET.P^{-1} > 1$). Even under the most extreme increases in temperature and reductions in precipitation, only an exceedingly small minority of long-term conditions crossed the aridity index water-limited threshold. This is consistent with the maintenance of an energy-limited regime by southern Quebec catchments, found by Valencia Giraldo et al. (2023), under even the most perturbed observed temperature (-2 to +6°C) and precipitation (±20%) conditions. When considering hydrological resilience as the maintenance of discharge as the dominant catchment release function over AET, Lake Papineau remained hydrologically resilient even for precipitation reductions of as much as -20% with respect to baseline CMIP5 forcings. This contrasts with the conditions of catchments in drought-prone regions (CA, USA), for example, where droughts induce shifts across the aridity index threshold from one year to the next (Maurer et al., 2022). Whereas decreases in precipitation have the potential to transition the dominant catchment release function from discharge to AET ($AET.P^{-1} > 0.5$), the Lake Papineau catchment is relatively insensitive to changes in temperature alone. This is consistent with the findings of Yang et al. (2018), who identified greater sensitivity of catchment hydrological responses to precipitation changes than to temperature increases to be a common phenomenon under unchanging land cover conditions. This has further been demonstrated to be the case for the hydrology of southern Quebec (Aygün et al., 2022) and elsewhere in Canada (Rasouli et al., 2022).

Lacustrine groundwater demonstrates a potential role in attenuating the impact of extreme changes in future climatic conditions for Lake Papineau. On the REF period mean long-term basis, GW_{Net} (1.8 $Mm^3.yr^{-1}$) contributed 3% of total annual inflows to Lake Papineau (**Table 4.3**), a value similar to those obtained by Harris et al. (*in prep*., Thesis Chapters 2 and 3), albeit lower than the contribution simulated using a Modflow groundwater flow model (7%; 4.8 $Mm^3.yr^{-1}$). With the addition of the baseflow groundwater contribution, GW_{Total} represented 19% of REF period lake inflows, again broadly consistent with Modflow results (23%). Results under mean baseline CMIP5 conditions, however, diverged from those obtained using Modflow. While FUT2 GW_{Net} ensemble mean volumetric increases, for example, were the same order of magnitude for both the residual water budget here (+0.7 $Mm^3.yr^{-1}$) and Modflow (+0.2 $Mm^3.yr^{-1}$), neither GW_{Net} nor GW_{Total} changes were significant for either future period using Modflow, but were when using the residual water budget technique here (+39% and +12%, respectively). Neither method, however, yielded significant changes in the relative contributions of these two variables to total inflows, which remained comparable to those observed during the REF period.

The results presented here using the residual water budget technique should be viewed as approximating those of the more hydrogeologically-robust Modflow model, with potential overestimation of the contribution of GW_{Net} under perturbed climatic forcings. Notwithstanding the greater uncertainties inherent to the residual water budget technique (Trask et al., 2017), perturbed conditions presented an altogether different portrait than that seen under baseline CMIP5 forcings. GW_{Net} volumes consistently increasing under even the most extreme climatic perturbations, constituting up to 11% of total annual inflows when temperature increased by 3.0°C with an accompanying 30% decrease in precipitation (CE2; RCP4.5; FUT2) (**Figure 4.7d**). GW_{Total} constituted at most 34% of total lake budget inflows under the same *d*P, *d*T, in comparison to 19% under REF conditions (**Table 4.3**). Conversely, with a similarly important increase in precipitation (+30%), GW_{Total} decreased to 12% of total inflows. While important, these relative contributions were not outside the range of estimates from lakes in comparable hydrogeological and climatic contexts. Using a lake water budget, Cardille et al. (2004), for example, found that residual GW_{Net} constituted between 31% and 92% of total inflows to Allequash Lake (1.1 km^2; WI, USA). For lakes in this same study region, Cardille et al. (2009) perturbed observed climatic conditions and similarly found that the contribution of GW_{Net} to total inflows decreased with increasing precipitation, consistent with the findings for Lake Papineau here.

4.5.2 Uncertainty associated with the analysis

The perturbation methodology implemented here contrasts with approaches more frequently found in the literature, such as using climate analogues or ‘trading space for time’, whereby observed climatic conditions for one site are exchanged for those of a site whose conditions reflect anticipated future changes (Leterme et al., 2012). However, the CMIP5 scenarios serving as the baselines for perturbed conditions here have the benefit of having been bias-corrected against observations to better reflect local climatic phenomena. This quantile-quantile bias-correction method tends to incompletely represent distribution extremes, particularly for precipitation (Roy et al., 2024). Consequently, perturbing these forcings allows the evaluation of changes in precipitation volumes without modifying their underlying distribution. Perturbing individual climate variables such as temperature and precipitation has the potential, however, to yield results inconsistent with the physical dependencies between these variables (Chen et al., 2018; Chen et al., 2021; Meyer et al., 2019). For example, altering precipitation amounts independently of temperature-driven changes in atmospheric moisture capacity and energy availability. Perturbed scenarios of increased temperature paired with decreased precipitation, for instance, are potentially improbable owing to the established Clausius-Clapeyron relation, wherein every 1°C increase in air temperature allows the atmosphere to retain approximately 7% more water. However, Martel et al. (2021) note that this relationship is location-dependent and varies due to factors such as rainfall duration and intensity.

The apparent resilience of the studied catchment is contingent on the manner in which AET is estimated. Aspects of this complex hydroclimatic phenomenon that were not explicitly considered here include the dominant role of the vapor pressure deficit over air temperature in driving AET in cold, energy-limited environments (Li et al., 2022; Vadeboncoeur et al., 2018). Though the vapor pressure deficit drives land-atmosphere humidity gradients, stomatal closure due to water stress can dampen this effect (Cai et al., 2024; Jaramillo et al., 2022). In failing to account for the impact of variables such as specific air humidity, the PET calculation suggested by Oudin et al. (2005), along with other temperature-based formulas, potentially overestimated PET with respect to alternatives such as Penman-Monteith (Duan et al., 2017). Using a temperature-based PET calculation thus potentially impacted the thresholds identified for the partitioning of Q and AET and the shifts in the dominant catchment release regime. Still other authors have pointed to the potential underestimation of AET with certain formulas and recommended the use of more complex Earth system models to account for phenomena such as AET reduction through CO_2-induced stomatal closure (Byrne et al., 2024; Yang et al., 2019). Nevertheless, Pimentel et al. (2023) concluded that temperature-based PET formulas, such as Jensen and Haise (1963) and Hargreaves and Samani (1985), were adequate in energy-limited contexts. Testing the impact of alternative PET formulations would be informative in future research.

The choice of the HydroBudget water budget model (HB) for estimating lake water budget components presents several potential limitations, including the inability to explicitly represent changes in sub-daily precipitation intensity, as climatic forcings are provided at a daily time step and water budget components are simulated at a monthly resolution. The extent to which changes in precipitation characteristics would affect estimates of groundwater contributions to Lake Papineau (baseflow or GW_{Net}) therefore remains uncertain. Anderson et al. (2024), for example, showed that at annual and seasonal timescales, lower streamflow percentiles (i.e., low flows) were generally less responsive to precipitation changes than higher flows across U.S. catchments for the 1981-2022 period. They further noted that summer discharge often exhibited limited sensitivity to summer precipitation, attributing this behavior to soil moisture deficits driven by elevated PET and sustained groundwater contributions. In contrast, Kinnard et al. (2022) found that observed summer low flows in southern Quebec watersheds were most sensitive to summer precipitation.

The future partitioning of annual precipitation into catchment Q and AET and the ability of the study catchment to maintain hydrological resilience, even under more extreme perturbed CMIP5 forcings presented here, depends on additional assumptions related to the use of HB. As the Budyko framework was integrated into model calibration to constrain the feasible space of the evaporative index under observed conditions (Harris et al., *in prep*, Thesis Chapter 2), HB model parameters were assumed here to be capable of simulating the catchment hydrologic response under conditions radically different from those under which they were calibrated. The HB parameter governing maximum soil reservoir content, for example, calibrated under observed conditions, may not adequately reflect reservoir capacity under future extreme conditions, resulting in unrealistic AET. The relatively limited variation in Tixeront-Fu ω values, within the narrow range of 0.16 (from 2.13 to 2.29), under even the most perturbed climatic forcings with respect to long-term observed conditions, may be a further indication of HB model limitations in accounting for extreme climatic forcings. Heidari et al. (2021), however, found minimal change in Tixeront-Fu ω values under contrasting future climatic conditions for forested catchments (USA) using water budget components derived from the Variable Infiltration Capacity (VIC) model. This is also broadly consistent with the limited deviation in ω values found by Ibrahim et al. (2024) for catchments on the global-scale, and by Abatzoglou and Ficklin (2017) for USA catchments characterized by similar hydroclimatic conditions as the study site.

While not investigated here, changes in land cover and forest composition could be induced by extreme shifts in the future climatic forcings of either the baseline CMIP5 scenarios or their perturbed conditions (Boulanger et al., 2022, Périé & de Blois, 2016). Duarte et al. (2024), for example, identified significant increases in deciduous forest coverage, with associated loss of mixed forest coverage, in the northeastern USA under RCP4.5 forcings. Although these changes were exacerbated under RCP8.5, the authors found no significant change in discharge for this region under either RCP, despite significant increases in AET. Consideration for the potential impacts of ephemeral disturbances to land cover (e.g., forest harvesting, wildfires, and insect infestation) on Lake Papineau catchment hydrological resilience was equally absent here. While the cumulative effects of these landscape alterations have been shown to induce significant long-term decreases in low flow conditions (Coble et al., 2020; Gronsdahl et al., 2019; Segura et al., 2020), particularly when exacerbated by the impacts of climate change (Hou & Wei, 2024), other findings have pointed to inconsistencies concerning these impacts (Hou et al., 2022; Mirus et al., 2017). In their study of the Marmot Creek Research Basin (9.4 km^2; AB, Canada), Harder et al. (2015) found that forest harvesting did not have a discernable impact on catchment discharge, attributing this to hydrological resiliency. This finding contrasts with those of Buttle et al. (2018), who found no evidence of hydrological recovery for catchments in the Turkey Lakes Watershed (TLW; Ontario, Canada) 15 years after forest harvesting.

4.5.3 Implications of extreme hydrological changes in lake watersheds

Though lacustrine groundwater has the potential to mitigate the effects of extreme future climatic forcing, care should be exercised when broadly applying results to other lakes, even those set in analogous hydroclimatic settings. de Lavenne et al. (2022) found that energy-limited French and Swedish catchments with higher baseflow contributions to runoff and a large presence of lakes were more capable of attenuating hydrological sensitivity to climate anomalies. Similarly, Quin & Destouni (2018) found in their study of Swedish lakes that the presence of downgradient lakes and wetlands and their combined storage capacity were critical in attenuating discharge variability. Catchments in the Turkey Lakes Watershed containing lakes were also shown to sustain low flows, in contrast to those in which lakes were absent, a phenomenon which the authors attributed to the contribution of groundwater (Hudson et al., 2021; Leach et al., 2020). The presence of smaller lakes and wetlands (together constituting 15% of Lake Papineau catchment area) is potentially responsible in part for sustaining the groundwater contribution to Lake Papineau and maintaining lake hydrological resilience more broadly.

The role of lacustrine groundwater in sustaining the water budget of lakes in cold and humid climates identified here, both when summer contributions of other components were reduced and under more extreme future climatic forcings, has not been previously investigated. To place these findings in a broader hydrological context, insight can be drawn from studies examining the role of wetlands in mitigating similar climate-driven impacts. Using the Budyko framework, Creed et al. (2014) showed that North American catchments with higher wetland coverage were better able to maintain discharge regimes under increasing temperature conditions, highlighting the buffering capacity of landscape water storage. More broadly, wetlands have demonstrated hydrological resilience to extended drought periods (Tetzlaff et al., 2024), with this capacity attributed to the dampening effect of groundwater. Consistent with this interpretation, wetlands have been shown to reduce the severity of summer low flows in Canada (Ameli & Creed, 2019a, b; Blanchette et al., 2022; Fossey et al., 2016; Wu et al., 2023). Goyette et al. (2023), for example, found that increasing wetland area in southern Quebec catchments partially compensated for projected reductions in future summer low flow conditions under mid-century CMIP5 ensemble forcings, although this effect diminished toward the end-of-the-century. Importantly, Wu et al. (2023) also note that other studies report opposing responses, with reduced wetland extent associated with increased low flow volumes. Taken together, these findings suggest that lakes and wetlands may play analogous, yet context-dependent, roles in buffering climate change impacts, underscoring the need for continued investigation of lake-groundwater interactions, with the relatively protected Lake Papineau catchment providing an ideal setting for such research.

4.6 Conclusion

Ongoing climate change is modifying the hydrology of cold and humid climates, impacting groundwater recharge volumes, exacerbating low flow conditions, and shifting the balance of catchment water budgets between discharge and evapotranspiration. Understanding under what conditions a catchment or lake maintains hydrological resilience and which hydrological processes can mitigate climate change impacts is of growing interest. The aim of this study was to evaluate the hydrological resilience of a Canadian Shield lake (Lake Papineau; Quebec, Canada) and its catchment to extreme future climatic forcings, beyond those anticipated under a CMIP5 ensemble forced by RCP4.5 and RCP8.5 emissions scenarios. The response of the Lake Papineau water budget to perturbed CMIP5 forcings was evaluated using the catchment water budget model (HydroBudget) for the simulation of runoff and baseflow to the lake. These budget components, combined with direct precipitation and evaporation from the lake, enabled the net lacustrine groundwater exchange to be estimated as the residual of the lake water budget.

Characterization of the catchment response to extreme perturbed temperature and precipitation forcings was translated through the Budyko framework, illustrating the maintenance of an energy-limited aridity regime in all but the most extreme cases. Whereas baseline CMIP5 forcings, even under the more pessimistic RCP8.5 scenario, were largely incapable of fundamentally altering lake and catchment hydrology, relatively modest additional increases in temperature and reductions in precipitation with respect to baseline future CMIP5 conditions were able to transition the hydrological regime from discharge- to actual evapotranspiration-dominant. In parallel, lacustrine groundwater was shown to compensate for reduced inflows from other budget components, buffering the severity of extreme climate change, and helping to maintain Lake Papineau hydrological resilience under certain conditions.

These results show that available techniques can be used to characterize the impact of extreme climate change on lake hydrological resilience. They demonstrate that future conditions, only modestly different from those associated with a CMIP5 ensemble, can overcome this resilience and fundamentally alter long-term hydrology. Lacustrine groundwater may act to mitigate these impacts on lakes in cold and humid climates and efforts should be undertaken to better characterize this contribution and protect landscape features associated with groundwater recharge.

4.7 References

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4.8 Tables

Table 4.1 CMIP5 GCM-RCP baseline climate change scenarios

GCM-RCP-ensemble member	Institution Name	Name	RCP
ACCESS1-0_rcp45_r1i1p1	Commonwealth Scientific and Industrial Research Organisation, Bureau of Meteorology (Australia) – Bi et al. (2013)	A10	4.5
ACCESS1-3_rcp85_r1i1p1		A13	8.5
bcc-csm1-1-m_rcp45_r1i1p1	Beijing Climate Center, China Meteorological Administration (China) – Wu et al. (2014)	B1M	4.5
BNU-ESM_rcp85_r1i1p1	College of Global Change and Earth System Science, Beijing Normal University (China) – Ji et al. (2014)	BNU	8.5
CanESM2_rcp45_r1i1p1	Canadian Centre for Climate Modelling and Analysis (Canada) – von Salzen et al. (2013)	CE2	4.5
CMCC-CMS_rcp45_r1i1p1	Centro Euro-Mediterraneo per i Cambiamenti Climatici (Italy) – Fogli et al. (2009)	CMS	4.5
GFDL-CM3_rcp45_r1i1p1	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA) – Donner et al. (2011)	GF3	4.5
GISS-E2-R_rcp45_r6i1p3	National Aeronautics and Space Administration, Goddard Institute for Space Studies (USA) – Schmidt et al. (2006)	GIR	4.5
inmcm4_rcp45_r1i1p1	Institute for Numerical Mathematics (Russia) – Volodin et al. (2010)	INM	4.5
MIROC-ESM-CHEM_rcp85_r1i1p1	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology (Japan) – Watanabe et al. (2011)	MIC	8.5
MIROC-ESM_rcp45_r1i1p1		MIE	4.5
MRI-ESM1_rcp85_r1i1p1	Meteorological Research Institute (Japan) – Yukimoto et al. (2011)	MRE	8.5

Table 4.2 Changes to annual temperature and precipitation under baseline CMIP5 conditions

		A10	A13*	B1M	BNU*	CE2	CMS	GF3	GIR	INM	MIC*	MIE	MRE*	Ensemble ****
Δ Temperature (°C)	**FUT1-REF**	+2.7	+2.9	+1.8	+3.8	+3.3	+2.6	+3.8	+2.4	+0.9	+4.9	+3.4	+2.4	+2.9 ± 1.0
	FUT2-REF	+3.7	+5.0	+2.2	+6.9	+4.0	+3.5	+4.5	+2.7	+1.6	+7.9	+4.5	+4.3	+4.2 ± 1.8
Δ Precipitation (mm)	**FUT1-REF**	+93 [+9%]	+228 [+21%]**	-18 (n.s.)***	+164 [+15%]	+86 [+8%]	+52 (n.s.)	+214 [+20%]	+107 [+10%]	+71 (n.s.)	+246 [+23%]	+138 [+13%]	+124 [+11%]	+125 ± 78 [+12 ± 7%]
	FUT2-REF	+107 [+10%]	+340 [+31%]	-7 (n.s.)	+209 [+19%]	+37 (n.s.)	+231 [+21%]	+154 [+14%]	+136 [+13%]	+61 (n.s.)	+305 [+28%]	+115 [+11%]	+253 [+23%]	+162 ± 108 [+15 ± 10%]

* Indicates RCP8.5 (otherwise RCP4.5).
** Precipitation changes in brackets correspond to percent change relative to the REF period.
*** Non-significant changes (Student's t-test, $p < 0.05$)
**** Ensemble member uncertainties correspond to ± one standard deviation.

Table 4.3 Lake water budget inflow and outflow volumes ($Mm^3.yr^{-1}$), contributions to total inflows or outflows (%), and relative change (%) for the REF, FUT1, and FUT2 periods

		Outflows		Inflows				Δ Total groundwater
	Period	**Δ Discharge**	**Δ Evaporation**	**Δ Precipitation**	**Δ Runoff**	**Δ Baseflow**	**Δ GW_{Net}**	
12-member baseline GCM-RCP	**REF***	61.6 ± 10.7 (89%)**	7.5 ± 0.4 (11%)	14.3 ± 1.7 (21%)	42.0 ± 8.0 (60%)	11.0 ± 2.3 (16%)	1.8 ± 1.6 (3%)	12.8 ± 2.4 (19%)
	FUT1	+6.6 (-1%) [+11%]***	+1.2 (+1%) [+16%]	+1.6 (n.s.****) [+12%]	+5.2 (n.s.) [+13%]	n.s.	+0.5 (+0%) [+27%]	+0.9 (n.s.) [+7%]
	FUT2	+7.6 (-1%) [+12%]	+1.7 (+1%) [+23%]	+2.1 (n.s.) [+15%]	+5.8 (n.s.) [+14%]	n.s.	+0.7 (+1%) [+39%]	+1.5 (n.s.) [+12%]

* REF period values are ensemble mean volumes (Mm^3), with uncertainties corresponding to ± one standard deviation, and percent contribution to inflows and outflows given in parentheses.

** Values in parenthesis correspond to percent change in contribution to total inflows or outflows relative to the REF period.

*** Values in brackets correspond to percent change relative to the REF period.

**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$)

Table 4.4 Mean catchment aridity index (AI), evaporative index (EI), and fitted Tixeront-Fu ω for the baseline GCM-RCP scenarios and under perturbed precipitation and temperature conditions

		Period	Aridity index ($PET.P^{-1}$)		Evaporative index ($AET.P^{-1}$)		Tixeront-Fu ω	
12-member baseline GCM-RCP		REF	0.54 ± 0.01*		0.44 ± 0.00		2.28 ± 0.04	
			***d*P**	***d*P, *d*T****	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**
Precipitation perturbation	**-30%**	**FUT1**	0.79 ± 0.03	0.86 ± 0.06	0.56 ± 0.01	0.59 ± 0.02	2.29 ± 0.08	2.29 ± 0.07
	-20%		0.70 ± 0.03	0.75 ± 0.05	0.51 ± 0.01	0.54 ± 0.02	2.25 ± 0.09	2.24 ± 0.08
	-10%		0.62 ± 0.03	0.67 ± 0.04	0.47 ± 0.01	0.50 ± 0.02	2.22 ± 0.08	2.20 ± 0.07
	0%		0.56 ± 0.02	0.61 ± 0.04	0.44 ± 0.01	0.46 ± 0.02	2.20 ± 0.09	2.18 ± 0.08
	+10%		0.50 ± 0.02	0.55 ± 0.04	0.41 ± 0.01	0.43 ± 0.02	2.19 ± 0.09	2.16 ± 0.08
	+20%		0.46 ± 0.02	0.50 ± 0.03	0.38 ± 0.01	0.40 ± 0.02	2.17 ± 0.09	2.14 ± 0.08
	+30%		0.43 ± 0.02	0.46 ± 0.03	0.36 ± 0.01	0.37 ± 0.01	2.17 ± 0.09	2.13 ± 0.08
	-30%	**FUT2**	0.82 ± 0.06	0.88 ± 0.08	0.57 ± 0.03	0.60 ± 0.03	2.28 ± 0.09	2.28 ± 0.09
	-20%		0.72 ± 0.05	0.77 ± 0.07	0.52 ± 0.03	0.55 ± 0.03	2.24 ± 0.09	2.24 ± 0.08
	-10%		0.64 ± 0.05	0.69 ± 0.06	0.48 ± 0.03	0.50 ± 0.03	2.22 ± 0.10	2.21 ± 0.08
	0%		0.57 ± 0.04	0.63 ± 0.05	0.45 ± 0.02	0.47 ± 0.03	2.19 ± 0.10	2.17 ± 0.08
	+10%		0.52 ± 0.04	0.56 ± 0.05	0.42 ± 0.02	0.43 ± 0.03	2.18 ± 0.10	2.15 ± 0.09
	+20%		0.48 ± 0.04	0.52 ± 0.04	0.39 ± 0.02	0.41 ± 0.02	2.16 ± 0.10	2.13 ± 0.09
	+30%		0.44 ± 0.03	0.48 ± 0.04	0.36 ± 0.02	0.38 ± 0.02	2.16 ± 0.10	2.13 ± 0.10
			***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**
Temperature perturbation	**+0.0°C**	**FUT1**	0.56 ± 0.02	0.58 ± 0.13	0.44 ± 0.01	0.45 ± 0.08	2.20 ± 0.09	2.22 ± 0.10
	+0.5°C		0.57 ± 0.02	0.60 ± 0.13	0.45 ± 0.01	0.45 ± 0.07	2.19 ± 0.08	2.21 ± 0.09
	+1.0°C		0.59 ± 0.02	0.61 ± 0.13	0.45 ± 0.01	0.46 ± 0.07	2.18 ± 0.08	2.20 ± 0.09
	+1.5°C		0.60 ± 0.03	0.63 ± 0.13	0.46 ± 0.01	0.47 ± 0.07	2.18 ± 0.08	2.19 ± 0.09
	+2.0°C		0.62 ± 0.03	0.64 ± 0.14	0.47 ± 0.01	0.48 ± 0.07	2.17 ± 0.08	2.18 ± 0.09
	+2.5°C		0.63 ± 0.03	0.66 ± 0.14	0.47 ± 0.01	0.48 ± 0.07	2.16 ± 0.07	2.18 ± 0.09
	+3.0°C		0.65 ± 0.03	0.67 ± 0.14	0.48 ± 0.01	0.49 ± 0.08	2.16 ± 0.07	2.17 ± 0.09
	+0.0°C	**FUT2**	0.57 ± 0.04	0.60 ± 0.14	0.45 ± 0.02	0.46 ± 0.08	2.19 ± 0.10	2.21 ± 0.11
	+0.5°C		0.59 ± 0.04	0.61 ± 0.14	0.45 ± 0.01	0.46 ± 0.07	2.19 ± 0.09	2.20 ± 0.10
	+1.0°C		0.60 ± 0.04	0.63 ± 0.14	0.46 ± 0.01	0.47 ± 0.08	2.18 ± 0.08	2.19 ± 0.10
	+1.5°C		0.62 ± 0.05	0.65 ± 0.14	0.47 ± 0.01	0.48 ± 0.08	2.18 ± 0.09	2.19 ± 0.10
	+2.0°C		0.63 ± 0.05	0.66 ± 0.15	0.47 ± 0.01	0.48 ± 0.08	2.17 ± 0.08	2.18 ± 0.10
	+2.5°C		0.65 ± 0.05	0.68 ± 0.15	0.48 ± 0.01	0.49 ± 0.08	2.16 ± 0.08	2.18 ± 0.10
	+3.0°C		0.67 ± 0.05	0.69 ± 0.15	0.49 ± 0.01	0.50 ± 0.08	2.17 ± 0.08	2.17 ± 0.10

* Values represent ensemble means for the 30-year periods, with uncertainties corresponding to one standard deviation.

** Results indicated with *d*P, *d*T for a given precipitation perturbation (*d*P) include all associated temperature perturbations (*d*T), and vice-versa.

4.9 Figures

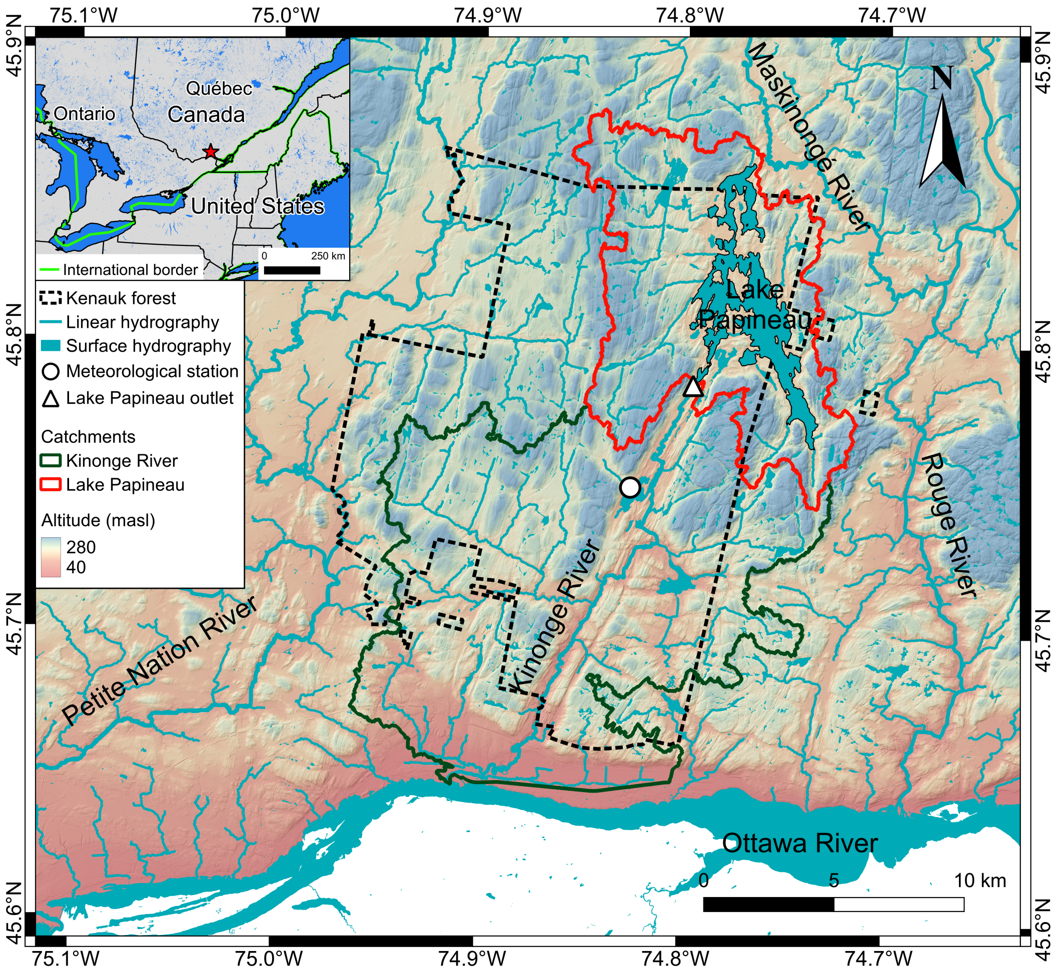

Figure 4.1 Location of the study area and Lake Papineau catchment in the Outaouais region of southern Quebec (Canada), with lake outlet gauging station and meteorological station.

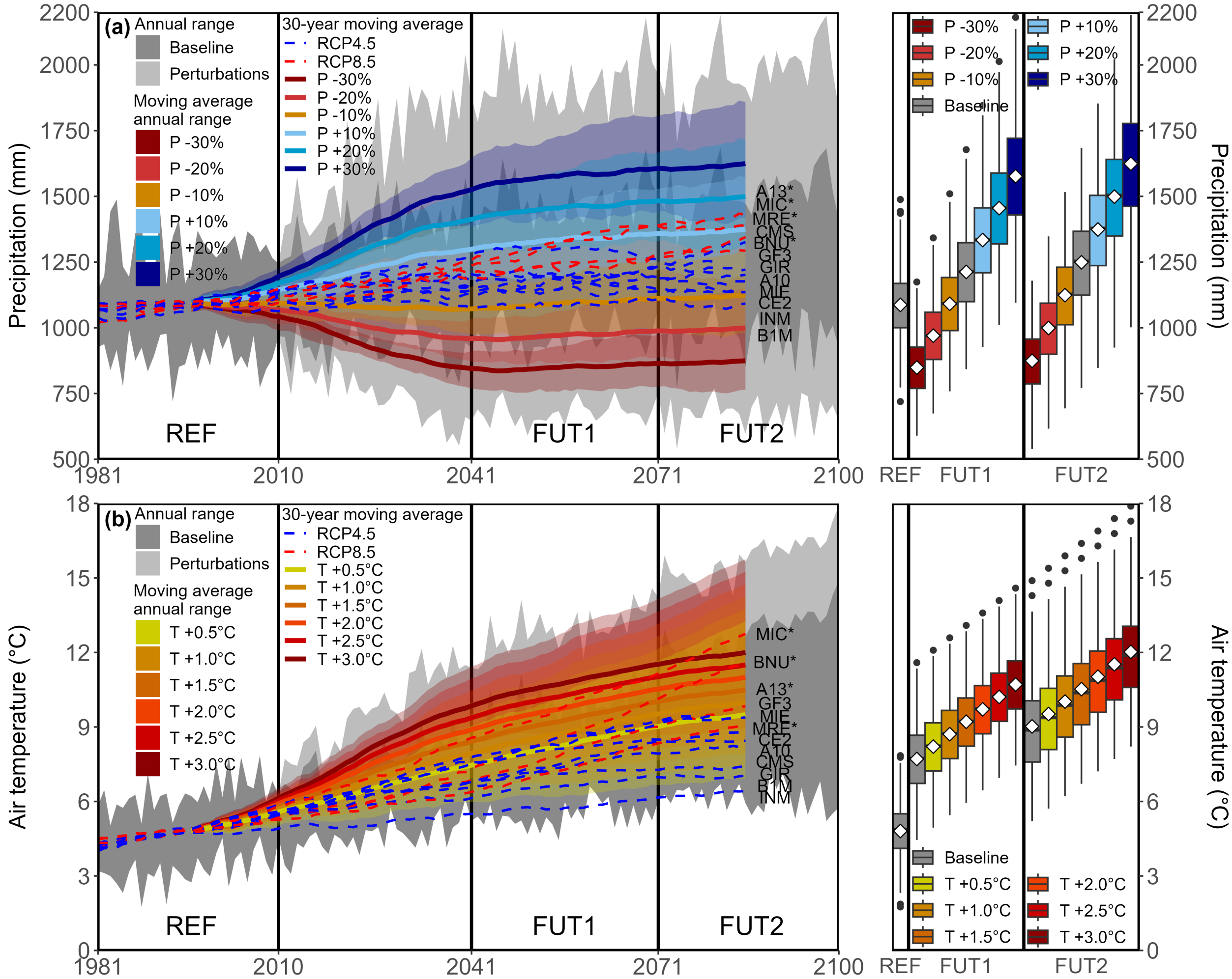

Figure 4.2 30-year moving average of CMIP5 GCM-RCP ensemble conditions and their perturbed conditions for precipitation (a) and temperature (b). Grey shaded regions and boxplots present ranges of annual conditions, while colored regions correspond to extremities of 30-year perturbation moving averages. The interim period between REF and FUT1 periods corresponds to a ramping-up of precipitation and temperature perturbations and is excluded from analysis.

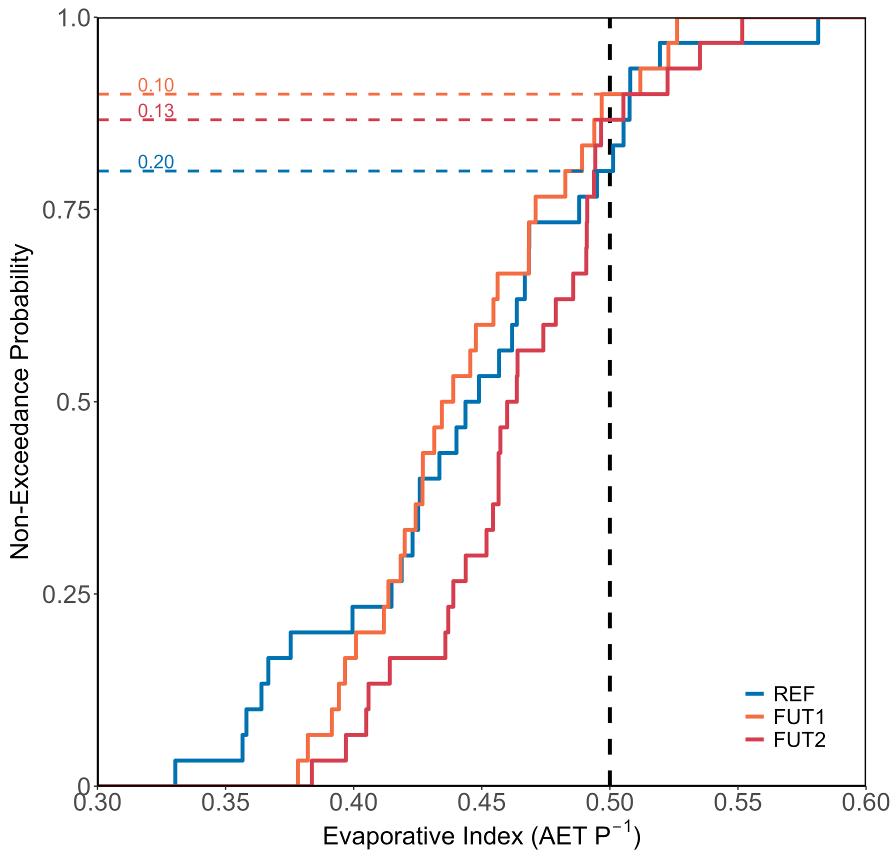

Figure 4.3 Example for the MIC scenario of empirical cumulative distribution functions of the evaporative index (EI) for quantifying the probability of exceeding AET.$P^{-1} > 0.5$

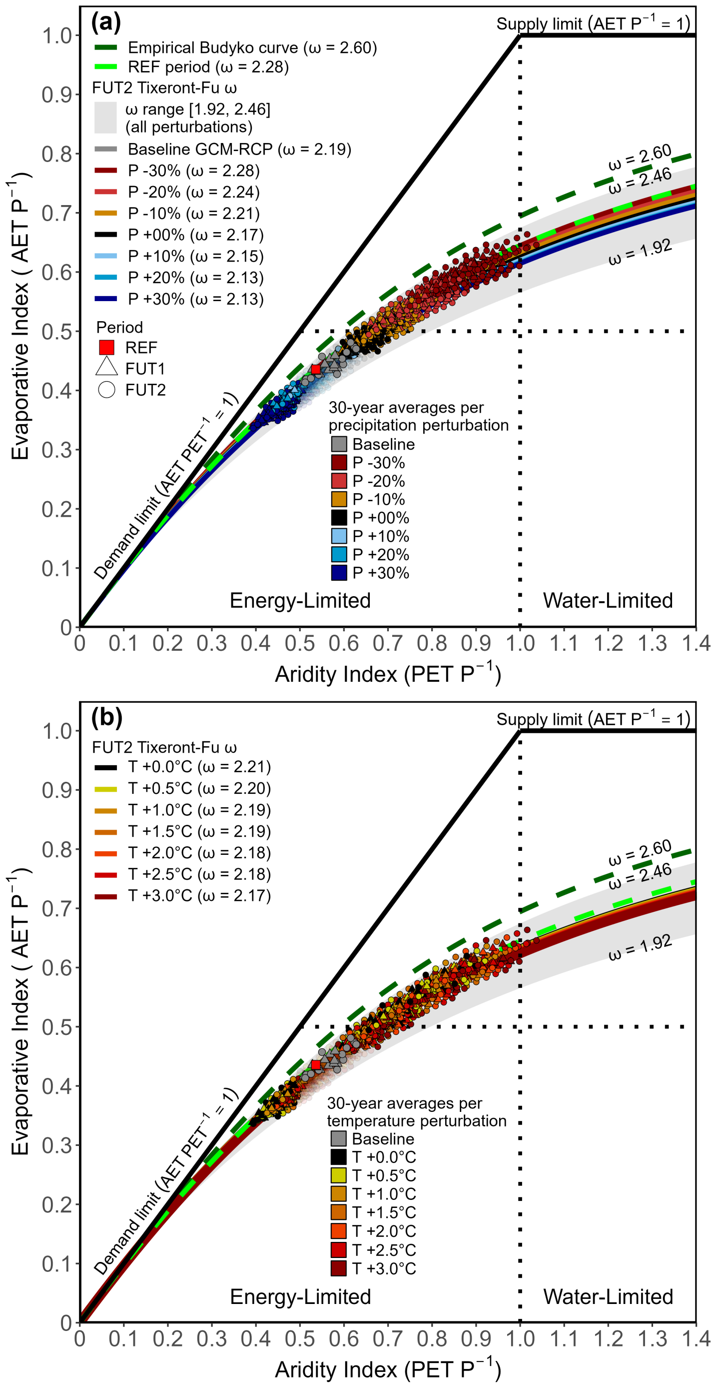

Figure 4.4 Long-term (30-year) catchment hydroclimatic conditions plotted in Budyko space for baseline CMIP5 GCM-RCP conditions and perturbations to precipitation (a) and temperature (b). Transparent points indicate future perturbed conditions that are not significantly different from both the REF period and the corresponding baseline FUT1 or FUT2 periods (Tukey HSD, $p < 0.05$). Tixeront-Fu curves correspond to mean FUT2 conditions per perturbation.

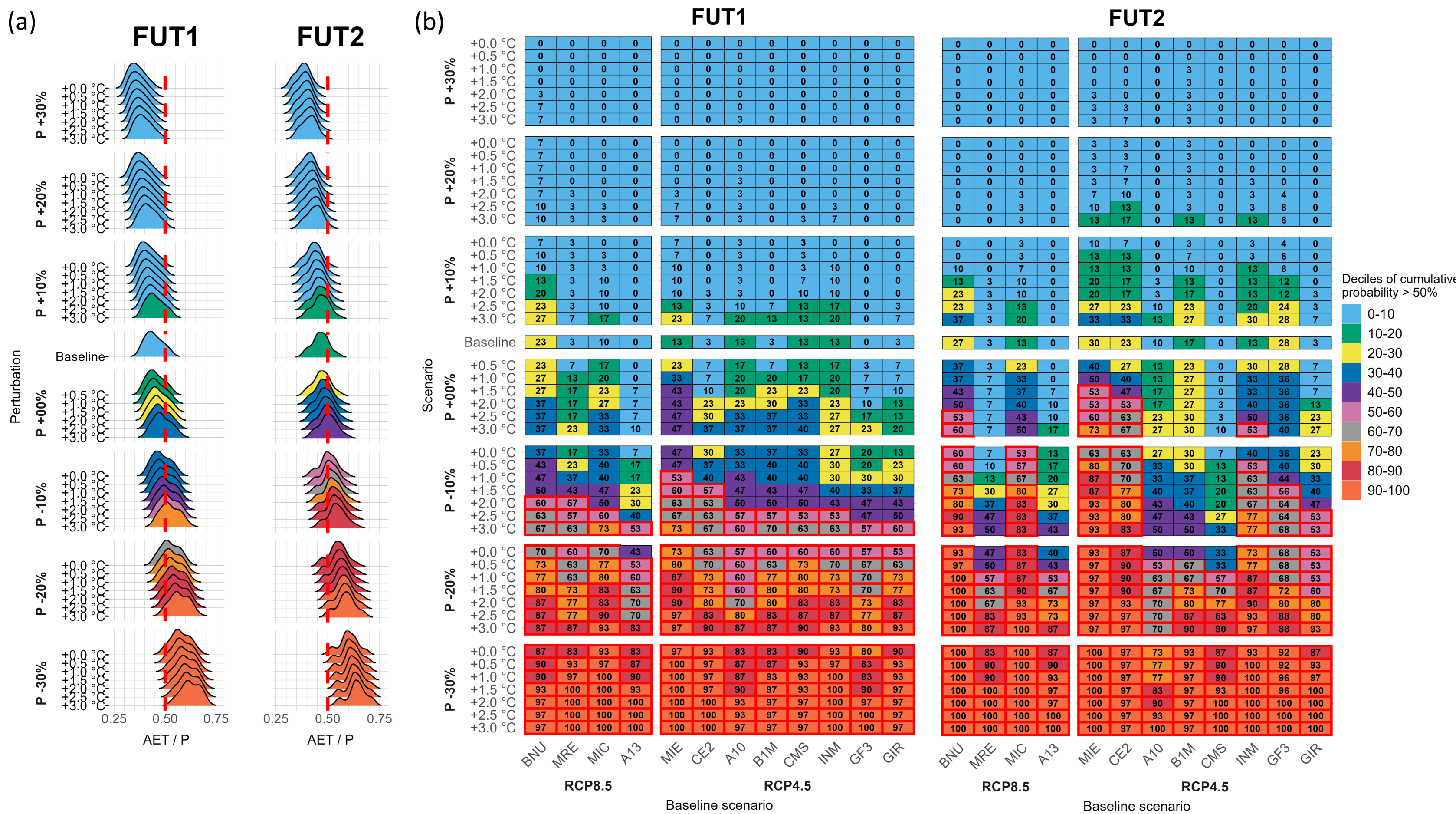

Figure 4.5 Example of kernel density estimates of the catchment evaporative index for both future periods for all MIC perturbed conditions (a) and table for all 588 perturbed scenarios (b). Colors differentiate percentage of probability distribution associated with AET.P^{-1} > 0.5, with red highlighted cells identifying AET dominance over discharge.

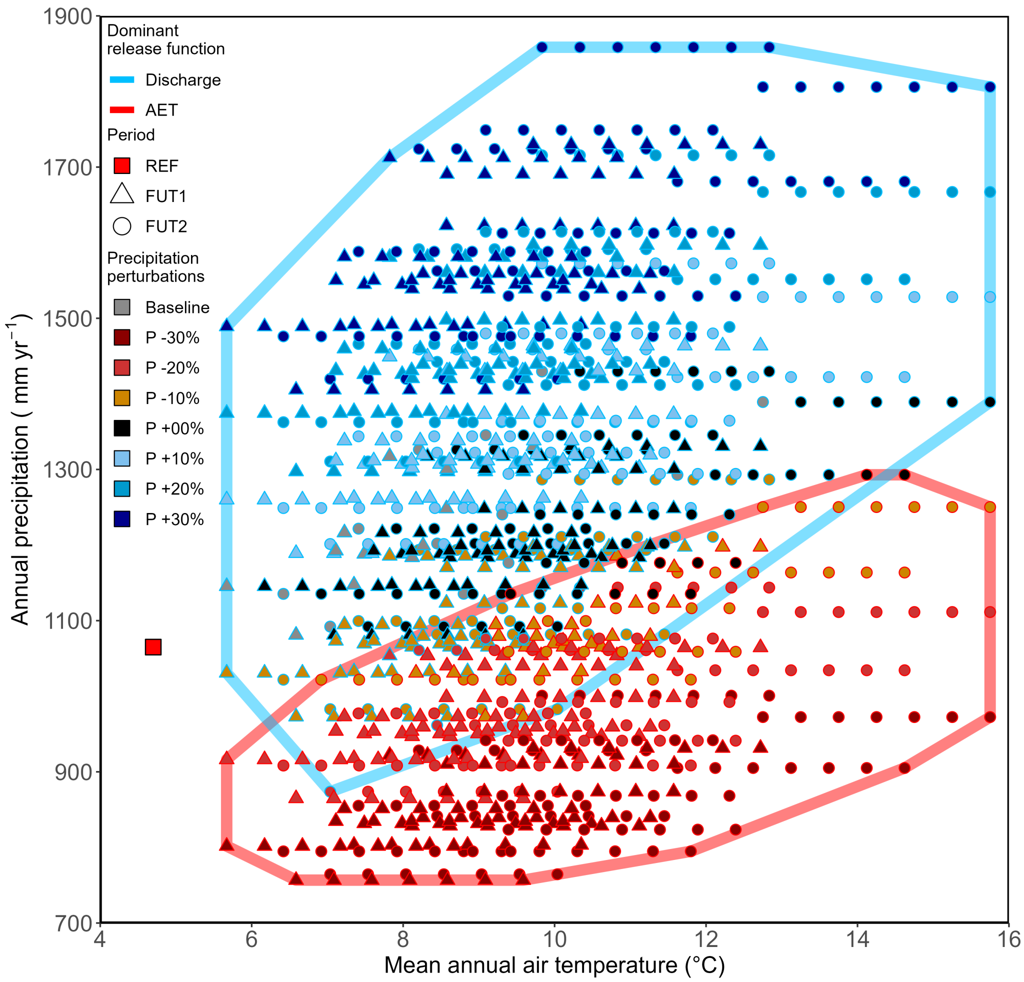

Figure 4.6 Mean long-term FUT1 and FUT2 period perturbed precipitation and temperature conditions classified by change in precipitation to baseline CMIP5 GCM-RCP scenarios, with identification of conditions under which catchment release is dominated by either discharge or actual evapotranspiration.

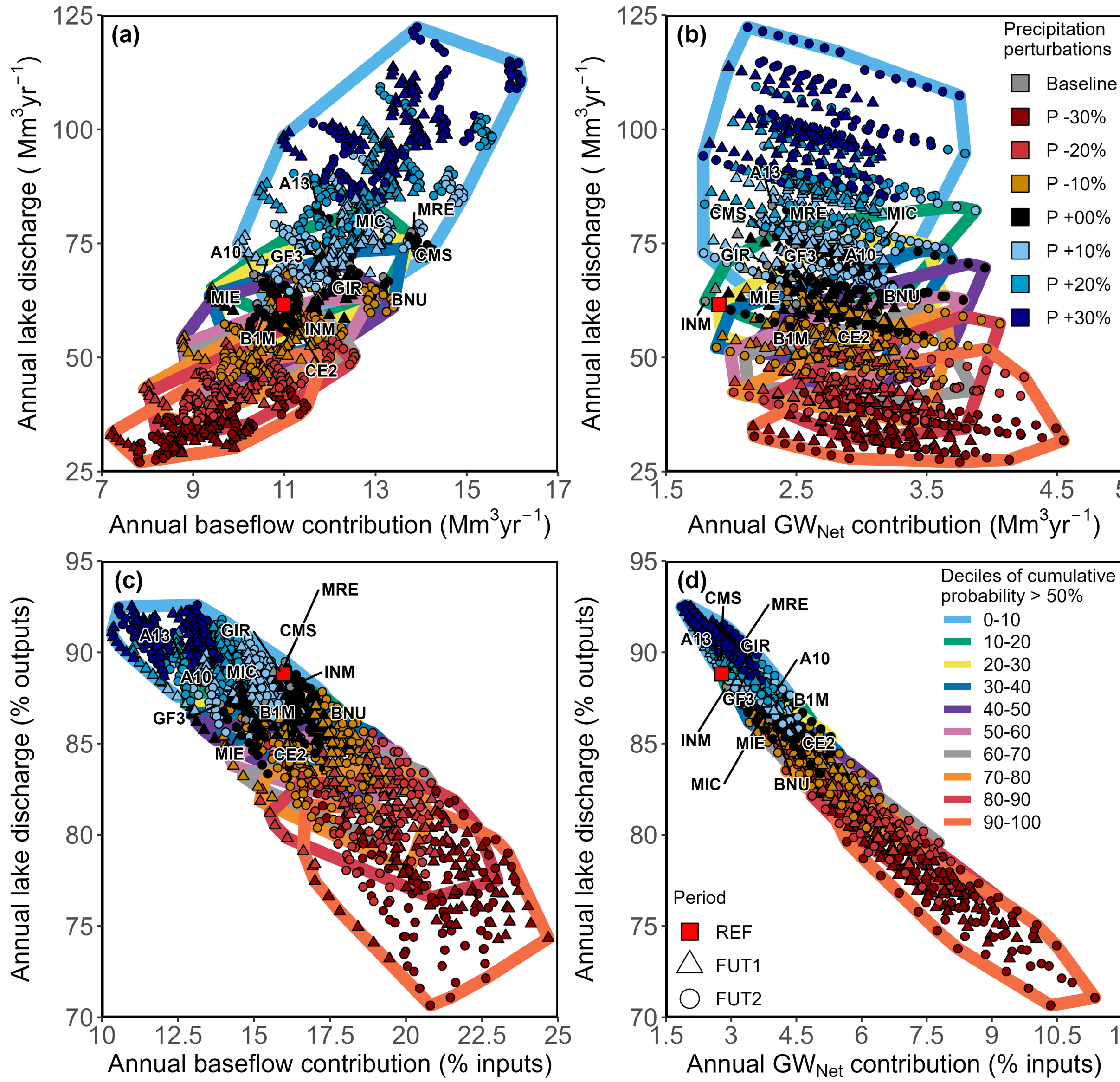

Figure 4.7 Mean long-term lake discharge volumes as a function of both baseflow (a) and net lacustrine groundwater (b) volumes, with the same relationships as percentages of total lake budget inflows and outflows (c, d). Points are classified by perturbations to precipitation and grouped by importance of AET functioning as the dominant catchment release. Location of baseline CMIP5 ensemble conditions for the FUT2 period are identified.

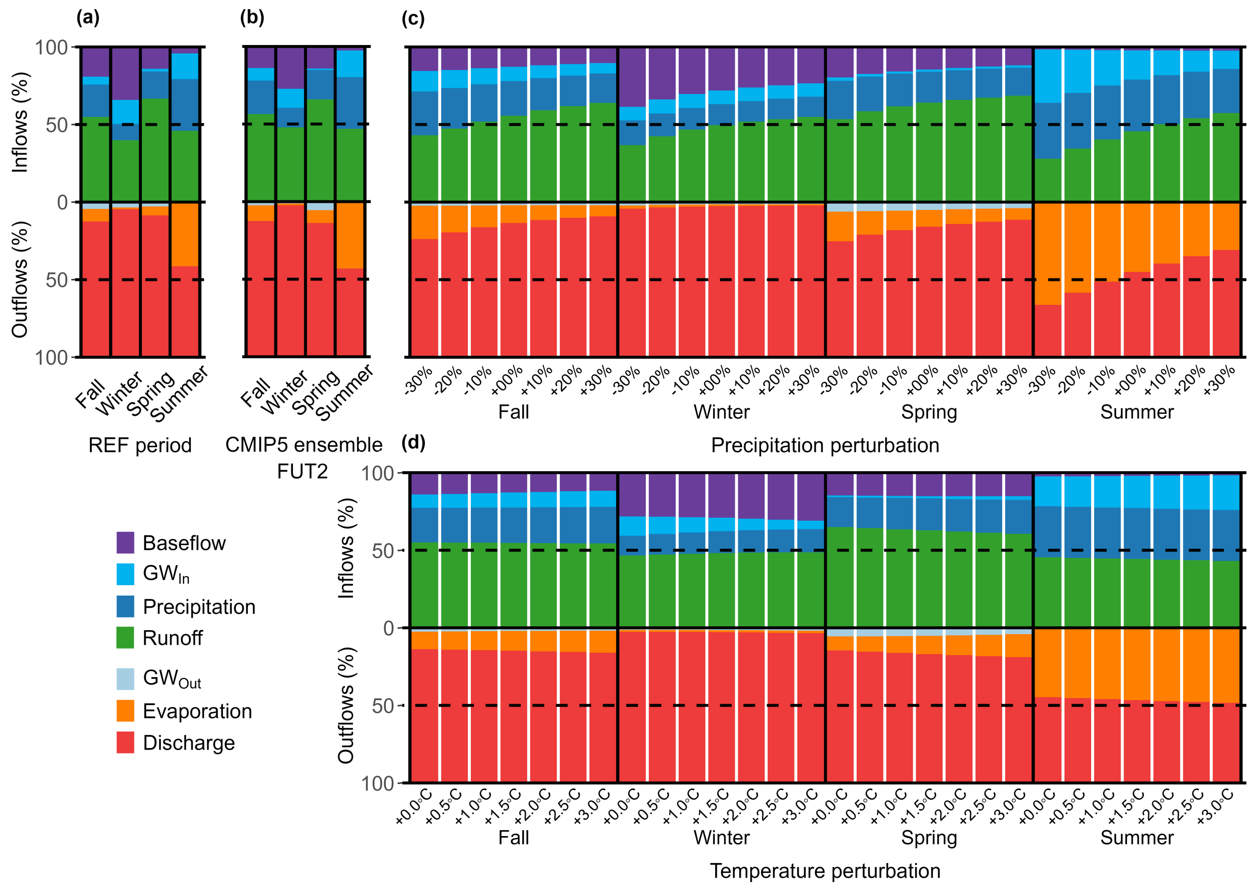

Figure 4.8 Mean long-term seasonal lake water budget contributions to total inflows or outflows under REF conditions (a), baseline CMIP5 conditions for the FUT2 period (b), perturbed FUT2 CMIP5 conditions with respect to precipitation changes (*d*P, *d*T) (c), and perturbed FUT conditions with respect to temperature changes (*d*P, *d*T) (d)

4.10 Appendix

Table A4.1 Future annual changes for FUT1 and perturbed precipitation conditions in Lake Papineau water budget inflow and outflow volumes ($Mm^3.yr^{-1}$) and relative change (%) compared to the REF period

			Outputs				Inputs								Δ Total groundwater	
		Period	Δ Discharge		Δ Evaporation		Δ Precipitation		Δ Runoff		Δ Baseflow		Δ GW_{Net}			
			***d*P**	***d*P, *d*T***	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**
Precipitation perturbation	**-30%**	**FUT1**	-24.9** [-40%]***	-27.0 [-44%]	+1.2 [+16%]	+1.9 [+25%]	-3.1 [-22%]	-3.1 [-22%]	-19.4 [-46%]	-21.4 [-51%]	-2.0 [-19%]	-1.9 [-17%]	+0.9 [+48%]	+1.3 [+70%]	-1.2 [-9%]	-0.6 [-5%]
	-20%		-14.7 [-24%]	-17.1 [-27%]	+1.2 [+16%]	+1.9 [+25%]	-1.5 [-11%]	-1.5 [-11%]	-11.5 [-27%]	-13.7 [-33%]	-1.2 [-11%]	-1.0 [-9%]	+0.7 [+38%]	+1.1 [+59%]	n.s.****	n.s.
	-10%		-4.2 [-7%]	-6.7 [-11%]	+1.2 [+16%]	+1.9 [+25%]	n.s.	n.s.	-3.3 [-8%]	-5.6 [-13%]	n.s.	n.s.	+0.6 [+31%]	+0.9 [+51%]	n.s.	+0.8 [+6%]
	0%		-	+3.5 [+6%]	-	+2.0 [+27%]	-	+1.6 [+12%]	-	+2.5 [+6%]	-	+0.6 [+5%]	-	+0.9 [+49%]	-	+1.4 [+11%]
	+10%		+17.7 [+29%]	+14.9 [+24%]	+1.2 [+16%]	+1.9 [+25%]	+3.2 [+23%]	+3.2 [+23%]	+14.1 [+34%]	+11.6 [+28%]	+1.1 [+10%]	+1.2 [+11%]	+0.4 [+25%]	+0.8 [+43%]	+1.5 [+12%]	+2.0 [+16%]
	+20%		+28.9 [+47%]	+26.2 [+43%]	+1.2 [+16%]	+1.9 [+25%]	+4.8 [+34%]	+4.8 [+34%]	+23.2 [+55%]	+20.7 [+50%]	+1.7 [+16%]	+1.8 [+16%]	+0.4 [+24%]	+0.8 [+42%]	+2.1 [+17%]	+2.5 [+20%]
	+30%		+40.2 [+65%]	+37.5 [+61%]	+1.2 [+16%]	+1.9 [+25%]	+6.4 [+45%]	+6.4 [+45%]	+32.3 [+77%]	+29.9 [+71%]	+2.2 [+21%]	+2.3 [+21%]	+0.4 [+24%]	+0.7 [+41%]	+2.7 [+21%]	+3.1 [+24%]

* Results indicated with *d*P, *d*T for a given precipitation perturbation (*d*P) include all associated temperature perturbations (*d*T) and vice-versa.
** All values are mean changes in Mm^3 with respect to the REF period.
*** Values in brackets correspond to percent change relative to the REF period.
**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$).

Table A4.2 Future annual changes for FUT1 and perturbed temperature conditions in Lake Papineau water budget inflow and outflow volumes ($Mm^3.yr^{-1}$) and relative change (%) compared to the REF period

			Outputs				**Inputs**								**Δ Total groundwater**	
		Period	**Δ Discharge**		**Δ Evaporation**		**Δ Precipitation**		**Δ Runoff**		**Δ Baseflow**		**Δ GW_{Net}**			
			***d*T**	***d*P, *d*T***	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**
Temperature perturbation	**+0.0°C**	**FUT1**	-	+7.2** [+12%]***	-	+1.2 [+16%]	-	+1.6 [+12%]	-	+5.9 [+14%]	-	n.s.****	-	+0.6 [+32%]	-	+0.8 [+7%]
	+0.5°C		+5.7 [+9%]	+6.2 [+10%]	+1.4 [+19%]	+1.4 [+19%]	+1.6 [+12%]	+1.6 [+12%]	+4.4 [+11%]	+5.0 [+12%]	n.s.	n.s.	+0.6 [+33%]	+0.7 [+37%]	+1.1 [+8%]	+1.0 [+8%]
	+1.0°C		+4.8 [+8%]	+5.4 [+9%]	+1.6 [+22%]	+1.6 [+22%]	+1.6 [+12%]	+1.6 [+12%]	+3.7 [+9%]	+4.2 [+10%]	n.s.	n.s.	+0.7 [39%]	+0.8 [+44%]	+1.2 [+10%]	+1.2 [+9%]
	+1.5°C		+4.0 [+7%]	+4.5 [+7%]	+1.9 [+25%]	+1.9 [+25%]	+1.6 [+12%]	+1.6 [+12%]	+3.4 [+7%]	+3.5 [+8%]	n.s.	n.s.	+0.8 [+46%]	+0.9 [+50%]	+1.4 [+11%]	+1.3 [+10%]
	+2.0°C		n.s.	+3.7 [+6%]	+2.1 [+28%]	+2.1 [+28%]	+1.6 [+12%]	+1.6 [+12%]	n.s.	n.s.	+0.6 [+5%]	+0.4 [+4%]	+0.9 [+52%]	+1.0 [+57%]	+1.5 [+12%]	+1.5 [+12%]
	+2.5°C		n.s.	n.s.	+2.4 [+31%]	+2.4 [+31%]	+1.6 [+12%]	+1.6 [+12%]	n.s.	n.s.	+0.6 [+6%]	+0.5 [+4%]	+1.1 [+59%]	+1.2 [+63%]	+1.7 [+13%]	+1.6 [+13%]
	+3.0°C		n.s.	n.s.	+2.6 [+34%]	+2.6 [+34%]	+1.6 [+12%]	+1.6 [+12%]	n.s.	n.s.	+0.7 [+6%]	+0.5 [+5%]	+1.2 [+65%]	+1.3 [+70%]	+1.8 [+14%]	+1.8 [+14%]

* Results indicated with *d*P, *d*T for a given precipitation perturbation (*d*P) include all associated temperature perturbations (*d*T) and vice-versa.
** All values are mean changes in Mm^3 with respect to the REF period.
*** Values in brackets correspond to percent change relative to the REF period.
**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$).

Table A4.3 Future annual changes for FUT2 and perturbed precipitation conditions in Lake Papineau water budget inflow and outflow volumes ($Mm^3.yr^{-1}$) and relative change (%) compared to the REF period

			Outputs				**Inputs**								**Δ Total groundwater**	
		Period	**Δ Discharge**		**Δ Evaporation**		**Δ Precipitation**		**Δ Runoff**		**Δ Baseflow**		**Δ GW_{Net}**			
			***d*P**	***d*P, *d*T***	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**	***d*P**	***d*P, *d*T**
Precipitation perturbation	**-30%**	**FUT2**	-24.6** [-40%]***	-26.7 [-43%]	+1.7 [+23%]	+2.5 [+33%]	-2.8 [-20%]	-2.8 [-20%]	-19.4 [-46%]	-21.3 [-51%]	-1.7 [-16%]	-1.7 [-15%]	+1.1 [+62%]	+1.5 [+85%]	n.s.****	n.s.
	-20%		-14.2 [-23%]	-16.6 [-27%]	+1.7 [+23%]	+2.6 [+33%]	-1.2 [-8%]	-1.2 [-8%]	-11.4 [-27%]	-13.6 [-32%]	-0.8 [-7%]	n.s.	+0.9 [+52%]	+1.3 [+73%]	n.s.	+0.6 [+5%]
	-10%		n.s.	-6.0 [-10%]	+1.7 [+23%]	+2.5 [+33%]	n.s.	n.s.	n.s.	-5.3 [-13%]	n.s.	n.s.	+0.8 [+44%]	+1.2 [+64%]	n.s.	+1.3 [+10%]
	0%		-	+4.6 [+7%]	-	+2.6 [+34%]	-	+2.1 [+15%]	-	+3.0 [+7%]	-	+0.9 [+8%]	-	+1.1 [+62%]	-	+2.0 [+16%]
	+10%		+19.0 [+31%]	+16.3 [+27%]	+1.7 [+23%]	+2.5 [+33%]	+3.8 [+26%]	+3.8 [+26%]	+14.9 [+36%]	+12.4 [+30%]	+1.5 [+14%]	+1.6 [+14%]	+0.7 [+36%]	+1.0 [+55%]	+2.2 [+17%]	+2.6 [+20%]
	+20%		+30.5 [+50%]	+27.8 [+45%]	+1.7 [+23%]	+2.5 [+33%]	+5.4 [+38%]	+5.4 [+38%]	+24.1 [+58%]	+21.7 [+52%]	+2.2 [+20%]	+2.2 [+20%]	+0.6 [+35%]	+1.0 [+53%]	+2.8 [+22%]	+3.1 [+25%]
	+30%		+42.1 [+68%]	+39.3 [+64%]	+1.7 [+23%]	+2.5 [+33%]	+7.0 [+49%]	+7.0 [+49%]	+33.4 [+80%]	+31.1 [+74%]	+2.8 [+25%]	+2.8 [+25%]	+0.6 [+34%]	+0.9 [+52%]	+3.4 [+26%]	+3.7 [+29%]

* Results indicated with *d*P, *d*T for a given precipitation perturbation (*d*P) include all associated temperature perturbations (*d*T) and vice-versa.
** All values are mean changes in Mm^3 with respect to the REF period.
*** Values in brackets correspond to percent change relative to the REF period.
**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$).

Table A4.4 Future annual changes for FUT2 and perturbed temperature conditions in Lake Papineau water budget inflow and outflow volumes ($Mm^3.yr^{-1}$) and relative change (%) compared to the REF period

			Outputs				**Inputs**								**Δ Total groundwater**	
		Period	**Δ Discharge**		**Δ Evaporation**		**Δ Precipitation**		**Δ Runoff**		**Δ Baseflow**		**Δ GW_{Net}**			
			***d*T**	***d*P, *d*T***	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**	***d*T**	***d*P, *d*T**
Temperature perturbation	**+0.0°C**	**FUT2**	-	+8.2** [+13%]***	-	+1.7 [+23%]	-	+2.1 [+15%]	-	+6.4 [+15%]	-	+0.7 [+6%]	-	+0.8 [+44%]	-	+1.4 [+11%]
	+0.5°C		+6.8 [+11%]	+7.3 [+12%]	+2.0 [+26%]	+2.0 [+26%]	+2.1 [+15%]	+2.1 [+15%]	+5.0 [+12%]	+5.6 [+13%]	n.s.****	n.s.	+0.8 [+45%]	+0.9 [+49%]	+1.7 [+13%]	+1.6 [+12%]
	+1.0°C		+5.9 [+10%]	+6.4 [+10%]	+2.2 [+29%]	+2.2 [+29%]	+2.1 [+15%]	+2.1 [+15%]	+4.2 [+10%]	+4.8 [+12%]	+0.9 [+8%]	n.s.	+0.9 [+52%]	+1.0 [+56%]	+1.8 [+14%]	+1.7 [+14%]
	+1.5°C		n.s.	+5.6 [+9%]	+2.5 [+32%]	+2.5 [+32%]	+2.5 [+15%]	+2.1 [+15%]	n.s.	+4.0 [+10%]	+0.9 [+8%]	n.s.	+1.1 [+58%]	+1.1 [+63%]	+2.0 [+15%]	+1.9 [+15%]
	+2.0°C		n.s.	n.s.	+2.7 [+36%]	+2.7 [+36%]	+2.1 [+15%]	+2.1 [+15%]	n.s.	n.s.	+0.9 [+8%]	n.s.	+1.2 [+65%]	+1.3 [+69%]	+2.1 [+16%]	+2.0 [+16%]
	+2.5°C		n.s.	n.s.	+2.9 [+39%]	+2.9 [+39%]	+2.9 [+15%]	+2.1 [+15%]	n.s.	n.s.	+0.9 [+9%]	n.s.	+1.3 [+71%]	+1.4 [+76%]	+2.2 [+18%]	+2.2 [+17%]
	+3.0°C		n.s.	n.s.	+3.2 [+42%]	+3.2 [+42%]	+2.1 [+15%]	+2.1 [+15%]	n.s.	n.s.	+0.9 [+9%]	n.s.	+1.4 [+78%]	+1.5 [+83%]	+2.4 [+19%]	+2.3 [+18%]

* Results indicated with *d*P, *d*T for a given precipitation perturbation (*d*P) include all associated temperature perturbations (*d*T) and vice-versa.
** All values are mean changes in Mm^3 with respect to the REF period.
*** Values in brackets correspond to percent change relative to the REF period.
**** Non-significant changes (Wilcoxon signed-rank test, $p < 0.05$).

CHAPTER 5
CONCLUSION

5.1 Synthesis of principal results

Lakes are critical water resources in post-glacial landscapes, such as those found across large swaths of Canada, where they are largely connected to rivers, wetlands, and aquifers. Although lake-groundwater exchanges are not well documented, they could be critical to sustaining lake hydrology in the context of changing climatic conditions. The aim of this research was to investigate how relatively accessible methods can be implemented for quantifying the long-term past, current, and future groundwater contributions to a moderate-sized boreal drainage lake where available observation data are limited. Lake Papineau (13 km^2), situated in a largely undeveloped, forested catchment (94 km^2) in southern Quebec, served as an ideal environment for assessing the importance of groundwater in lake water budgets in cold and humid climates. Specific objectives were 1) to estimate groundwater flow into a southern boreal lake with limited available monitoring data, 2) to assess the impact of climate change on the water budget of lakes in cold and humid climates, and 3) to understand the thresholds of hydrological resilience of a southern boreal lake exposed to extreme climatic change. These specific objectives were addressed and presented in three articles that are in preparation for publication and that constitute Chapters 2 to 4 of this thesis.

This thesis showed that the long-term lacustrine groundwater contribution to a boreal lake could be quantified through a combination of methods that can be relatively easily implemented when monitoring data is only of limited duration (here, six hydrological years) (Chapter 2). Long-term past hydrometric conditions (i.e., stage and discharge) were reconstituted for Lake Papineau using a machine learning technique (artificial neural networks). When combined with long-term past precipitation, evaporation, and estimates of runoff and baseflow from a catchment water budget model, calibrated using the parametric Budyko framework for the partitioning of catchment outflows (i.e., discharge and actual evapotranspiration), lacustrine groundwater was solved as the residual of a lake water budget, constituting 4% of total inflows to the lake. Hence, this chapter successfully estimated groundwater contributions to a southern boreal lake, overcoming the challenges of limited and uncertain observation data, through the novel integration of the Budyko framework into a water budget approach (specific objective 1).

Chapter 3 of the thesis built on these results by quantifying seasonal and annual lacustrine groundwater contributions to Lake Papineau using an approach that more explicitly accounted for the hydrogeological context of the study site. A Modflow groundwater flow model was calibrated against observed lake hydrometric conditions and piezometric heads, with lacustrine groundwater quantified as 7% of long-term total lake inflows, echoing the conclusion of Chapter 2 that groundwater is a non-negligible component of Lake Papineau hydrology. Long-term seasonal lacustrine groundwater contributions were demonstrated to play an important role in sustaining lake hydrology during periods of reduced inflows from other budget components, such as vertical inflow during winter and baseflow during summer. The Modflow model was further used to simulate future conditions based on an ensemble of CMIP5 scenarios, enabling an evaluation of lake hydrological resilience to climate change. The stabilizing role of lacustrine groundwater under future climate conditions was evidenced by the absence of significant changes, highlighting the buffering capacity of this contribution when other variables were impacted. The Lake Papineau water budget was deemed to be relatively hydrologically resilient to the climate change forcings of the CMIP5 ensemble, with lacustrine groundwater likely playing a critical role in mitigating these impacts. Results help inform the capacity of lakes in cold and humid climates to remain hydrologically resilient under changing climatic conditions (specific objective 2).

This thesis further investigated the capacity of boreal lakes to maintain hydrological resilience under more extreme future climatic conditions, using combinations of modified CMIP5 precipitation volumes and increased temperatures (Chapter 4). Given the demonstrated relative hydrological resilience of the lake to baseline CMIP5 future climate conditions, including those of the more pessimistic RCP8.5 emissions scenario, this chapter sought to describe under which conditions this resilience might be overcome. With respect to baseline CMIP5 future conditions, modifications such as either a mean annual temperature increase of +1.5°C, in absence of any changes to precipitation, or +2.5°C, in conjunction with a decrease of 10% in annual precipitation, were sufficient to tip the hydrological regime of lakes in cold and humid environments from discharge- to evapotranspiration-dominant. Responses of the lake water budget to perturbations further emphasized the importance of the lacustrine groundwater contribution under increasing temperature and reductions in precipitation. The identification of thresholds of temperature and precipitation combinations allowed for an appreciation of which future conditions might constitute tipping points in the maintenance of hydrological resilience for southern boreal lakes, and the role of groundwater in dampening the effects of extreme climate change (specific objective 3).

5.2 New insights

One of the principal results of this study was to estimate the long-term groundwater contributions to a southern Quebec boreal drainage lake water budget in the context of limited observation data. Such estimates are rarely undertaken, particularly for lakes in cold and humid climates. This was made possible by using the Budyko framework in a novel manner to constrain catchment water budget components (i.e., discharge and actual evapotranspiration). Groundwater contributions for the same boreal lake were also estimated using a Modflow groundwater flow model, making use of available observations of lake hydrometric conditions and piezometric head. Despite the different uncertainties associated with each method, the contribution of lacustrine groundwater to the water budget of Lake Papineau was of the same order of magnitude with both approaches. This consistency lends credence to the importance of the lacustrine groundwater contribution to lake water budgets in this climatic and hydrogeological context, and the utility of accessible approaches in overcoming the constraint of limited available data common to nearly all lake-groundwater investigations.

This study further demonstrated that lacustrine groundwater is an essential component of seasonal lake hydrology, sustaining lake inflows during summer, when other sources are limited (i.e., the baseflow groundwater contribution). The importance of seasonal groundwater contributions is particularly important in cold and humid climates that are currently facing important seasonal shifts due to global warming. The finding here that lacustrine groundwater further acts in mitigating the effects of anticipated future climate conditions on lake hydrology is an important contribution to the study of lake-groundwater interactions, as such potential roles are seldom investigated. Based on these results, future studies of lake-groundwater exchanges should systematically account for lacustrine groundwater contributions in the study of long-term lake resilience to climate change, rather than assume, as is often the case, that they are negligible.

This study was among the first to identify potential tipping points in the modification of boreal lake catchment hydrological regimes induced by extreme future climatic conditions. Lakes in this hydroclimatic context were shown here as capable of transitioning from a discharge- to evapotranspiration-dominant regime under relatively modest changes to temperature and precipitation conditions with respect to those anticipated under even the more pessimistic RCP8.5 emissions scenario of the CMIP5 project. Lacustrine groundwater, estimated using the accessible residual water budget technique, was shown to be relatively unaffected by even the most extreme future climatic conditions and, as such, could potentially dampen the impact of losses from less resilient lake water budget components. These results underscore the value of accounting for lacustrine groundwater in the management of surface water resources, and ensuring that lake catchment landscape features contributing to groundwater recharge are adequately protected.

5.3 Implementation of methods in the study of other lakes

The various methods implemented in this thesis could be readily transferred to the study of lakes in similar hydroclimatic and hydrogeological contexts as those of Lake Papineau (i.e., drainage lakes situated in energy-limited regions where groundwater is likely not the primary inflow or outflow). These caveats reflect characteristics of Lake Papineau, notably the role of discharge as the dominant lake outflow, and the hypotheses underlying the use of inferred actual evapotranspiration (AET_{P-Q}) within the Budyko framework. In the case of seepage lakes (i.e., lakes without a surface water outlet), for example, lake catchment AET could not be estimated in the same manner (i.e., as the difference between P and Q) and an alternative would be needed. Similarly, in the case of kettle lakes (i.e., small lakes lacking permanent runoff and largely groundwater dependent), lake catchment size and the greater importance of groundwater pose difficulties in the closure of the annual catchment water budget, thus adding additional complexity to using inferred AET_{P-Q}. Setting aside these particular contexts, the methods presented here could easily complement other investigations of lake-groundwater exchanges built around short-term field-based measurements (e.g., seepage meters and stable water isotope mass balances), and could potentially provide evidence for important lacustrine groundwater contributions that more spatially or temporally punctual observations might fail to convey. Conversely, while the characterization of long-term net exchanges is pertinent to these investigations, the true extent of groundwater inflows or outflows is potentially masked.

5.4 Recommendations for future research

This thesis demonstrated that a robust estimate of the contribution of lacustrine groundwater to the water budgets of lakes in cold and humid climates is possible, even when monitoring data only consist of a few hydrological years. Continuing observations (at minimum, lake stage at the outlet) on the medium- and long-term (spanning several decades), particularly as changes in climatic conditions as a result of anthropogenic climate change are beginning to manifest, would assist in further constraining estimates for each lake water budget component, corroborate the characterization of long-term hydroclimatic conditions by the parametric Budyko framework, and increase the confidence in modeling results calibrated against longer observation time series. Continuing these observations at Lake Papineau would ensure the place of the site among other long-term natural laboratories, acting both as sentinels of potential deteriorations to lake environments induced by intensifying climate change, and testing grounds for monitoring the role of groundwater in mitigating these effects.

While this thesis presented the promising ability of a machine learning technique to reproduce observed conditions with reasonable accuracy, reconstituted past conditions occasionally violated the atmospheric demand limit ($AET.PET^{-1} = 1$) of the Budyko framework. Integrating evaporative demand into ANN model training would help to better constrain reconstituted conditions and avoid inconsistencies with the Budyko framework.

Although Lake Papineau was shown to be hydrologically resilient to future climatic conditions under both a CMIP5 ensemble and certain perturbations to the latter, some not altogether implausible future conditions constituted thresholds by which this resilience can be destabilized and fundamentally alter lake hydrology. Accounting for the most up-to-date simulations of future global climate, with the availability of successive CMIP iterations, would be informative in identifying if thresholds remain consistent.

This study consistently demonstrated the importance of groundwater contributions (both lacustrine groundwater and the baseflow groundwater contribution) in sustaining long-term and seasonal boreal lake hydrology. These contributions, particularly that of lacustrine groundwater, have been shown to be even more critical under significantly warmer and likely wetter future climatic conditions. Inherent catchment hydrological resilience, and the role of groundwater in mitigating the full extent of climate changes on lake hydrology, should not necessarily be assumed, despite the findings presented here. This is especially true should long-term conservation and management plans not consider the risks of alterations to land use that might limit groundwater recharge or modify landscape hydrological connectivity between lakes and wetlands.

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