Storyline Analytical Framework for Understanding Future Severe Low-Water Episodes and Their Consequences

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Abstract.

The 2021 drought highlighted the vulnerability of Quebec's water resources and the potential for widespread consequences in a region that is generally perceived as having abundant water. This study uses a storyline approach to explore the plausible impacts of future drought conditions for an event similar to what occurred in 2021, but under two different warming scenarios corresponding to increases of 2°C and 3°C in global surface temperatures compared to preindustrial levels. The scenario-based approach employs analogues derived from a large ensemble of regional climate simulations combined with simulations generated by a hydrological model to offer a comprehensive understanding of both climate and hydrological conditions during, and leading up to, these potential future events. ~~This approach allowed for enhanced collaboration with water management experts and other stakeholders to project the possible impacts of climate change on serious water deficits in Quebec.~~ Results indicate a further deterioration in river conditions, particularly under a +3°C global temperature rise. In the hardest-hit areas of the province under that scenario, future low-water levels under an event similar to 2021 would persist for a month longer and river ~~streamflows~~ streamflow would drop by an additional 50%, thus falling short of the threshold required to maintain the health of ecosystems for an extended period of time and suggesting significant impacts on ecosystems and human activities. ~~This study also highlights the need for improved systematic data collection during meteorological and hydrological droughts in Quebec, particularly with respect to their impacts on human activities and ecosystems~~ Storyline approaches offer potential as a communication tool to foster collaboration with water management experts and other stakeholders, particularly in cases where impact-inducing thresholds are not well understood. By linking future river conditions to a real event that affected Southern Quebec, these approaches may help facilitate discussions on the potential impacts of climate change on water deficits in the region.

1 Introduction

The province of Quebec in Canada is generally perceived as a region with abundant water, since spring snowmelt recharges groundwater and ensures that most streams maintain water flow throughout the year, while preventing most multi-year droughts (Dubois et al., 2021; Assani, 2023). However, recent years have shown that the region is not impervious to low-water episodes. For example, Quebec's agricultural areas faced moderate to severe drought conditions in 2001, 2002 and for 8 of the 12 years between 2010 and 2021, each event resulting in financial impacts of tens of millions of dollars (Nand and Qi, 2023). A drought in 2012 also severely affected the boreal forest (Houle et al., 2016), while, more recently, the extreme 2023 wildfire season in northern Quebec followed one of the driest and warmest seasons on record (Boulanger et al., 2024).

~~Analyzing hydrological~~ Hydrological droughts in colder regions ~~can be challenging~~ are complex phenomena to analyze due to the added interplay of rainfall ~~, snow and temperatures~~ and snow-driven recharge. The main factors influencing low water levels during summer differ according to the specific characteristics and geographical location of the basin. In Europe, for example, 50% of droughts are due to a rainfall deficit, while the remaining 50% (and often the worst) are caused by a series of other phenomena, either in isolation or in combination, such as warm snow seasons that lead to a lack of recharge in spring, rainfall deficits that extend into snowfall deficits, or delayed snow or glacier melt due to cold conditions (Van Loon and Van Lanen, 2012; Van Loon et al., 2015). Even when a single type of drought is examined, such as the lack of snowmelt-induced aquifer recharge, the dominant factors causing them can vary depending on the location. In Austria, for example, snowmelt droughts are primarily caused by warm and dry winter and spring conditions, while in Norway, this type of drought is mainly controlled by winter precipitation alone (Van Loon et al., 2015). In southern Quebec, the total amount of rainfall after the melting of the snowpack is generally the main predictor of the intensity of low-water conditions in summer, followed by the total amount of evapotranspiration (Kinnard et al., 2022). However, in certain watersheds, other variables, such as the maximum snow water equivalent (SWE_{max}), the date of onset of melting and the duration of snowmelt can explain water scarcity to the same extent as evapotranspiration (Kinnard et al., 2022). This is because during low-water periods in summer, a considerable portion of streamflow is derived from groundwater flow, and a prolonged and intense spring thaw helps recharge aquifers.

A significant rise in temperature is anticipated in eastern Canada due to human-induced climate change, which is very likely to shorten the duration of snow cover and could decrease SWE_{max} by 2.5 to 7.5% per decade through 2050 in southern Quebec, relative to 1981-2015 (Mudryk et al., 2018; Derksen et al., 2019; Lee et al., 2021). Increasing temperatures will result in higher total annual precipitation, but this increase will mainly be constrained to spring and winter, with minimal projected changes in summer and fall (Alberti-Dufort et al., 2022; Lee et al., 2021). This rise in annual precipitation is expected to enhance groundwater recharge on average. However, this will be accompanied by more pronounced seasonal variations, leading to increased recharge rates in winter and decreased rates in summer (Dubois et al., 2021, 2022). Coupled with higher evapotranspiration rates due to rising temperatures, summer water availability in southern Quebec is therefore projected to decline in the future (Bonsal et al., 2019; Alberti-Dufort et al., 2022; Lee et al., 2021). Consequently, the latest studies suggest that a reduction in average summer flow and an increase in the number of extreme low-flow events are likely for watersheds

in Quebec (Aygün et al., 2019; Bonsal et al., 2019; Thackeray et al., 2019; Charron et al., 2021; MELCCFP, 2022a; Kinnard et al., 2022).

A decrease in available water during ~~the~~ summer months, coupled with a higher demand due to population growth and anthropogenic climate change~~in various sectors (such as agriculture, industry and municipal services), ,~~ could exacerbate scarcity, decrease water quality and give rise to conflicts over water usage (Mehdi et al., 2015; Furber et al., 2016; Wheaton and Kulshreshtha, 2017; Osman, 2018; Chilima et al., 2021). Despite some advances on this issue in recent years, the implications of acute water shortages in Quebec are not yet well documented or understood, making it difficult to anticipate their consequences, especially for cases of more extreme drought conditions (Charron et al., 2019, 2020; Leveque et al., 2021; Knowles et al., 2023; Nand and Qi, 2023). It is still unclear who will suffer the most from water deficits, which regions are most vulnerable and to what extent.

Unlike droughts, climate change studies related to flooding can rely on well-defined metrics to evaluate the areas most vulnerable to future floods and help develop adaptation strategies. This is because extreme events such as 20- or 100-year floods are frequently used in urban planning and regulatory frameworks. ~~Infrastructure is~~ Infrastructures are designed to withstand specific thresholds, and maps are produced to indicate which neighbourhoods will be affected and damaged when events exceed them. In contrast, droughts emerge slowly over long periods of time, often remaining undetected in water-rich areas until they are already severe enough to significantly impact human activities and ecosystems. Furthermore, although Quebec has regulations regarding water withdrawals, it lacks specific low-water thresholds that would trigger emergency protocols, such as those used in the neighbouring province of Ontario (Ontario Ministry of Natural Resources et al., 2010; Berthot et al., 2020). This situation makes it difficult to predict the impacts of future severe droughts in Quebec and similarly hinders the development of effective climate change adaptation strategies.

Recently, storyline approaches have begun to be explored in climate change research and may provide a robust framework for projecting the impacts of future extreme events in the absence of clear thresholds, due to their event-based nature (Shepherd et al., 2018; Shepherd, 2019; Sillmann et al., 2021; Matte et al., 2022; Baulenas et al., 2023; Caviedes-Voullième and Shepherd, 2023). ~~Indeed, storylines differ from traditional~~ Traditional climate change projections ~~, which are probabilistic, by employing climate science along with other techniques to project specific past events~~ evaluate changes in extreme events by examining the potential shifts in the frequency or intensity of events with a specified magnitude or probability of occurrence, such as a 100-year drought. These projections often utilize multi-model ensembles, where changes are assessed through the ensemble median and/or the likelihood of increase or decrease across the ensemble for future scenarios. In contrast, climate storylines offer a way to simplify complex climate information by linking it to stakeholders' past experiences and projecting how specific events may evolve in the future. For example, van der Wiel et al. (2021) focused on the 2018 European drought and projected this high-impact event under future climatic conditions in a physically consistent manner to assess how that one event might change if it were to occur again in the future. Consequently, the storyline approach focuses on the plausibility of the future scenario rather than its likelihood, and ~~avoids~~ can avoid the need to pinpoint specific damage-inducing thresholds ~~(e.g., a 20-year flood)~~ by constructing the future scenario based on an event that already caused ~~damage~~ known damages in the past. Storylines have been applied in both climatological and hydrological research to effectively illustrate future extreme events such as

droughts, floods and storms ~~(Schaller et al., 2020; van der Wiel et al., 2021; Chan et al., 2022; Gessner et al., 2022)~~(Schaller et al., 2020; v

Storylines can be constructed using various methodologies ~~. One approach involves~~ (Fossa Riglos et al., 2024). Physical climate storylines (PCS) involve using a climate or weather forecast model to recreate ~~the~~ a singular high-impact event and explore alternative realities, for example by modifying the initial conditions or by using a pseudo-global-warming approach (e.g., Hazeleger et al., 2015; Gessner et al., 2022; Matte et al., 2022). ~~Another methodology involves searching for analogues of the event~~ Scenario-based approaches (SBA), on the other hand, do not recreate the event, but instead search for adequate analogues within a simulated dataset that includes both historical and future climate conditions ~~(e.g., van der Wiel et al., 2021)~~ (e.g., van der Wiel et al., 2021; Faranda et al., 2023; Liao et al., 2024). This approach thus involves defining the event of interest using ~~indicators~~ metrics that can accurately capture its intensity and main characteristics, while also being flexible and reliable enough to identify comparable events in the simulated data. For example, in their study related to a severe drought in Europe, van der Wiel et al. (2021) examined three different types of metrics associated with ~~water~~ precipitation deficits: the average deficit during the most severe drought months (M1), the regression slope of the ~~deficit~~ deficits in the months preceding the peak deficit (M2) and a temporal regression of the deficit time series (M3). Alternatively, rather than focusing on specific historical events, SBAs may involve searching large ensembles for unprecedented climate conditions, such as multiple consecutive dry seasons, to identify worst-case scenarios which can then be used for stress-testing systems (Chan et al., 2023).

~~This~~ Our study aims to employ a storyline approach similar to that described in van der Wiel et al. (2021) to project ~~a recent drought event~~ the recent 2021 Quebec drought into future climate conditions corresponding to an increase of 2°C and 3°C in global surface temperatures compared to preindustrial levels~~, using analogues taken from~~ . We use a SBA to first identify adequate analogues of the meteorological drought using a large ensemble of regional climate simulations. ~~This study goes one step further than van der Wiel et al. (2021)~~ We then investigate the associated hydrological drought by also making use of a hydrological model to project streamflow data during the drought event, thus also contrasting present and future hydrological conditions. ~~Finally, by selecting a severe drought that recently affected southern Quebec as the event of interest for this study, we are able to work alongside water management experts and other stakeholders to build a detailed understanding of the socioeconomic and environmental impacts of that event and describe the possible outcomes of climate change on future severe water shortages. This integrated approach will provide valuable information for the development of effective adaptation strategies. Section 2 describes the data used for the analysis~~ The data used and the experimental framework are described in Sect. 2, while Sect. 3 presents the 2021 drought event used as ~~a~~ reference, as well as its present and future analogues derived from ~~a~~ the large ensemble of simulations. Finally, Sect. 4 examines the ~~cascade of socioeconomic and environmental consequences linked to the potential outcomes of future severe water scarcity events~~ potential uses of climate storylines as a communication tool for discussing the impacts of future extreme droughts, as well as presenting the limitations of our study. Concluding remarks are provided in Sect. 5.

2 Methodology

2.1 Stakeholder consultation

Documenting the impacts of previous drought events was essential to better understand the potential outcomes of future events described by the storyline approach. However, there is a known underreporting of water scarcity events in Quebec, in part due to the common belief in an abundant water supply (Nand and Qi, 2023). This is exacerbated when it comes to ecosystems, because prevalent monitoring systems primarily focus on human water usage and rarely align with the data gathering requirements necessary to evaluate the exposure, sensitivity and adaptive capacity of wildlife and vegetation (Kovach et al., 2019; Berthot et al., 2020). Consequently, impacts on ecosystems are largely unreported unless they affect human activities.

Hence, with the objective to enhance our understanding of the impacts of previous droughts across the province, a questionnaire was circulated amongst the forty Watershed organizations ~~(*Organisme de bassin versant*[1])~~ mandated to assess the current state of the water resource throughout Quebec. It asked the respondent to identify up to ten recent hydrological droughts, classify their intensity and probable causes and then list the documented or perceived socioeconomic and environmental consequences. Through this process, a total of 87 water scarcity incidents were reported with varying levels of detail regarding their impacts on human and environmental usage. To complement this knowledge base, interviews were conducted with select stakeholders to deepen our understanding of past events in specific complex sectors such as the Quebec Metropolitan area or Lake Saint-Jean.

~~Although~~ While this consultation is not the ~~main focus of this study (see Audet et al. (2024) – in French only – for a more detailed explanation of the methodology and breakdown of the results), certain findings will be discussed in Sect. 4. These findings provide valuable insights that enhance the understanding of the effects of previous drought events , thus enriching the discussion on the possible~~ primary focus of the study, it provides valuable insights into the consequences of past drought events. Consequently, some of the findings will be discussed to enrich the conversation on the potential impacts of future droughts. ~~By combining the qualitative data from the questionnaire with the quantitative insights drawn from the storylines, it becomes possible to obtain a more comprehensive understanding of the potential impacts of future severe droughts.~~ For more details on the methodology and a detailed breakdown of the results, readers are encouraged to refer to Audet et al. (2024) (available in French only) and Appendix D specifically. The questionnaire itself is also included in the Supplementary Materials, though it is available only in French.

While several years, including 2001, 2002, 2010, 2012, and 2018, were highlighted by stakeholders, the 2021 low-water event emerged from the consultation as the longest and most severe drought in recent years in southern Quebec. Further analysis of meteorological data, presented in the following sections, confirmed the severity of the 2021 drought, with most of the spring, summer, and autumn periods experiencing severe or worse drought conditions. This validated the decision to focus the study on 2021.

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[1]~~Independent bodies with the mandate to assess the current state of the water resource in their region and determine the priority actions that ought to be taken to improve the efficiency of water management~~

2.2 Observational data

Historical precipitation and temperature data were obtained from the ERA5-Land reanalysis (Muñoz Sabater et al., 2021), which is a reconstruction of surface conditions using a 9 km spatial grid-mesh derived from the ERA5 reanalysis. ~~Historical streamflow records were taken~~

Historical streamflow data were obtained from the Hydroclimatological Atlas of Southern Quebec, which ~~includes a retrospective analysis of streamflow data for approximately 10,000 gauged and ungauged river segments~~ covers the period from 1970 to the present ~~(Lachance-Cloutier et al., 2017; MELCCFP, 2022b). This represents all watersheds in excess of 50 km^2 in the southern part of the province, but leaves out river segments significantly affected by dams and other anthropogenic activities~~ (and spans the entire region of Southern Quebec, as seen in Fig. 1 ~~, bottom right). The retrospective analysis is performed by combining streamflow measurements from various locations in the province and the output of the~~ (MELCCFP, 2022b). The dataset is a reconstruction of past hydrology combining six simulations from the HYDROTEL hydrological model driven by gridded ~~observation data, using~~ observational temperature and precipitation data. Furthermore, it incorporates observed streamflow measurements through an optimal interpolation ~~method (Lachance-Cloutier et al., 2017).~~ technique to provide the most accurate estimate of past streamflow conditions across gauged and ungauged watersheds, accounting for both model and observational uncertainties (Lachance-Cloutier et al., 2017). Finally, to ensure robustness for ungauged river segments, HYDROTEL is calibrated using a regional calibration technique, identifying optimal parameter sets for each of the 6 simulations across 70 gauged watersheds.

HYDROTEL itself is a physically-based, semi-distributed hydrological model that is operationally employed by the Government of Quebec for streamflow forecasting (Fortin et al., 2001). Unlike conceptual models, which fully rely on empirical relationships and simplified assumptions to represent hydrological processes, HYDROTEL employs a more detailed set of physical equations to simulate various aspects of water movement and distribution within a watershed, such as infiltration, runoff, snowmelt or evapotranspiration. However some components, such as subsurface runoff, are still fairly simple in their representation. The model divides the landscape into computational units called "Relatively Homogeneous Hydrological Units" (RHHUs), which are defined based on land use, soil type, and topographical characteristics such as slope and aspect. In the configuration used for the Atlas, the average size of RHHUs is 11 km^2, forming a hydrological network comprising 28,035 river segments throughout Southern Quebec. Streamflow at each segment is calculated as the sum of upstream contributions and runoff/baseflow from neighboring RHHUs. Results are reported for 9,665 river segments, specifically those with watersheds larger than 50 km^2 and not subject to significant anthropogenic influences, such as dams with daily or weekly management practices. Comprehensive details on model configuration, calibration procedures, and validation results are provided in MELCCFP (2024).

Although six distinct model versions exist, only the "MG24HQ" configuration of HYDROTEL was selected for the present study due to computational constraints within the experimental framework, as it showcases the best performance in simulating summer streamflow (MELCCFP, 2024).
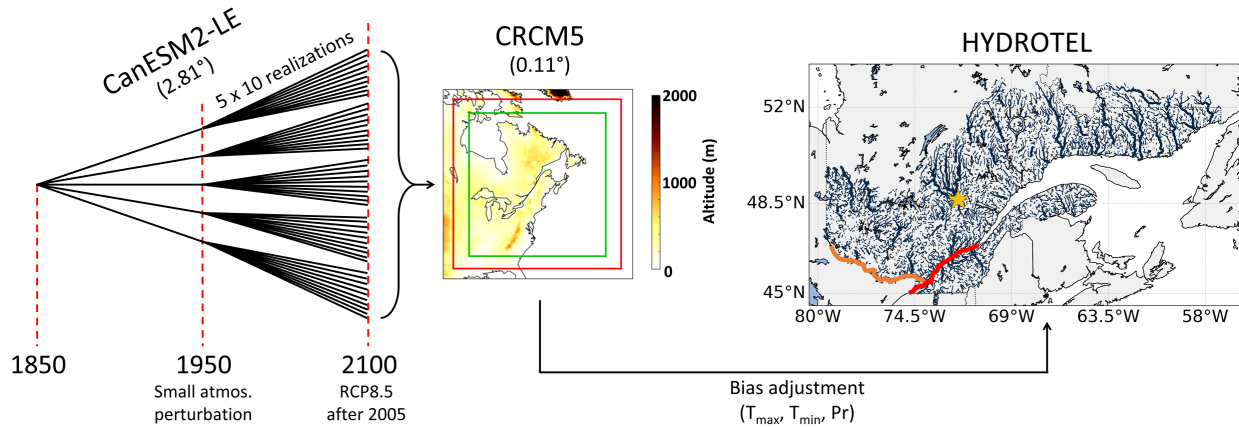
Figure 1. Experimental framework for the production of the ClimEx Large Ensemble (atmospheric and hydrological simulations). Fifty realizations from the CanESM2 Large Ensemble are used to drive the CRCM5 regional climate model from 1950 to 2100 using the RCP8.5 emissions scenario. Results are then bias adjusted and used in the HYDROTEL hydrological model to produce streamflow data. The ~~bottom-right~~ rightmost figure shows the spatial domain and river network of the Hydroclimatological Atlas of Southern Quebec, along with key locations for this paper: the St. Lawrence River and Ottawa River are outlined in red and orange, respectively, while Lake Saint-Jean is noted with a yellow star. Adapted from Leduc et al. (2019).

2.3 Experimental framework

The ~~storyline approach described in van der Wiel et al. (2021) requires a significant~~ experimental framework can be seen in Fig. 1. SBAs require a large number of climate simulations, as an ~~adequately sized~~ adequately-sized sample of simulated counterpart events is required to identify appropriate analogues. ~~These~~ The base meteorological data were obtained from the ClimEx Large Ensemble ~~(LE)~~ project (www.climex-project.org; Leduc et al. (2019)), which consists of 50 perturbed simulations produced using the fifth-generation Canadian Regional Climate Model (CRCM5; Martynov et al. (2013); Šeparović et al. (2013)). The CRCM5 was developed by the ESCER Centre (*Centre pour l'Étude et la Simulation du Climat à l'Échelle Régionale*) at the Université du Québec à Montréal, in collaboration with Environment and Climate Change Canada.

Temperature, specific humidity, surface pressure and winds produced by the large initial-condition ensemble (50 realizations) of the second generation of the Canadian Earth System Model (CanESM2-LE; Fyfe et al. (2017)) were used to drive the boundaries of the CRCM5 every 6 hours for the period 1950-2100 (Fig. 1). It used observed radiative forcings until 2005 and the RCP8.5 emissions scenario afterwards (Riahi et al., 2011). For this experiment, the CRCM5 grid-mesh was set at a 0.11° horizontal resolution and winds were spectrally nudged from 500-hPa to the model top. For a more detailed description of the models and setup of the ClimEx experiment, see Leduc et al. (2019).

~~The output of these climate simulations was then bias corrected before being used as input by the HYDROTEL hydrological model. Bias adjustment was applied to~~ HYDROTEL requires daily surface temperature and precipitation data as input. These

variables were taken from the CRCM5, then bias adjusted using a Detrended Quantile Mapping technique (DQM; Gennaretti et al. (2015))~~technique, using 50 bins to build~~. DQM is a variant of quantile mapping that first removes the trend in the data, typically through a polynomial fit (in this case, a fourth-degree polynomial), after which a correction is applied to the residuals. Specifically, the residuals are sorted into bins based on their empirical quantiles, and a transfer function ~~linking the model to the NRCANmet dataset. The latter is a spatial~~ is trained on the differences between each bin of the simulated and the reference datasets during a common time period. This transfer function is then used to correct the whole simulation. In this study, DQM was applied to each day of the year and each grid cell individually, using a ± 15-day window around each day and separating data into 50 bins. The reference dataset used for the correction was the NRCANmet dataset, a spatially interpolated kriging of station data on a 10 km grid ~~covering~~ that covers all of Canada, produced by Natural Resources Canada (Hutchinson et al., 2009). ~~For~~ Since ClimEx is a single model large ensemble, all 50 simulations were pooled together to construct the transfer function. Finally, for precipitation, the ~~quantile mapping~~ adjustment method was modified to combine DQM with a Generalized Pareto distribution in the upper tail of the distribution (Roy et al., 2023). This modification was added in order to improve the correction of the most extreme precipitation events compared to using a standard DQM technique, but should not play a role in the results presented here, as we focus on dry conditions.

~~HYDROTEL is a semi-distributed physically based hydrological model used operationally for streamflow forecasting by the government of Quebec (Fortin et al., 2001). It is partly modular in nature, with some controls on the physical representation of channel routing, the vertical water budget and, importantly for this work, potential evapotranspiration (PET). The HYDROTEL configuration used for this study (MG24HQ) uses the definition of PET provided by McGuinness and Bordne (1972) (see Sect. 2.4.1 for more details). The simulations were performed~~ The bias-adjusted temperature and precipitation data were subsequently used as input in HYDROTEL to generate 50 streamflow simulations covering Southern Quebec from 1955 ~~onwards and generated streamflow data throughout southern Quebec~~ to 2100 (MELCCFP, 2024). The configuration and calibration of HYDROTEL for these simulations are identical to that used for the historical reconstruction described in Sect. 2.2, guaranteeing that the simulated streamflow are consistent with the reference product. Figure S1 presents a validation of the streamflow driven by ClimEx during the historical period over a few watersheds.

Two future periods were selected to investigate the effects of human-induced climate change on extreme low-water episodes, specifically targeting global average temperature rises of 2°C and 3°C above preindustrial levels. The specific periods corresponding to the warming levels within each ClimEx realization were determined by using a 30-year centered moving window to compute global 2 m temperature increases compared to the 1850-1900 period within the driving model CanESM2-LE, locating the first instance when the 30-year window crosses these warming thresholds.

2.4 Drought indicators

2.4.1 Meteorological drought indicator

Various metrics have been developed to represent meteorological droughts (Palmer, 1965; McKee et al., 1993; Vicente-Serrano et al., 2010; Staudinger et al., 2014). Of these, the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano

et al. (2010)) is a standardized index that measures the deviation of the water budget (difference between precipitation and evapotranspiration; $P - PET$) aggregated over a certain number of months (e.g., SPEI-3_{AUG} aggregates the water budget from June to August). It has been used in various studies both internationally and in Canada and Quebec to describe the severity and duration of droughts (Tam et al., 2019, 2023; Solaraju-Murali et al., 2019, 2021). It also notably serves as the main drought indicator on the ClimateData.ca portal, the Canadian web portal that provides national climate change information (Cannon, 2024; Lavoie et al., 2024). Consequently, the SPEI was selected as the drought indicator to represent surface conditions for this analysis. The SPEI is computed by following these steps:

1. Compute the monthly water budget ($P - PET$).

2. Aggregate the water budget over a given number of months. In this study, aggregations of 3 and 6 months were used.

3. For a given month, aggregation length and calibration period (e.g., water budgets aggregated from June to August over 1992-2021), fit a statistical model to the empirical distribution of water budgets and get their probability of exceedance. Based on suggestions from multiple studies, a three-parameter log-logistic distribution was employed for this step (Stagge et al., 2015; Tam et al., 2023).

4. Transform the probabilities of exceedance back to a normal distribution. Values below -1, -1.5 and -2 are typically used as thresholds that represent mild, severe and extreme drought conditions, respectively (McKee et al., 1993; Stagge et al., 2015).

~~Because the storyline approach used here requires identifying suitable analogues~~ SBA storylines are constructed by identifying analogues of a past high-impact event within a large ensemble of simulated climate data. To facilitate this, it was crucial to ensure that ~~the final normal distributions would be comparable, despite potential biases in ClimEx or despite a warmer and drier future climate. Therefore, the calibration of the~~ SPEI distributions could be compared across the reference (observed) climate, ClimEx during the historical period, and future ClimEx simulations. To address this, the three-parameter log-logistic distribution ~~and subsequent standardization was independently performed~~ was calibrated independently for each realization and ~~each~~ time period (~~both~~ historical and future)~~to maintain consistency in the range of SPEI values~~, ensuring consistent SPEI value ranges. While preferable for traditional climate change projections, a single calibration of SPEIs during the historical period only would have complicated finding relevant future events, as those with similar SPEIs to the past would offer little new insight — an issue also noted by van der Wiel et al. (2021) with the M3 metric —, while those with lower SPEIs would be more difficult to relate to the 2021 drought. Using separate calibrations for the past and future enables the identification of events with a similar probability and annual progression as 2021, but relative to their respective climatologies.

Access to potential evapotranspiration (PET) data is required for calculating the water budget needed for the SPEI. ~~For this analysis, PET was calculated using the~~ As a physically-based hydrological model, HYDROTEL computes its own PET based on the provided temperature data. The model configuration used for this study employed the PET definition provided in McGuinness and Bordne (1972), which takes into account both temperature and latitude. Therefore, this definition was also

chosen for the computation of SPEIs in order to have a consistent definition between the meteorological and hydrological droughts. It is defined as:

$$PET[mm\,day^{-1}] = a\frac{S_0}{\lambda}T_a + b\frac{S_0}{\lambda} \qquad (1)$$

where the coefficients a and b represent empirical values, S_0 [MJ m-2 day-1] denotes the extraterrestrial solar radiation based on a solar constant of 1367 W/m^2, λ stands for the latent heat of vaporization [MJ kg-1] and T_a indicates the air temperature [°C]. The values for $a = 0.0052$ and $b = 0.0875$ were adopted, as specified by Tanguy et al. (2018). This definition was chosen in order to have a consistent definition of PET with HYDROTEL, the hydrological model used in this study.

Finally, despite the standardization process, it was deemed essential to validate that the anomalies in the water budget were similar between the bias-adjusted ClimEx data and ERA5-Land, since the observed and simulated SPEIs are calculated as deviations from their respective climatology. Our findings indicate that, with the exception of the winter season where both datasets are coherent, the water budget in the bias-adjusted ClimEx data is consistently below that of ERA5-Land. However, more importantly, anomalies are similar across both datasets (Fig. S1S2).

2.4.2 Hydrological drought indicators

Establishing a direct link between low streamflow values and their on-the-ground consequences is challenging, as impact-inducing thresholds are often unknown. Even when such thresholds exist in the literature or in regulations, they are not always well adapted to truly represent local conditions. The 7Q2 metric (2-year minimum of the 7-day average flow), for instance, plays a crucial role in Quebec for setting water withdrawals limits in a way that they maintain the health of river ecosystems. However, that metric has been criticized in recent years and deemed insufficient to truly represent the needs of ecosystems, with ongoing efforts to replace it with another indicator better suited to represent the geomorphological conditions of rivers and be more robust in the context of a changing climate (Berthot et al., 2020, 2021). Furthermore, for both ecosystems and human activities, water levels often hold greater relevance than streamflow; however, such data is rarely available, and especially not on a broad spatial scale. A storyline approach is valuable here, as the 2021 drought is known to have caused multiple negative impacts and surpassed key thresholds (see Sect. 3.1.1 and 3.1.2). Various hydrological indicators were thus used to character-ize the exceptional intensity and duration of the 2021 drought (Table 1). These indicators were specifically selected as they encapsulate crucial , as well as the future events, to ensure a consistent framework for assessing and comparing the potential impacts of climate change on hydrological droughts similar to 2021. The selected indicators capture key aspects of river con-ditions, thereby facilitating a better comprehension of how extreme the historical event was enhancing our understanding of the extreme nature of the 2021 event across different facets of the hydrological cycle(e.g., such as the timing of the low-water season or and the minimum summer flow). In Sect. 4, these indicators will be used in conjunction with findings from the stakeholder survey to investigate the potential links between the event's socioeconomic and environmental impacts and deviations in these indicators. Additionally, applying the same indicators and thresholds to the future events will allow for a consistent approach to assess and compare the potential impacts of future droughts, thus helping gain an understanding of how much more severe their consequences could be. .

The low-water season (LWS) described in Table 1 was defined as the period of the year when streamflow remains below Q_{thresh}, defined as:

$$Q_{thresh} = \overline{Q} - 0.85\left(\overline{Q} - 7Q2\right) \tag{2}$$

where $\overline{Q}$ is the annual average flow and $7Q2$ is the minimum 7-day average flow with a return period of 2 years. The LWS begins when streamflow is below Q_{thresh} for a continuous period of 7 days (after May 1st) and ends when it exceeds the threshold for 7 continuous days, such that:

$$LWS_{start} = \min\{doy \mid Q_i < Q_{thresh} \wedge \forall i \in \{doy, \ldots, doy+6\} \wedge doy > 121\} \tag{3}$$

$$LWS_{end} = \min\{doy \mid Q_i > Q_{thresh} \wedge \forall i \in \{doy, \ldots, doy+6\} \wedge doy > LWS_{start}\} \tag{4}$$

where doy is the day of the year.

It should also be noted that when an indicator in Table 1 is defined using a threshold, such as Q_{thresh} or 7Q2, the threshold is defined using data from the historical period only.

Finally, the bias adjustment of ClimEx data does not guarantee that simulated streamflow data will not be biased compared to observations, since nonlinear effects might come into play in both the hydrological model and the calculation of the hydrological indicators. For the construction of the future indicators, it is therefore preferable to apply a second adjustment step to the indicators themselves (Grenier et al., 2019). For that reason, future hydrological indicators for the historical event under +2 and +3°C scenarios were constructed by calculating the average difference between the 10 best analogues in the future and historical time periods, and then applying this difference onto the observed indicator (Fig. S2). The modification was carried out by applying the relative change as a multiplier for flow-related metrics, whereas an absolute change was applied to metrics measured in days. This methodology also follows the one employed for the creation of future hydrological indicators in the Hydroclimatological Atlas of Southern Quebec (MELCCFP, 2024).

3 Results

2.1 Construction of the analogues

Years with documented severe drought conditions The specific methodology employed to identify analogues within the single-model large ensemble can have a significant impact on the analogues identified within the simulated dataset (van der Wiel et al., 2021). In our study, appropriate analogues were identified using the stakeholder survey mentioned in Sect. 2.1, as well as an examination of a technique similar to the M3 method described in van der Wiel et al. (2021), which used temporal correlation, but using a series of multiple SPEIs. Indeed, SPEI-3 indices from May through November, along with the SPEI-6 for May and October, were used as targets during the search for analogues within the ClimEx dataset, alongside a weighting mask to assign

Table 1. Indicators used to describe the low-water episode and its consequences

Indicator	Definition	Use
$7Q_{min}$	Minimum 7-day average flow (from May to November).	Indicates the highest stress exerted on the stream for a given year (Ismail et al., 2021).
$n_{days<7Q2}$	The total number of days (from May to November) below a threshold characterized by the minimum 7-day average flow with a return period of 2 years (7Q2).	The 7Q2 is used as an 'environmental flow' in Quebec and plays a crucial role in various regulatory functions to maintain the health of river ecosystems, including setting limits for water withdrawals (Berthot et al., 2020, 2021).
$n_{days<7Q10}$	The total number of days (from May to November) below a threshold characterized by the minimum 7-day average flow with a return period of 10 years (7Q10).	The 7Q10 was originally designed to protect water quality under the USA Federal Clean Water Act and represents the lowest flow necessary to preserve the dilution capacity of rivers. This indicator serves here as a metric for extreme low flow with negative consequences on water quality and ecosystems (Berthot et al., 2020, 2021).
$LWS_{start|end|duration}$	Start date, end date and duration of the low-water season as defined by Eq. 2 to 4.	The start and end dates of the low water season influence various activities, including sowing schedules and fish reproduction (Morales-Marín et al., 2019; Nand and Qi, 2023). In addition, the duration of this season can indicate the severity and duration of drought conditions.
$\overline{Q}_{MAM|JJA|SON}$	Average seasonal flow.	The seasonal flow anomaly provides a good estimate of the general intensity of water scarcity and can serve as a proxy for impacts on run-of-river dams.
$14Q_{max}$	Maximum 14-day averaged flow.	Approximation of the freshet volume, which plays a significant role in groundwater recharge and fish reproduction (Morales-Marín et al., 2019).

greater importance to areas experiencing mild to extreme droughts (see below). These weights successfully highlighted the area most affected during the 2021 drought, with a good correlation with the river sections where $Q7_{min}$ exhibited the most extreme (negative) anomalies. This approach also proved effective for other years with significant droughts identified within the 1992-2021 period (Fig. S3).

More precisely, the identification of analogues within ClimEx was carried out through the following steps (Fig. 2):
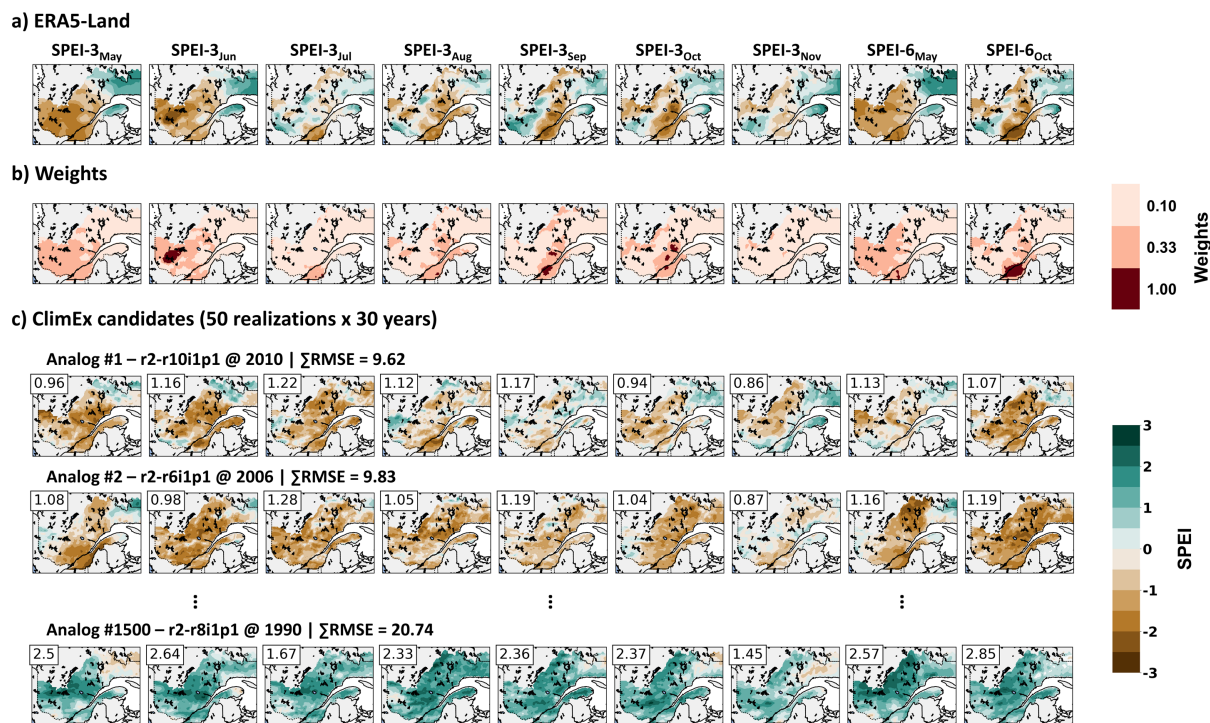
Figure 2. The assessment of candidate analogues is performed by comparing various SPEI indicators (columns) between a) ERA5-Land and c) 1500 candidates (50 realizations x 30 years) from the ClimEx Large Ensemble. For each candidate (rows in c), a weighted RMSE is calculated for each SPEI (top-left corner of each image) and then aggregated. Weights (b) are allocated based on SPEI values in ERA5-Land.

1. Calculate the SPEI-3 for all months from May to November, and the SPEI-6 for May and October, using the year 2021 for ~~data. Although multiple yearssuch as 2002, 2010, 2012 and 2018 were also highlighted by stakeholders as notably dry,~~ and using 1500 candidates over a 30-year span for ClimEx (50 realizations x 30 years).

335

2. Apply a weighting mask based on the categories specified by McKee et al. (1993) for each SPEI value derived from ERA5-Land to emphasize lower values, namely:

   (a) 1 if SPEI $\leq$ -2 (extreme drought)

   (b) 0.33 if -2 $<$ SPEI $\leq$ -1 (mild drought)

   (c) 0.1 for all other values

340

3. Calculate a weighted root mean square error (RMSE) for each grid cell within the domain, comparing the SPEI values from ERA5-Land against each of the 1500 ClimEx candidates.

4. Sum the RMSEs for each ClimEx candidate.

The 1500 possible candidates within ClimEx for each period (historical, +2°C and +3°C) were then sorted according to their total RMSEs, cumulated over the spatial domain of HYDROTEL and the 9 SPEI metrics analyzed (Fig. 2). The 10

345 candidates with the lowest total RMSE were selected as the 10 best analogues to 2021. This step was accomplished separately for the historical and the future periods. Figure S4 presents a validation of the monthly mean anomalies in precipitation, evapotranspiration and streamflow between the observed 2021 ~~low-water event emerged as both the longest and most severe drought in recent years in the southern parts of Quebec. As detailed in the next section, an analysis of SPEI values for~~ and the average of the 10 best ClimEx analogues for the historical period across a few watersheds.

350 On the hydrological side, the previously-described bias adjustment of ClimEx data does not guarantee that simulated streamflow indicators will not be biased compared to observations, since nonlinear effects might come into play in both the hydrological model and the calculation of the hydrological indicators. For the construction of the future indicators, it is therefore preferable to apply a second adjustment step to the indicators themselves (Grenier et al., 2019). For that reason, future hydrological indicators for the historical event under +2 and +3°C scenarios were constructed by first calculating the

355 indicators for the 10 best analogues, averaging them over the future and historical time periods separately, and applying that difference to the observed indicator (Fig. 3). This modification was carried out by applying the relative change as a multiplier for flow-related metrics, whereas an absolute change was applied to metrics measured in days. This methodology is also used for the computation of the future hydrological indicators in the Hydroclimatological Atlas of Southern Quebec (MELCCFP, 2024).

360 Figure 4 presents a comparison of the hydrological indicators for the 2021 event, for the top two analogues of 2021 in the historical period and for the average of the 10 best analogues. Additional verifications have shown that while the selection of the best analogues is sensitive to the weighting scheme, and that ~~region and year showed that most of spring, summer and fall remain under severe drought conditions (SPEI ≤ -1.5)or worse. Consequently, the year~~ the average of the best n analogues thus becomes unstable when the number is too low, the results were robust and stable with 10 selections (not shown). The average

365 of the 10 best analogues (Fig. 4c) replicates the spatial patterns and intensity of the 2021 ~~was chosen as~~ drought particularly well for key indicators like $7Q_{min}$ or $LWS_{duration}$, although it overestimates the freshet volume and spring flow. It also adequately reproduces other indicators such as $\overline{Q}_{JJA|SON}$, $LWS_{start|end}$ and $n_{days<7Q2|7Q10}$, though individual members sometimes provide a more accurate match in specific instances. For example, while the best match (*r2-r10i1p1* in Fig. 4b) excels in replicating LWS_{start}, it ends too early for LWS_{end}. The second best match (*r2-r8i1p1* in Fig. 4b) exhibits the

370 opposite issue. Therefore, overall, the average of the ~~focus of this study.~~ 10 best analogues performs adequately well and offers a solid representation of the 2021 drought for the chosen hydrological indicators (Fig. 4).

3 Results

3.1 Analysis of the 2021 drought in Southern Quebec

Anomalies of precipitation and evapotranspiration for the year 2021, along with associated SPEI values, are shown in Fig. 5a-c

375 (December-May) and d-f (May-October), whereas Fig. 5g-j ~~depict~~ depicts the differences between 2021 and the 1992-2021
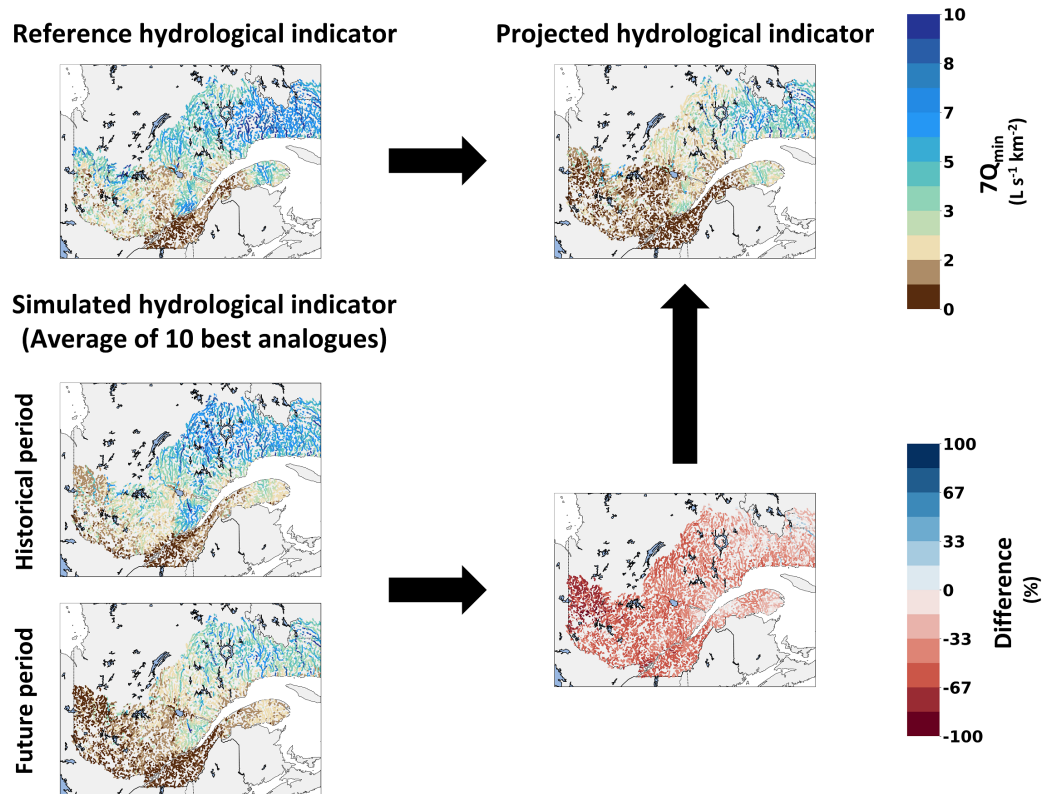
Figure 3. Diagram of the building process for the future hydrological indicators. The difference between simulated analogues from future and historical scenarios is combined with the reference hydrological indicator in the future.

average for key hydrological indicators taken from Table 1. Note that the climatological mean of $n_{days<7Q2}$ and $n_{days<7Q10}$ would not be meaningful, since the threshold is by definition exceeded every 2 and 10 years only. Therefore, these two indicators are presented in absolute terms rather than as anomalies.

Severe drought conditions (SPEI < -1.5) were already detected in May after an unusually warm and dry winter and spring
380 (Fig. 5c), leading to a reduction in freshet volumes of up to 67% below average in most of the province (Fig. 5g) and causing the onset of summer-like conditions in rivers 45 to 60 days earlier than usual (Fig. 5j).

Drought conditions did not improve during summer and fall (Fig. 5f), with exceptionally low precipitation especially in the St. Lawrence River valley, which, combined to high temperatures and evapotranspiration, led to extreme drought conditions (SPEI < -2) in that region. As pointed out by Kinnard et al. (2022), the lack of summer rainfall and high evapotranspiration
385 led to extremely low streamflow throughout the province, but especially south of the St. Lawrence River (Fig. 5h). In that area, which is the most densely populated of Quebec and contains most of the agricultural land, anomalies in summer flow were as severe as -85% or more compared to the 1992-2021 average, while the rest of the province still faced streamflow at about 50% of the normal rate. The $7Q_{min}$, indicative of the maximum stress on a stream within a given year, also reached its lowest
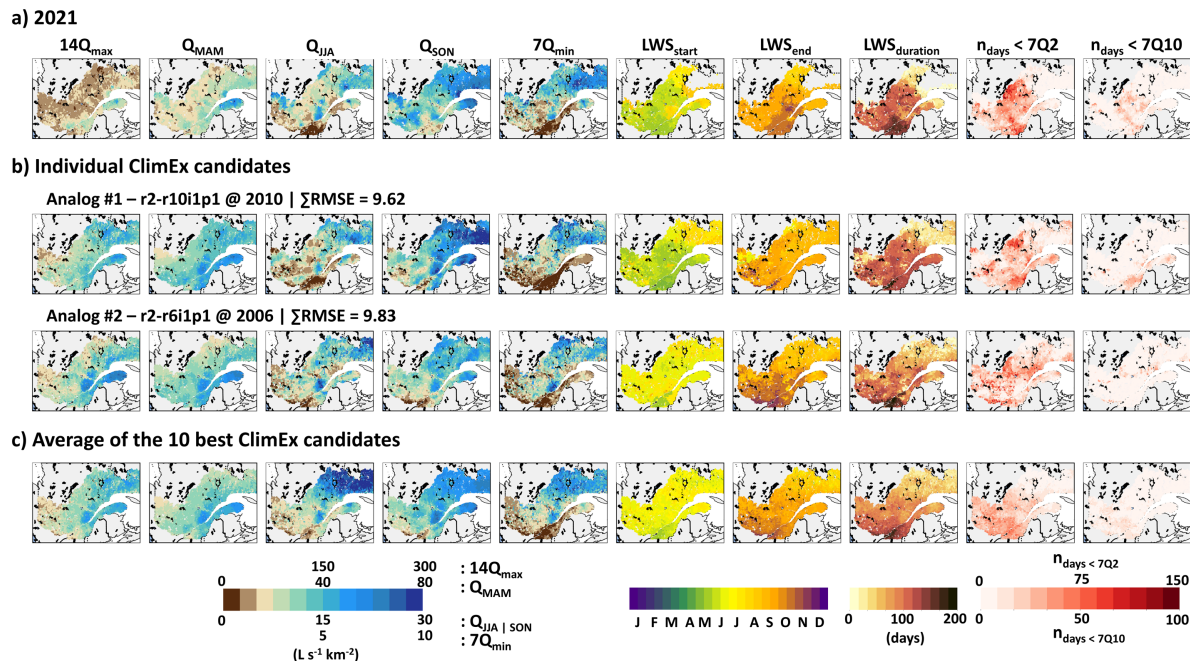
Figure 4. Comparison of hydrological indicators between (a) the 2021 low-water episode, (b) the first two best ClimEx candidates within the historical period and c) the average of the 10 best ClimEx candidates.

point of the 1992-2021 period in many river sections of that region during 2021, with anomalies also ranging between -50% and -85% in the most affected areas (Fig. 5i). Furthermore, those affected rivers experienced at least 30 days with flow below the environmental threshold (7Q2), with some segments having over 90 days below this limit (Fig. 5m), and 14 days or more below the 7Q10 (Fig. 5n).

Anomalies for the end of the low-water season (Fig. 5k) match the spatial pattern shown in the May-October precipitation deficit and the SPEI-6$_{OCT}$ very well (Fig. 5e-f). Delays of up to a month can be seen in the driest areas, while substantial rainfall in the eastern and western parts of the province, particularly in September (not depicted), alleviated drought conditions there and helped end the LWS at a date close to the 1992-2021 average. Combined with the early onset of the LWS, the low-water season was extended by more than two months beyond the usual duration in the areas most affected by the 2021 drought (Fig. 5h).

The 2021 drought thus resulted in unprecedented hydrological stress in southern Quebec and around the Lake Saint-Jean area, with significant reductions in streamflow and an extended low-water season. Despite some late seasonal precipitation that alleviated drought conditions in some parts of the province, the south shore of the St. Lawrence River remained critically affected, showcasing the vulnerability of this densely populated and agriculturally important area to extreme drought events.
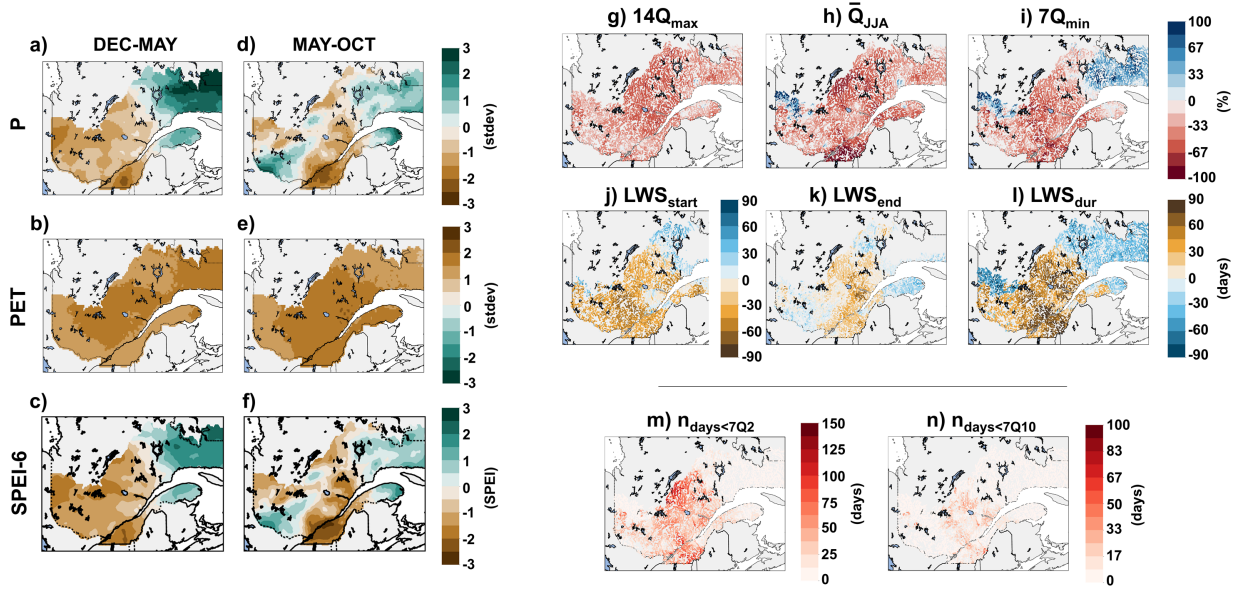
Figure 5. Standard deviation anomalies of precipitation (P) and potential evapotranspiration (PET) in 2021 relative to the 1992-2021 average, along with SPEI-6 values, for a-c) December to May and d-f) May to October. g-l) Anomalies in 2021 for the $14Q_{max}$, $\overline{Q}_{JJA}$, $7Q_{min}$, LWS_{start}, LWS_{end} and LWS_{dur} hydrological indicators compared to the 1992-2021 average. m-n) Absolute values reached in 2021 for $n_{days<7Q2}$ and $n_{days<7Q10}$.

3.2 ~~Present and future analogues in the ClimEx Large Ensemble~~

3.1.1 Reported environmental consequences

405 ~~It is crucial to identify indicators that best describe the event of interest for the storyline, since this choice can significantly influence the analogues that are detected within the simulated dataset (van der Wiel et al., 2021). Appropriate analogues were identified using a technique similar to the M3 method described in van der Wiel et al. (2021), which used temporal correlation. A series of SPEI-3 indices from May through November, along with the SPEI-6 for May and October, were used as targets during the search for analogues within the ClimEx dataset, alongside a weighting mask to assign greater importance to areas~~

410 ~~experiencing mild to extreme droughts (see below). These weights successfully highlighted the area most affected during the~~ Despite having access to the survey described in Sect 2.1, impacts of 2021 ~~drought, with a good correlation with the river sections where $Q7_{min}$ exhibited the most extreme (negative) anomalies. This approach also proved effective for other years with significant droughts identified within the 1992-2021 period (Fig. S3).~~

~~More precisely, the identification of analogues within ClimEx was carried out through the following steps (Fig. 2):~~

415 ~~Calculate the SPEI-3 for all months from May to November, and the SPEI-6 for May and October, using the year~~ on ecosystems remain mostly local and anecdotal in nature. This is in line with other studies that have noted a lack of consistent

data collection before, during and after drought periods that could help build causal relationships between low-water episodes and their impacts on ecosystems (Kovach et al., 2019). However, multiple stakeholders, especially in the area south of the St. Lawrence River, either directly acknowledged a decline in water quality in 2021 for ERA5-Land and using 1500 candidates over a 30-year span for ClimEx (50 realizations x 30 years). Apply a weighting mask based on the categories specified by McKee et al. (1993) for each SPEI value derived from ERA5-Land to emphasize lower values, namely:

1. 1 if SPEI ≤ -2 (extreme drought)

2. 0.33 if SPEI ≤ -1 (mild drought)

3. 0.1 for all other values

Calculate a weighted root mean square error (RMSE) for each grid cell within the domain, comparing the SPEI values from ERA5-Land against each of or indirectly highlighted this issue by noting higher treatment costs for municipalities or mass fish mortality events. Furthermore, while only a few Watershed organizations reported it, it was noted that the decrease in freshet volume and the early arrival of low-water levels adversely affected submerged plant species to the 1500 ClimEx candidates. Sum the RMSEs for each ClimEx candidate. benefit of invasive alien plant species such as *Phragmites australis*. This can be problematic, since native aquatic plants often provide crucial shelter for numerous species of fish and serve as spawning grounds, so their disappearance could lead to reduced fish populations and biodiversity (Boyer et al., 2009; Plourde-Lavoie et al., 2017; Hud . Furthermore, a brief and weak freshet could result in fish being trapped in the floodplain or having no access to spawning areas, in elevated juvenile fish mortality rates and in the desiccation of fish eggs (Plourde-Lavoie et al., 2017).

The assessment of candidate analogues is performed by comparing various SPEI indicators (columns) between a) ERA5-Land and c) 1500 candidates (50 realizations x 30 years) from the ClimEx Large Ensemble. For each candidate (rows in c), a weighted RMSE is calculated for each SPEI (top-left corner of each image) and then aggregated. Weights (b) are allocated based on SPEI values in ERA5-Land.

3.1.2 Reported socioeconomic consequences

Comparison of hydrological indicators between (a) the 2021 low-water episode, (b) the first two best ClimEx candidates within the historical period and c) the average of the 10 best ClimEx candidates.

The 1500 possible candidates within ClimEx for each period (historical, +2°C and +3°C) were then sorted according to their total RMSEs, cumulated over the spatial domain of HYDROTEL and the 9 SPEI indicators analyzed (Fig. 2). The 10 candidates with the lowest total RMSE were selected as the 10 best analogues to 2021. This step was accomplished separately for the historical and the future periods.

Figure 4 presents a comparison of the hydrological indicators for the Recent studies, as well as results from the stakeholder survey, indicate that municipalities and economic sectors in the southernmost parts of Quebec have become increasingly vulnerable to water scarcity in recent years (Charron et al., 2019, 2020; Leveque et al., 2021; Knowles et al., 2023; Nand and Qi, 2023) . According to Watershed organizations, some cities now face recurrent challenges in providing drinking water during summer

months, even under normal conditions. Others have had to limit new developments due to concerns over water availability (Audet et al., 2024). Almost 40% of Quebec's population relies on surface water from rivers and lakes, excluding the St. Lawrence River, with another 30% sourced from groundwater (MELCCFP, 2018). Although municipalities sourcing their water directly from the St. Lawrence River did not experience severe water shortages in 2021~~event, for the top two analogues of~~, the St. Lawrence River valley itself, which is the province's most densely populated area with extensive agricultural lands, is already under significant stress for both surface and groundwater resources (e.g., Carrier et al., 2013; Larocque et al., 2015)~~.~~. In 2021~~in the historical period and for the average of the 10 best analogues. The average of the 10 best analogues (Fig. 4c)replicates the spatial patterns and intensity of the~~, municipalities relying on surface water reported difficulties due to reduced availability and quality. Many issued boil water advisories, faced increased treatment costs, and imposed non-essential water use restrictions. One municipality set up a new pumping system to draw additional water from the Lake of Two Mountains (the Ottawa River delta, at its confluence with the St. Lawrence River). Groundwater-dependent municipalities also faced similar restrictions, while some individuals and farms relying on private wells had to deepen their existing wells or dig new ones (Audet et al., 2024).

In agriculture, over 55% of water is used for livestock and fish farming, with the remainder allocated to cleaning, washing produce, and irrigation. Notably, 95% of Quebec's agricultural land is allocated to field crops and hay, with the majority still being rainfed, while irrigation is primarily limited to valuable crops like cranberries and various other fruits and vegetables (Charron et al., 2019, 2020; Nand and Qi, 2023). Thus, the 2021 ~~drought particularly well for key indicators like $7Q_{min}$ or $LWS_{duration}$, although it overestimates the freshet volume and spring flow. It also adequately reproduces other indicators such as $\overline{Q}_{JJA|SON}$, $LWS_{start|end}$ and $n_{days<7Q2|7Q10}$, though individual members sometimes provide a more accurate match in specific instances. For example, while the best match (r2-r10i1p1 in Fig. 4b) excels in replicating LWS_{start}, it ends too early for LWS_{end}. The second best match (r2-r8i1p1 in Fig. 4b) exhibits the opposite issue. Therefore, on the whole, the average of the 10 best analogues performs adequately well and offers a solid representation of the~~ drought caused significant reductions in crop yields, and, though the full economic impact has not yet been quantified, past droughts have resulted in financial losses in the tens of millions (Nand and Qi, 2023). Some farmers also incurred additional costs, employing water tanker trucks to replenish basins and supply livestock (Nand and Qi, 2023; Audet et al., 2024).

The recreational tourism industry also suffered. Low streamflow throughout the summer led to decreased water levels in rivers and lakes, limiting boating and water-based activities, including canoeing, kayaking, and paddleboarding. Poor water quality further restricted swimming (Audet et al., 2024). While 2021 ~~drought for the chosen hydrological indicators (Fig. 4).~~ likely impacted industries such as pulp and paper production and hydroelectric generation, no public data on these specific consequences was available.

3.2   ~~Future hydrological droughts~~The 2021 drought under future climatic conditions

~~Future hydrological indicators were produced by averaging the 10 best analogues in ClimEx, as detailed in Sect. 2.4.2 and illustrated in Fig. S2.~~ Figures 6 and 7 resemble Fig. 5, but they illustrate the change in the 2021 drought under the +2°C and +3°C warming scenarios relative to the historical event. More detailed versions for all hydrological indicators are shown in the
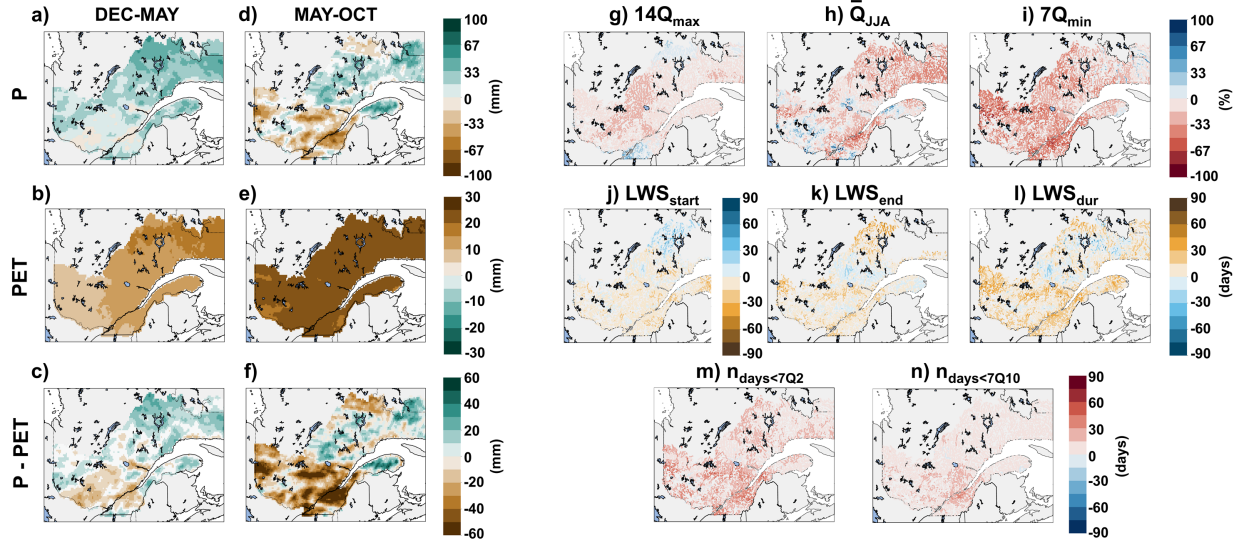
Figure 6. Precipitation (P) and potential evapotranspiration (PET) anomalies under the +2°C scenario with respect to the 2021 conditions, along with the anomalies in the water budget ($P - PET$) for a-c) December to May and d-f) May to October. g-n) Anomalies for the hydrological indicators in the +2°C scenario with respect to the 2021 conditions.
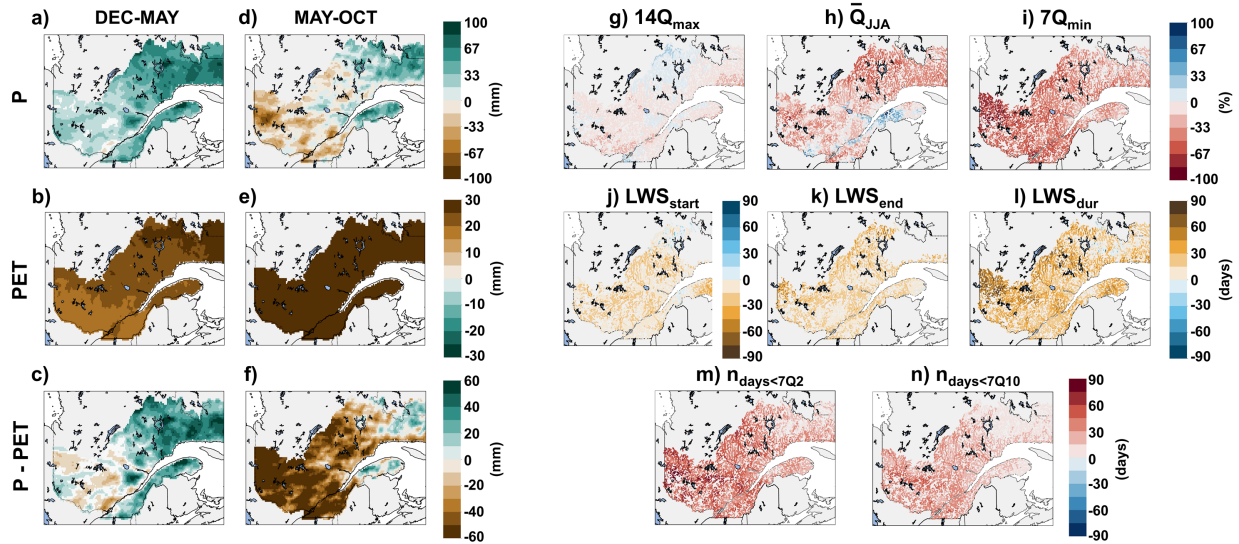
Figure 7. Same as Fig. 6, but for the +3°C scenario.

Supplementary Materials (Fig. ~~S4 to S13).~~ S6 to S15). Futhermore, Fig. S5 presents monthly mean anomalies in precipitation, evapotranspiration and streamflow for the average of the 10 best ClimEx analogues during the historical period, under +2°C and under +3°C for a few watersheds.

The 2021 event under +2°C warming conditions shows a rise in winter and spring precipitation compared to the historical event (Fig. 6a), particularly in the northern regions, in accordance with IPCC projections (Lee et al., 2021). This increase in precipitation is offset by an increase in PET throughout the province (Fig. 6b), resulting in a slight reduction in the water budget in southern areas and a minor increase in northern regions (Fig. 6c). As a result, spring freshet volumes remain mostly within
490 ±15% of 2021 levels (Fig. 6g), while the start date of the low-water season also remains similar to 2021 (Fig. 6j).

Conditions during summer and fall are generally drier than 2021, especially in the southern and western parts of the province (Fig. 6d), although September still features significant rainfall in both the eastern and western parts of the province (not shown). Due to higher temperatures, the future scenario also features a substantial increase in evapotranspiration that affects the whole province (Fig. 6e). This leads to a net deficit in water balance that affects all areas that ~~had~~ have suffered from the 2021 drought,
495 but now also reaches the western parts of the province that had been less impacted during the historical event (Fig. 6d). Rainfall in September ~~had contributed~~ did contribute to ending the low-water season between late September and mid-October ~~during the 2021 event.~~ in 2021. As this rainfall episode still occurs in the future scenario, the LWS ends at a similar time of the year (Fig. 6k). Combined with a similar start in the LWS with respect to 2021, this means that the duration of the LWS is either the same as in 2021, or only slightly longer (Fig. 6l).

500 As a result of the drier conditions, the average streamflow in summer for many river segments shows an additional reduction of up to 33% compared to 2021, although a small improvement can be noted south and west of the province where precipitation is higher than in 2021 (Fig. 6h). The $7Q_{min}$ was already significantly below average in 2021, and the analogues indicate a further decline of this metric across the entire province, with an additional reduction of 15-50% compared to 2021 (Fig. 6i). As a result, under the +2°C scenario, the total number of days below the environmental flow threshold ($n_{days<7Q2}$) increases
505 by 15 to 30 days for numerous river segments (Fig. 6m).

The 2021 event under +3°C warming conditions is generally in agreement with the +2°C scenario, but shows even stronger reductions in streamflow and water availability across the province due to rising temperatures and evapotranspiration. The only exception is in winter and spring, where a further increase in precipitation leads to a rise in the net water balance for most of the province compared to 2021 (Fig. 7c). However, this does not result in a higher $14Q_{max}$, which remains similar to
510 the historical event (Fig. 7g) potentially due to the increase in precipitation being balanced by more winter thaw and higher winter streamflow. This could also explain why the low-water season for the analogue under a +3°C scenario begins 2-4 weeks earlier than in 2021 (mid-May compared to early June) for numerous river sections north of the St. Lawrence River (Fig. 7j), especially since precipitation is still well below the historical average despite the future increase.

Precipitation changes in summer and fall under the +3°C warming conditions closely resemble those in the +2°C scenario,
515 but PET increases are significantly greater and lead to a net water balance loss of more than 60 mm over most of the southern and western parts of the province (Fig. 7f). This causes a further reduction in the average seasonal streamflow across the province (Fig. 7h) and also negatively affects the $7Q_{min}$ metric, which displays a reduction of 33-67% compared to the already low levels of 2021 (Fig. 7i). The rise in $n_{days<7Q2}$ is thus very pronounced under the +3°C scenario, with some segments experiencing an increase of up to 60 days (Fig. 7m). Given the already high number of days recorded in 2021, this implies
520 that many rivers could experience up to 100 days below the environmental flow threshold, with some potentially reaching 150

days. Under that scenario, it is particularly concerning that the more severe low-flow metric (7Q10) is exceeded by most rivers across the province for a duration of 25 to 60 days (Fig. 7n). ~~As discussed in Sect. 4, this~~ This would suggest unprecedented impacts on ecosystems, water quality and human uses.

Finally, as a consequence of both the decrease in precipitation and the significant rise in evapotranspiration, the LWS concludes up to a month later compared to 2021 for many river sections under +3°C conditions, bringing low-water conditions into early November in the southern parts of the province (Fig. 7k). ~~Under that scenario~~As a result from both an earlier onset and a later conclusion of the LWS, there is a total increase of 15 to 45 days of the LWS throughout most of the province compared to 2021 ~~, as a result from both an earlieronset and a later conclusion of the LWS (Fig. 7l).~~ under that scenario. (Fig. 7l).

4 Discussion

Water availability is a cornerstone of ecological and human systems, and its scarcity progressively impacts both the functioning of ecosystems and the health of populations in cascading effects. For instance, drought conditions diminish critical habitats for plants and animals reliant on water, leading to biodiversity loss and degradation of ecosystem services offered by wetlands, rivers, and other aquatic systems (Parisi et al., 2018; Bond et al., 2019; Mehdi et al., 2015; Furber et al., 2016; Wheaton and Kulshreshtha, . In turn, the disruption of these ecological functions diminishes the availability of clean water for human consumption and agricultural use, compounding the challenges to community well-being. As water scarcity intensifies, it creates competition among various sectors: municipal water supply systems, agriculture, recreational tourism, ecological needs, and more.

There is no universally accepted indicator or threshold that indicates when water scarcity begins to significantly impact ecosystems, drinking water systems, and other human uses. Additionally, Quebec currently lacks a formal low-water alert system, such as the one in place in Ontario (Ontario Ministry of Natural Resources et al., 2010), which complicates the assessment of the effects of meteorological and hydrological droughts on human activities. The Ontarian system, which includes regulatory restrictions and actions for each alert level, provides a framework that would help assess the escalating impacts of a drought as it unfolds, as well as the water management strategies necessary to face such events. However, as previously discussed, the 2021 drought had numerous documented adverse effects on Southern Quebec. Although the hydrological indicators used in this study must be interpreted qualitatively regarding their causal relationship with observed impacts, the storyline lens still offers valuable insights into the potential severity of future extreme droughts. Our results indicate that, should a drought comparable to the 2021 event occur in the future — particularly under +3°C warming conditions — water scarcity would be considerably exacerbated. As noted earlier, with the exception of freshet volumes, all low-flow indicators suggest progressively worsening conditions under the projected climate scenarios. These changes could lead to substantial ecological degradation and a diminished capacity of ecosystems to provide critical services for human activities. Notably, despite the aforementioned criticisms of the 7Q2 as a measure of ecosystem needs (Berthot et al., 2020), the increasing number of days falling below this threshold raises significant concerns. Extended droughts, coupled with rising temperatures, will not only exacerbate water quality and availability issues but could also lead to irreversible changes to aquatic ecosystems, thereby threatening biodiversity and the essential ecosystem services reliant on stable water conditions. This situation could further strain municipal water

supplies, agriculture, and other vital sectors, as evidenced by the 2021 drought, which highlighted Quebec's vulnerability to the impacts of droughts.

In light of the risks posed by climate change and increasingly frequent drought events, the storyline approach offers a valuable framework for understanding, communicating, and preparing for future droughts in collaboration with stakeholders. Indeed, stakeholders possess intimate knowledge of their local water systems and retain memories of the real impacts of past events. Storylines foster dialogue between stakeholders and climate scientists by making climate data more accessible and relevant for decision-making, particularly for developing effective response measures. Unlike broad, abstract projections like "Future 100-year droughts will be n days longer," which can fail to provide concrete insights into the specifics of what a 100-year drought might entail, storylines offer more actionable and tangible scenarios. For example, a storyline based on our results might specify: "An event analogous to the 2021 drought, but occurring under a +3°C global temperature increase, could last 30 days longer and result in a 50% reduction in the minimum seven-day average streamflow observed in 2021 for rivers located south of the St. Lawrence River" This context-rich and event-driven approach enables stakeholders to identify vulnerabilities based on 2021 and adapt their systems by extrapolating potential future conditions. For instance, if a municipality was just one week away from experiencing a water shortage during the 2021 drought, understanding that a future event of similar magnitude might last a month longer, thus surpassing the capacity of their system, may prompt proactive climate adaptation planning such as bolstering water conservation measures, investing in infrastructure improvements, or exploring alternative water sourcing strategies.

Additionally, the storyline method might encourage a more collaborative and informed dialogue among stakeholders, enabling better coordination across sectors such as water management, urban planning, agriculture, and public health by grounding future projections in recent, real-world examples. A second phase is planned for mid-2025 and will focus on further investigating how storylines can deliver actionable insights through close collaboration with stakeholders in select watersheds that experienced significant impacts from the 2021 drought.

4.1 Limitations

We recognize that there are a certain number of limitations to the current analysis. The use of a single hydrological model, namely HYDROTEL, is one of them. It is well known that using multiple hydrological models provides a better representation of the uncertainty (Castaneda-Gonzalez et al., 2022). Furthermore, HYDROTEL is primarily geared toward surface water dynamics and employs simplified representations of soil and groundwater processes and interactions. Although the methodology used in this study to generate future indicators – which involves applying the climate change signal onto the reconstructed streamflow data that leverages observed stream gauges through optimal interpolation – partially mitigates this limitation, HYDROTEL cannot reproduce low-flow conditions as well as fully integrated surface-groundwater models.

Another constraint on simulating future low flows is HYDROTEL's current dependence on a relatively simplistic definition of PET, which relies only on near-surface temperature and latitude (McGuinness and Bordne, 1972). Although other definitions of PET are available in HYDROTEL, they all rely on that single variableprimarily on temperature. Internal testing has shown the climate change signal to be relatively insensitive to the selection of PET among the currently available definitions (not shown),

but this conclusion might differ if more physically-based formulas that included variables like solar radiation or humidity were available for comparison.

590   However, it is essential to note that the primary objective of this study was not to achieve exact modelling of future low flows, but to produce plausible, physically coherent low-flow indicators reminiscent of a recent event to stimulate conversations with stakeholders about the effects of water scarcity in future climates in southern Quebec. The constructed scenarios offer valuable insights into potential future conditions and emphasize the importance of preparedness for water shortages. Additionally, as outlined in the ~~subsequent~~ previous section, these scenarios lay the groundwork for dialogues on the environmental and socioe-

595   conomic repercussions of such an event and underscore the necessity of implementing robust water management strategies to ensure the sustainability and resilience of water resources in Quebec.

Although this study mainly examines water availability, it must be noted that future projections occur within a framework of anticipated increased water demand, which, in Quebec, is primarily driven by population growth (Charron et al., 2019, 2020; Da Silva et al., 2020; Achkar, 2023). The province is well-known for its high per capita daily water consumption and the

600   residential sector alone currently represents 41% of the province's water usage (Charron et al., 2019). Based on data from Institut de la Statistique du Québec (2022), the population is projected to increase by 6% by 2030 relative to 2021, reaching 13% by 2050 and 17% by 2066. This growth could further strain the already scarce resources during severe droughts~~like that of the analogues presented in this study~~. However, several strategies are already being implemented to reduce water consumption and bring it closer to the Canadian average, which might help mitigate part of the increase in demand resulting from population

605   growth in the coming decades (Government of Quebec, 2019).

5   ~~Discussion~~

5   Conclusions

~~Water availability is critical and, similarly to other vital resources, its scarcity progressively affects the health of communities and populations through a cascading series of impacts (Parisi et al., 2018; Bond et al., 2019). Climate change, which modifies~~

610   ~~the climate system and causes a reduction in water availability during summer due to increasing temperatures, could trigger a series of effects, starting with the deterioration of habitats for plants and animals reliant on water, resulting in a loss of biodiversity and the ecological services offered by wetlands and river systems (Mehdi et al., 2015; Furber et al., 2016; Wheaton and Kulshro . These alterations subsequently impact human activities because of the diminished quality and availability of water, eventually influencing the well-being of the population. Furthermore, water scarcity can lead to competition over resource usage and~~

615   ~~conflicts between different purposes, whether for human needs or ecological functions.~~

~~The discussion presented in this section is inspired by the results of the stakeholder survey (Sect. 2.1). Notably, because the survey was event-centric in nature, in the sense that it asked to report the consequences of the droughts for each event individually, it supported the storyline approach and helped investigate the cascade of consequences that occurred in 2021 and during other droughts. It also facilitated the extrapolation of those consequences into future climate conditions by employing~~

620   ~~descriptors for the future events that were directly connected to 2021 (e.g. "an analogous event under a +3°C temperature~~

increase would last 30 days longer and have its $7Q_{min}$ reduced by half"). Although we recognize that these findings are anecdotal in nature, these results constitute a valuable first step that offers perspectives on the impacts of historical droughts and help initiate a dialogue on water shortages in Quebec .

5.1 Environmental consequences

625 Depiction of river ecosystems. a) Under normal spring conditions, b) under diminished flow conditions and c) additional effects from severe or extended low-flow conditions. Facultative Wetland species (FACW) are flora that typically occur in wetlands but can be found elsewhere on occasion, while Obligate Wetland species (OBL) exist almost exclusively in wetlands. Adapted from Audet et al. (2024).

Despite the survey, impacts on ecosystems were difficult to identify unless they had affected human activities. Even when
630 relevant data were available, it was mostly punctual and anecdotal in nature. This is in line with other studies that have noted a lack of consistent data collection before, during and after drought periods that could help build causal relationships between low-water episodes and their impacts on ecosystems (Kovach et al., 2019). Even environmental flow metrics have been deemed insufficient to truly represent the needs of ecosystems, with ongoing efforts in Quebec to replace the 7Q2 indicator with another indicator better suited to the geomorphological conditions of rivers and more robust in the context of a changing climate
635 (Berthot et al., 2020, 2021).

Therefore, the effects of the 2021 drought on ecosystems, when analyzed through the lens of the storyline approach, must still be viewed from a qualitative standpoint. The persistently low flow throughout the year, ranging from reduced seasonal streamflow to exceptionally low $7Q_{min}$, all indicate deteriorated water quality conditions (e.g., reduced pollutant dilution, higher water temperatures, decreased oxygen availability, eutrophication and lower pH levels in some rivers) (Zohary and Ostrovsky, 2011;
640 . During the survey, multiple stakeholders, especially in the area south of the St. Lawrence River, either directly acknowledged a decline in water quality in 2021 or indirectly highlighted this issue by noting higher treatment costs for municipalities or mass fish mortality events. Furthermore, while only a few Watershed organizations reported it, it was noted that the decrease in freshet volume and the early arrival of low-water levels adversely affected submerged plant species to This study used a storyline approach to reflect on the plausible impacts of severe drought conditions in Quebec based on a recent event. A series of SPEIs
645 from spring to fall was used to identify analogous events within a large ensemble of climate simulations, both in present and future climates, while a hydrological model was employed to assess the impacts of those drought conditions on river streamflow throughout Southern Quebec. This model was used to explore the potential consequences of a drought similar to the benefit of invasive alien plant species such as *Phragmites australis*. This can be problematic, since native aquatic plants often provide crucial shelter for numerous species of fish and serve as spawning grounds, so their disappearance could lead to reduced fish
650 populations and biodiversity (Boyer et al., 2009; Plourde-Lavoie et al., 2017; Hudon et al., 2016; Mejia et al., 2023). Furthermore, a brief and weak freshet could result in fish being trapped in the floodplain or having no access to spawning areas, in elevated juvenile fish mortality rates and in the desiccation of fish eggs (Plourde-Lavoie et al., 2017). Figure **??** provides a diagrammatic illustration of the impacts of low-water episodes on plant and fish species, comparing normal spring conditions to diminished flow conditions and severe or extended low-flow conditions.

As mentioned earlier, except for the freshet volume, all low-flow indicators become notably worse under ~~one that occurred in 2021, but which would occur under global warming scenarios of~~ +2°C and +3°C ~~conditions, suggesting the possibility of severe ecological degradation if extreme drought conditions similar to 2021 were to occur again in a warmer climate. Although the 7Q2 has been criticized as an insufficient benchmark for assessing ecosystem needs (e.g., Berthot et al., 2020), the significant rise in the number of days falling below this threshold and the 7Q10~~ compared to preindustrial levels. The results indicate a significant deterioration in river conditions, particularly under a +3°C ~~rise in global temperatures, is worrying. This situation could further strain already vulnerable ecosystems in a future climate, with potential long-term impacts on biodiversity and ecosystem services. The combined effects of higher temperatures and extended droughts could cause irreversible alterations to aquatic habitats, further endangering the survival of native species and the overall health of the ecosystem (Fig. ??c).~~ temperature rise, with both an extended duration of low-water conditions and reduced river flows.

5.1 ~~Socioeconomic consequences~~

~~Recent studies, as well as results from the stakeholder survey, indicate that some municipalities and some economic sectors in southern Quebec have become more vulnerable to water scarcity in recent years (Charron et al., 2019, 2020; Leveque et al., 2021; Knowles . Some cities now face recurrent challenges in providing drinking water to their population in summer, even under normal conditions , while others have had to restrict new developments due to potential water scarcity (Audet et al., 2024). In Quebec, almost 40% of the population is supplied with surface water from rivers or lakes, excluding the St. Lawrence River which accounts for another 30%, while groundwater provides the remaining 30% (MELCCFP, 2018). Although municipalities sourcing their water directly from the St. Lawrence River have not experienced severe water shortages, the St. Lawrence River valley itself, which is the province's most densely populated area with extensive agricultural lands, is already under significant stress for both surface and groundwater resources (e.g., Carrier et al., 2013; Larocque et al., 2015). As previously highlighted by the SPEI-6$_{OCT}$ and hydrological metrics like the 7Q$_{min}$ and LWS$_{duration}$, that region was also the most impacted by the 2021 drought (Fig. 5). Consequently, in 2021, numerous municipalities relying on surface water reported difficulties due to decreased water availability and quality. This situation prompted them to issue boil water advisories, bear increased water treatment costs, limit non-essential water usage and, in one instance, set up a pumping system to draw additional water from the Lake of Two Mountains (where the Ottawa River delta meets the St. Lawrence River, near Montreal). Municipalities dependent on groundwater also had to impose similar usage restrictions to conserve their water supply, while some individuals and farms relying on private wells had to either deepen their existing wells or dig new ones (Audet et al., 2024).~~

In the ~~agricultural sector, over 55% of water is used for livestock and fish farming, while the remainder is distributed among the cleaning of buildings, the washing of fruits and vegetables and irrigation. Notably, 95% of Quebec's agricultural land is allocated to field crops and hay, with the majority being rainfed, whereas irrigation is primarily limited to valuable crops like cranberries and various other fruits and vegetables (Charron et al., 2019, 2020; Nand and Qi, 2023). Consequently, the~~ absence of clear impact-inducing thresholds, but with documented impacts in 2021 ~~drought resulted in reduced crop yields throughout the agricultural industry and, although the economic impact of the 2021 drought on the agricultural sector has not yet been quantified, previous droughts resulted in financial losses amounting to tens of millions of dollars (Nand and Qi, 2023)~~

. Furthermore, according to the survey, some farmers faced additional significant expenses, as they had to employ water tanker trucks to replenish basins and provide water to their livestock (Nand and Qi, 2023; Audet et al., 2024).

The recreotourism industry also experienced several impacts . In numerous regions, streamflow was exceptionally low for the entire summer, leading to decreased water levels in rivers and lakes. This had a detrimental effect on marinas, sometimes severely limiting boating activities. In smaller rivers, low water levels also hindered the use of canoes, kayaks and paddleboards. Swimming was also restricted due to poor water quality (Audet et al., 2024). Finally, while the conditions in 2021 likely caused losses in industries such as pulp and paper production or hydroelectric generation, no public information on that topic could be found.

As mentioned previously, all low-flow indicators suggest worsening conditions for the future 2021 analogues, indicating additional strain and adverse effects on municipal water supply systems, agriculture, recreational tourism and various other sectors. The 2021 drought highlighted the vulnerability of Quebec's water resources and the potential for widespread consequences. The magnitude of the future drought as described by the storyline approach suggests that the impacts could be even more significant, necessitating urgent and comprehensive water management strategies that do not yet exist in the regulatory framework of the province to address these challenges effectively. In fact, future analogues show even lower seasonal streamflow and $7Q_{min}$ than in 2021, while the LWS in the St. Lawrence Valley begins earlier and ends later, indicating a longer and harsher summer season that could further deplete available water resources.

This study used a storyline approach to discuss the plausible impacts of severe drought conditions in Quebec based on a recent event. By analyzing the evolution of SPEIs from spring to fall, analogous events were identified within a large ensemble of climate simulations, both in present and future climates, offering a comprehensive understanding of future drought conditions akin to those of 2021 in two different warming level scenarios.

These , these storylines can provide a framework for stakeholders to gain a clearer understanding of future droughts , by linking them to an event that they are already familiar with. Indeed, by building a storyline based on the 2021 drought, we were able to effectively explore the potential consequences of similar future eventsunder increases in global temperature of +2°C and +3°CSimilarly, storylines can also help in climate change adaptation planning by building upon the vulnerabilities identified during historical extreme events. However, there is a need for for this to be fully effective, improved systematic data collection with regards is needed with respect to the impacts of meteorological and hydrological droughts on human activities and even more so on ecosystems in Quebec and Canada, as these are currently seldom reported or difficult to access. Research is also required on the effects of climate change on groundwater and its recharge, particularly during extreme droughts, as there is currently a scarcity of literature in this area despite the central role of aquifers in the water supply of Quebec. Enhancing the groundwater monitoring network, both spatially and temporally, is essential to address these research deficiencies and generate the data required to shape effective water management policies.

Lacking a comprehensive understanding of these factors, the implementation of adaptation strategies could become significantly more challenging or may even result in maladaptive outcomes (e.g. increasing the reliance on aquifers without an assessment of how vulnerable they are to extreme droughts). Yet, without measures to improve resilience against water shortages in Quebec, a region typically abundant in water but lacking adequate regulatory systems to manage water usage disputes,

it is anticipated that various adverse socioeconomic and environmental consequences will occur. Potential impacts may include

725 a significant reduction in biological diversity and deterioration of ecosystem services, diminished agricultural yields or greater dependence on irrigation, increased expenses for water purification, a halt of residential expansion in areas with scarce water resources and a rise in disputes over water-related issues.

However, it is also important to recognize the adaptive capacity of ecosystems and the potential for recovery. With proper management and conservation efforts, the resilience of aquatic environments can be enhanced. Initiatives such as restoring

730 river connectivity and improving water quality can mitigate some of the negative impacts observed during low-water periods. Moreover, increasing awareness and involving local communities in water conservation practices offers a hopeful perspective towards sustaining biodiversity and ecosystem services even under challenging conditions. This work aimed to improve our understanding of future drought conditions at the provincial scale, but the distributed nature of HYDROTEL means that hydrological indicators were nonetheless computed at a local scale. The current study thus lays the foundation for future

735 work, particularly through stakeholder engagement and local-scale impact assessments. A second phase of the project, planned for mid-2025, will focus on deepening these efforts by working closely with stakeholders in a few of the watersheds most affected by the 2021 drought to further explore how storylines can provide actionable insights.

Future studies should focus on integrating more localized data and predictive models to refine the accuracy of drought projections and their impacts, as well as gaining a better understanding of the climatic causes behind hydrological and

740 groundwater droughts in the region. Collaborative efforts between climatologists, hydrologists, biologists and policy makers are essential to develop more robust adaptation strategies that can be implemented effectively. Furthermore, exploring the environmental and socioeconomic implications of droughts through interdisciplinary research (Matte et al., 2024) will provide deeper insightsinto the cascading effects of water shortages and inform better regulatory and community response strategies. Such proactive approaches are crucial to mitigating the adverse effects of future droughts and improving the resilience of

745 communities in Quebec and similar regions around the world.

Code availability. The code used in this research can be found on GitHub at the following link: https://github.com/Ouranosinc/CASCADES/

Author contributions. G.R.G. was the lead author of the manuscript, aided by L.P.C.; É.C. initially examined the storyline approach with help from G.R.G., L.P.C., and D.M., which was later advanced by G.R.G. who also performed the climatological and hydrological analyzes. K.A. managed the stakeholder survey and contributed to the socioeconomic evaluation, which was led by L.d.A.; D.T. and R.P. led the

750 environmental impact assessment. All authors provided crucial feedback and helped refine the research, analysis and manuscript.

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References

Achkar, M.-B.: Développement d'un modèle conceptuel pour l'évaluation de la demande en eau urbaine future : application à une ville québécoise, Master's thesis, Polytechnique Montréal, 2023.

775 Alberti-Dufort, A., Bourduas Crouhen, V., Demers-Bouffard, D., Hennigs, R., Legault, S., Cunningham, J., Larrivée, C., and Ouranos: Quebec; Chapter 2 in Canada in a Changing Climate: Regional Perspectives Report, Government report, Government of Canada, Ottawa (ON), Canada, 2022.

Assani, A. A.: Extreme Hydrological Drought in Southern Quebec (Canada): Natural and Anthropogenic Factors Interactions on its Spatio-Temporal Variability, International Journal of Environmental Sciences and Natural Resources, 32, https://doi.org/10.19080/ijesnr.2023.32.556348, 2023.

780

Audet, K., Montel, B., Crespel, D., Tarte, D., Parent, R., Silva, L. D., Paccard, M., Rondeau-Genesse, G., and Roques, J.: Conséquences Attendues Survenant en Contexte d'Aggravation des Déficits d'Eau Sévères au Québec (CASCADES), Tech. rep., Groupe AGÉCO, Nada Conseils, T2 Environnement, Ouranos, Montreal (QC), Canada, 2024.

Aygün, O., Kinnard, C., and Campeau, S.: Impacts of climate change on the hydrology of northern midlatitude cold regions, Progress in

785 Physical Geography: Earth and Environment, 44, 338–375, https://doi.org/10.1177/0309133319878123, 2019.

Baulenas, E., Versteeg, G., Terrado, M., Mindlin, J., and Bojovic, D.: Assembling the climate story: use of storyline approaches in climate-related science, Global Challenges, 7, https://doi.org/10.1002/gch2.202200183, 2023.

Berthot, L., St-Hilaire, A., Caissie, D., El-Jabi, N., Kirby, J., and Ouellet-Proulx, S.: Southern Quebec environmental flow assessments: spatial and temporal scales sensitivity, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 45, 358–371,

790 https://doi.org/10.1080/07011784.2020.1834881, 2020.

Berthot, L., St-Hilaire, A., Caissie, D., El-Jabi, N., Kirby, J., and Ouellet-Proulx, S.: Environmental flow assessment in the context of climate change: a case study in Southern Quebec (Canada), Journal of Water and Climate Change, 12, 3617–3633, https://doi.org/10.2166/wcc.2021.254, 2021.

Bond, N. R., Burrows, R. M., Kennard, M. J., and Bunn, S. E.: Water Scarcity as a Driver of Multiple Stressor Effects, p. 111–129, Elsevier,

795 https://doi.org/10.1016/b978-0-12-811713-2.00006-6, 2019.

Bonsal, B., Peters, D., Seglenieks, F., Rivera, A., and Berg, A.: Changes in freshwater availability across Canada; Chapter 6 in Canada's Changing Climate Report, Government report, Government of Canada, Ottawa (ON), Canada, 2019.

Boulanger, Y., Arseneault, D., Bélisle, A. C., Bergeron, Y., Boucher, J., Boucher, Y., Danneyrolles, V., Erni, S., Gachon, P., Girardin, M. P., Grant, E., Grondin, P., Jetté, J.-P., Labadie, G., Leblond, M., Leduc, A., Puigdevall, J. P., St-Laurent, M.-H., Tremblay, J., and Waldron,

800 K.: The 2023 wildfire season in Québec: an overview of extreme conditions, impacts, lessons learned and considerations for the future, Canadian Journal of Forest Research, https://doi.org/10.1139/cjfr-2023-0298, 2024.

Boyer, C., Verhaar, P. M., Roy, A. G., Biron, P. M., and Morin, J.: Impacts of environmental changes on the hydrology and sedimentary processes at the confluence of St. Lawrence tributaries: potential effects on fluvial ecosystems, Hydrobiologia, 647, 163–183, https://doi.org/10.1007/s10750-009-9927-1, 2009.

805 Cannon, A. J.: The Impact of "Hot Models" on a CMIP6 Ensemble Used by Climate Service Providers in Canada: Do Global Constraints Lead to Appreciable Differences in Regional Projections?, Journal of Climate, 37, 2141–2154, https://doi.org/10.1175/jcli-d-23-0459.1, 2024.

Carrier, M., Lefebvre, R., Rivard, C., Parent, M., Ballard, J., Benoit, N., Vigneault, H., Beaudry, C., Malet, X., Laurencelle, M., Gosselin, J., Ladevèze, P., Thériault, R., Beaudin, I., Michaud, A., Pugin, A., Morin, R., Crow, H., Gloaguen, E., Bleser, J., Martin, A., and Lavoie, D.: Portrait des ressources en eau souterraine en Montérégie Est, Government report, Government of Quebec (MELCCFP), Quebec City (QC), Canada, 2013.

Castaneda-Gonzalez, M., Poulin, A., Romero-Lopez, R., Turcotte, R., and Chaumont, D.: Uncertainty sources in flood projections over contrasting hydrometeorological regimes, Hydrological Sciences Journal, 67, 2232–2253, https://doi.org/10.1080/02626667.2022.2137415, 2022.

Caviedes-Voullième, D. and Shepherd, T. G.: Climate storylines as a way of bridging the gap between information and decision-making in hydrological risk, PLOS Climate, 2, e0000 270, https://doi.org/10.1371/journal.pclm.0000270, 2023.

Chan, W. C., Arnell, N. W., Darch, G., Facer-Childs, K., Shepherd, T. G., Tanguy, M., and van der Wiel, K.: Current and future risk of unprecedented hydrological droughts in Great Britain, Journal of Hydrology, 625, 130 074, https://doi.org/10.1016/j.jhydrol.2023.130074, 2023.

Chan, W. C. H., Shepherd, T. G., Facer-Childs, K., Darch, G., and Arnell, N. W.: Storylines of UK drought based on the 2010–2012 event, Hydrology and Earth System Sciences, 26, 1755–1777, https://doi.org/10.5194/hess-26-1755-2022, 2022.

Charron, C., St-Hilaire, A., Ouarda, T. B., and van den Heuvel, M. R.: Water Temperature and Hydrological Modelling in the Context of Environmental Flows and Future Climate Change: Case Study of the Wilmot River (Canada), Water, 13, 2101, https://doi.org/10.3390/w13152101, 2021.

Charron, I., Beauchemin, A., Blais-Gagnon, A., Delmotte, S., Ducruc, S., Dugré, D., Landry, F., Jego, G., Michaud, A., Morrissette, R., and St-Arnaud, R.-M.: Recherche participative d'alternatives durables pour la gestion de l'eau en milieu agricole dans un contexte de changement climatique (RADEAU1), Government report, MAPAQ, Quebec City (QC), Canada, 2019.

Charron, I., Beauchemin, A., Blais-Gagnon, A., Boivin, C., Delmotte, S., Ducruc, S., Dugré, D., Landry, F., Lefebvre, R., Jego, G., Gosselin, J.-S., Michaud, A., Morrissette, R., Raynauld, M., St-Arnauld, R.-M., Vallée, J., and Valleros, A.: Recherche participative d'alternatives durables pour la gestion de l'eau en milieu agricole dans un contexte de changement climatique (RADEAU2), Government report, MAPAQ, Quebec City (QC), Canada, 2020.

Chilima, J. S., Blakley, J., Diaz, H. P., and Bharadwaj, L.: Understanding Water Use Conflicts to Advance Collaborative Planning: Lessons Learned from Lake Diefenbaker, Canada, Water, 13, 1756, https://doi.org/10.3390/w13131756, 2021.

Da Silva, L., Pineault, K., and Rondeau-Genesse, G.: Vulnérabilité des sources d'approvisionnement en eau potable du territoire de la CMQ face aux changements climatiques, Technical report, Ouranos, Montreal (QC), Canada, 2020.

Derksen, C., Burgess, D., Duguay, C., Howell, S., Mudryk, L., Smith, S., Thackeray, C., and Kirchmeier-Young, M.: Changes in snow, ice, and permafrost across Canada; Chapter 5 in Canada's Changing Climate Report, Government report, Government of Canada, Ottawa (ON), Canada, 2019.

Dormoy-Boulanger, J.: L'impact des changements climatiques sur la dynamique des cyanobactéries dans la rivière aux Brochets, Québec, Master's thesis, Université du Québec à Montréal (UQÀM), 2021.

Dubois, E., Larocque, M., Gagné, S., and Meyzonnat, G.: Simulation of long-term spatiotemporal variations in regional-scale groundwater recharge: contributions of a water budget approach in cold and humid climates, Hydrology and Earth System Sciences, 25, 6567–6589, https://doi.org/10.5194/hess-25-6567-2021, 2021.

Dubois, E., Larocque, M., Gagné, S., and Braun, M.: Climate Change Impacts on Groundwater Recharge in Cold and Humid Climates: Controlling Processes and Thresholds, Climate, 10, 6, https://doi.org/10.3390/cli10010006, 2022.

Faranda, D., Pascale, S., and Bulut, B.: Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought, Environmental Research Letters, https://doi.org/10.1088/1748-9326/acbc37, 2023.

Fortin, J.-P., Turcotte, R., Massicotte, S., Moussa, R., Fitzback, J., and Villeneuve, J.-P.: Distributed Watershed Model Compatible with Remote Sensing and GIS Data. I: Description of Model, Journal of Hydrologic Engineering, 6, 91–99, https://doi.org/10.1061/(ASCE)1084-0699(2001)6:2(91), 2001.

Fossa Riglos, M. F., Díaz, L. B., Hernández, V., Sörensson, A. A., Osman, M., Rivera, J., Robledo, F., and Prudente, C.: Climate storylines as a tool for interdisciplinary dialogue on risk decision-making: Analyzing a severe drought in southeastern South America, Environmental Science amp; Policy, 160, 103 848, https://doi.org/10.1016/j.envsci.2024.103848, 2024.

Furber, A., Medema, W., Adamowski, J., Clamen, M., and Vijay, M.: Conflict Management in Participatory Approaches to Water Management: A Case Study of Lake Ontario and the St. Lawrence River Regulation, Water, 8, 280, https://doi.org/10.3390/w8070280, 2016.

Fyfe, J. C., Derksen, C., Mudryk, L., Flato, G. M., Santer, B. D., Swart, N. C., Molotch, N. P., Zhang, X., Wan, H., Arora, V. K., Scinocca, J., and Jiao, Y.: Large near-term projected snowpack loss over the western United States, Nature Communications, 8, https://doi.org/10.1038/ncomms14996, 2017.

Gennaretti, F., Sangelantoni, L., and Grenier, P.: Toward daily climate scenarios for Canadian Arctic coastal zones with more realistic temperature-precipitation interdependence, Journal of Geophysical Research: Atmospheres, 120, 11,862–11,877, https://doi.org/10.1002/2015JD023890, 2015.

Gessner, C., Fischer, E. M., Beyerle, U., and Knutti, R.: Multi-year drought storylines for Europe and North America from an iteratively perturbed global climate model, Weather and Climate Extremes, 38, 100 512, https://doi.org/10.1016/j.wace.2022.100512, 2022.

Government of Quebec: Stratégie québécoise d'économie d'eau potable - Horizon 2019-2025, Government report, Government of Quebec, Quebec City (QC), Canada, 2019.

Grenier, P., Firlej, A., Blondlot, A., Logan, T., and Ricard, M.-P.: The issue of properly ordering climate indices calculation and bias correction before identifying spatial analogs for agricultural applications, Climate Services, 16, 100 122, https://doi.org/10.1016/j.cliser.2019.100122, 2019.

Hazeleger, W., van den Hurk, B., Min, E., van Oldenborgh, G., Petersen, A., Stainforth, D., Vasileiadou, E., and Smith, L.: Tales of future weather, Nature Climate Change, 5, 107–113, https://doi.org/10.1038/nclimate2450, 2015.

Houle, D., Lajoie, G., and Duchesne, L.: Major losses of nutrients following a severe drought in a boreal forest, Nature Plants, 2, https://doi.org/10.1038/nplants.2016.187, 2016.

Hudon, C., Gagnon, P., Poirier Larabie, S., Gagnon, C., Lajeunesse, A., Lachapelle, M., and Quilliam, M.: Spatial and temporal variations of a saxitoxin analogue (LWTX-1) in Lyngbya wollei (Cyanobacteria) mats in the St. Lawrence River (Québec, Canada), Harmful Algae, 57, 69–77, https://doi.org/10.1016/j.hal.2016.06.001, 2016.

Hutchinson, M. F., McKenney, D. W., Lawrence, K., Pedlar, J. H., Hopkinson, R. F., Milewska, E., and Papadopol, P.: Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum–Maximum Temperature and Precipitation for 1961–2003, Journal of Applied Meteorology and Climatology, 48, 725–741, https://doi.org/10.1175/2008jamc1979.1, 2009.

Institut de la Statistique du Québec: Mise à jour 2022 des perspectives démographiques du Québec et de ses régions, 2021-2066, Bulletin sociodémographique, 26, 1–11, statistique.quebec.ca/fr/fichier/mise-a-jour-2022-perspectives-demographiques-quebec-regions-2021-2066.pdf, 2022.

Ismail, H., Rowshon, M. K., Shanono, N., Nasidi, N., and D.A., U.: Hydrological Modelling For Evaluating Climate Change Impacts On Streamflow Regime In The Bernam River Basin Malaysia, FUDMA JOURNAL OF SCIENCES, 5, 219–230, https://doi.org/10.33003/fjs-2021-0503-707, 2021.

885 Kinnard, C., Bzeouich, G., and Assani, A.: Impacts of summer and winter conditions on summer river low flows in low elevation, snow-affected catchments, Journal of Hydrology, 605, 127 393, https://doi.org/10.1016/j.jhydrol.2021.127393, 2022.

Knowles, N., Scott, D., and Steiger, R.: Sustainability of snowmaking as climate change (mal)adaptation: an assessment of water, energy, and emissions in Canada's ski industry, Current Issues in Tourism, 27, 1613–1630, https://doi.org/10.1080/13683500.2023.2214358, 2023.

Kovach, R. P., Dunham, J. B., Al-Chokhachy, R., Snyder, C. D., Letcher, B. H., Young, J. A., Beever, E. A., Pederson, G. T., Lynch, A. J., Hitt,
890 N. P., Konrad, C. P., Jaeger, K. L., Rea, A. H., Sepulveda, A. J., Lambert, P. M., Stoker, J., Giersch, J. J., and Muhlfeld, C. C.: An Integrated Framework for Ecological Drought across Riverscapes of North America, BioScience, 69, 418–431, https://doi.org/10.1093/biosci/biz040, 2019.

Lachance-Cloutier, S., Turcotte, R., and Cyr, J.-F.: Combining streamflow observations and hydrologic simulations for the retro-spective estimation of daily streamflow for ungauged rivers in southern Quebec (Canada), Journal of Hydrology, 550, 294–306,
895 https://doi.org/10.1016/j.jhydrol.2017.05.011, 2017.

Larocque, M., Meyzonnat, G., Ouellet, M. A., Graveline, M. H., Gagné, S., Barnetche, D., and Dorner, S.: Projet de connaissance des eaux souterraines de la zone de Vaudreuil-Soulanges - Rapport scientifique, Government report, Government of Quebec (MELCCFP), Quebec City (QC), Canada, 2015.

Lavoie, J., Caron, L.-P., Logan, T., and Barrow, E.: Canadian climate data portals: A comparative analysis from a user perspective, Climate
900 Services, 34, 100 471, https://doi.org/10.1016/j.cliser.2024.100471, 2024.

Leduc, M., Mailhot, A., Frigon, A., Martel, J.-L., Ludwig, R., Brietzke, G. B., Giguère, M., Brissette, F., Turcotte, R., Braun, M., and Scinocca, J.: The ClimEx Project: A 50-Member Ensemble of Climate Change Projections at 12-km Resolution over Europe and North-eastern North America with the Canadian Regional Climate Model (CRCM5), Journal of Applied Meteorology and Climatology, 58, 663 – 693, https://doi.org/10.1175/JAMC-D-18-0021.1, 2019.

905 Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J., Engelbrecht, F., Fischer, E., Fyfe, J., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T.: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]., p. 553–672,
910 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.006, 2021.

Leveque, B., Burnet, J.-B., Dorner, S., and Bichai, F.: Impact of climate change on the vulnerability of drinking water intakes in a northern region, Sustainable Cities and Society, 66, 102 656, https://doi.org/10.1016/j.scs.2020.102656, 2021.

Liao, Z., An, N., Chen, Y., and Zhai, P.: On the possibility of the 2022-like spatio-temporally compounding event across the Yangtze River Valley, Environmental Research Letters, 19, 014 063, https://doi.org/10.1088/1748-9326/ad178e, 2024.

915 Martynov, A., Laprise, R., Sushama, L., Winger, K., Šeparović, L., and Dugas, B.: Reanalysis-driven climate simulation over CORDEX North America domain using the Canadian Regional Climate Model, version 5: model performance evaluation, Climate Dynamics, 41, 2973–3005, https://doi.org/10.1007/s00382-013-1778-9, 2013.

Matte, D., Christensen, J. H., Feddersen, H., Vedel, H., Nielsen, N. W., Pedersen, R. A., and Zeitzen, R. M. K.: On the Potentials and Limitations of Attributing a Small-Scale Climate Event, Geophysical Research Letters, 49, https://doi.org/10.1029/2022gl099481, 2022.

920   Matte, D., Christensen, J. H., Drews, M., Sobolowski, S., Paquin, D., Lynch, A., Bremer, S., Engholm, I., Brunet, N. D., Kolstad, E. W., Kettleborough, H., Thompson, V., Bevacqua, E., Heinrich, D., Pryor, S. C., Böhnisch, A., Feser, F., Prein, A. F., Fischer, E., and Leduc, M.: How to engage and adapt to unprecedented extremes, Bulletin of the American Meteorological Society, https://doi.org/10.1175/bams-d-24-0138.1, 2024.

McGuinness, J. L. and Bordne, E. F.: A comparison of lysimeter-derived potential evapotranspiration with computed values, Government
925   report, Agricultural Research Service and Ohio Agricultural Research and Development Center, 1972.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: Eighth Conference on Applied Climatology, Anaheim, California, 1993.

Mehdi, B., Lehner, B., Gombault, C., Michaud, A., Beaudin, I., Sottile, M.-F., and Blondlot, A.: Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies, Agriculture, Ecosystems and
930   Environment, 213, 47–60, https://doi.org/10.1016/j.agee.2015.07.019, 2015.

Mejia, F. H., Ouellet, V., Briggs, M. A., Carlson, S. M., Casas-Mulet, R., Chapman, M., Collins, M. J., Dugdale, S. J., Ebersole, J. L., Frechette, D. M., Fullerton, A. H., Gillis, C., Johnson, Z. C., Kelleher, C., Kurylyk, B. L., Lave, R., Letcher, B. H., Myrvold, K. M., Nadeau, T., Neville, H., Piégay, H., Smith, K. A., Tonolla, D., and Torgersen, C. E.: Closing the gap between science and management of cold-water refuges in rivers and streams, Global Change Biology, 29, 5482–5508, https://doi.org/10.1111/gcb.16844, 2023.

935   MELCCFP: Stratégie québécoise de l'eau 2018-2030, Government report, Government of Quebec, 2018.

MELCCFP: Guide de l'Atlas hydroclimatique du Québec méridional, Government report, Direction principale de l'expertise hydrique (DPEH), Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP), Government of Quebec, Quebec City (QC), Canada, 2022a.

MELCCFP: Hydroclimatic Atlas of Southern Quebec - 2022 Edition, https://www.cehq.gouv.qc.ca/atlas-hydroclimatique/, accessed: 2025-
940   02-01, 2022b.

MELCCFP: Rapport technique de l'Atlas hydroclimatique du Québec méridional, Government report, Direction principale de l'expertise hydrique (DPEH), Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP), Government of Quebec, Quebec City (QC), Canada, 2024.

Morales-Marín, L., Rokaya, P., Sanyal, P., Sereda, J., and Lindenschmidt, K.: Changes in streamflow and water tempera-
945   ture affect fish habitat in the Athabasca River basin in the context of climate change, Ecological Modelling, 407, 108 718, https://doi.org/10.1016/j.ecolmodel.2019.108718, 2019.

Muñoz Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, Earth System Science Data, 13, 4349–4383, https://doi.org/10.5194/essd-
950   13-4349-2021, 2021.

Mudryk, L. R., Derksen, C., Howell, S., Laliberté, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P. J., and Brown, R.: Canadian snow and sea ice: historical trends and projections, The Cryosphere, 12, 1157–1176, https://doi.org/10.5194/tc-12-1157-2018, 2018.

Nand, V. and Qi, Z.: Potential of implementing irrigation in rainfed agriculture in Quebec: A review of climate change-induced challenges
955   and adaptation strategies, Irrigation and Drainage, 72, 1165–1187, https://doi.org/10.1002/ird.2840, 2023.

Ontario Ministry of Natural Resources, Ontario Ministry of the Environment, Ontario Ministry of Agriculture, Food and Rural Affairs, Ontario Ministry of Municipal Affairs and Housing, Ontario Ministry of Research and Innovation, Association of Municipalities of Ontario, and Conservation Ontario: Ontario Low Water Response, Tech. rep., Government of Ontario, Toronto (ON), Canada, 2010.

Osman, A.: Water use conflict: A characterization and water quantity study in an agriculturally stressed subcatchment in southwestern Ontario, Master's thesis, University of Guelph, 2018.

Palmer, W. C.: Meteorological Drought, Government report, Office of Climatology, U.S. Weather Bureau, Washington, D.C., 1965.

Parisi, A., Monno, V., and Fidelibus, M.: Cascading vulnerability scenarios in the management of groundwater depletion and salinization in semi-arid areas, International Journal of Disaster Risk Reduction, 30, 292–305, https://doi.org/10.1016/j.ijdrr.2018.03.004, 2018.

Plourde-Lavoie, P., Archer, M., Gagnon, K., and Sirois, P.: Les variations de niveau du lac Saint-Jean : effets sur la reproduction des poissons dans les habitats en milieux humides riverains, Milieux aquatiques, 142, 66–77, https://doi.org/10.7202/1042015ar, 2017.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P.: RCP 8.5—A scenario of comparatively high greenhouse gas emissions, Climatic Change, 109, 33–57, https://doi.org/10.1007/s10584-011-0149-y, 2011.

Roy, P., Rondeau-Genesse, G., Jalbert, J., and Élyse Fournier: Climate scenarios of extreme precipitation using a combination of parametric and non-parametric bias correction methods in the province of Québec, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 0, 1–17, https://doi.org/10.1080/07011784.2023.2220682, 2023.

Schaller, N., Sillmann, J., Müller, M., Haarsma, R., Hazeleger, W., Hegdahl, T. J., Kelder, T., van den Oord, G., Weerts, A., and Whan, K.: The role of spatial and temporal model resolution in a flood event storyline approach in western Norway, Weather and Climate Extremes, 29, 100 259, https://doi.org/10.1016/j.wace.2020.100259, 2020.

Shepherd, T. G.: Storyline approach to the construction of regional climate change information, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 475, 20190 013, https://doi.org/10.1098/rspa.2019.0013, 2019.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N. W., Wilby, R. L., and Zenghelis, D. A.: Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Climatic Change, 151, 555–571, https://doi.org/10.1007/s10584-018-2317-9, 2018.

Sillmann, J., Shepherd, T. G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., and Zscheischler, J.: Event-Based Storylines to Address Climate Risk, Earth's Future, 9, https://doi.org/10.1029/2020ef001783, 2021.

Solaraju-Murali, B., Caron, L.-P., Gonzalez-Reviriego, N., and Doblas-Reyes, F. J.: Multi-year prediction of European summer drought conditions for the agricultural sector, Environmental Research Letters, 14, 124 014, https://doi.org/10.1088/1748-9326/ab5043, 2019.

Solaraju-Murali, B., Gonzalez-Reviriego, N., Caron, L.-P., Ceglar, A., Toreti, A., Zampieri, M., Bretonnière, P.-A., Samsó Cabré, M., and Doblas-Reyes, F. J.: Multi-annual prediction of drought and heat stress to support decision making in the wheat sector, npj Climate and Atmospheric Science, 4, https://doi.org/10.1038/s41612-021-00189-4, 2021.

Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., Van Loon, A. F., and Stahl, K.: Candidate Distributions for Climatological Drought Indices (SPI and SPEI), International Journal of Climatology, 35, 4027–4040, https://doi.org/10.1002/joc.4267, 2015.

Staudinger, M., Stahl, K., and Seibert, J.: A drought index accounting for snow, Water Resources Research, 50, 7861–7872, https://doi.org/10.1002/2013WR015143, 2014.

Tam, B. Y., Szeto, K., Bonsal, B., Flato, G., Cannon, A. J., and Rong, R.: CMIP5 drought projections in Canada based on the Standardized Precipitation Evapotranspiration Index, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 44, 90–107, https://doi.org/10.1080/07011784.2018.1537812, 2019.

Tam, B. Y., Cannon, A. J., and Bonsal, B. R.: Standardized precipitation evapotranspiration index (SPEI) for Canada: assessment of probability distributions, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 48, 283–299, https://doi.org/10.1080/07011784.2023.2183143, 2023.

Tanguy, M., Prudhomme, C., Smith, K., and Hannaford, J.: Historical gridded reconstruction of potential evapotranspiration for the UK, Earth System Science Data, 10, 951–968, https://doi.org/10.5194/essd-10-951-2018, 2018.

Thackeray, C. W., Derksen, C., Fletcher, C. G., and Hall, A.: Snow and Climate: Feedbacks, Drivers, and Indices of Change, Current Climate Change Reports, 5, 322–333, https://doi.org/10.1007/s40641-019-00143-w, 2019.

van der Wiel, K., Lenderink, G., and de Vries, H.: Physical storylines of future European drought events like 2018 based on ensemble climate modelling, Weather and Climate Extremes, 33, 100 350, https://doi.org/10.1016/j.wace.2021.100350, 2021.

Van Loon, A. F. and Van Lanen, H. A. J.: A process-based typology of hydrological drought, Hydrology and Earth System Sciences, 16, 1915–1946, https://doi.org/10.5194/hess-16-1915-2012, 2012.

Van Loon, A. F., Ploum, S. W., Parajka, J., Fleig, A. K., Garnier, E., Laaha, G., and Van Lanen, H. A. J.: Hydrological drought types in cold climates: quantitative analysis of causing factors and qualitative survey of impacts, Hydrology and Earth System Sciences, 19, 1993–2016, https://doi.org/10.5194/hess-19-1993-2015, 2015.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696 – 1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Wheaton, E. and Kulshreshtha, S.: Environmental Sustainability of Agriculture Stressed by Changing Extremes of Drought and Excess Moisture: A Conceptual Review, Sustainability, 9, 970, https://doi.org/10.3390/su9060970, 2017.

Zohary, T. and Ostrovsky, I.: Ecological impacts of excessive water level fluctuations in stratified freshwater lakes, Inland Waters, 1, 47–59, https://doi.org/10.5268/iw-1.1.406, 2011.

Šeparović, L., Alexandru, A., Laprise, R., Martynov, A., Sushama, L., Winger, K., Tete, K., and Valin, M.: Present climate and climate change over North America as simulated by the fifth-generation Canadian regional climate model, Climate Dynamics, 41, 3167–3201, https://doi.org/10.1007/s00382-013-1737-5, 2013.