

# **Evaluation of Impacts of Climate Change on water availability in Umiujaq, Nunavik**

Mario Garavito

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## Abstract

Water is key in climate change adaptation. The impacts of climate change will primarily manifest themselves through water, with changes in the frequency and intensity of extreme hydroclimatic events such as floods and droughts. Understanding climate change influence is crucial for assessing future water availability and developing sustainable management plans. Vulnerability to these changes differs by region and community, geographic location, nature of climate change impacts, and human factors. The Nunavik region in northern Canada is experiencing some of the most rapid changes in climate in the world, with disproportionately large temperature increases, alterations in precipitation regimes, and thawing of permafrost, among others. This investigation aims to evaluate the impact of climate change on water availability in the Umiujaq community (Nunavik) and propose strategies to reduce the effects of these impacts. In order to achieve these goals, a hydrological model of the basin has been developed and calibrated using the Soil and Water Assessment Tool (SWAT), satellite and local data, and the SWAT Calibration and Uncertainty Programs (SWAT-CUP). Due to a lack of data, a model was first developed for the *Grande Riviere de la Baleine* watershed (Kuujuuarapik) and then transposed to Umiujaq. The hydrological model was successfully calibrated and validated (NSE = 0.81, RSR = 0.43, PBIAS = 5.2: NSE = 0.68, RSR = 0.56, PBIAS = 0.9). Then, the model was forced with Canadian downscaled climate data (CMIP5) under three emission scenarios (RCP 2.6, RCP4.5, and RCP8.5) to develop a quantitative analysis of the future water cycle's evolution. The results showed a slight increase in precipitation with global warming and a considerable reduction in snow content due to the higher temperatures. A faster and easier snow melting would happen yearly, bringing an earlier streamflow peak in the river. In the worst-case scenario (RCP8.5), the peak streamflow will move from June 17 to May 8 (40 days), which could result in lower water availability during the summer. To address these impacts, two strategies were analyzed: increase the storage capacity of the community and resort to an alternative water source,

i.e., groundwater. The first one could be a solution in the short term, while the second one would be more reliable in the long term. However, the community is already facing difficulty in providing a reliable water supply throughout the year, so swift and concerted action from both the community and relevant authorities is of the essence in tackling this issue head-on.

**KEYWORDS:** Climate change, water availability, SWAT, hydrological modelling, Northern Communities.

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# 1. Introduction

## 1.1. Background

There is now an almost complete political and scientific consensus that climate change is a reality and anthropogenic, i.e., human-made (Cook et al., 2016). As a result, various governments are scrambling to develop and implement mitigation strategies to prevent the warming from being drastic. However, because of the climate system's inertia, a certain level of warming is inevitable, and adaptation measures are necessary to cope with the unavoidable consequences. Understanding the impact of climate change on the water sector is vital for the global economy as all sectors depend on water availability and are vulnerable to water-related disasters. The effects of climate change will be primarily felt through the hydrological regime, which will change the frequency and intensity of extreme weather events. These impacts fall under three main categories: too little water - droughts, water shortages, too much water - floods, and too dirty water - pollution (Babel et al., 2020; Veettil & Mishra, 2016). The existing tension between water availability and demand is expected to be exacerbated by climate change. It may include drought, altered water availability frequency, and flooding (Gesualdo et al., 2019).

Vulnerability to these changes differs by region and community depending on geographic location, nature of climate change impacts, and human factors (Ford et al., 2018). In that sense, northern regions are receiving increasing attention from the scientific community, the general public, as well as decision-makers due to their noticeably rapid response to ongoing climate change, which raises concerns about the integrity of ecosystems, the sustainability of water resources, and altered hydrological risks under climate change scenarios (Aygün et al., 2020; Hu et al., 2017).

One of these Northern Regions is Nunavik, a vast region located in northern Quebec, Canada. This remote and pristine region, characterized by its stunning landscapes, unique wildlife, and rich cultural heritage, is facing significant challenges due to climate change. Scientific evidence suggests

that Nunavik is experiencing the impacts of climate change at an accelerated rate, which is having profound effects on its environment and communities (Bush & Lemmen, 2019).

To mitigate the consequences, communities must have information to create or adapt water management strategies. This necessity emphasizes the importance of assessing water resource dynamics under climate change (Andresen et al., 2019; Lemieux, Fortier, Molson, et al., 2020; Marin et al., 2020). Hydrologic modeling is used to answer questions where water excess or scarcity is essential and provide information for policymakers or decision-makers.

## 1.2. Objectives of the Study

The general objective of this study is to understand the effects of climate change on water availability in the Umiujaq community (Nunavik) and propose strategies to mitigate the negative effects of these variations, if any. The specific objectives of the study are:

- Develop a hydrological model of the Umiujaq watershed even though the watershed's hydrological data (precipitation and streamflow) are short and of dubious quality.
- Run climate change scenarios or Representative Concentration Pathways – (RCP) 2.6, 4.5 and 8.5 in the homologous Umiujaq water basin for future years.
- Evaluate future changes in precipitation, streamflow, and water availability in Umiujaq and propose strategies to mitigate the consequences of the temperature increase.

## 1.3. Overview of the Methodology

The following research methodology was used to achieve the mentioned objectives. Firstly, as there is not enough data in Umiujaq, an auxiliary watershed model was required to calibrate and validate the simulation. Data from the *Grande Riviere de la Baleine* (Kuujuuarapiq) was compiled, and a hydrological model was developed using SWAT. Secondly, this model was calibrated and validated using SWAT-CUP Software. Then, the model was transposed to the Umiujaq watershed with the specific data compiled for this region. Afterward, the model was forced with Canadian downscaled

climate data (CMIP5) under three emission scenarios (RCP 2.6, RCP4.5 and RCP8.5) to develop a quantitative analysis of the future water cycle's evolution. Finally, using the WEAP system, two water management strategies were proposed to mitigate some of the impacts found. A more complete description of the methodology, including a flowchart, is presented in Chapter 3.

#### **1.4. Thesis organization**

After this introduction (Chapter 1), this thesis includes five chapters, a list of references, and appendices. Chapter 2 presents a literature review focusing on hydrological modeling, climate change, and water management. Chapter 3 presents the study areas considered in this investigation (Nunavik, and specifically Umiujaq), and a detailed description of the methodology and data used to develop the thesis. The results and outputs of the models are then presented and discussed in Chapter 4, with an additional analysis of the strategies suggested. Finally, Chapter 5 summarizes the main findings of the research, outlines some conclusions, and gives a few recommendations for future investigations.

## 2. Literature Review

### 2.1. Hydrological modelling

#### 2.1.1. Description

The birth of hydrologic modelling can be traced to the 1850s when Mulvany developed a method for computing the time of concentration and used it in the rational method for computing peak discharge. The rational method is still used for urban drainage design. Several advances and progress were made until the decade of the 1960s, when the computer revolution and hydrologic modelling took a giant leap forward. Computers provided the power for computations that were not available before (Singh, 2018).

Hydrologic modelling involves formulating mathematical models to represent the hydrologic processes such as precipitation, snowmelt, interception, evapotranspiration, infiltration, sub-surface flow, surface flow, and the interaction between them (Islam, 2011). Hydrologic modelling is used to answer environmental transport questions where water excess, scarcity, or dissolved or solid content is of primary importance. A hydrologic model simulates a flux, flow, or water storage change with time within one or more components of the natural hydrologic cycle (Ogden, 2021).

These models have been classified into different groups. Refsgaard et al. (2022) proposed a classification that reflects the degree of understanding of hydrological processes that can be built into the model (Figure 1).

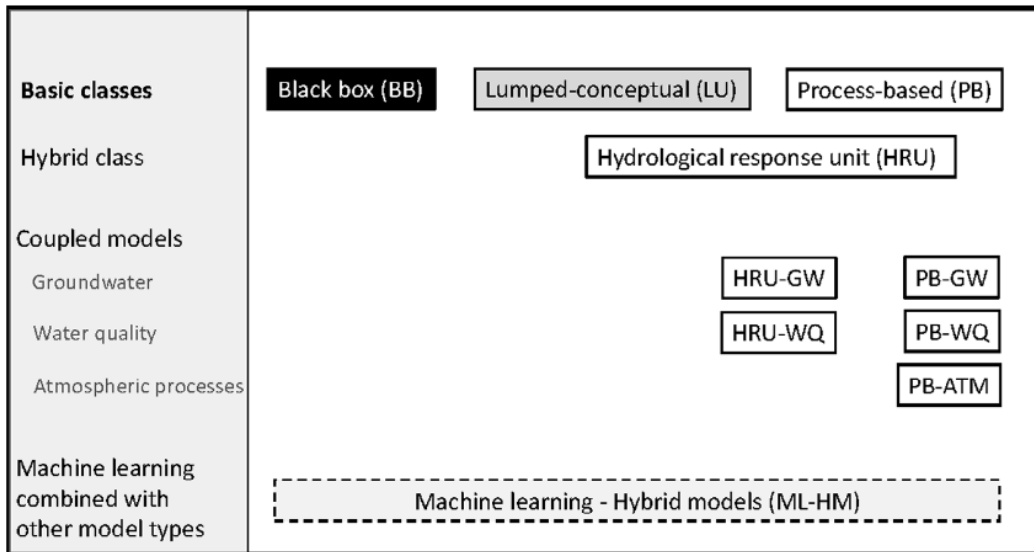


Figure 1 Classification of hydrological models (Refsgaard et al., 2022)

Black box models (BB) are empirical with mathematical equations that are developed without considering any understanding of the underlying hydrological processes. Lumped models (LU) include some concepts reflecting the understanding of hydrological processes but are not an attempt to describe the actual processes – they only attempt to capture the observed/known dynamic between key variables, often using simplifications and empirical equations. Process-based models (PB) (also called physics-based models) apply point scale equations of hydrological processes and a spatially distributed representation of the catchment.

Models can be lumped (LU), semi-distributed (SD) or distributed (D) depending on how the watershed is spatially discretized. In lumped models (LU), all equations are upscaled to represent hydrological response at the catchment scale. On the other hand, semi-distributed models discretize the watershed into homogeneous polygons that are selected by some criteria.

Hydrological Response Unit (HRU) are a way for semi-distributed models to account for variability within a subwatershed. HRUs are areas corresponding to a unique combination of some key characteristics such as soil type, vegetation, topography, and climate forcing within a catchment into one calculational unit (HRU), so that a catchment, on one hand, includes several HRUs with

detailed process descriptions and on the other hand has a lumped-conceptual representation of other processes (Refsgaard et al., 2022).

The fully distributed rainfall-runoff model is the most sophisticated and computationally demanding representation of watershed processes. In this representation, parameters are distributed over the watershed using discretization schemes based on a grid/mesh with resolutions similar to groundwater models (Anderson et al., 2015). Surface runoff modelling is used to understand catchment yields and responses, estimate water availability, changes over time, and forecasting. Choosing a rainfall-runoff model is based on the modelling purpose, such as understanding and answering specific questions about the hydrological process; assessing the frequency of runoff events, or estimating runoff yield for management purposes. In conclusion, modeling runoff helps better understand hydrologic phenomena and how changes affect the hydrological cycle (Sitterson et al., 2018).

### **2.1.2. Model Uncertainty**

Despite progresses in representing different processes, hydrological models' outputs remain highly uncertain. Their uncertainty stems from input and calibration data, model structure, and parameters. In addition to these sources, uncertainties can stem from the model initial and boundary conditions (Moges et al., 2021). The different causes and interactions of these four sources of hydrological model uncertainty are summarized in Figure 2.

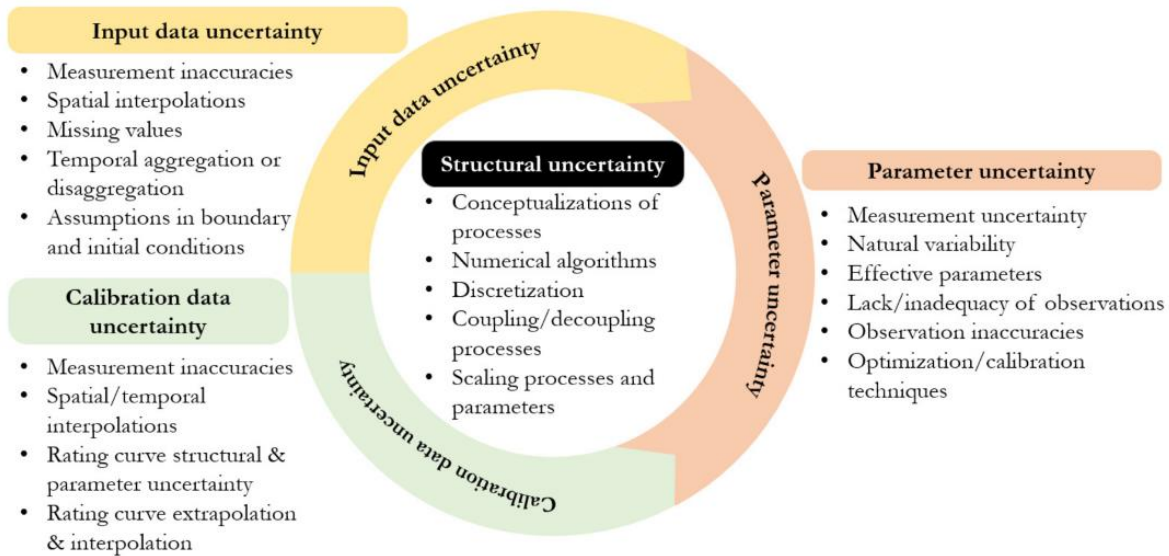


Figure 2 The different sources of hydrological model uncertainty and examples of their causes (Moges et al., 2021).

Similarly, Abbaspour (2015) divided the model uncertainty into conceptual model uncertainty, input uncertainty, and parameter uncertainty. The conceptual model uncertainty (or structural uncertainty) could result the following situations: a) Model uncertainties due to simplifications in the conceptual model, b) Model uncertainties due to processes occurring in the watershed but not included in the model, c) Model uncertainties due to processes that are included in the model, but their occurrences in the watershed are unknown to the modeler, and d) Model uncertainties due to processes unknown to the modeler and not included in the model either. Likewise, input uncertainty results from errors in input data, such as rainfall, and, more importantly, the spread of data points to large areas in distributed models. And parameter uncertainty generally occurs because of the inherent non-uniqueness of parameters in inverse modeling. Parameters represent processes. The fact that the processes can compensate for each other gives rise to many sets of parameters that produce the same output signal. This is known as equifinality which implies that various combinations of precipitation, evaporation, runoff, and other hydrological processes can result in the same observed water flow patterns or levels in a watershed. This concept highlights the

challenge of precisely predicting hydrological behaviors, especially in complex and dynamic systems, due to the potential for different hydrological models or scenarios to produce similar outcomes.

Models that can produce results close to the true values and with low uncertainty are preferred over others. Hence, when models are employed to make forecasts or as a tool for decision-making processes, it is essential to quantify and, if possible, reduce the uncertainty of their results. This can be accomplished by: (a) collecting more data, (b) developing more robust models, and (c) using effective techniques to extract and assimilate information from the collected data (Liu & Gupta, 2007).

It is important to note that to calibrate a model, assess its sensitivity to parameters and estimate the uncertainty of its results, modelers must have a good understanding of mathematical concepts beyond the traditional technical background in hydrology required to set up models. Moreover, there are remaining obstacles, such as computational cost and the existence of multiple plausible models that must be dealt with before frameworks for calibration and uncertainty analysis can be applied systematically (Herrera et al., 2022).

The Soil and Water Assessment Tool (SWAT), a physically-based and continuous-time model, was developed to assist water resource managers in assessing water supplies while facilitating automated calibration and uncertainty analysis (J. G. Arnold et al., 2012).

### 2.1.3. SWAT

The Soil & Water Assessment Tool (SWAT) is a small watershed to river basin-scale model used to simulate surface and ground water quality and quantity and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control, and regional management in watersheds (SWAT, 2023). SWAT was developed by the United States Department of Agriculture

(USDA), and it allows for the assessment of complex watersheds by dividing the system into subwatersheds or subbasins, which are generally delineated such that the entire area drains to a single outlet. SWAT requires specific information about the topography, land use and land cover, soil characteristics, and weather parameters of a watershed and models the physical processes associated with the movement of water (Neitsch, S., et al., 2011) .

### 2.1.3.1. Hydrological cycle

Numerous hydrological processes can be simulated by SWAT, including but not limited to surface run-off, groundwater discharge, lateral flow, streamflow, snowmelt, evapotranspiration, groundwater recharge, and soil moisture dynamics (Zaremehrijardy et al., 2022). In Figure 3, there is a representation of the main components of the hydrological cycle modeled in SWAT.

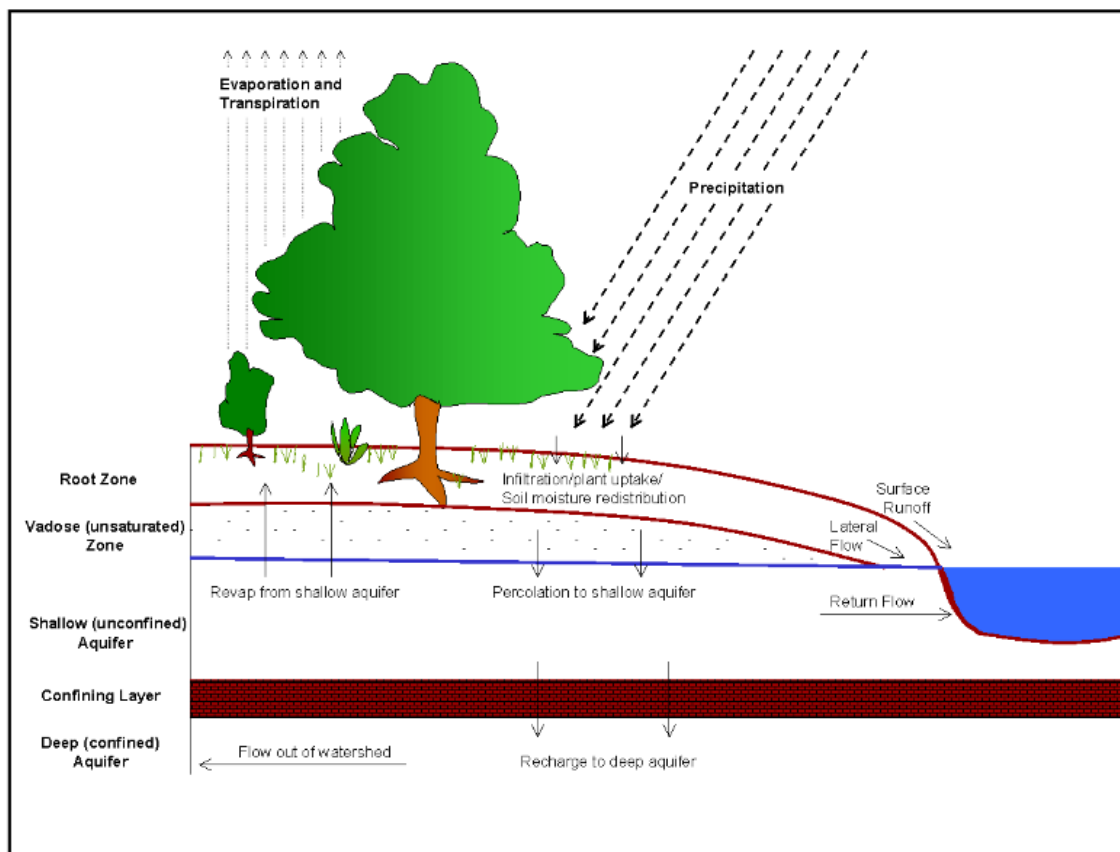


Figure 3 Components of the hydrological cycle modeled in SWAT (Neitsch, S., et al., 2011).

SWAT simulations are based on two phases of the hydrologic cycle – the land phase and the routing phase. The land phase controls the quantity and quality of water going into the main channel from the watershed, and the routing phase controls the movement of water and sediments through the channel to the outlet (Neitsch, S., et al., 2011).

The hydrologic cycle, as simulated by SWAT, is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (P_i - Q_{surf} - E_a - Q_{seep} - Q_{gw})$$

Where,

- $SW_t$ : final water content (mm)
- $SW_0$ : initial water content (mm)
- $t$ : time (days)
- $P_i$ : amount of precipitation on day  $i$  (mm)
- $Q_{surf}$ : amount of surface runoff on day  $i$  (mm)
- $E_a$ : amount of evapotranspiration on day  $i$  (mm)
- $Q_{seep}$ : amount of percolation on day  $i$  (mm)
- $Q_{gw}$ : amount of return flow on day  $i$  (mm)

#### 2.1.3.2. Precipitation

SWAT differentiates precipitation as rainfall or snowfall while comparing air temperature with a snowfall temperature parameter (SFTMP). As a result, the model keeps track of the volume and areal extent of snowpack, as well as the corresponding snowmelt, as described in the following equations:

$$SNO_t = SNO_0 + \sum_{i=1}^t (P_i - E_{i,sub} - SNOMLT_i)$$

$$SNOMLT_i = b_{i,mlt} * SNOCOV_i + \left( \frac{T_{i,snow} + T_{i,max}}{2} - SMTMP \right)$$

$$b_{i,mlt} = \left( \frac{SMFMX + SMFMN}{2} + \frac{SMFMX - SMFMN}{2} \right) * \sin \left( \frac{2\pi}{365} (i - 81) \right)$$

Where,

- $SNO_t$ : snow water equivalent at time “t” (mm)
- $SNO_0$ : initial snow water equivalent (mm)
- $E_{i,sub}$ : water equivalent of snow sublimation (mm)
- $SNOMLT_i$ : water equivalent of nowmelt (mm)
- $B_{i,mlt}$ : melt factor (mm/°C/day)
- $SNOCOV_i$ : fraction of HRU covered by snow
- $T_{i,snow}$ : snowpack temperature (°C)
- $T_{i,max}$ : maximum air temperature (°C)
- $SMTMP$ : snow melt base temperature (°C)
- $SMFMX$ : maximum snowmelt rate (mm/°C/day)
- $SMFMN$ : minimum snowmelt rate (mm/°C/day)

### 2.1.3.3. Surface runoff

Surface runoff is the water that flows over the land surface. It is another major component of the water cycle. Generally, the runoff is the precipitation that was not infiltrated or lost through evapotranspiration, abstraction, or other depression. SWAT employs some empirical/conceptual methods (e.g., Penman-Monteith method for potential evapotranspiration calculation, and Soil Conservation Service [SCS] curve number method for surface runoff simulation) formulated in the USA. These methods lead to one of the merits of SWAT, i.e., minimal input data is required for modelling (Neitsch, S., et al., 2011).

The SCS curve number method is an empirical method developed for estimating rainfall-runoff relationships for small watersheds across the United States. The following equations govern this method:

$$Q_{surf} = \frac{(P_i - I_a)^2}{(P_i - I_a + S)}$$

$$S = 25.4 \left( \frac{1000}{CN} - 1 \right)$$

Where,

- $Q_{surf}$ : accumulated runoff (mm)
- $P_i$ : amount of precipitation on day  $i$  (mm)
- $I_a$ : initial abstractions (mm) and often equal to 0.2 times “ $S$ ”
- $S$ : hydraulic retention parameter (mm)
- $CN$ : the curve number of the land cover area of interest

Runoff will only occur when  $P_i > I_a$ . A graphical solution for different curve number ( $CN$ ) values is presented in the Figure 4.

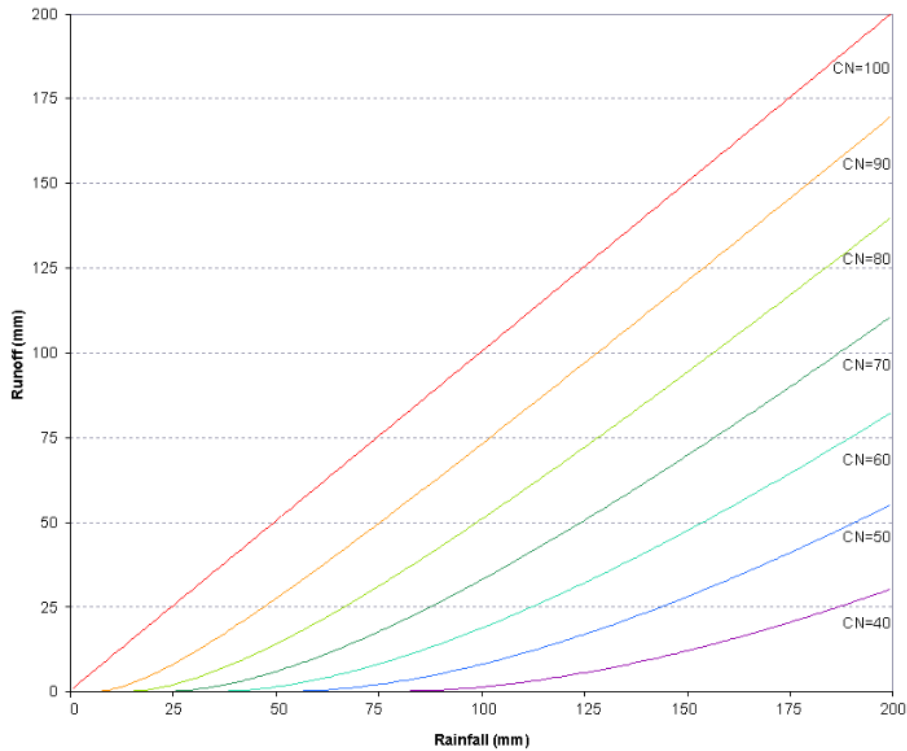


Figure 4 Relationship of runoff to rainfall in SCS curve number method (Neitsch, S., et al., 2011)

#### 2.1.3.4. SWAT worldwide

With nearly 4000 publications as of 2023, the Soil and Water Assessment Tool (SWAT) is clearly one of the most extensively used ecohydrological models worldwide (J. G. Arnold et al., 2012; Tan et al., 2020). This is partially because it is an open-source tool containing various add-ons, such as SWAT calibration and uncertainty or sensitivity analysis programs SWAT CUP (Abbaspour et al., 2007). Furthermore, SWAT has been compared with other watershed models, and it has stood out in terms of functionality, availability, applicability to a wide range of watersheds and scales, ease of implementation, and efficiency (Fazeli Farsani et al., 2019; Keller et al., 2023).

The software has been used to study water quality processes (Kondo et al., 2021; Qi et al., 2020; Shrestha et al., 2019), soil erosion and conservation scenarios (Mukundan et al., 2010; A. Pandey et al., 2021), land use and cover changes (Feng & Shen, 2021; Siqueira et al., 2021) and hydrological processes (Grusson et al., 2015; Zahabiyoum et al., 2013).

In particular, SWAT has been used to analyze the impacts of climate change on hydrological systems around the world, for example, the Volta River basin, West Africa (Sood et al., 2013), Lake Victoria, Kenya (Githui et al., 2009), the Upper Narew and the Barycz, Poland (Marcinkowski et al., 2017), Laguna del Sauce, Uruguay (Aznarez et al., 2021), and Tamor River Basin, Nepal (Bhatta et al., 2019). In Canada, Bhatti et al. (2021) investigated the impacts across eastern, central, and western Prince Edward Island (PEI), and Shrestha et al. (2017) based their study on the Athabasca River Basin in Alberta.

The studies focused their analyses on different impacts according to the specific characteristics of the community or region, i.e., hydropower, water quantity, water quality, etc., providing relevant information for policymakers and water resource planners and managers.

The software SWAT is particularly suitable for this study due to its capabilities in modeling hydrological processes and assessing the impacts of climate change on water resources. Its global popularity and extensive utilization in various regions worldwide highlight its effectiveness and reliability in analyzing watershed systems, making it a valuable tool for understanding the potential implications of climate change in the study area of Umiujaq, Nunavik.

## 2.2. Climate change

### 2.2.1. Description

Climate change refers to a long-term shift in the Earth's climate system that can significantly alter temperature, precipitation patterns, sea level, and extreme weather events (IPCC, 2014). In recent history, climate change is primarily caused by human activities, including the burning of fossil fuels, deforestation, and other land-use changes. These activities release greenhouse gases into the atmosphere, which trap heat and contribute to the warming of the planet (US EPA, 2015). Climate change significantly impacts natural and human systems, including changes in ecosystems, food and water security, and public health (UNEP, 2021).

Given the global oceans' tremendous size and heat capacity, it takes a massive amount of heat energy to raise Earth's average yearly surface temperature even a small amount. The roughly 1 degree Celsius increase in global average surface temperature that has occurred since the pre-industrial era (1880-1900) might seem small, but it means a significant increase in accumulated heat. Figure 5 shows the Yearly surface temperature compared to the 20th-century average from 1880–2022. Blue bars indicate cooler-than-average years; red bars show warmer-than-average years (NOAA National Centers for Environmental Information, 2023).

Changes in global temperature and average atmospheric carbon dioxide (1880-2021)

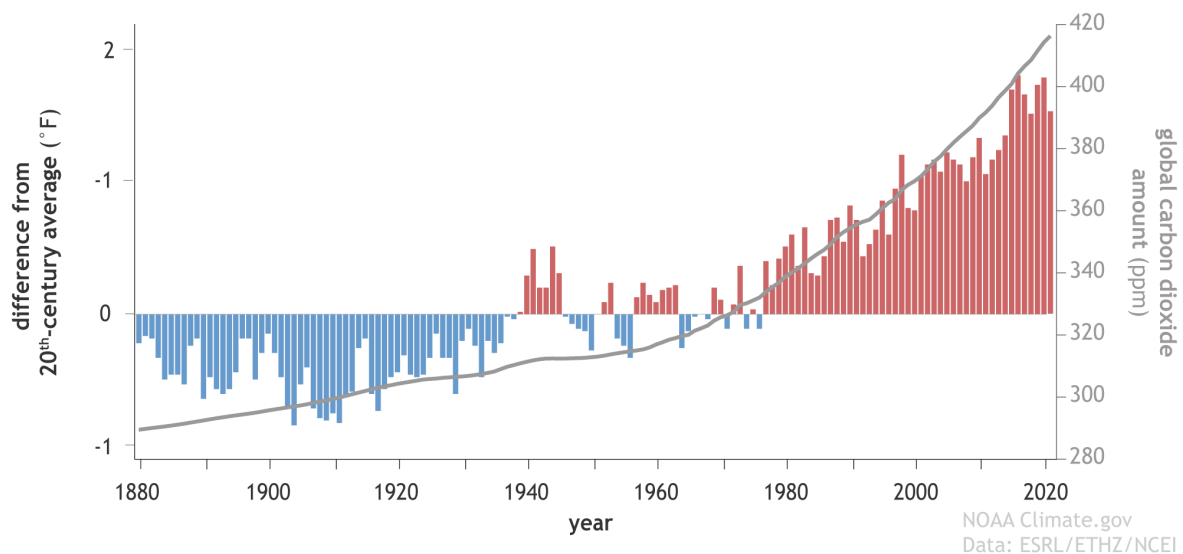


Figure 5 Yearly temperature compared to the twentieth-century average (red and blue bars) from 1880–2021, plus atmospheric carbon dioxide concentrations (gray line) (NOAA National Centers for Environmental information, 2023)

In Canada, weather records show that every year since 1998 has been warmer than the 20th-century average. This means that a whole generation of Canadians has never experienced what most modern history considered a “normal” Canadian climate (Climate Atlas of Canada, 2019). This modern global warming is a sudden departure from the temperatures that have been typical for the past 10,000 years (Marcott et al., 2013). And, unlike other climate changes occurring naturally throughout Earth's history, human activities are responsible (Crowley, 2000).

One of the main reasons why humans are responsible for climate change is that they have increased the concentration of greenhouse gases in the atmosphere by burning fossil fuels. Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, trap heat from the sun and warm up the planet. According to NASA (n.d.), the atmospheric carbon dioxide level for February 2023 was 419 parts per million (ppm), which is higher than at any time in at least the last 800,000 years. Figure 5 presents the atmospheric carbon dioxide concentration (gray line) from 1880 to 2020.

The impacts of climate change are observed in many ecosystems and human systems worldwide. In the Sixth Assessment Report (AR6), IPCC reports how worldwide climate change increasingly affects marine, freshwater and terrestrial ecosystems and ecosystem services, water and food security, settlements and infrastructure, health and well-being, and economies and culture, especially through compound stresses and events. Figure 6 presents some of those impacts in terrestrial, freshwater, and ocean ecosystems in different regions worldwide. It is highlighted the confidence in attribution to climate change. Similarly, in Figure 7 observed impacts of climate change on human systems are summarized. It is signaled if climate change increases adverse or positive impacts in those systems.

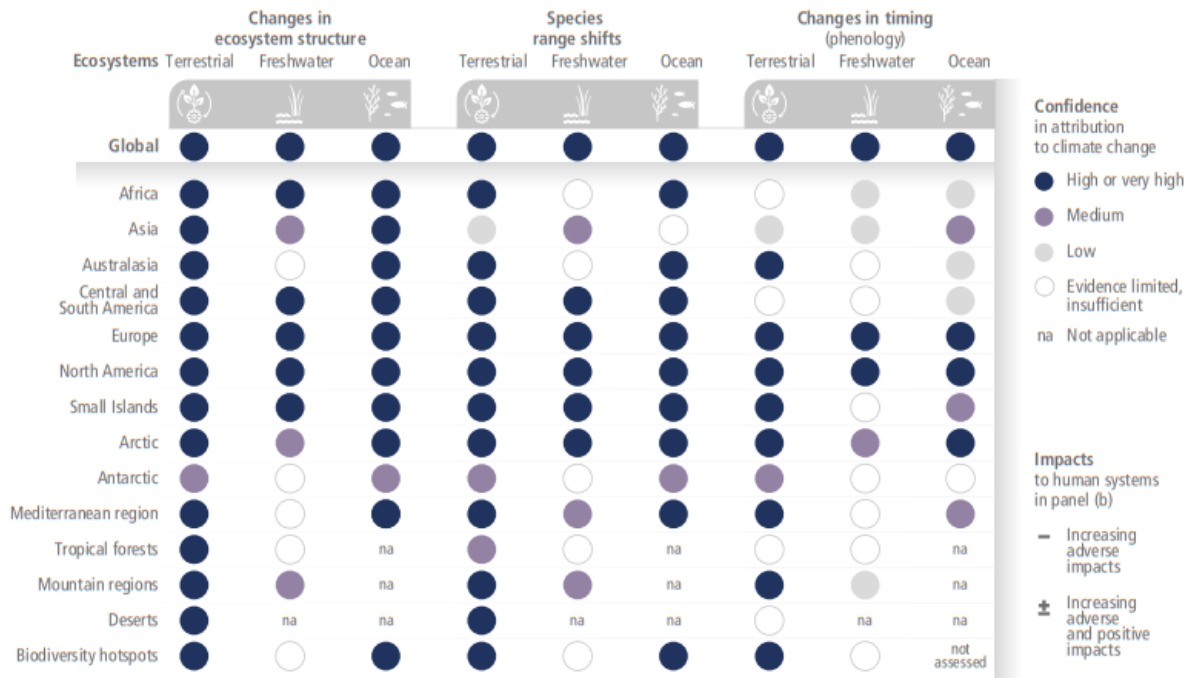


Figure 6 Observed impacts of climate change on ecosystems (IPCC, 2022)

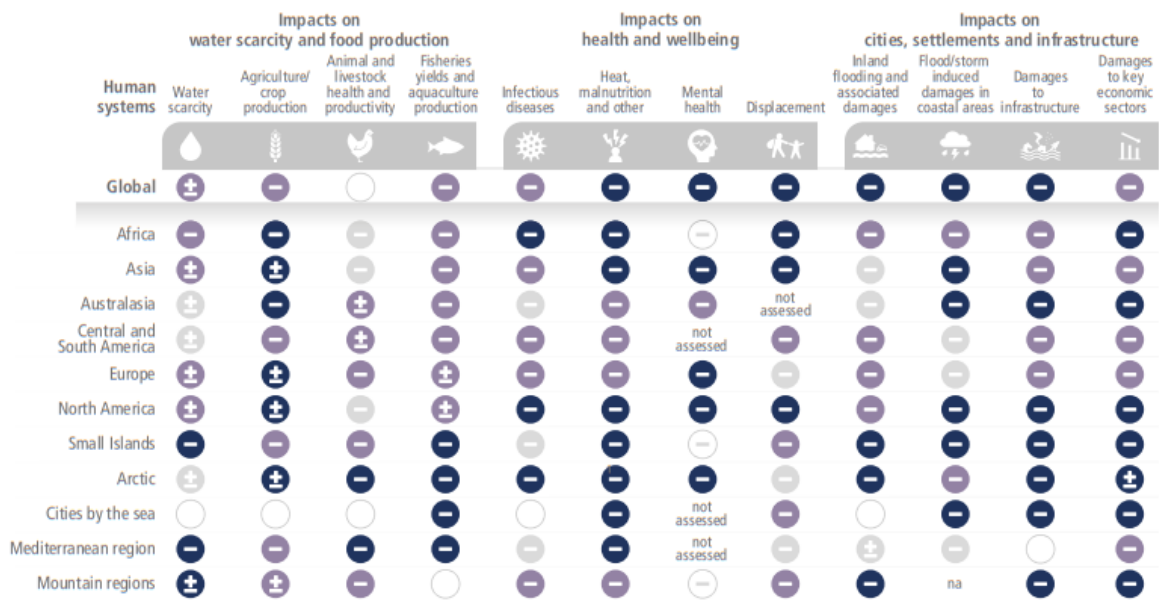


Figure 7 Observed impacts of climate change on human systems (IPCC, 2022)

According to the Government of Nunavut (2011), Northern Canada will face a range of specific consequences due to climate change. These include rising temperatures, permafrost thaw, reduced sea ice cover, changing precipitation patterns, and increased frequency of extreme weather events.

The warming trend is expected to disrupt the delicate balance of ecosystems, leading to shifts in vegetation, changes in wildlife distribution, and increased vulnerability of certain species. Additionally, permafrost thaw can cause infrastructure damage, such as destabilized buildings, roads, and pipelines. The reduction in sea ice cover affects marine ecosystems and the traditional livelihoods of Indigenous communities who rely on ice for transportation, hunting, and fishing. Changes in precipitation patterns can impact water availability, affecting freshwater ecosystems and the availability of safe drinking water. Finally, the heightened occurrence of extreme weather events, such as storms and flooding, poses risks to infrastructure, food security, and community well-being. These consequences underscore the urgent need for adaptation strategies and collaborative efforts to mitigate the impacts of climate change in Northern Canada.

### 2.2.2. Climate change scenarios

Climate change scenarios are descriptions of possible future conditions of the climate system and the human-environment interactions that influence it. They are based on different assumptions about greenhouse gas emissions, socio-economic development, land use change, and other climate factors. The Intergovernmental Panel on Climate Change (IPCC) has developed a framework for creating and using climate change scenarios for its Fifth Assessment Report (AR5), which consists of Representative Concentration Pathways (RCPs) (O'Neill et al., 2020).

RCPs are four scenarios of atmospheric greenhouse gas concentrations and radiative forcing levels by 2100, ranging from 2.6 to 8.5 W/m<sup>2</sup>. They represent different mitigation efforts to limit or increase emissions and different natural feedbacks that amplify or dampen human-induced warming. RCPs are used as inputs to global and regional climate models to project changes in temperature, precipitation, sea level rise, and other physical variables under different levels of warming (IPCC, 2014).

The RCPs are named according to the radiative forcing target level for 2100. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents. The four selected RCPs were considered to be representative of the literature. They included one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6), and one very high baseline emission scenario (RCP8.5) (Van Vuuren et al., 2011). They are representative because they are one of several scenarios with similar radiative forcing and emissions characteristics. An overview of the four RCPs is presented in Table 1.

<b>RCP</b>	<b>DESCRIPTION</b>	<b>PUBLICATION</b>
<b>RCP 8.5</b>	Rising radiative forcing pathway leading to 8.5 W/m <sup>2</sup> (~1370 ppm CO <sub>2</sub> eq) by 2100	(Riahi et al., 2007)
<b>RCP 6.0</b>	Stabilization without overshoot pathway to 6 W/m <sup>2</sup> (~850 ppm CO <sub>2</sub> eq) at stabilization after 2100	(Fujino et al., 2006; Hijioka et al., 2008)
<b>RCP 4.5</b>	Stabilization without overshoot pathway to 4.5 W/m <sup>2</sup> (~650 ppm CO <sub>2</sub> eq) at stabilization after 2100	(Clarke et al., 2007; Smith & Wigley, 2006; Wise et al., 2009)
<b>RCP 2.6</b>	Peak radiative forcing at ~3 W/m <sup>2</sup> (~490 ppm CO <sub>2</sub> eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m <sup>2</sup> by 2100)	(Van Vuuren et al., 2006, 2007)

*Table 1 Overview of Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011)*

The Fifth Assessment Report was elaborated by three different Working Groups: WGI: The Physical Science Basis, WGII: Impacts, Adaptation and Vulnerability, and WGIII: Mitigation of Climate Change. Figure 8 compares carbon dioxide emissions (GtCO<sub>2</sub>/yr) for the four Representative Concentration Pathways. The Working Group III (WGIII) scenario categories summarize the wide range of emission

scenarios published in the scientific literature and are defined based on CO<sub>2</sub>-eq concentration levels (in ppm) in 2100.

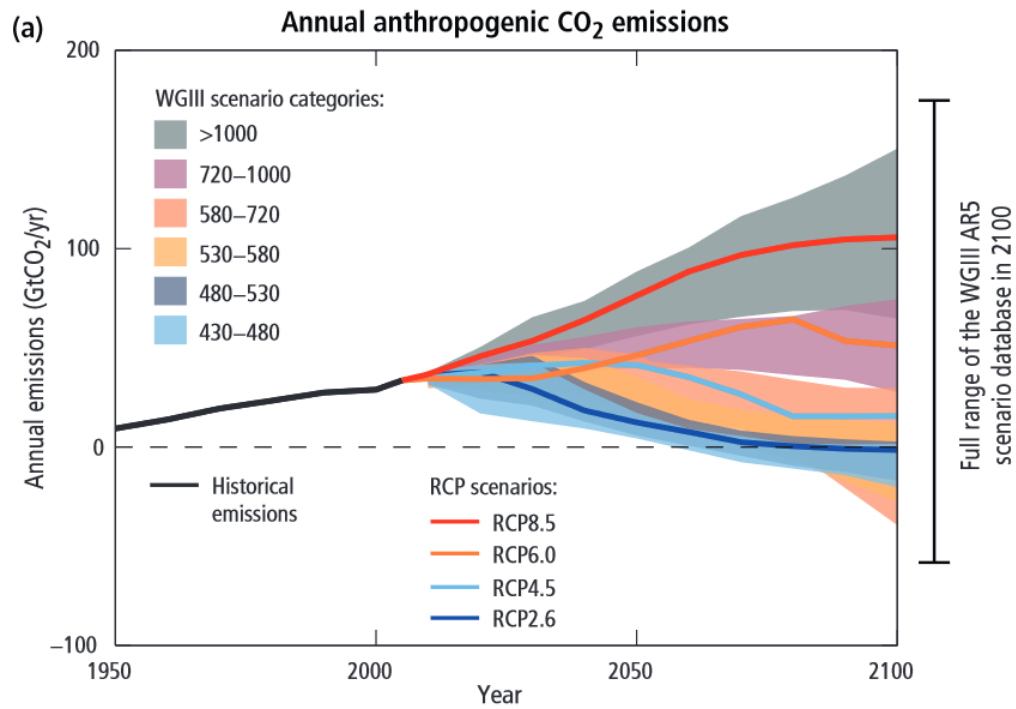


Figure 8 Emissions of carbon dioxide (CO<sub>2</sub>) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories used in WGIII (Working Group III) (IPCC, 2014)

Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5. The Arctic region will continue to warm more rapidly than the global mean (IPCC, 2014).

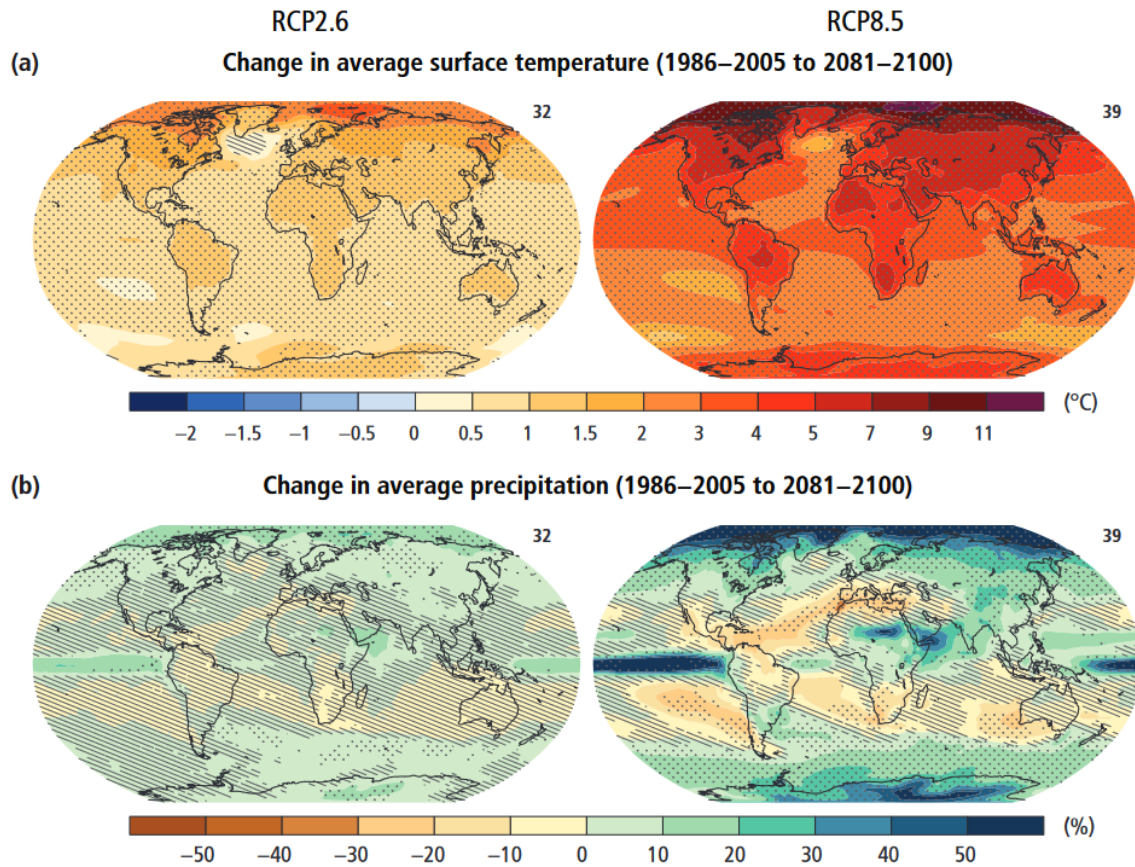


Figure 9 Change in average surface temperature (a) and change in average precipitation (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. (IPCC, 2014)

In Figure 9, the number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability.

Changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario (IPCC, 2014).

In addition, IPCC has been working on the Sixth Assessment Report (AR6) since 2017. In 2021 was released Climate Change 2021: The Physical Science Basis, the Working Group 1 contribution to the AR6. Then, Climate Change 2022: Impacts Adaptation and Vulnerability and Climate Change 2022: Mitigation of Climate Change, the Working Group II and Working Group III contributions were published. And finally, Climate Change 2023: synthesis report was released on 20 March 2023 to inform the 2023 Global Stocktake under the United Nations Framework Convention on Climate Change (IPCC, 2023).

In the AR6, five Shared Socioeconomic Pathways (SSPs) were proposed to complement the RCP scenarios from AR5. SSPs are five narratives of alternative socio-economic futures that describe how human societies may evolve regarding population growth, economic development, urbanization, education, health, equity, governance, and other factors that affect adaptation and mitigation capacities and challenges. SSPs span a wide range of plausible futures from high to low challenges for both mitigation and adaptation. SSPs are used to assess the impacts of climate change on natural and human systems and the potential for adaptation and mitigation responses under different socio-economic conditions (O'Neill et al., 2017).

Figure 10 presents a summary of the main characteristics of the five Shared Socioeconomic Pathways, comparing them in terms of the challenges to adaptation and mitigation.

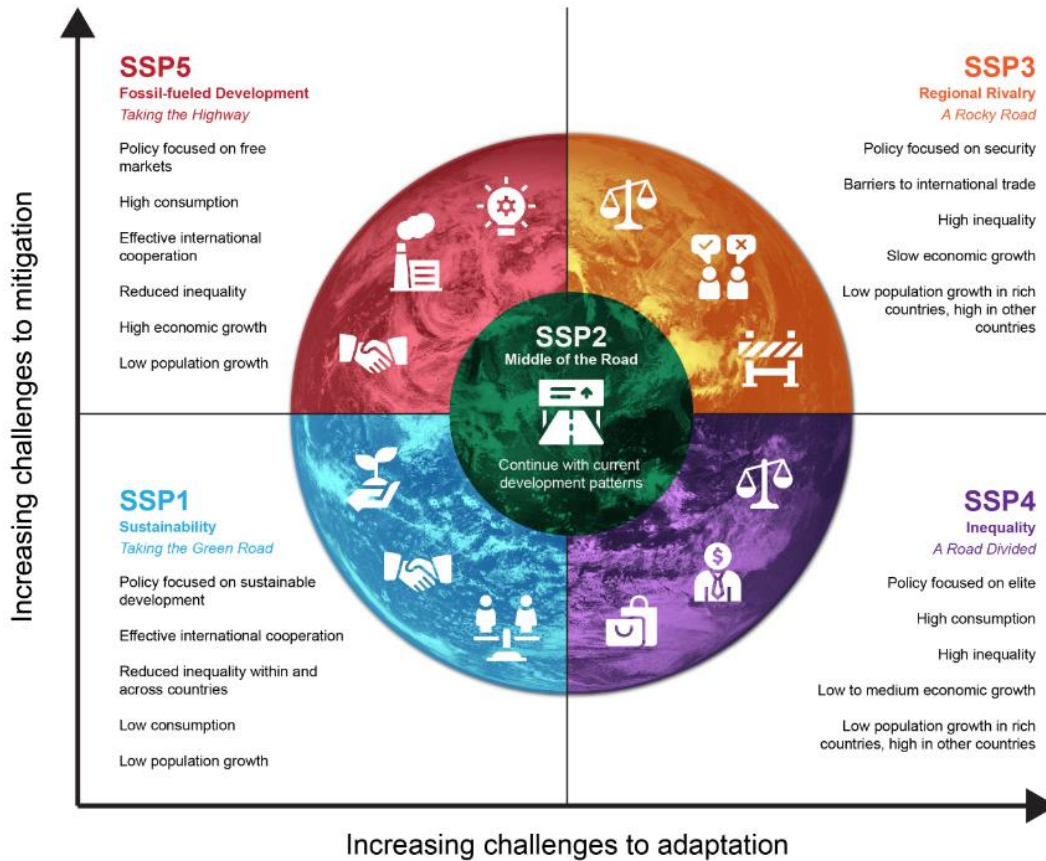


Figure 10 Shared Socioeconomic Pathways (SSPs) (ClimateData.ca, 2023)

Currently, widely used RCP scenarios are based on how future greenhouse gas concentrations will change. In contrast, SSP scenarios are predict how climate change will change in response to socio-economic indicators such as population, economy, land use, and energy change (Lee et al., 2017). The four RCPs are consistent with certain socio-economic assumptions. Still, they are being substituted with the shared socioeconomic pathways, which are anticipated to provide flexible descriptions of possible futures within each RCP. Unfortunately, by the moment when this research was done, downscaled data from AR6 was not found.

### 2.2.3. Global Climate Models (GCMs)

Climate change scenarios (RCPs and SSPs) are used as input for global climate models (GCMs), which simulate the physical processes of the climate system and project how the climate will change over time. GCMs are important tools in the assessment of climate change. These numerical coupled

models represent various earth systems, including the atmosphere, oceans, land surface, and sea-ice. They offer considerable potential for studying climate change and variability (Fowler et al., 2007).

Climate models divide the globe into a three-dimensional grid of cells representing specific geographic locations and elevations. Each component (atmosphere, land surface, ocean, and sea ice) has equations calculated on the global grid for a set of climate variables such as temperature. In addition to model components computing how they change over time, the different parts exchange heat, water, and momentum fluxes. They interact with one another as a coupled system (Setzer, 2023).

To coordinate and compare the output of different GCMs under various scenarios of greenhouse gas emissions, the Coupled Model Intercomparison Project (CMIP) was created as a framework. CMIP provides a common set of experiments and protocols for GCMs to follow and produces a large ensemble of climate projections that can be used for scientific research and policymaking. The latest phase of CMIP is CMIP6, which contributed to the IPCC 6th Assessment Report. An important part of CMIP is to make the multi-model output publicly available in a standardized format for analysis by the wider climate community and users. The objective is to better understand past, present, and future climate change arising from natural, unforced variability or in response to changes in radiative forcings in a multi-model context. (Eyring et al., 2016)

Though GCMs are important for the assessment of climate change, including the application of climate change scenarios to hydrological models, a transformation process to bridge the gaps between large-scale climate model variables and local-scale meteorological variables is required (Fowler et al., 2007). Thus, considerable effort in the climate community has focussed on the development of techniques to bridge the gap, known as 'downscaling'.

#### 2.2.4. Downscaling

Although GCMs are valuable predictive tools, they cannot account for fine-scale heterogeneity of climate variability and change due to their coarse resolution. Numerous landscape features, such as mountains, water bodies, infrastructure, land-cover characteristics, and climate system components such as convective clouds and coastal breezes have scales much finer than 100–500 kilometers. Such heterogeneities are important for decision-makers who require information on potential impacts on crop production, hydrology, species distribution, etc. at scales of 10–50 kilometers (Sylwia Trzaska & Emilie Schnar, 2014).

The process of deriving fine-scale climate information from coarse GCM output is called downscaling. Downscaling adds more details to the GCM output so that it reflects the sub-grid scale variations and differences more realistically. Figure 11 presents a visual representation of the concept of downscaling.

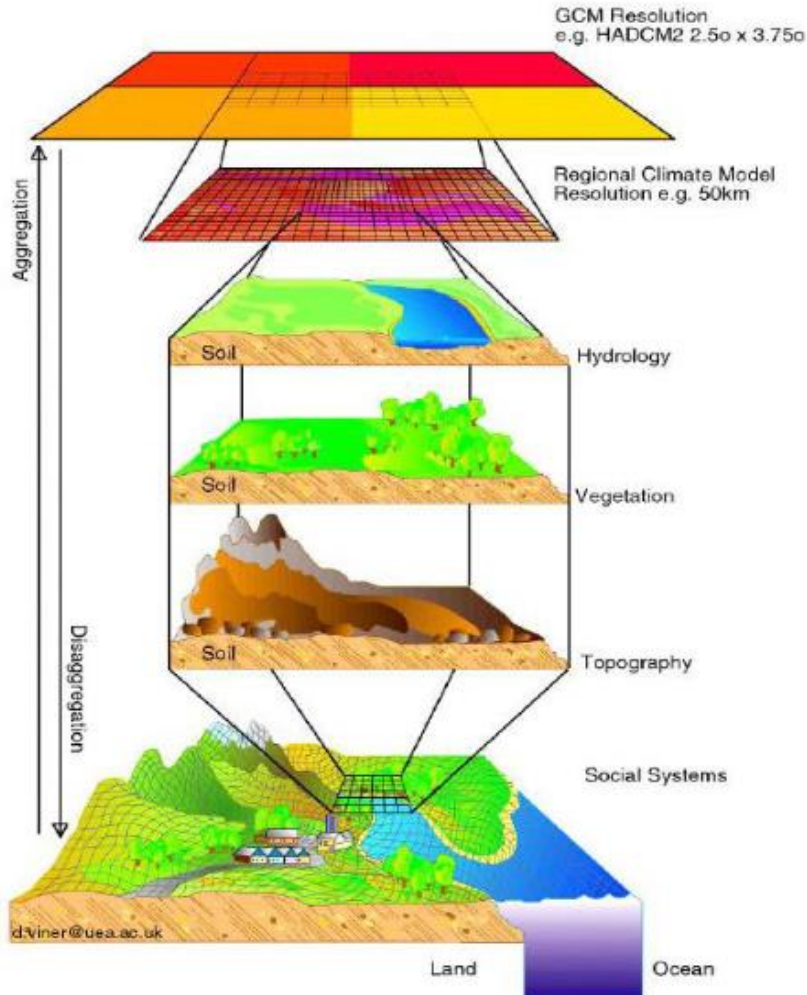


Figure 11 Conceptual diagram of spatial downscaling (Viner, 2012 as cited in Sylwia Trzaska & Emilie Schnar, 2014).

Two broad classes of downscaling methods are used to estimate higher-resolution climate projections from lower-resolution GCM projections: dynamical and statistical.

#### 2.2.4.1. Dynamical downscaling

Dynamical downscaling is performed using high-resolution regional climate models (RCMs), either nested in GCM simulations or reanalyzed atmospheric fields. Due to higher spatial resolution and, subsequently, relatively detailed representation of topographic features and surface characteristics of the underlying ground, mesoscale atmospheric processes, such as tropical disturbances or orographic effects, can be directly resolved by RCMs (Böhner & Bechtel, 2018).

Dynamical downscaling involves using a regional climate model (RCM) that covers a limited area, typically 5,000 km x 5,000 km, with a horizontal resolution of 50 km or less. The RCM simulates the physical processes of the atmosphere and land surface, such as cloud formation, radiation, precipitation, and soil hydrology, based on mathematical equations that are solved using a three-dimensional grid. The RCM requires the GCM's boundary conditions to provide the regional simulation's large-scale meteorological forcing. Dynamical downscaling can capture the effects of local topography, land-sea contrast, and other regional features that the GCM does not represent well. However, dynamical downscaling is computationally expensive and sensitive to the biases and uncertainties of the GCM and the RCM (Xu et al., 2019).

Wilby et al. (2009) provide a comprehensive review of the advantages and limitations of dynamical downscaling and the challenges and opportunities for future research. They discuss the physical basis, technical aspects, and applications of dynamical downscaling and compare it with other downscaling methods, such as statistical downscaling and empirical-statistical downscaling. They also highlight the uncertainties and biases that arise from dynamical downscaling and suggest ways to evaluate and improve the performance and reliability of RCMs.

Different dynamical downscaling methods for projecting future regional climate change scenarios exist, such as the time-dependent downscaling method, the pseudo global warming method, and the bias correction methods. These methods differ in accounting for changes in large-scale circulation and regional feedback under different greenhouse gas emission scenarios (Xu et al., 2019).

Nevertheless, Tapiador et al. (2020) came to the conclusion that the dynamic downscaling may only be necessary for purposes beyond pure research. They claim that this approach has several limitations, such as high computational costs, uncertainties in boundary conditions, and difficulties

in representing complex physical processes. Tapiador et al. suggests that alternative methods, such as statistical downscaling and machine learning, could provide more accurate and efficient projections of local climate variability and change. Likewise, the authors highlight the need for more observational data and better evaluation metrics to improve the quality and reliability of regional climate information.

#### 2.2.4.2. Statistical Downscaling

Statistical downscaling rests on empirical relationships between large-scale atmospheric variables (predictors) and local surface variables (predictands). The most straightforward method has the predictand as a function of the predictor(s), but other types of relationships have been used (Wilby & Fowler, 2010).

Statistical downscaling has a significant advantage: it is computationally efficient and allows the consideration of a large set of climate scenarios. Over time, the variation in projected change is far more significant among the various models than among emissions scenarios. Therefore, to fully account for this uncertainty, a multi-model ensemble is the most appropriate approach (Salathe Jr et al., 2007).

The main statistical downscaling techniques are Weather typing (weather classification schemes), Regression methods (transfer functions), and Weather generators. Each technique has strengths and weaknesses and some context where its application is favored.

- **Weather typing** is a statistical downscaling method that uses atmospheric circulation patterns to classify local meteorological variables. The main advantage of this method is that local variables are closely linked to global circulation. However, reliability depends on having a static relationship between large-scale circulation patterns and local climate. For watershed modelling, where hourly or daily precipitation is a crucial variable, this method

may not always be helpful because, typically, the correlation between local precipitation and large-scale circulation patterns is not strong (Chen et al., 2012). The technique is also valid for a wide variety of environmental variables as well as multi-site applications. Nevertheless, weather typing schemes are often local, an inadequate basis for simulating rare or extreme events, and entirely dependent on stationary circulation-to-surface climate relationships (Wilby et al., 2002). Additionally, this method assumes that the attributes of the weather patterns will remain the same in the future.

- **The regression method** is a type of statistical downscaling technique that establishes a statistical relationship between global variables (such as atmospheric pressure) and local variables (such as precipitation) based on historical observations. Regression methods rely on statistics to extrapolate data to higher resolutions based on the identified relationship between predictors and predictands. However, a recognized limitation of all regression-based methods is the underprediction of observed variance and a lack of a stable relationship between current and future climate (predictors and predictands) (Keller et al., 2022). The problem is particularly acute for daily precipitation downscaling because of the relatively low predictability of local amounts by large-scale forcing alone (Wilby & Fowler, 2010).
- **The weather generator** method is a type of statistical downscaling that uses a stochastic model to generate synthetic weather data at a local scale based on large-scale atmospheric predictors. It can produce multiple scenarios of daily weather variables, such as precipitation, temperature, humidity, wind speed, and solar radiation, consistent with the observed historical data and the projected future climate (Keller et al., 2022). In WGEN (for Weather Generator) models, the statistical process underlying the non-precipitation variables is a first-order vector (i.e., multiple variables modelled simultaneously)

autoregression (Wilks & Wilby, 1999). Wilby *et al.* (2002) established a Statistical Down Scaling Model, SDSM. It is a conditional weather generator that uses atmospheric circulation indices and regional moisture variables to estimate time-varying parameters (e.g., precipitation and temperature) that describe the daily weather at individual sites/station. SDSM is a valuable method because multiple, low-cost, single-site scenarios for daily climate parameters can be generated quickly and rapidly for different climate forcing conditions (Keller *et al.*, 2022).

Table 2 presents the strengths and weaknesses of the main statistical downscaling methods. Overall, there is no a better downscaling technique. Each plan should be carefully evaluated in the context of the intended application.

Method	Strengths	Weaknesses
<b>Weather typing</b> (e.g., analog method, hybrid approaches, fuzzy classification, self-organizing maps, Monte Carlo methods)	<ul style="list-style-type: none"> <li>• Yields physically interpretable linkages to surface climate.</li> <li>• Versatile (e.g., applicable to surface climate, air quality, flooding, erosion, etc.).</li> <li>• Compositing for analysis of extreme events.</li> </ul>	<ul style="list-style-type: none"> <li>• Requires additional task of weather classification.</li> <li>• Circulation-based schemes can be insensitive to future climate forcing.</li> <li>• May not capture intra-type variations in surface climate.</li> </ul>
<b>Regression methods</b> (e.g. linear regression,	<ul style="list-style-type: none"> <li>• Relatively straightforward to apply.</li> </ul>	<ul style="list-style-type: none"> <li>• Poor representation of observed variance.</li> </ul>

neural networks, canonical correlation analysis, kriging)	<ul style="list-style-type: none"> <li>• Employs full range of available predictor variables.</li> </ul>	<ul style="list-style-type: none"> <li>• May assume linearity and/or normality of data.</li> </ul>
	<ul style="list-style-type: none"> <li>• Off-the-shelf solutions and software are available.</li> </ul>	<ul style="list-style-type: none"> <li>• Poor representation of extreme events.</li> </ul>
<b>Weather generators</b> (e.g., Markov chains, stochastic models, spell length methods, storm arrival times, mixture modelling)	<ul style="list-style-type: none"> <li>• Production of large ensembles for uncertainty analysis or long simulations for extremes.</li> </ul>	<ul style="list-style-type: none"> <li>• Arbitrary adjustment of parameters for future climate.</li> </ul>
	<ul style="list-style-type: none"> <li>• Spatial interpolation of model parameters using landscape.</li> </ul>	<ul style="list-style-type: none"> <li>• Unanticipated effects to secondary variables of changing precipitation parameters.</li> </ul>
	<ul style="list-style-type: none"> <li>• Can generate sub-daily information.</li> </ul>	

*Table 2 Strengths and weaknesses of the main statistical downscaling methods (Wilby & Fowler, 2010)*

### 2.2.5. Impacts on water availability

Climate change is a global phenomenon that affects the hydrologic cycle and freshwater resources in various ways. According to (Gleick, 2019), climate change impacts water resources by altering temperature, precipitation patterns, storm frequency and intensity, snow and ice dynamics, sea level rise, and aquatic ecosystems. These impacts can significantly affect human health, food security, energy production, biodiversity conservation, and water management. Therefore, it is essential to scientifically explore the interrelated mechanisms between climate change and water resources based on empirical evidence and theoretical models.

The study of the impacts of climate change on water availability is a topic that has been discussed previously, but its relevance has notably increased in the last few years. In the Scopus database, a quantitative search result illustrates how the number of publications using the terms “impacts” + “climate change” + “water availability” has increased exponentially. Figure 12 exemplifies the growing pattern in using this concept in academic, peer-reviewed journals. For example, just in 2022 the number of publications was 348.

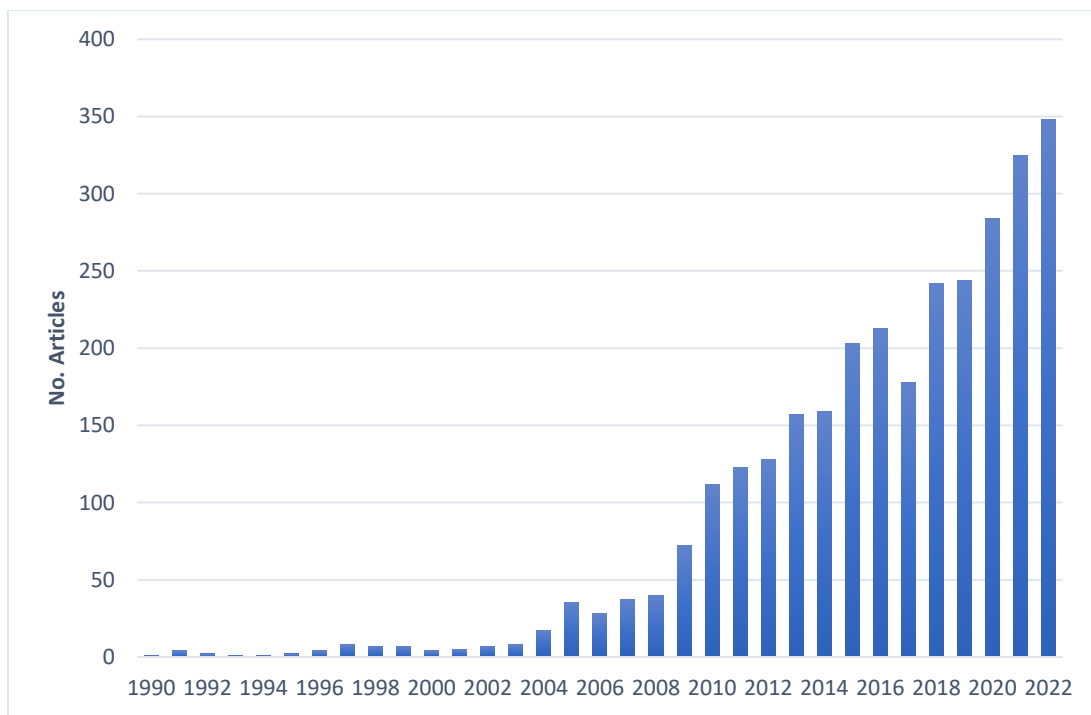


Figure 12 Number of publications containing “Impacts” + “climate change” + “water availability” in academic literature (1990 – 2022). Source: Scopus database

Water availability has been studied in several regions and with different goals. To mention a few:

- Dallison et al. (2021) analyzed the impacts of climate change on future water availability for hydropower and public water supply in Wales, UK. They found an increased occurrence of too low streamflow to satisfy the Public Water Supply and a decrease in annual abstraction volume resulting in a loss of generation potential.

- Mohammed et al. (2017) evaluated extreme flows and water availability of the Brahmaputra River (Bangladesh) under 1.5 and 2 °C global warming scenarios. The study concluded that floods would be more frequent and flood magnitudes greater, with greater water availability.
- Rocha et al. (2020) investigated the impacts of climate change on reservoir water availability, quality, and irrigation needs in a water-scarce Mediterranean region (southern Portugal). The results indicated that climate change would negatively impact reservoir availability, especially under RCP8.5. Additionally, future domestic water supply could be constrained by water quality problems related with phosphorus loads.
- Siqueira et al. (2021) analyzed the effects of climate and land cover changes on water availability in a Brazilian Cerrado basin. They found that riparian reforestation and soil and water conservation practices did not necessarily enhance water availability in the simulations.
- Aygün et al. (2020) presented an exhaustive review of the literature on historical and projected future changes in cold region hydrology in response to climate change. The most consistent and salient hydrological responses to historical and projected climate change were an earlier occurrence of snowmelt floods, an overall increase in water availability and streamflow during winter, and a decrease in water availability and streamflow during the warm season.

In particular, these researches have been done with an emphasis in Canada, among others:

- Bonsal et al. (2020), studied the current and future vulnerabilities for the western Canadian freshwater availability. They observed that the most significant and widespread impact is streamflow seasonality characterized by earlier spring freshets, increased winter, and decreased summer flow.

- Huaranga Alvarez et al. (2014) evaluated climate change's impact on managing the three reservoirs in the Lièvre River watershed, Quebec. Results showed that more significant quantities of water would have to be stored in the Lièvre River watershed in the future to decrease the risk of flooding in the Montreal Archipelago.
- Leveque et al. (2021) highlighted key risk factors along the impact chain of climate change on water supply security, from precipitation and runoff to surface water quality and availability at drinking water intakes, using the Province of Quebec as study area. The study emphasized how climate change increases the seasonal risks of water supply insecurity in a northern region, thereby increasing socioeconomic and public health risks.

## 2.3. Water management

### 2.3.1. Description

As meeting future water demands becomes more uncertain and water scarcity continuously increases, societies become more vulnerable to a wide range of risks associated with inadequate water supply in quantity and/or quality (WWAP , 2012). In that sense, allocating limited water resources, environmental quality, and policies for sustainable water use are issues of increasing concern. Conventional supply-oriented simulation models are not always adequate. Over the last decade, an integrated approach to water development has emerged, placing water supply projects in the context of demand-side issues, water quality, and ecosystem preservation (Sieber & Purkey, 2015).

Integrated water resources management (IWRM) is an approach widely accepted internationally as the way forward for efficient and equitable water management and related resources (Giupponi & Gain, 2017). One of the most used definitions of IWRM was given by the Global Water Partnership (GWP, 2012) as “a process which promotes the coordinated development and management of

water, land, and related resources to maximize economic and social welfare equitably without compromising the sustainability of vital ecosystems and the environment.”

The target of IWRM is to strive to facilitate the sustainable management of water resources by fostering information exchange and helping to match the needs for solutions to water problems with available tools, assistance, and resources. Water resources managers use management rules developed from hydrological conditions reflecting the current climate. They also make planning decisions based on the recent past (Huaringa Alvarez et al., 2014). The IWRM lists numerous models to assist in water allocation and management, among which the Water Evaluation and Planning (WEAP) model is one of the most useful models applied in many countries (Li et al., 2015).

Effective IWRM models must address the two systems shaping the water management landscape. First, factors related to the bio-physical system, namely climate, topography, land cover, surface water hydrology, groundwater hydrology, soils, water quality, and ecosystems, shape water availability and its movement through a watershed. Second, factors related to the socio-economic management system, mainly driven by human demand for water, shape how available water is stored, allocated, and delivered within or across watershed boundaries (Yates et al., 2005).

### **2.3.2. Water Evaluation And Planning (WEAP)**

Water management is a pressing challenge in many areas. How to distribute scarce water resources, protect water quality and ensure sustainable water use are growing concerns. Therefore, a model that not only focuses on water supply but also the relation with demand-side factors, water quality, and ecosystem conservation is required. The Water Evaluation and Planning System (WEAP) is a tool that aims to apply this approach to water resources planning.

Operating on the basic principle of water balance accounting, WEAP can be applied to municipal and agricultural systems, single subbasins, or complex river systems. Moreover, WEAP can address

a wide range of issues, e.g., sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation and energy demands, pollution tracking, ecosystem requirements, and project benefit-cost analyses (Sieber & Purkey, 2015). WEAP was created in 1988 as an initiative of the Stockholm Environment Institute.

Technically speaking, WEAP provides a comprehensive, flexible, and user-friendly framework for planning and policy analysis, which applies to complex water systems. WEAP can represent water resource systems incorporating natural inflows, precipitation, evaporation, and evapotranspiration as input data. Operational features, which can be specified as steady-state or time-varying, are represented including storage and release of water by reservoirs, physical discharge controls at reservoirs outlets, water flow in channels, consumptive demands, and hydropower release (Li et al., 2015).

WEAP operates on the basic principle of a water balance. The analyst represents the system's various supply sources (e.g., rivers, creeks, groundwater, reservoirs, and desalination plants); withdrawal, transmission, and wastewater treatment facilities; water demands; pollution generation; and ecosystem requirements. The data structure and level of detail can be easily customized to meet the needs and data availability for a particular system and analysis.

According to the Stockholm Environment Institute (2023), WEAP applications generally include several steps:

- Study definition: The time frame, spatial boundaries, system components, and configuration of the problem are established.

- Current accounts: A snapshot of actual water demand, pollution loads, resources and supplies for the system are developed. This can be viewed as a calibration step in the development of an application.
- Scenarios: A set of alternative assumptions about future impacts of policies, costs, and climate, for example, on water demand, supply, hydrology, and pollution can be explored.
- Evaluation: The scenarios are evaluated about water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

In recent years, WEAP has been widely employed by researchers and water resources planners. For example, Hatamkhani et al. (2023) use WEAP to incorporate ecosystem services value into the optimal development of hydropower projects. Similarly, Olabiwonnun et al. (2022) studied a sustainable low flow using a hydropower reservoir for ecological water management using a WEAP model. On the other hand, several authors have used WEAP to evaluate water shortage situations worldwide. For example, Afghanistan (Hekmatnia et al., 2022), Thailand (Chalermchai Pawattana, 2021), Ethiopia (Teklu et al., 2019) and the United States (Brown et al., 2019).

#### 2.4. Novelty of the study

As shown along this literature review, the pressing issue of climate change has garnered global attention, prompting researchers to investigate its multifaceted impacts on various ecosystems. While numerous studies have explored the effects of climate change on water availability in different regions, the novelty of the present thesis lies in its unique focus on the remote northern community of Umiujaq, Nunavik. Unlike the majority of prior research, which has predominantly concentrated on more temperate and urban environments, this study pioneers a fresh perspective by delving into the challenges faced by a northern community that is disproportionately vulnerable to the repercussions of climate change and provides some adaptation measures based on the results of the investigation.

### 3. Study area and Methodology

#### 3.1. Research Methodology

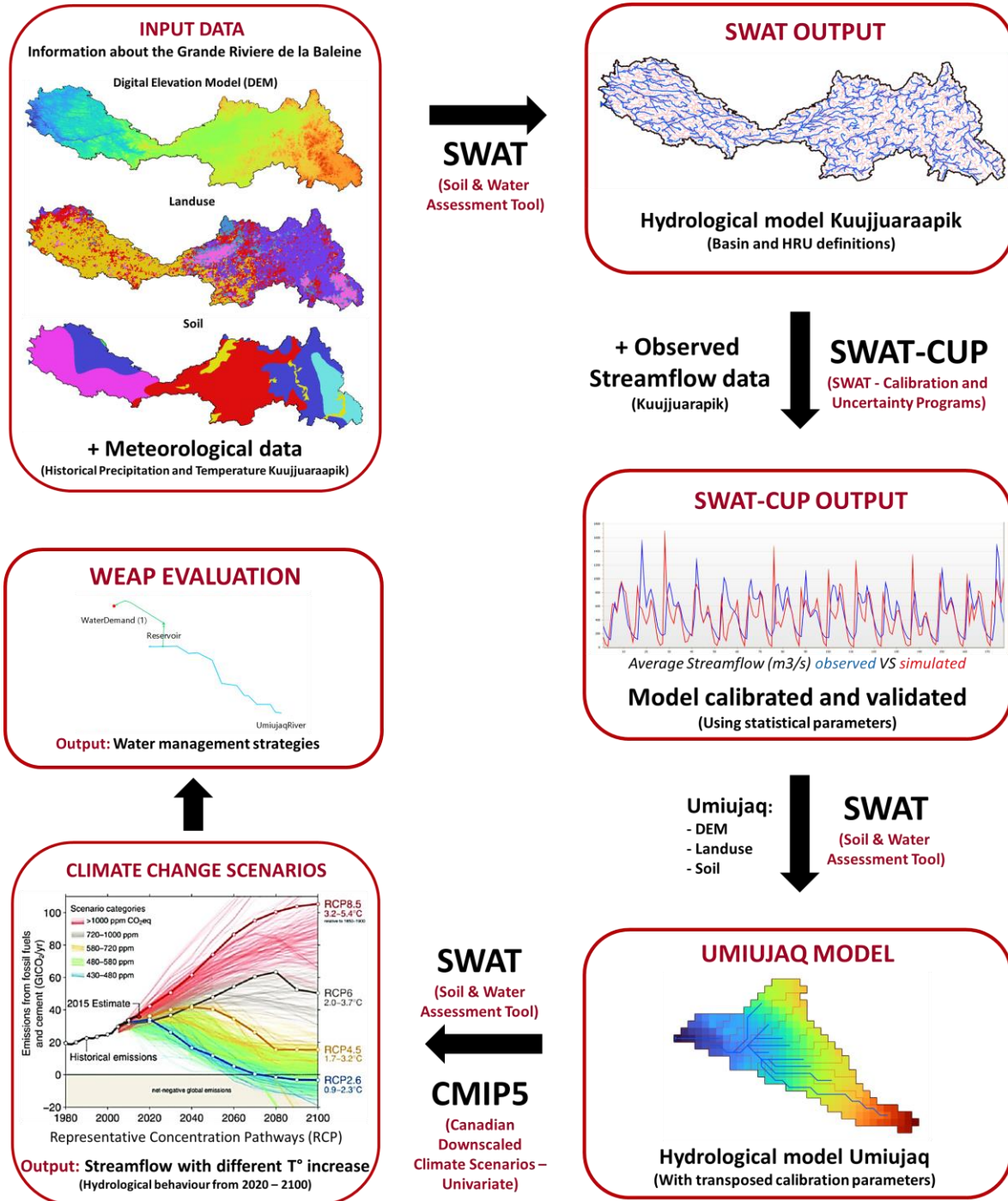


Figure 13 Outline of the research methodology.

Figure 13 presents an outline of the research methodology that was used in this research project.

Each step is explained below, and the results will be discussed in the next chapter. It starts by

compiling the data for modelling the *Grande Riviere de la Baleine* watershed in the Soil and Water Assessment Tool (SWAT). Once developed, the model must be calibrated and validated using the SWAT-CUP software (Abbaspour, 2015). Then, the model is transposed to the Umiujaq watershed with the specific data for this region. With this model, three different climate change scenarios are forced, generating the results that will analyze the impacts of climate change in this watershed. Finally, with WEAP, some water management strategies are proposed to mitigate some effects.

## 3.2. Study Area

### 3.2.1. Nunavik

Nunavik is a region located in the northern part of Quebec, north of the 55th parallel. It covers approximately 500,000 km<sup>2</sup>, representing more than one-third of Quebec's territory. The region is home to over 13,000 people who live in 14 villages spread along the Ungava Bay, Hudson Strait and Eastern Hudson Bay coasts (The Canadian Encyclopedia, 2023).

The Inuit have inhabited the northern Quebec territory of Nunavik for more than 4,000 years. Over the past 300 years, the most substantial and long-standing contact between the Inuit of Nunavik and Europeans was with Anglican missionaries, traders, and the Hudson's Bay Company. Inuit were a nomadic people. It was only in the early 1950s that Inuit adopted a more sedentary lifestyle by establishing residence in permanent villages (Makivik Corporation, 2013).

Nunavik is one of four Inuit homelands in Canada that make up Inuit Nunangat. The political, cultural and economic administrations of Nunavik are managed by the Makivik Corporation (Indigenous Peoples Atlas of Canada, 2023). A map of the Nunavik region is presented in Figure 14 (CCEK - Comité consultatif de l'environnement Kativik, n.d.).



Figure 14 Map of Nunavik (CCEK - Comité consultatif de l'environnement Kativik, n.d.)

### 3.2.2. Umiujaq

Umiujaq is a northern village and an Inuit community in Nunavik in northern Quebec, Canada.

Umiujaq was established at the foot of a hill that resembles an overturned umiaq (the traditional Inuit walrus-skin boat) (Makivvik Corporation, 2023). It's located 15 km north of Lake Tasiujaq (Richmond Gulf or Lac Guillaume-Delisle), an immense inland bay connected to the Hudson Bay via a rocky gulch resembling a canyon. The sheltered maritime environment features sporadic black spruce and larch, but the surrounding area is characterized by shrub tundra, discontinuous permafrost (mostly palsa bogs), and thermokarst lakes.

Umiujaq was established in 1986 by Inuit from Kuujuaaraapik, 160 km to the south, who decided to relocate to the region where they hoped to better preserve their traditional lifestyle in an area

where fish and game were not threatened by development (Centre d'études Nordiques (CEN), 2022b). Specifically, the Inuit had requested that a new community be built north of Kuujjuaraapik, given the proximity of the Great Whale River hydroelectric project. As a result, nearly one-third of the Inuit from Kuujjuaraapik moved to Umiujaq in 1986.

Currently, the community fills its reservoir of raw water, with an approximate size of 16,000 m<sup>3</sup>, pumping water from a river with a small watershed (600 Ha.) compared with other rivers in the region. Figure 15, Figure 16, and Figure 17 show the characteristics of elevation, land use, and soil. The output of the watershed was located in the place where the community pumps the water. The reservoir stores raw water near the water treatment plant. Then, water is treated with filtration, and disinfection with UV and chlorine. Finally, treated water is stored in a tank and then distributed to the population by trucks to fill household water tanks. According to Lemieux et al. (2016), the community has an average consumption of 108 L/person/day.

The watershed has a contrast elevation of 300 meters from the highest point to where the water is extracted. In this area, according to the USGS Global Land Cover Characterization (GLCC) database (Earth Resources Observation And Science (EROS) Center, 2017), 80% of the land is wooded tundra, 19% is mixed tundra, and approximately 1% is shrubland. In terms of the soil, according to the FAO/Unesco Soil Map of the World (Food and Agriculture Organization of the United Nations (FAO), n.d.), this area is 100% lithosols or soils which are limited in depth by a continuous coherent hard rock within 10 cm of the surface (FAO, 1974).

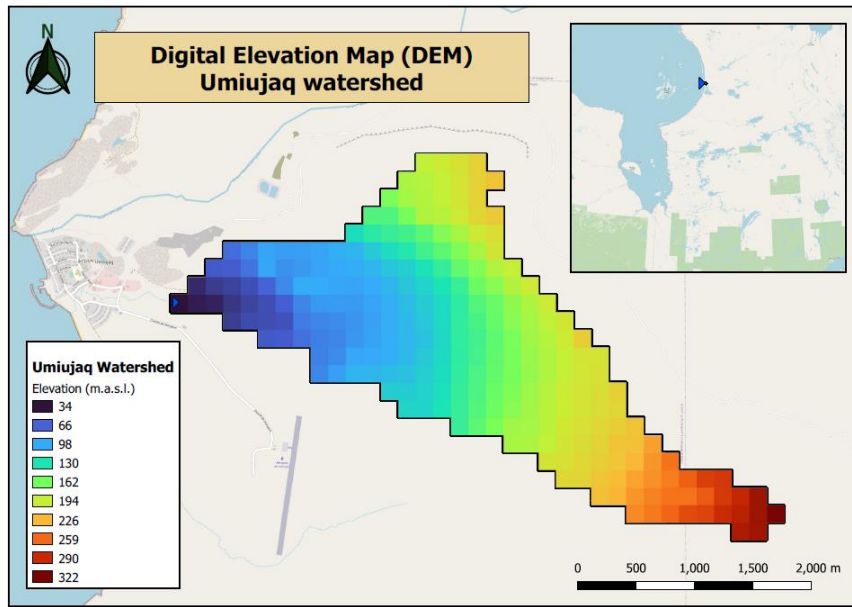


Figure 15 Digital Elevation Map (DEM) Umiujaq Watershed

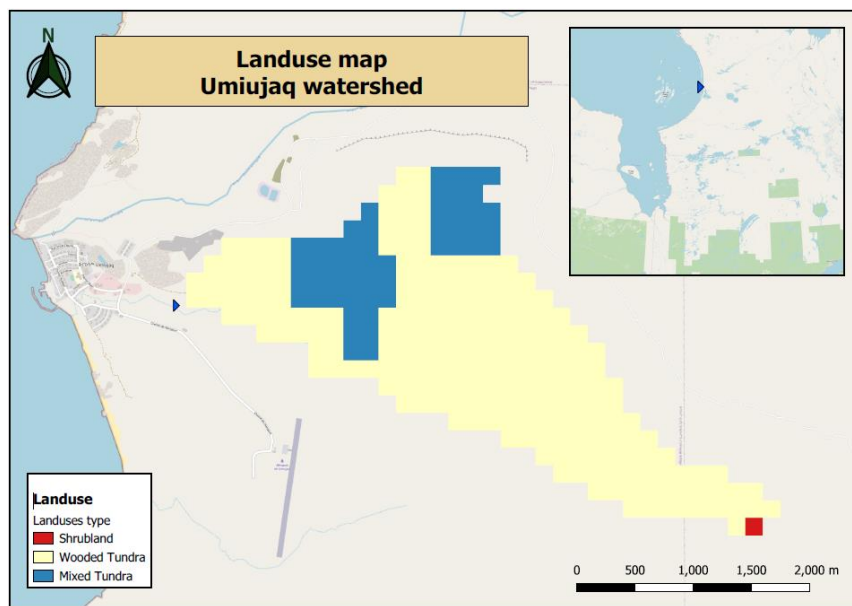


Figure 16 Landuse map Umiujaq Watershed

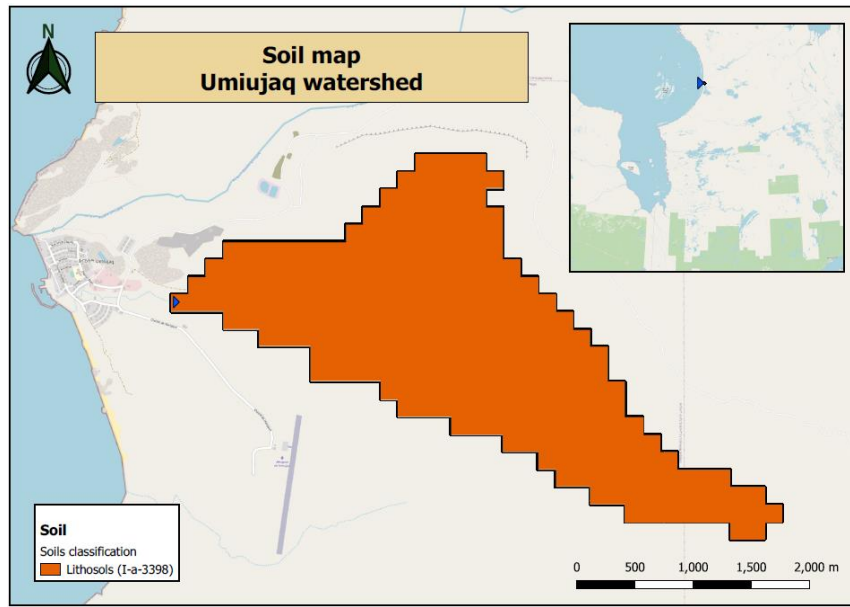


Figure 17 Soil map Umiujaq Watershed

### 3.2.3. Kuujjuaraapik

In northern regions, there exists a significant gap in terms of weather data availability and coverage. Specifically, Umiujaq lacks essential weather and streamflow data for the development of the hydrological model. Given this limited availability, a rainfall-runoff model was developed for a nearby watershed with better data. The river is the *Grande Riviere de la Baleine*, and the data (including the streamflow) was obtained from a station close to the village of Kuujjuaraapik. The watershed close to Kuujjuaraapik is relevant and adequate to Umiujaq due to their shared geographic proximity and their location within the Nunavik region in northern Quebec, Canada.

Kuujjuaraapik (little great river) is Nunavik's southernmost village. It is also unique as it is a bicultural community of Inuit and Cree. The Cree community is called Whapmagootsui (where there are whales, in the Cree language). This village is also officially designated Poste-de-la-Baleine, making it one of the few places in Canada with three official names (Makivik Corporation, 2013).

Kuujjuaraapik is located at the terrestrial boundary between the taiga and the tundra. The community is built on a sandy headland, at the mouth of the Great Whale River. Granites covered by a thick layer of sand characterize the region's soils (Centre d'études Nordiques (CEN), 2022a).

The Great Whale River flows 726 km from Lake Saint-Luson through Lake Bienville to southeastern Hudson Bay at Manitounuk Sound near Kuujjuarapik. With a drainage basin of 42,735 km<sup>2</sup>, the Great Whale River is one of the largest rivers of northern Québec (Nozais et al., 2021), achieving peak flows of around 1740 m<sup>3</sup>/s in late May and an annual average discharge of 700 m<sup>3</sup>/s (Bhiry et al., 2011).

The elevation, landuse and soil information in the watershed are presented In Figure 18, Figure 19, and Figure 20. The outlet is station 03ED001 (*Grande Riviere de la Baleine – QC*). The station records monthly mean discharge (m<sup>3</sup>/s) and has been active since 1961 (Environment and Climate Change Canada, 2023).

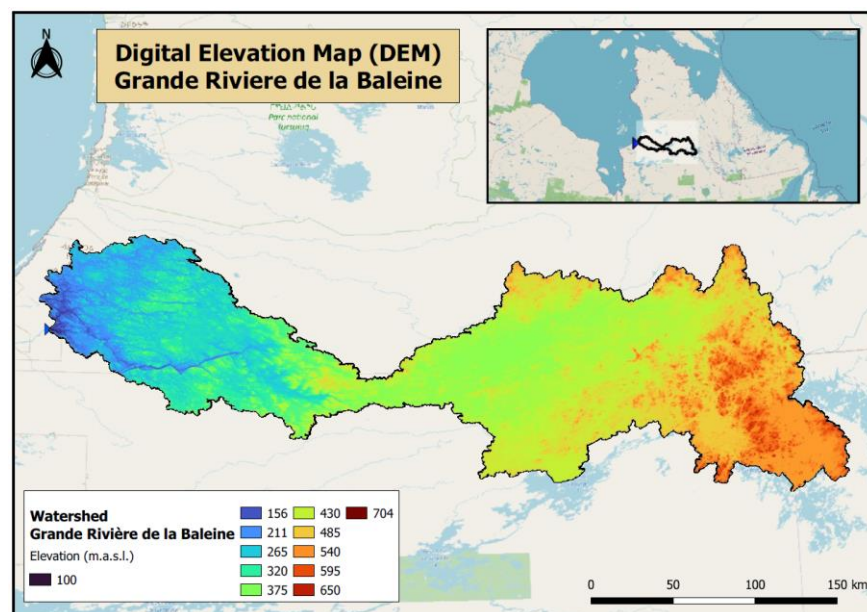


Figure 18 Digital Elevation Map (DEM) Grande Riviere de la Baleine (Kuujjuaraapik)

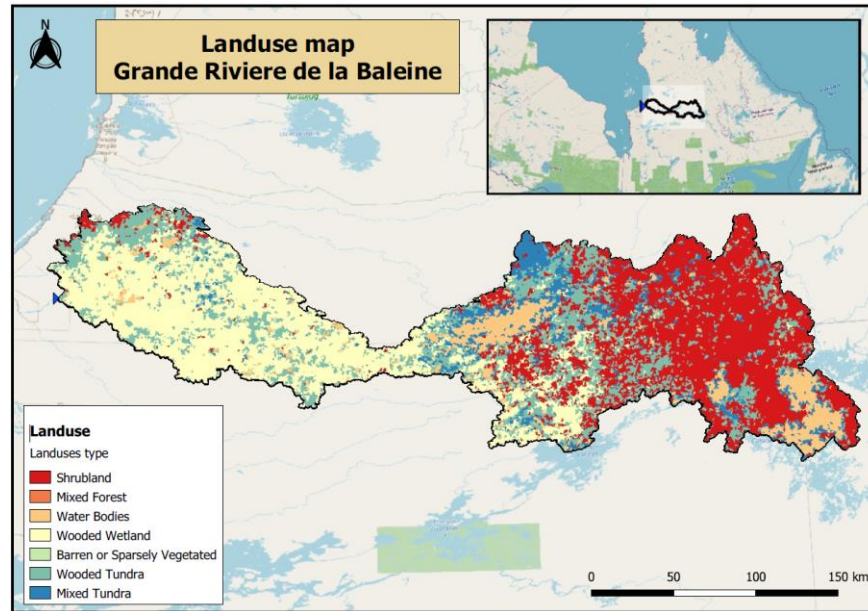


Figure 19 Landuse map Grande Riviere de la Baleine (Kuujuaaraapik)

The highest point of the watershed rises to 704 meters above sea level, and the station is 100 meters above sea level. The *Grande Riviere de la Baleine* is one of the principal rivers in the region, with an extension of approximately 36.300 km<sup>2</sup> (Gouvernement du Quebec, n.d.). In this area, the primary type of land is shrubland (31,2%), wooded wetland (31,0%), and wooded tundra (21,9%) (Earth Resources Observation And Science (EROS) Center, 2017).

Conversely, the watershed presents a mix of soils, including Orthic Podzols (Po), Lithosols (l), Dystric Cambisols (Bd) and Gelic Histosols (Ox). To facilitate the simulation of those soils and their characteristics, some regions are presented as a combination of several types of soils (using FAO classification). In the legend of Figure 20 are given the percentage and types of soils of the watershed and in Table 3, a brief description of each one.

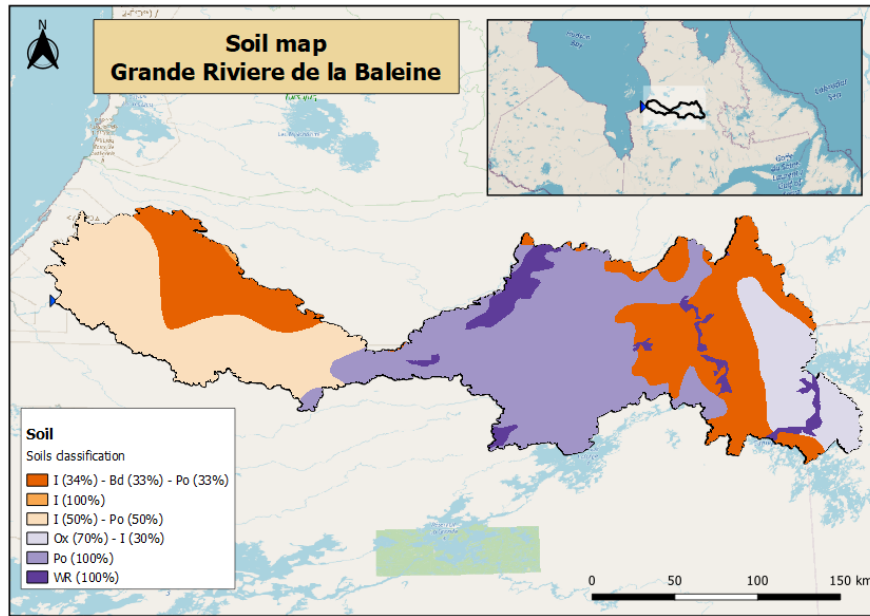


Figure 20 Soil map Grande Riviere de la Baleine (Kuujuaaraapik)

SOIL TYPE	DESCRIPTION
<b>Orthic Podzols (Po)</b>	Podzols which in all sub horizons has a ratio of percentage of free iron to percentage of carbon of less than 6, but which contains sufficient free iron to turn redder on ignition.
<b>Dystric Cambisols (Bd)</b>	Cambisols having an ochric A horizon and a base saturation (by NH <sub>2</sub> OAc) of less than 50 percent at least between 20 and 50 cm from the surface.
<b>Lithosols (I)</b>	Soils which are limited in depth by continuous coherent hard rock within 10 cm of the surface.
<b>Gelic Histosols (Ox)</b>	Histosols having permafrost within 200 cm of the surface.

Table 3 Soil type description (FAO, 1974)

### 3.3. SWAT Model development

#### 3.3.1. SWAT Input data

To develop the hydrological model, there are required three sets of input data:

- Geographic data: elevation, land use and soil information.

- Weather data: Precipitation, temperature, solar radiation, relative humidity, and wind speed.
- Water quantity: streamflow of the river modelled.

#### 3.3.1.1. Geographic data

Geographic information and maps are the basic spatial information that allows the hydrological models to be built. The elevation gives information about how and where the water runs off. At the same time, land and soil use influence various components of the hydrologic budget, such as evaporation, surface runoff, infiltration, and groundwater recharge (Öztürk et al., 2013).

Firstly, in Figure 15 and Figure 18, the Digital Elevation Model (DEM) of Umiujaq and Kuujjuaraapik were presented. A DEM is a representation of the topographic surface of the Earth, excluding surface objects like trees, buildings, etc. These topographic maps produced by Natural Resources Canada conform to Canada's National Topographic System (NTS). The standard scale used was 1:250,000 (Natural Resources Canada, 2015).

Secondly, the landuse maps presented in Figure 16 and Figure 19, have a resolution of 400m and were obtained through the U.S. Geological Survey and their Global Land Cover Characterization (GLCC). GLCC is a series of global land cover classification datasets based primarily on the unsupervised classification of 1-km AVHRR (Advanced Very High-Resolution Radiometer) 10-day NDVI (Normalized Difference Vegetation Index) composites. The AVHRR source imagery dates from April 1992 through March 1993 (Earth Resources Observation And Science (EROS) Center, 2017).

Thirdly, the digitized Soil Map of the World, at 1:5.000.000 scale, was used to generate Figure 17 and Figure 20. Even though the resolution of the FAO map is coarse, different studies have demonstrated that the accuracy of the simulation does not necessarily improve by increasing the resolution of the soil map (Mukundan et al., 2010; Ye et al., 2011). Soil units from the legend of the

soil map of the world comprise 106 soil and are grouped into twenty-six major soil groupings. The soils in the study areas are briefly explained in Table 3.

Finally, it's important to note that all maps had to be projected on the same coordinate system before being used in the software. For the Umiujaq and Kuujjuaraapik watersheds, the selected coordinate system was the UTM Zone 18N (EPSG:32618), which applies to the area between 78°W and 72°W, northern hemisphere between equator and 84°N, onshore and offshore. Bahamas. Canada - Nunavut; Ontario; Quebec. Colombia. Cuba. Ecuador. Greenland. Haiti. Jamaica. Panama. Turks and Caicos Islands. United States (USA). Venezuela (EPSG, 2020) .

**3.3.1.2. Climate data**

One of the reasons to select Kuujjuaraapik as the alternative watershed to calibrate and validate the hydrological model and then transpose the simulation was because it had consecutive data for precipitation and temperature and streamflow for a similar period. The years selected were from 1975 to 2003. The average precipitation, maximum and minimum temperature during 1975 to 2003 are presented in the Figure 21.

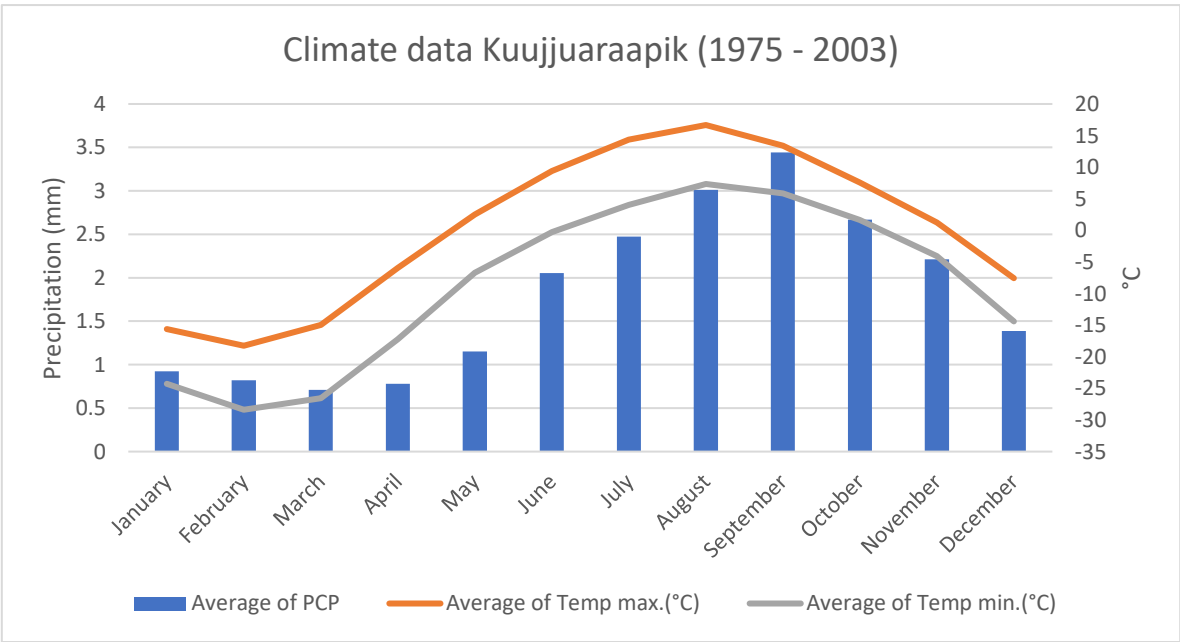


Figure 21 Average Precipitation (mm), temperature max and min (°C) for Kuujjuaraapik (1975 – 2003)

Daily total precipitation (mm) and maximum and minimum temperature (°C) were obtained from the station Kuujjuaraapik A (climate ID is 7103536), located on the Latitude 55° 17' 00" N and Longitude 77° 45' 00" W. Its elevation is 12.2 M.A.S.L. (Environment and Climate Change Canada, 2011).

The integrated SWAT weather generator (WGEN) was used for the other weather data (solar radiation, wind speed and relative humidity) (Richardson & Wright, 1984). WGEN is a stochastic weather generator that uses monthly and annual statistics to generate daily time series of the variables.

#### 3.3.1.3. Observed streamflow

The third set of input data required for modelling the watershed is the river's streamflow. This data is vital as it will be used to compare the preliminary results of the model and calibrate and validate its performance. Unfortunately, the river used for the Umiujaq community didn't have a flow meter or historical data, hindering this water body's calibration. During the summer of 2022, a flow meter was installed in the river. A future analysis could be done to validate the model generated in this research and have more accurate results for the community.

On the other hand, a station from the Government of Canada, located at latitude 55° 14' 15" N and Longitude 76° 59' 02" W, recorded daily streamflow (m<sup>3</sup>/s) in the *Grande Riviere de la Baleine* what allows the calibration and validation of this model. The ID of the station is 03ED001, and it has data for the following years: 1961-1972; 1974-2003; 2008-2016 (Environment and Climate Change Canada, 2023). This station is part of HYDAT, a relational database that contains computed data of: daily and monthly means of flow, water levels, and sediment concentrations (for sediment sites) (Environment and Climate Change Canada, 2010). In order to have continuity in the data, both for weather and water quantity, the period selected for the study was from 1975 to 2003.

### 3.3.2. Watershed and hydrological response units delineation

The first step of the research methodology is compiling the data required to develop the hydrological model. The data source was discussed in the numeral 3.3.1 SWAT Input data, and presented in Figure 18 to Figure 20. Then, the data has to be processed in SWAT, a small watershed-to-river basin-scale model used to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change (SWAT, 2023). SWAT is utilized within QGIS, a free and open-source Geographic Information System. Firstly, the watershed must be delineated. Based on the information of the Digital Elevation Map, a stream network is burned. Then, a basin outlet should be placed and selected. As mentioned, this outlet was placed where station 03ED001 (streamflow) is located.

Secondly, to set up a watershed simulation, the watershed must be divided into subunits. The first level of subdivision is the subbasin. Subbasins possess a geographic position in the watershed and are spatially related to one another, e.g. outflow from subbasin #5 enters subbasin #7. Next, the land area in a subbasin may be divided into hydrologic response units (HRUs). Hydrologic response units are portions of a subbasin that possess unique landuse/management/soil attributes (J.G. Arnold et al., 2012).

Once the HRU's definition is completed, the meteorological data is provided to the model. The precipitation and temperature information are set up in a daily format, with the starting date of the data and for the same period (1975 – 2003). The information about the weather station is also supplied (name, latitude, longitude, elevation). Finally, a warm-up period of three (3) years is selected. The warm-up period is the time necessary for the model to reach a steady state and, therefore, mimic the actual system. In this case, from 1975 to 1977.

The Figure 22 shows the division of the watershed of the *Grande Riviere de la Baleine* into 472 subbasins and the location of the outlet. Additionally, it's important to mention that the watershed was divided into 917 HRUs.

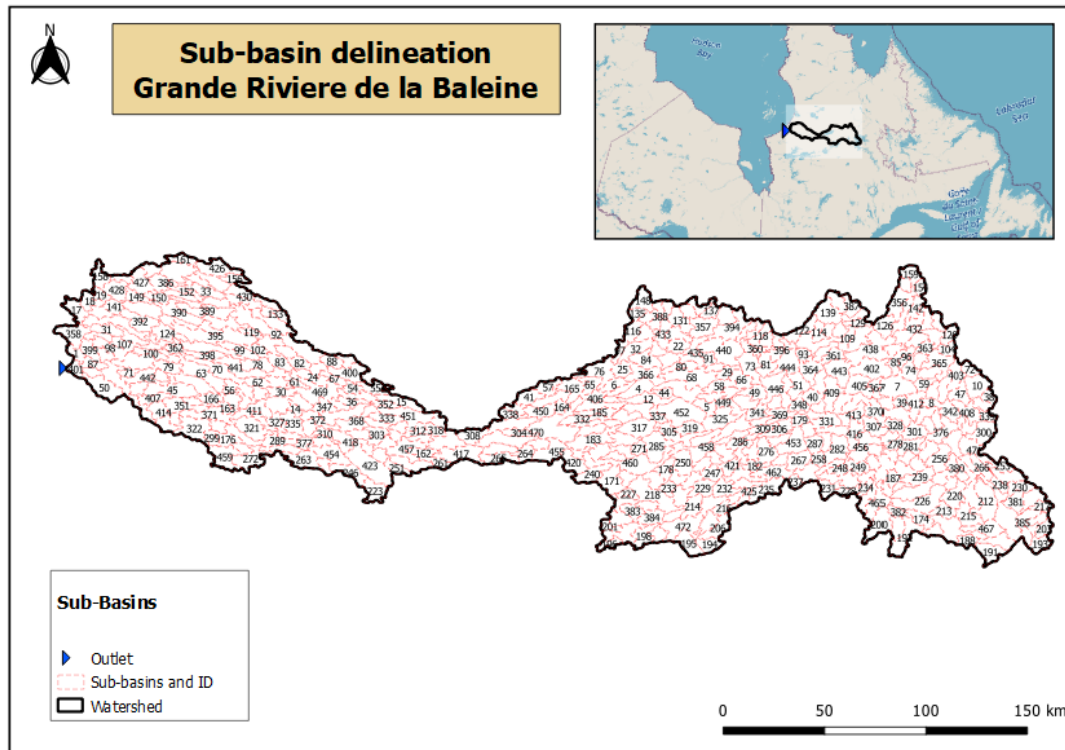


Figure 22 Sub-basins delineation Grande Riviere de la Baleine (Kuujjuaraapik)

### 3.3.3. Sensitivity analysis

The sensitivity analysis is the stage that comes before the calibration-validation procedures. The main purpose is to identify the parameters that strongly influence the modeled hydrological processes (Marin et al., 2020). This stage is important because, first, parameters represent processes, and sensitivity analysis provides information on the most important processes in the study region. And second, sensitivity analysis helps to decrease the number of parameters in the calibration procedure by eliminating the parameters identified as not sensitive (Abbaspour et al., 2018).

In SWAT – CUP, the software used for the calibration and validation, two types of sensitivity analysis are allowed: Global Sensitivity and One-at-a-time sensitivity analysis. One-at-a-time sensitivity shows a variable's sensitivity to the changes in a parameter if all other parameters are kept constant at some value. In a global sensitivity analysis, all the input factors are varied simultaneously, and the sensitivity is evaluated over the entire range of each input factor.

Abbaspour et al. (2018) also presented a guideline for a successful calibration using SWAT. According to them, after building the model with the best available data, a pre-calibration run of the parameters related to rainfall and snow parameters is necessary to identify their best values and then to fix them in the model without further change.

Additionally, Aygün et al. (2020) found that streamflow regimes in cold regions are mostly shaped by the distinct hydrological processes related to snow and frozen soil. Therefore, the snow parameters of the model gain a higher value in this context and were pre-calibrated before running a sensitive analysis and full calibration. The calibrated snow parameters, their description and range are presented in the Table 4:

Parameter	Description	Range
v__SMTMP.bsn	Snow melt base temperature (°C): The snow pack will not melt until the snow pack temperature exceeds a threshold value.	-20 – 20 (°C)
v__SFTMP.bsn	Snowfall temperature (°C): Mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain.	-20 – 20 (°C)

v__SMFMX.bsn	Melt factor for snow on June 21 (mm H <sub>2</sub> O/°C-day):  If the watershed is in the Northern Hemisphere, SMFMX will be the maximum melt factor. SMFMX and SMFMN allow the rate of snow melt to vary through the year. The variables account for the impact of snow pack density on snow melt.	0 - 20
v__SMFMN.bsn	Melt factor for snow on December 21 (mm H <sub>2</sub> O/°C-day):	0 - 20
v__TIMP.bsn	Snowpack temperature lag factor:  The influence of the previous day's snow pack temperature on the current day's snow pack temperature is controlled by a lagging factor. The lagging factor inherently accounts for snow pack density, snow pack depth, exposure and other factors affecting snow pack temperature.	0 - 1

Table 4 SWAT Snow parameters pre calibrated (J.G. Arnold et al., 2012).

After finding the best values for the snow parameters, a sensitivity analysis was done with some parameters that were found sensitive by other authors (see Marin et al., 2020; Shrestha et al., 2017).

These parameters, along with their description and range, are presented in Table 5.

Parameter	Description	Range
V__CANMX.hru	Maximum canopy storage (mm H <sub>2</sub> O).	0 - 100
V__GW_REVAP.gw	Groundwater "revap" coefficient.	0.02 - 0.2
V__GW_DELAY.gw	Groundwater delay time (days).	0 - 500
V__ESCO.hru	Soil evaporation compensation factor.	0 - 1

V__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H <sub>2</sub> O).	0 - 5000
V__ALPHA_BF.gw	Baseflow alpha factor (1/days).	0 - 1
R__CN2.mgt*	Initial SCS runoff curve number for moisture condition II.	35 – 98 (-0.4 – 0.4)
V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm H <sub>2</sub> O).	0 - 1000
R__SOL_AWC(..).sol*	Available water capacity of the soil layer (mm H <sub>2</sub> O/mm soil).	0 – 1 (-0.1 - 0.1)

*Table 5 SWAT parameters evaluated in sensitivity analysis*

*\* In SWAT-CUP, v\_\_ means the existing parameter value is to be replaced by a given value, while r\_\_ means an existing parameter value is multiplied by (1+ a given value). Some of the parameters are equivalent along the watershed, but others change their value in each HRU. These parameters should be calibrated with R\_ to avoid affecting and homogenizing these characteristics of the watershed.*

The parameters more sensitive, between the range of interest previously fixed, are selected and proceeded to start the next step: calibration and validation of the model.

#### 3.3.4. Calibration and validation of the model

Calibration refers to a procedure where the difference between model simulation and observation are minimized. Calibration is inherently subjective and intimately linked to model output uncertainty. The uncertainty stems from the fact that nearly all measurements are subject to some error, models are simplifications of reality, and the inferences are usually statistical in nature. Furthermore, because one can only measure a limited number of (noisy) data and because physical

systems are usually modeled by continuum equations, no calibration can lead to a single parameter set or a single output. In other words, if a single model fits the measurements, there will be many of them (Abbaspour et al., 2018).

In this research, the calibration was carried out in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) (Abbaspour, 2015). This program facilitates automated calibration and uncertainty analysis, highlighting the necessity for SWAT users to better understand overall hydrologic processes (Kondo et al., 2021). The observed data is daily streamflow ( $\text{m}^3/\text{s}$ ) and was explained in the section 3.3.1.3 Observed streamflow. This data is compared with the output of the model. In this study, Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970) was used as the objective function to identify the best simulation ranges of parameters due to its wide applicability and reliability in hydrological modelling (B. K. Pandey et al., 2019).

Moreover, SUFI-2 (Sequential Uncertainty Fitting) algorithm was used to calibrate. SUFI-2 operates by performing several iterations. In each iteration, the parameter ranges get smaller by zooming on a region of the parameter space, which produced better results in the previous iteration. For time-consuming large-scale models, SUFI-2 was found to be quite efficient (Abbaspour et al., 2015).

Calibration and validation are typically performed by splitting the available observed data into two datasets: one for calibration and another for validation. Data are most frequently split by time periods, carefully ensuring that the climate data used for both calibration and validation are not substantially different, i.e., wet, moderate, and dry years occur in both periods (Yew Gan et al., 1997). Validation is used to build confidence in the calibrated parameters. For this purpose, the calibrated parameter ranges are applied to an independent measured dataset, without further changes. For the Kuujjuaraapik watershed, observed data was divided into two periods: from 1978 to 1992 for calibration and from 1994 to 2003 for validation. The one-year gap (1993) is due to

missed data. A comparison of the data is presented below in Table 6. It can be seen how the average and the standard deviation are alike, which reflects that statistically are similar and that almost certainly both periods encapsulate wet and dry periods.

	<b>Calibration</b> <b>1978 - 1992</b>	<b>Validation</b> <b>1994- 2003</b>
<b>Data (Number of months)</b>	177	119
<b>Percentage of data</b>	59.8%	40.2%
<b>Monthly average (m<sup>3</sup>/s)</b>	519.6	477.1
<b>Standard deviation</b>	300.9	283.4

*Table 6 Calibration and Validation data*

Finally, to evaluate the model performance, Moriasi et al. (2007) recommended three quantitative statistics for hydrological models: Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR).

Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). It is defined by the equation:

$$NSE = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2}$$

Where Q is the streamflow, and m and s stand for measured and simulated, respectively, and the bar stands for average. The goal is maximizing the value, with the optimal value being 1 meaning the plot of observed data fits the simulation perfectly.

Percent bias (PBIAS) measures the average tendency of the simulated values to be larger or smaller than their observed ones. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation (hydroGOF, 2020). It is defined by the equation:

$$PBIAS = 100 * \frac{\sum_{i=1}^n (Q_m - Q_s)_i}{\sum_{i=1}^n Q_{m,i}}$$

Where Q is the streamflow, and m and s stand for measured and simulated, respectively, and the bar stands for average. Positive values indicate model underestimation and negative values indicate model over estimation.

The Ratio of the Root mean square error to the standard deviation of measured data (RSR) normalizes the Root Mean Squared Error (RMSE) using the standard deviation of observed values. It is defined by the equation:

$$RSR = \frac{\sqrt{\sum_{i=1}^n (Q_m - Q_s)_i^2}}{\sqrt{\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)^2}}$$

Where Q is the streamflow, and m and s stand for measured and simulated, respectively, and the bar stands for average. It varies from 0 to large positive values. The lower the RSR the better the model fit.

In Table 7 is shown Moriasi et al. evaluation proposal, with four performance rating: Very good, good, satisfactory, and unsatisfactory.

<b>PERFORMANCE RATING</b>	<b>NSE</b>	<b>RSR</b>	<b>PBIAS</b>
<b>Very good</b>	0.75 < NSE < 1.00	0.00 < RSR < 0.50	PBIAS < 10
<b>Good</b>	0.65 < NSE < 0.75	0.50 < RSR < 0.60	10 < PBIAS < 15
<b>Satisfactory</b>	0.50 < NSE < 0.65	0.60 < RSR < 0.70	15 < PBIAS < 25
<b>Unsatisfactory</b>	NSE < 0.50	RSR > 0.70	PBIAS > 25

*Table 7 General performance ratings for recommended statistics for a monthly time step (D. N. Moriasi et al., 2007).*

Once the model achieves an acceptable performance after several simulations in consecutive iterations, the calibration can be transposed to the Umiujaq watershed. It is important to mention that it is not a direct transfer of parameters, but a transfer by type of HRU. Therefore, if HRU parameters are correct in the first model, they should work in a second watershed with different distribution of land use.

With the data explained in section 3.2.2 Umiujaq, presented in Figure 15, Figure 16, and Figure 17, and with a similar methodology explained in 3.3.2 Watershed and hydrological response units delineation, the Umiujaq watershed is delineated. Figure 23 shows the division of the Umiujaq watershed into 13 subbasins and the outlet's location. Additionally, it's important to mention that the watershed was divided into 22 HRUs.

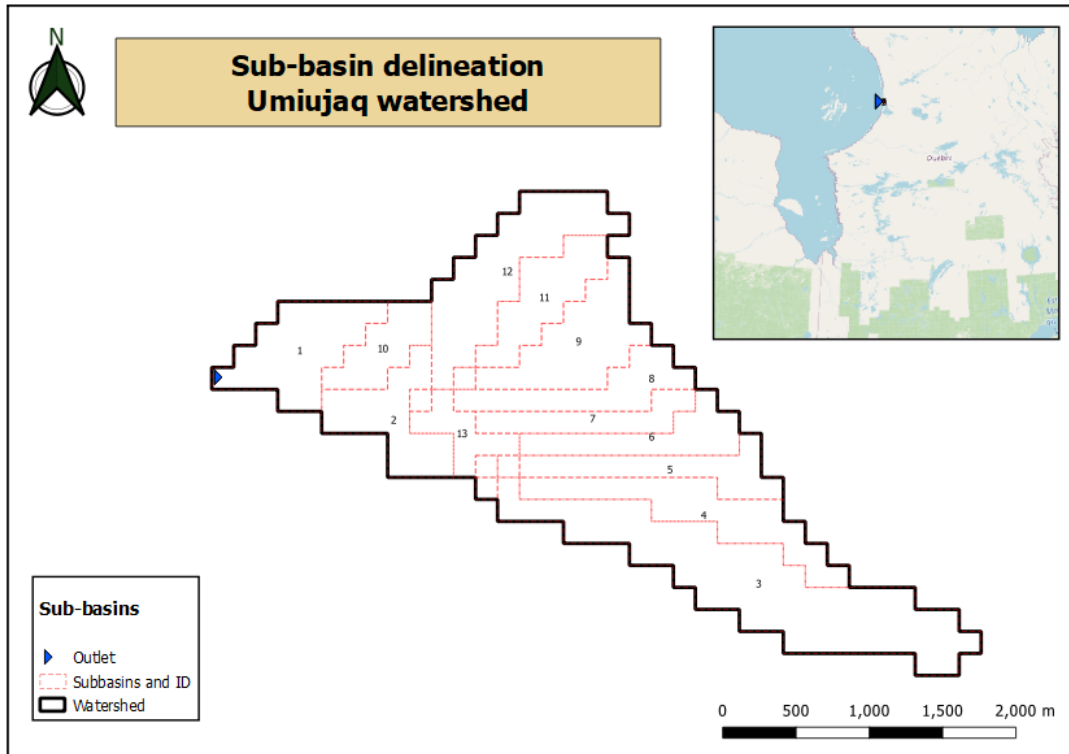


Figure 23 Sub-basins delineation Umiujaq watershed

### 3.4. Climate change scenarios

Once the model was developed, it can be forced using climate change scenarios. With this goal in mind, the Pacific Climate Impacts Consortium (PCIC) offers statistically downscaled daily Canada-wide climate scenarios at a gridded resolution of 300 arc-seconds (0.0833 degrees, or roughly 10 km) for the simulated period of 1950-2100. The variables available include minimum temperature, maximum temperature, and precipitation (Pacific Climate Impacts Consortium PCIC, 2019).

The Pacific Climate Impacts Consortium is a regional climate service at the University of Victoria that provides practical information on the physical impacts of climate variability and change in Canada's Pacific and Yukon Region regions (Pacific Climate Impacts Consortium PCIC, n.d.).

PCIP has available climate scenarios from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012) climate models, whose results were used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). This research analyses three

Representative Concentration Pathways (RCP) from the AR5: RCP 2.6, RCP 4.5, and RCP 8.5. The second-generation Canadian Earth System Model (CanESM2) (Environment and Climate Change Canada, 2017) was used.

Data is downloaded in a Network Common Data Form or NetCDF (in short), a data format, and a set of software libraries created to aid the scientific community. NetCDF holds spatial information in the form of latitudes and longitudes, time, and also scientific measurements in an easy-to-read manner. The Network Common Data Form (NetCDF) file format was developed by the Unidata project at the University Corporation for Atmospheric Research (UCAR) (National Snow and Ice Data Center NSIDC, 2023). Several methods exist to open and visualize a NetCDF file (.nc). In this research was used the library netCDF4 on Python. A copy of the code is shared in Appendix A: Python code for visualize and open climate data (NetCDF).

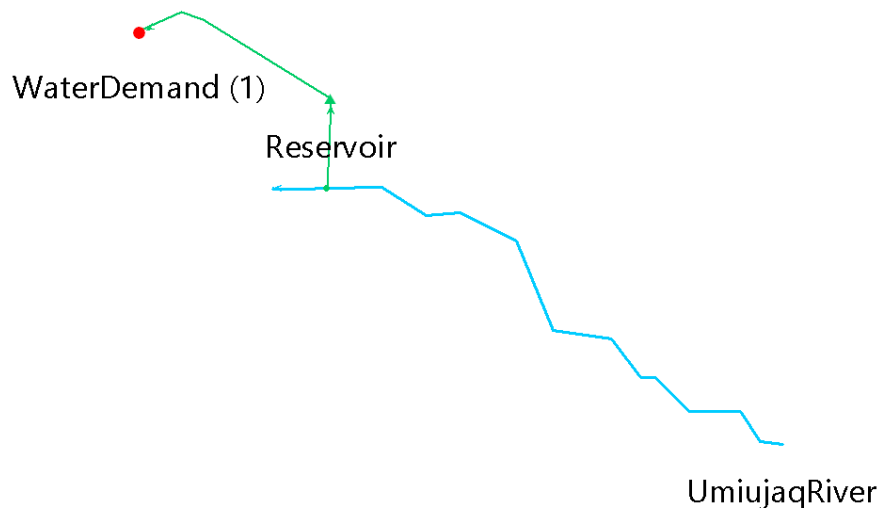
The World Meteorological Organization (2017) considers thirty years to be the minimum required to calculate the average climate, known as a climate normal. This period is to examine enough data that capture the influence of different forcing factors (natural and human-made). For example, the model should include the effect of both El Niño and La Niña events, as they affect climate differently. Simulations of future climate should include natural climate variability, so considering less than 30 years of data may reflect a trend that is different/opposite to that of longer term climate change (Environment and Climate Change Canada, 2018).

Following that recommendation, the three greenhouse gas concentration trajectories (or RCP's) were evaluated in three different periods of 30 years: 1993 – 2022, 2030 – 2059 and 2070 – 2099. The first one is used as the baseline data, while the second and third are used to analyse the consequences in the middle and long term.

### 3.5. Water Evaluation And Planning system (WEAP)

WEAP ("Water Evaluation And Planning" system) is a user-friendly software tool that takes an integrated approach to water resources planning. WEAP operates on the basic principle of a water balance and can simulate a broad range of natural and engineered components of body water systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. (Stockholm Environment Institute's U.S. Center, 2023).

WEAP was used to bring into the analyses the Umiujaq water consumption, their reservoir and how the streamflow variance due to climate change could affect them. To do that, firstly, a schema with the main components of the system is drawn. For Umiujaq, there is the river modelled, the reservoir, and the water demand for the community. Figure 24 presents this schema from WEAP software.



*Figure 24 WEAP schema for Umiujaq watershed*

Secondly, available data and assumptions are inserted in the system. For the scope of this research the following assumptions were made:

- **Streamflow:** the worst-case scenario (RCP8.5) is used as an example to evaluate the impacts in the community. Streamflow from the calibrated hydrological model is added to WEAP. The analysis is divided in two periods: from 2029 to 2059 and from 2069 to 2099.
- **Reservoir:** a reservoir with a capacity of 16000 m<sup>3</sup> is assumed to be continually filled during the summer (from July to September).
- **Water Demand:** according to Canada 2021 Census, the population in Umiujaq for 2021 was 541 (Statistics Canada, 2021). It is assumed that by 2023 the population is 550 people. Then, based on Lemieux et al. (2016), a consumption of 108 L/person/day is considered to calculate the annual water use rate.
- **Monthly variation:** based on the findings of Monte Staats in British Columbia (2014), a monthly consumption variation is assumed. The percentages with respect to the year consumption are presented in Table 8.

<b>Month</b>	<b>% Consumption</b>
<b>January</b>	6.75
<b>February</b>	6.63
<b>March</b>	6.60
<b>April</b>	7.11
<b>May</b>	8.40
<b>June</b>	9.78
<b>July</b>	13.15
<b>August</b>	12.46
<b>September</b>	8.98
<b>October</b>	6.82
<b>November</b>	6.55
<b>December</b>	6.75

*Table 8 Monthly water consumption variation*

- **Population growth:** it was assumed a population growth of 4,1% per year as it was the average growth from 2016 to 2021.

After the system is set up, the model is run to evaluate if the water demand can be supplied with the water available simulated under a climate change scenario. With the results, some strategies were proposed and discussed in the following chapter.

### 3.5.1. Accumulated Freezing Degree Days

With the ongoing impacts of climate change, including rising temperatures, the timing of river melting and freezing in northern Canada is likely to experience shifts. As temperatures increase, rivers may melt earlier in the year and freeze later than in the past. These changes have significant implications for the availability of water resources and the overall ecosystem dynamics. It is crucial to estimate and understand these changes to assess how the availability of the Umiujaq river may be affected.

One way to estimate the changes in river freezing and melting patterns is through the use of Accumulated Freezing Degree Days (AFDD). AFDD is a metric that quantifies the cumulative cooling effect of temperatures below freezing over a specific period. It helps in tracking the energy required for water to freeze and provides insights into the progression of river freezing. AFDD is calculated by subtracting the daily average temperature from the freezing point (usually 0°C) and summing these values over a defined time frame. By monitoring the AFDD values, hydrologists and researchers can estimate when a river is likely to freeze or thaw, considering the accumulated cooling effect of sub-freezing temperatures (National Snow and Ice Data Center, 2023; University Corporation for Atmospheric Research, 2010).

In this study, we consider the melting of the Umiujaq river on June 15th, 2022, and its freezing on October 15th, 2022, as the assumed timeline. Based on these known dates, we calculate the Accumulated Freezing Degree Days (AFDD) and Accumulated Thawing Degree Days (ATDD) up until those dates. These degree day values provide important indicators of the thermal conditions and

freezing/melting processes of the river. Subsequently, this information is compared with the results of climate change scenarios to evaluate when the river would melt and freeze in the future. Finally, in WEAP is updated the days when the river would be available to be pumped according to the estimation of AFDD.

## 4. Results and discussion

### 4.1. Calibration and validation

#### 4.1.1. First run

An important setback in model calibration is to start the process with an inadequate model. Failure to correctly set up a hydrologic model may not allow proper calibration and uncertainty analyses, leading to inaccurate parameter estimates and wrong model prediction. If the initial simulation is too different, calibration might often be of little help (Abbaspour et al., 2018).

After the hydrological model for the *Grande Riviere de la Baleine* was built according to the methodology presented in the previous chapter, a first run was done to evaluate the model's reliability. Figure 25 shows a graph where is compared the average monthly streamflow observed ( $m^3/s$ ) with the first simulation (the number on the x-axis represents the number of the month starting in January 1978 and finishing in December 1992). The comparison is made through the calibration period of data (1975 – 1992) with three years of warming up. The model generated a simulation with a similar annual behaviour matching some peaks. That means that the data and procedure used for building the model was satisfactory, and the hydrological model is ready for calibration and validation.

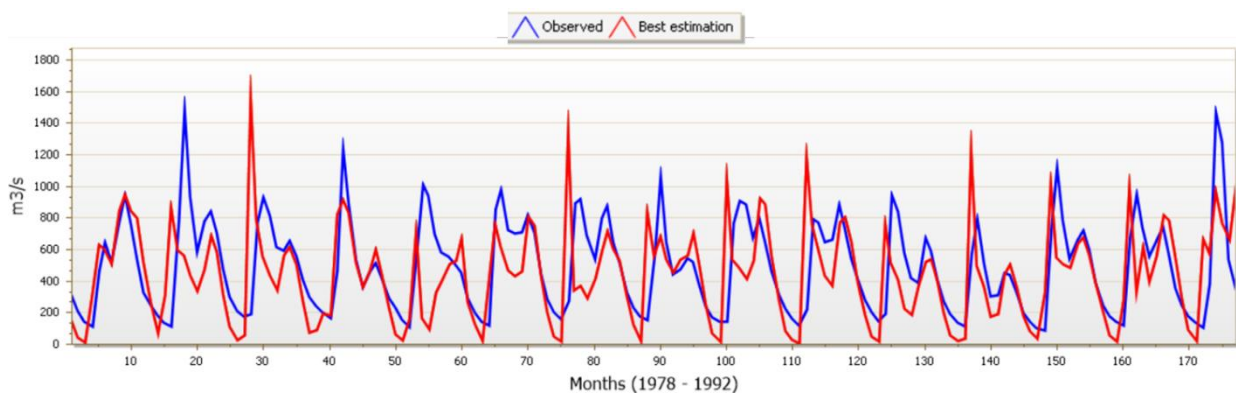


Figure 25 First model run Observed vs simulated average monthly streamflow ( $m^3/s$ ) between 1978 and 1992.

#### 4.1.2. Snow parameters calibration

As a first step, following the recommendations presented by Abbaspour et al. (2018) and Aygün et al. (2020), the snow parameters presented in Table 4 were calibrated with their respective initial range. Five (5) consecutive iterations were run, each with two hundred (200) simulations. After each iteration, a new parameter range was suggested by SWAT-CUP according to the results. Table 9 presents the parameters calibrated, the initial and final range, and the best value found. This value was fixed to the following calibration of other parameters.

Parameter	Initial Range	Final Range	Best value
v__SMTMP.bsn	-20 – 20 (°C)	-4.066 - 0.195 (°C)	-2.159
v__SFTMP.bsn	-20 – 20 (°C)	0.283 - 5.156 (°C)	2.878
v__SMFMX.bsn	0 - 20	1.144 - 3.442	1.770
v__SMFMN.bsn	0 - 20	0 - 1.739	0.195
v__TIMP.bsn	0 - 1	0.191 - 0.376	0.371

*Table 9 Snow Parameters, initial and final range, and best value*

Figure 26 shows the new comparison between the observed streamflow and the simulated one. It is visible how the two lines (observed and simulated) are more similar (compared with Figure 25), which means that the model is closer to the reality of the watershed. In the graph is also in green the 95PPU, or 95 Percent Prediction Uncertainty. This value is calculated at an output variable's 2.5% and 97.5% levels, disallowing 5% of the very bad simulations. The calibration goal is that the model result (95PPU) envelops most of the observations (Abbaspour, 2015). It is important to clarify that in this process the ran period was the calibrated one (1978 – 1992), as explained in the section 3.3.4 and in the Table 6.

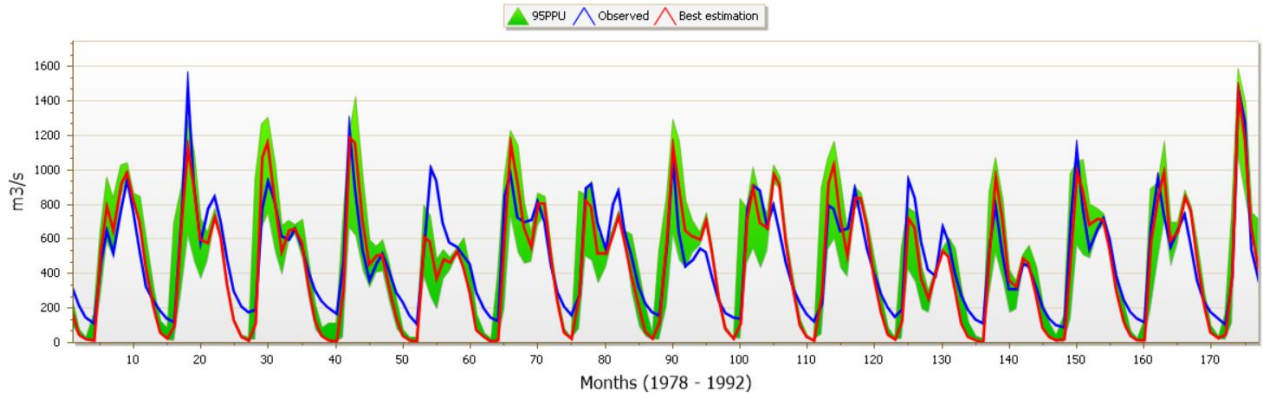


Figure 26 Observed vs simulated average monthly streamflow ( $m^3/s$ ) between 1978 and 1992, after snow parameters calibrated.

After this step, the model already had a very good performance according to the three quantitative statistics for hydrological models: Nash-Sutcliffe efficiency (NSE) = 0.77, percent bias (PBIAS) = 8.1, and ratio of the root mean square error to the standard deviation of measured data (RSR) = 0.47. However, the model still could be improved calibrating other parameters, so a sensitivity analysis was done to the parameters presented in Table 5.

#### 4.1.3. Sensitivity Analysis

As explained in section 3.3.3, the main purpose of sensitivity analysis is to identify the parameters that have the strongest influence on the hydrological processes modeled. A one-at-a-time sensitivity analysis was done with the parameters in Table 5. Each parameter was evaluated by varying its value while the other parameters were kept constant at some reference. Three simulations were run for each parameter having a range suggested by Shrestha et al. (2017). The results of the sensitivity analysis for the six parameters that had strongest influence on the model are presented In Figure 27, Figure 28, and Figure 29. In each graph, three simulations of each parameter are compared with the average monthly observed streamflow ( $m^3/s$ ) along the calibration period (1978 – 1992) .

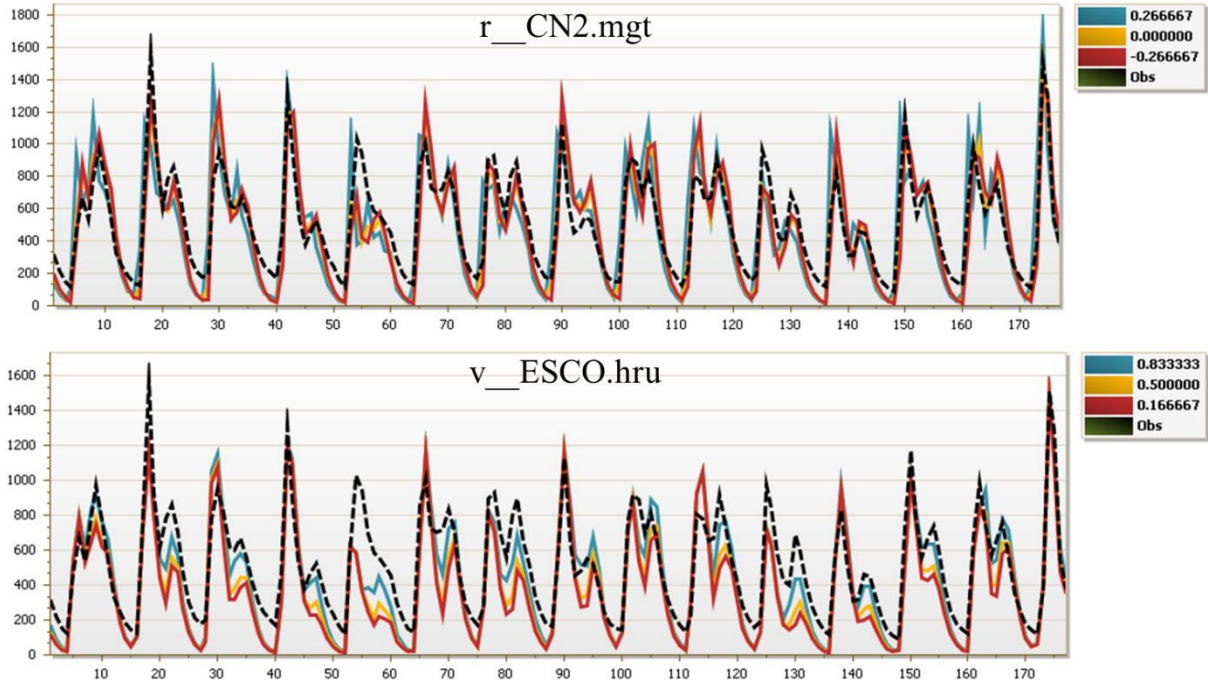


Figure 27 Sensitivity analysis for r\_CN2.mgt and v\_ESCO.hru.

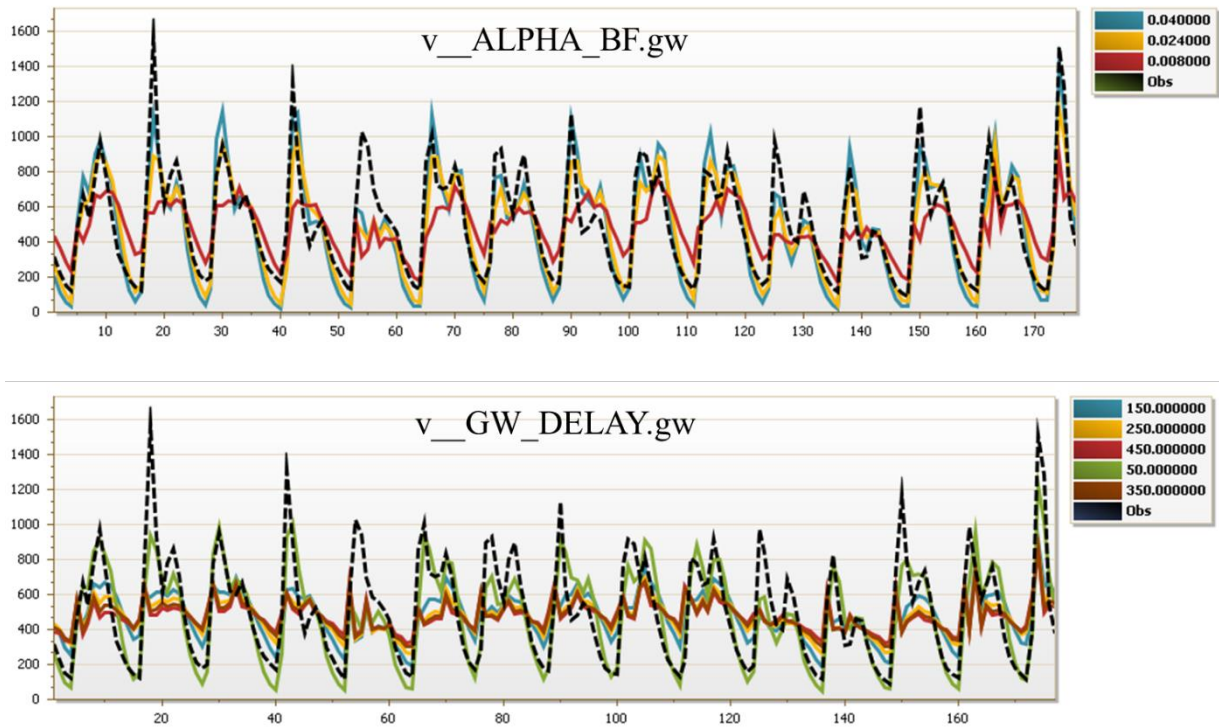


Figure 28 Sensitivity analysis for v\_ALPHA\_BF.gw and v\_GW\_DELAY.gw

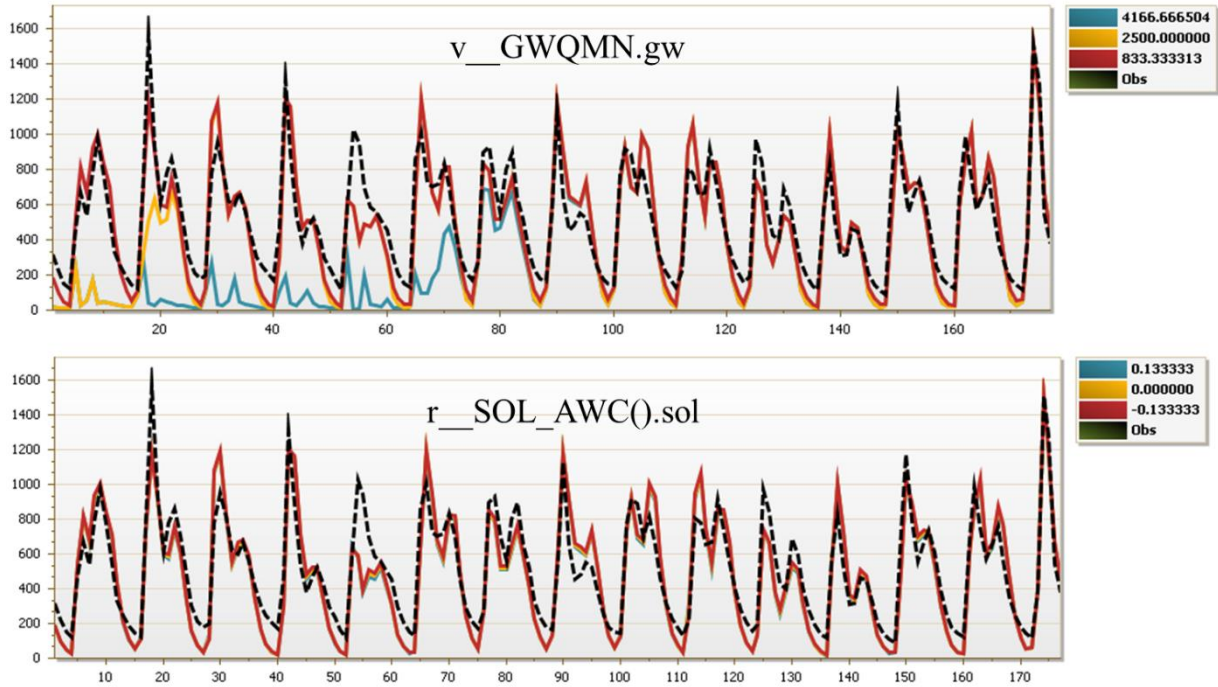


Figure 29 Sensitivity analysis for  $v\_GWQMN.gw$  and  $r\_SOL\_AWC().sol$

The graphs clearly illustrate the substantial impact of parameter variation on streamflow, providing evidence of their strong correlation. By systematically altering a specific parameter while keeping other variables constant, we observe a discernible pattern wherein even minor changes in the parameter result in significant fluctuations in streamflow output.

Having a different level of influence, each of these parameters impacts the watershed model. However, as the parameters keep constant at some value while changing only one, and there is no certainty that their value is correct, there could be other parameters with stronger influence in different combinations of parameters. To sum it up, the sensitivity of one parameter depends on the value of other parameters.

#### 4.1.4. Other parameters calibration

The six parameters with stronger influence were calibrated according to the methodology explained formerly. Four (4) consecutive iterations were run, each with two hundred (200) simulations. After each iteration, a new parameter range was suggested by SWAT-CUP according to the results. In

Table 10 are presented the parameters calibrated, the initial and final range, and the best value found.

Parameter	Initial Range	Final Range	Best value
v__GW_DELAY.gw	20 - 40	36.534 - 44.365	43.445
v__GWQMN.gw	0 - 1000	708.282 - 951.857	819.718
v__ALPHA_BF.gw	0 - 0.05	0.057 - 0.086	0.082
r__CN2.mgt	-0.4 - 0.4	-0.114 - 0.045	-0.079
v__ESCO.hru	0.85 - 1.00	0.935 - 0.978	0.941
r__SOL_AWC().sol	-0.1 - 0.1	-0.045 - 0.030	-0.026

Table 10 Other Parameters calibrated, initial and final range, and best value

In Figure 30 is again compared the behaviour of the hydrological model (red) with the average monthly observed streamflow ( $m^3/s$ ) (blue) after the calibration. When compared Figure 25 and Figure 30, the latter shows a remarkable better proximity between the simulated results and the observed data. That indicates that the calibration has been succesful.

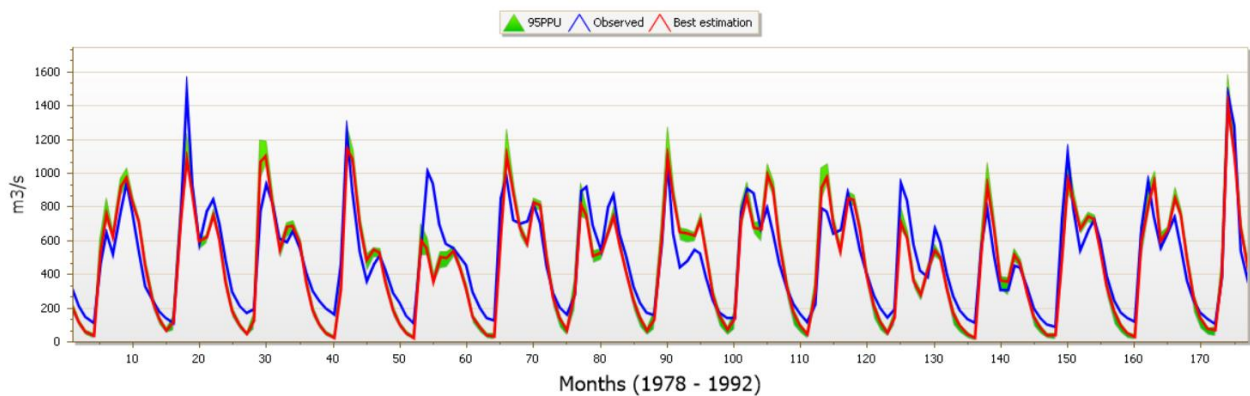


Figure 30 Observed vs simulated average monthly streamflow ( $m^3/s$ ) between 1978 and 1992, after other parameters calibrated.

Additionally, the three quantitative statistics for hydrological models proposed by Moriasi et al. also had better results, which reaffirms the model performance improvement. The new obtained values are: NSE = 0.81, PBIAS = 5.2 and RSR = 0.43. Based on the Table 7, the performance rating of the hydrological model in its calibration process was Very Good for the three quantitative statistics.

In Table 11 is presented a summary of the different results along the calibration process. The effort put into developing the hydrological model allowed the first run to have acceptable results. Then, the calibration of the snow parameters carried a model with outflows and behaviour very close to reality. Finally, other parameters were calibrated, and the value of the performance statistics was improved.

Quantitative Statistics	First Run	After Snow parameters calibrated	After other parameters calibrated
NSE	-0.16	0.77	0.81
RSR	1.08	0.47	0.43
PBIAS	9.1	8.1	5.2

Table 11 Summary of quantitative statistics results during calibration

#### 4.1.5. Validation

As mentioned in the Section 3.3.4 Calibration and validation of the model, validation is used to build confidence in the calibrated parameters. For this purpose, the calibrated parameter ranges are applied to an independent measured dataset, without further changes. As presented in the Table 6, the independent dataset or validation period is from 1994 to 2003.

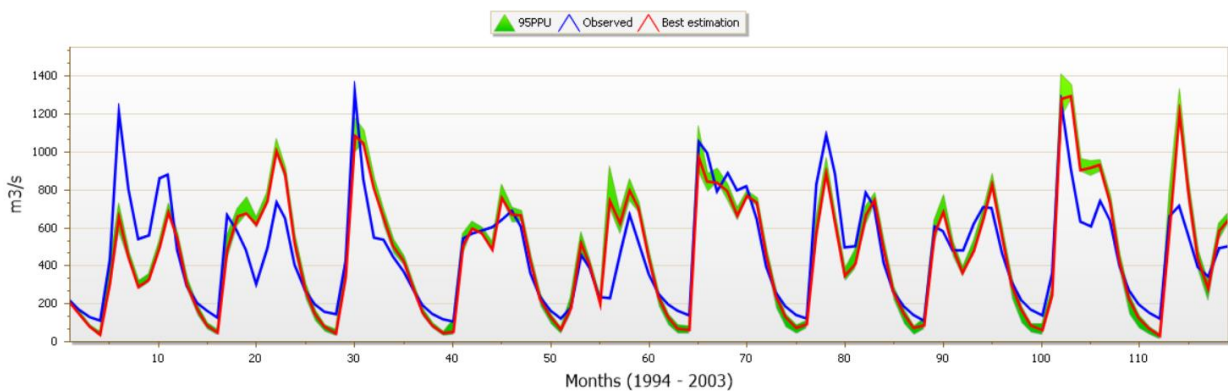


Figure 31 Observed vs simulated average monthly streamflow ( $m^3/s$ ) between 1994 – 2003 (Validation period)

Figure 31 compares the simulation results during the validation period with the observed data. The SWAT hydrological model of the *Grande Riviere de la Baleine* simulates the average monthly streamflow adequately. Statistically, the model has the following results: NSE = 0.68, PBIAS = 0.9

and RSR = 0.56. Although the outcome was better during the calibration period, according to the Moriasi et al. rating, the hydrological model has a good performance during validation.

Quantitative Statistics	Calibration		Validation	
	Value	Moriasi et al. Performance Rating (Table 7)	Value	Moriasi et al. Performance Rating (Table 7)
<b>NSE</b>	0.81	Very Good	0.68	Good
<b>RSR</b>	0.43	Very Good	0.56	Good
<b>PBIAS</b>	5.2	Very Good	0.9	Very Good

*Table 12 Quantitative statistics values during calibration and validation and equivalent performance rating*

In conclusion, a hydrological model for the *Grande Riviere de la Baleine* was developed, calibrated, and validated successfully. Then, the calibration was transposed to the Umiujaq watershed, presented in Figure 23. Once the goal model is developed, climate change scenarios can be forced into it.

Reinforcing and supporting the watershed transposing, Mengistu et al. (2019) mentioned that even though the calibration of hydrologic models is challenging for data scarce catchments, some methods have been proposed in literature. The most implemented method is the regionalization approach. Generally, this approach could be further classified by three. These are regionalization by spatial proximity, physical similarity and regression methods. In the spatial proximity approach, it is usually assumed that neighbouring catchments have homogenous physical and climatic characteristics and hence, have similar hydrological responses (Rafiei Emam et al., 2017). As a result of this, calibrated parameters could be transferred from gauged to ungauged neighbouring catchments. Calibration with regression methods consist of developing some empirical relationships between catchment descriptors (both physical and climatic) and model parameter values calibrated on gauged catchments (Rafiei Emam et al., 2017). The regionalization with physical similarity is based on the similarity between an ungauged catchment and one or more gauged donor catchments.

Merz and Blöschl (2004) simulated the water balance dynamics of 308 catchments using the regionalization approach for their calibration. One of the most important findings is that the methods based on spatial proximity alone perform significantly better than any of the regression methods based on catchment attributes. According to their results, spatial proximity is a better surrogate of unknown controls on runoff dynamics than catchment attributes. In that sense, the difference in land use presented between Kuujjuaraapik and Umiujaq is not that relevant, considering that their watersheds are nearby.

## 4.2. Climate change scenarios

### 4.2.1. Temperature change

As mentioned in the numeral 3.4 Climate change scenarios, three Representative Concentration Pathways (RCP): RCP 2.6, RCP 4.5, and RCP 8.5 were evaluated in three different periods of 30 years: 1993 – 2022, 2030 – 2059 and 2070 – 2099. The first was used as the baseline data, while the second and third were used to analyse the mid and long term consequences.

Based on the information presented in the numeral 2.2.2 and 3.4, and shown in Figure 8 and Figure 9, an average yearly temperature was estimated in Umiujaq for the three different RCPs. Figure 32 shows that, as expected, the higher the fossil fuel emissions, the higher the temperature increase (RCP 8.5). Even with a radical reduction in the emissions rate (RCP 2.6), a minimal increase in the average temperature is expected (below 2.0 °C).

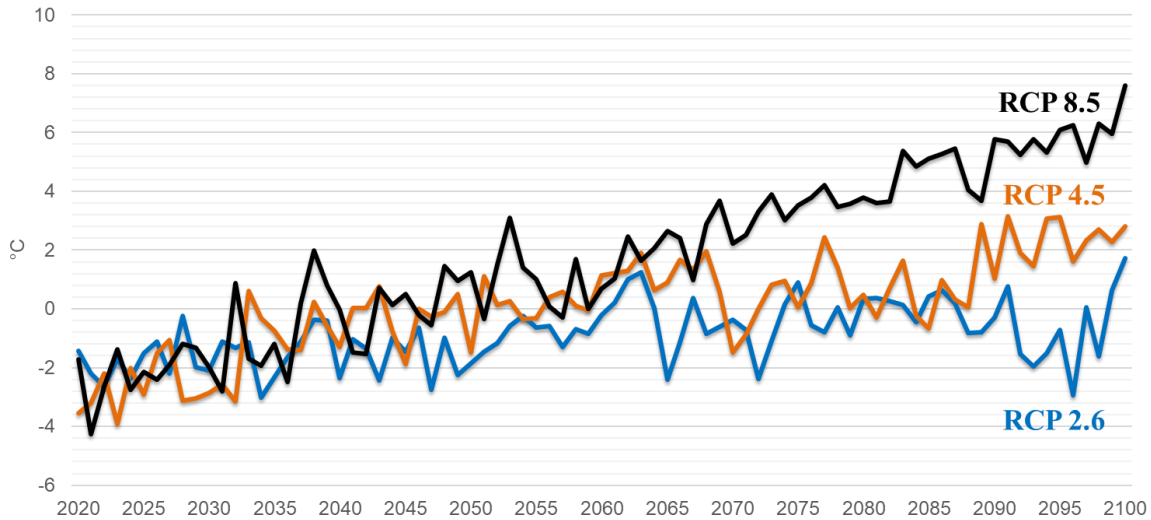


Figure 32 Average yearly temperature (°C) for different climate change scenarios in Umiujaq.

In accordance with the findings of the IPCC (2014), northern regions, like where Umiujaq is located, will continue to warm more rapidly than the global mean. Specifically, the increase of temperature in Umiujaq, compared with the global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005, is likely to be 1.5°C higher under RCP2.6, 2.4°C higher under RCP4.5 and 4.3°C higher under RCP8.5.

#### 4.2.2. Precipitation alteration

Similarly, monthly average precipitation is calculated from downscaled Pacific Climate Impacts Consortium data. A comparison of the monthly average precipitation for each Representative Concentration Pathway are presented in Figure 33, Figure 34 and Figure 35.

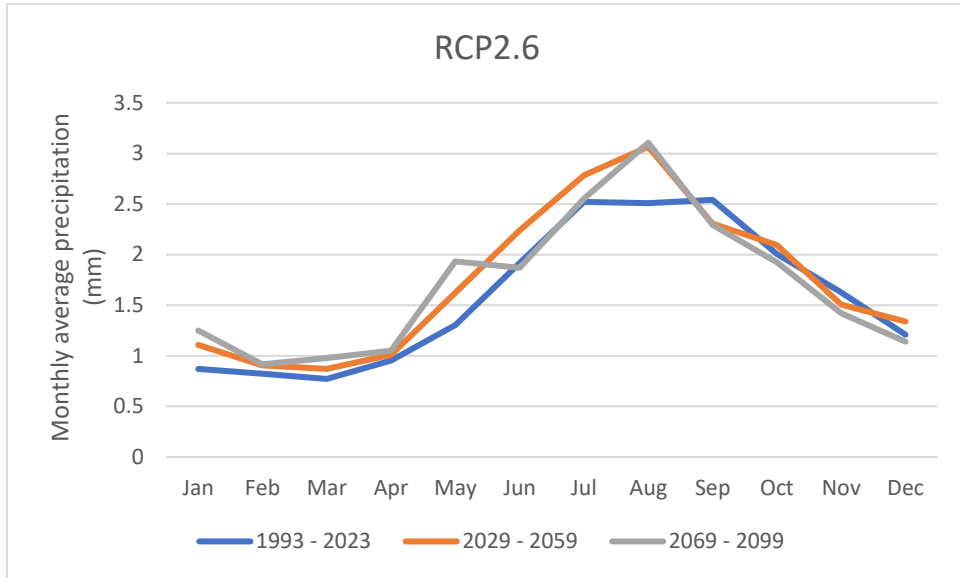


Figure 33 Monthly average precipitation (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP2.6

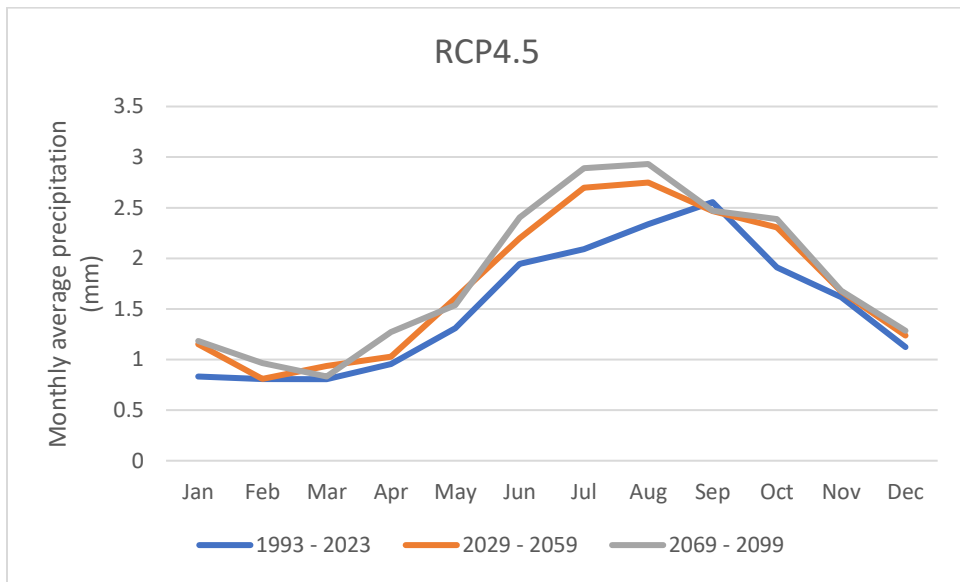
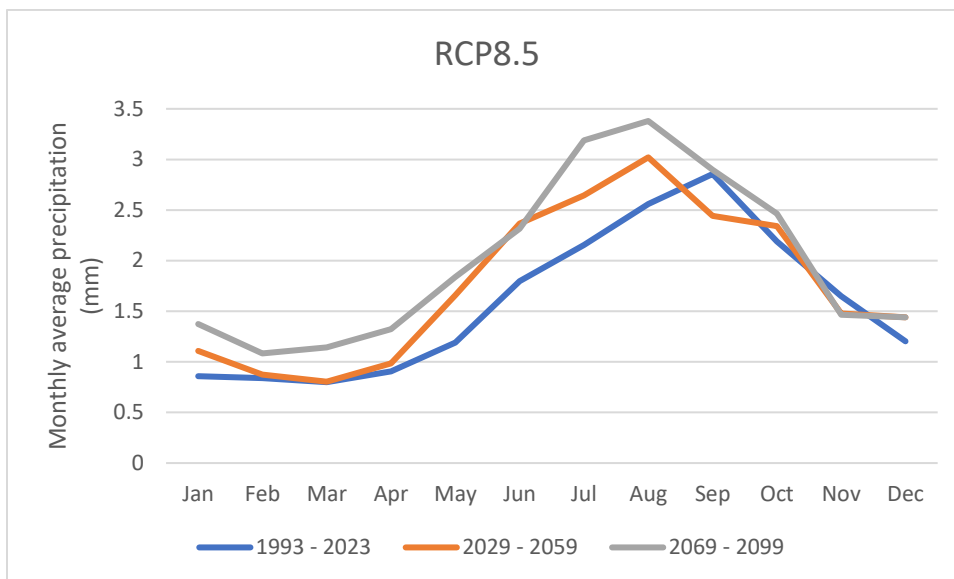


Figure 34 Monthly average precipitation (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP4.5



*Figure 35 Monthly average precipitation (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP8.5*

As a reference, it is expected that extreme precipitation intensifies with global warming over large parts of the globe as the concentration of atmospheric water vapor, which supplies the water for precipitation, increases in proportion to the saturation concentrations at a rate of about 6–7% per degree rise in temperature according to the thermodynamic Clausius–Clapeyron relationship. However, due to different interacting drivers of precipitation changes, the changes are not uniform in space and vary by region (Tabari, 2020).

In Umiujaq, precipitation is expected to increase with climate change under the three concentration pathways. While the rise under RCP2.6 is minimal during the evaluated periods, the increment will be higher at the end of the century and under RCP8.5.

In the worst-case scenario (RCP8.5), it is relevant to mention that in the medium-term and long term the peak of precipitation would move from September 9<sup>th</sup> to August 5<sup>th</sup>. In the period from 2069 to 2099, it would be almost an average monthly precipitation of 3.5 mm, which means more water available but also, more risk of flooding.

#### 4.2.3. Snow content change

Snow cover is an important component of northern environments. It influences a wide range of systems such as permafrost, surface runoff, and water levels during spring discharge, vegetation, and animal population dynamics. Snow cover also has important impacts at the local community level through its influence on access to territory, animal behavior, hunting, fresh water, snow clearing, and snow loads (Carl Barrette et al., 2020).

Similarly, snow has a significant influence on the weather and climate. Because snow is highly reflective, a vast amount of sunlight that hits the snow is reflected into space instead of warming the planet. The ground absorbs about four to six times more of the sun's energy without snow cover. The presence or absence of snow controls heating and cooling patterns over Earth's land surface more than any other single land surface feature (National Snow and Ice Data Center NSIDC, 2022).

Moreover, snow is an important component of the hydrological cycle and with its unique physical properties, it is an essential environmental variable directly affecting the Earth's energy balance. Proper description and assimilation of snow information into hydrological, land surface, meteorological and climate models is therefore important to address the impact of snow on various phenomena such as hydrological monitoring, avalanche forecast, and weather forecast, to predict snow water resources and to warn about snow-related natural hazards (Helmert et al., 2018)

However, measuring and estimating snow content is challenging due to its spatial and temporal variability and the limitations of existing methods and instruments. Nevertheless, with the hydrological model developed for Umiujaq, it is possible to estimate the snow content under the different climate change scenarios for the periods selected for the evaluation. To do that, the HRU output file is used, which contains summary information for each of the hydrological response units in the watershed. Specifically, the output variable with the desired information is SNOW\_CONT.

A comparison of monthly average snow content along the evaluation periods, under the different RCPs are shown in Figure 36, Figure 37, and Figure 38. Climate change will reduce the amount of snow accumulated. Analyzing the worst climate scenario (RCP 8.5), the increase in temperature will melt the snow faster each year. The number of days in a year with more than 50 mm of snow could be reduced in 53 days in the long-term period (2069 -2099), compared to the reference period (1993 – 2023). In the former, this quantity of snow would stay until March 25<sup>th</sup>, while currently the snow stays until May 18<sup>th</sup>.

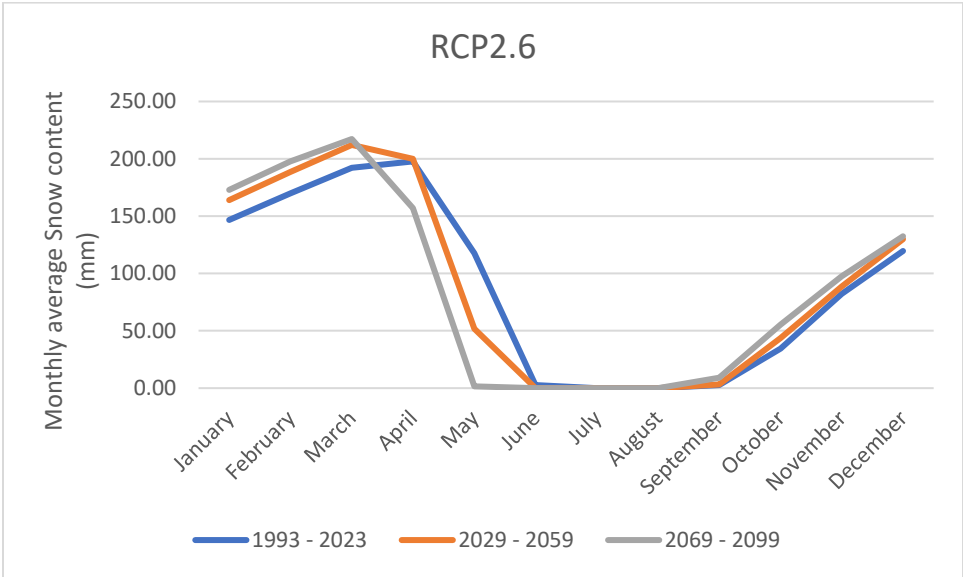


Figure 36 Monthly average Snow content (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP2.6

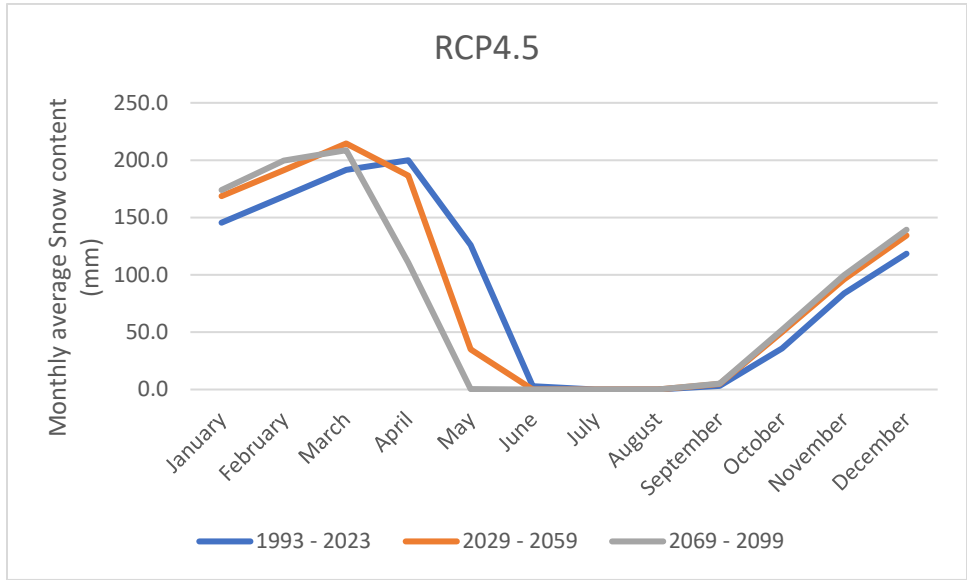


Figure 37 Monthly average Snow content (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP4.5

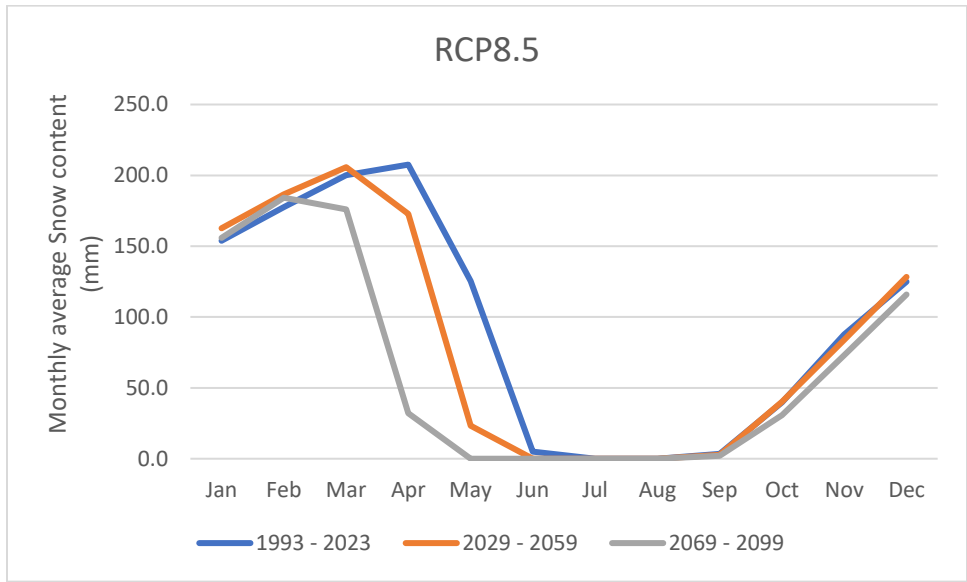


Figure 38 Monthly average Snow content (mm) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP8.5

The consequences for Northern Communities, as the Umiujaq one, for the earlier snowmelt are diverse. For instance, having their diets altered because of changing ecosystems and migration patterns; changing their modes and pathways of transportation; their cultural ways of life. Likewise, warmer temperatures will decrease access to winter road use for remote and northern communities, impacting the delivery of supplies like lumber for buildings and gasoline for vehicles.

Winter roads are often described as “lifelines” because they provide access to isolated regions where permanent, all-weather roads are limited or do not exist (Indigenous Climate Hub, 2022).

#### 4.2.4. Streamflow variation

Hydrological modelling is the process of using mathematical equations and computer models to simulate the movement of water through the hydrological cycle. In this thesis, a SWAT hydrological model of the Umiujaq watershed was developed to evaluate the impacts that climate change could have in the water availability of the community. The impacts will be evaluated by analyzing the variation in the river's streamflow that supply the community reservoir.

Streamflow is the model's main output, as it was used to calibrate and validate the Kuujjuarapik watershed (*Grande Riviere de la Baleine*). In Umiujaq, as explained in the Section 3.3.4 Calibration and validation of the model and presented in Figure 23, the streamflow is estimated at a point (output) where the community pumps the water from the river to their reservoir.

To facilitate the analysis, for each of the Representative Concentration Pathways, it was calculated the monthly average streamflow in the three different periods (1993 – 2023, 2029 – 2059, 2069 – 2099). Results are presented in Figure 39 (RCP2.6), Figure 40 (RCP4.5), and Figure 41 (RCP8.5).

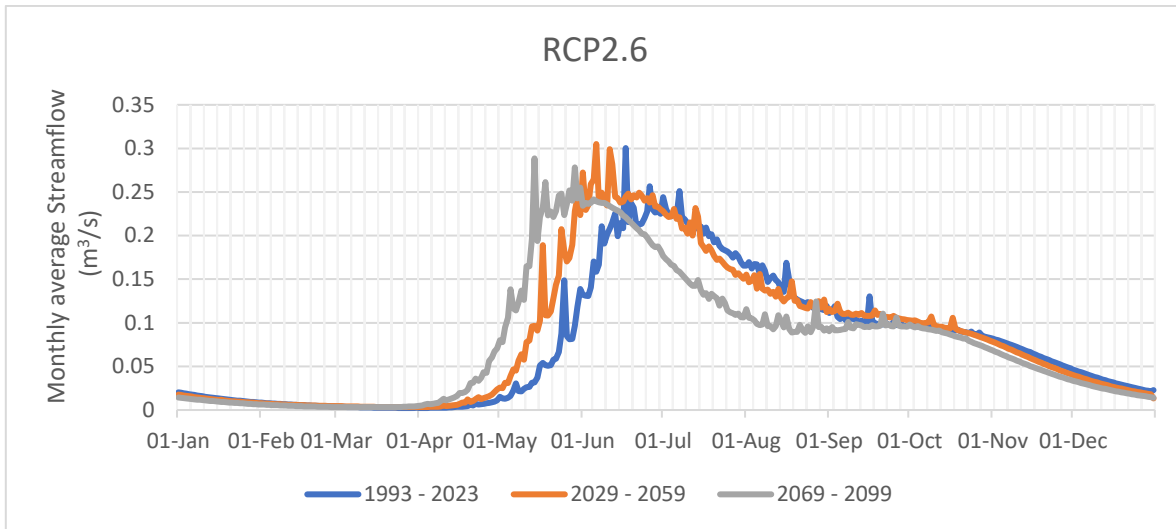


Figure 39 Monthly average Streamflow ( $m^3/s$ ) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP2.6

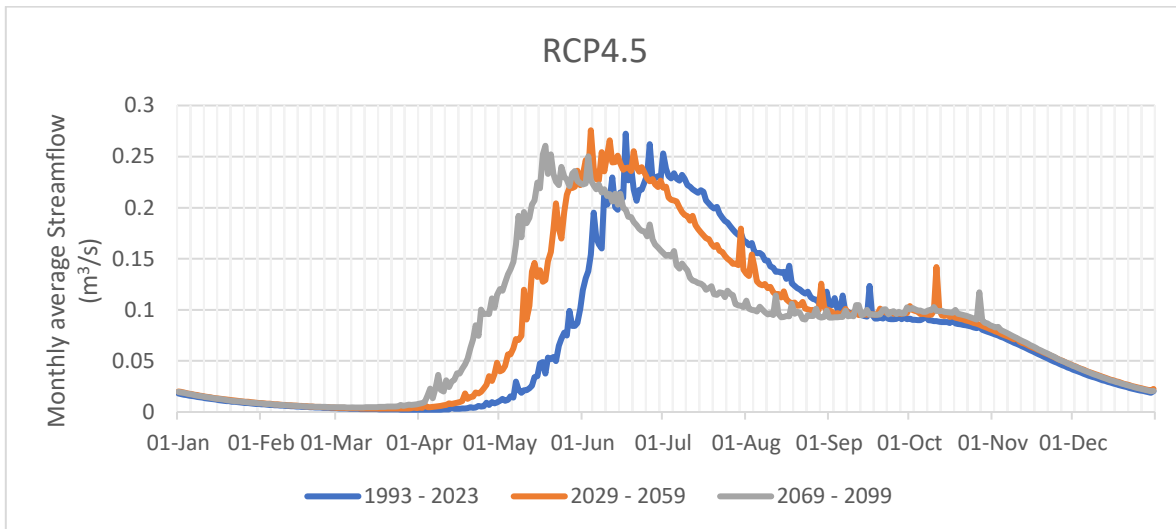


Figure 40 Monthly average Streamflow ( $m^3/s$ ) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP4.5

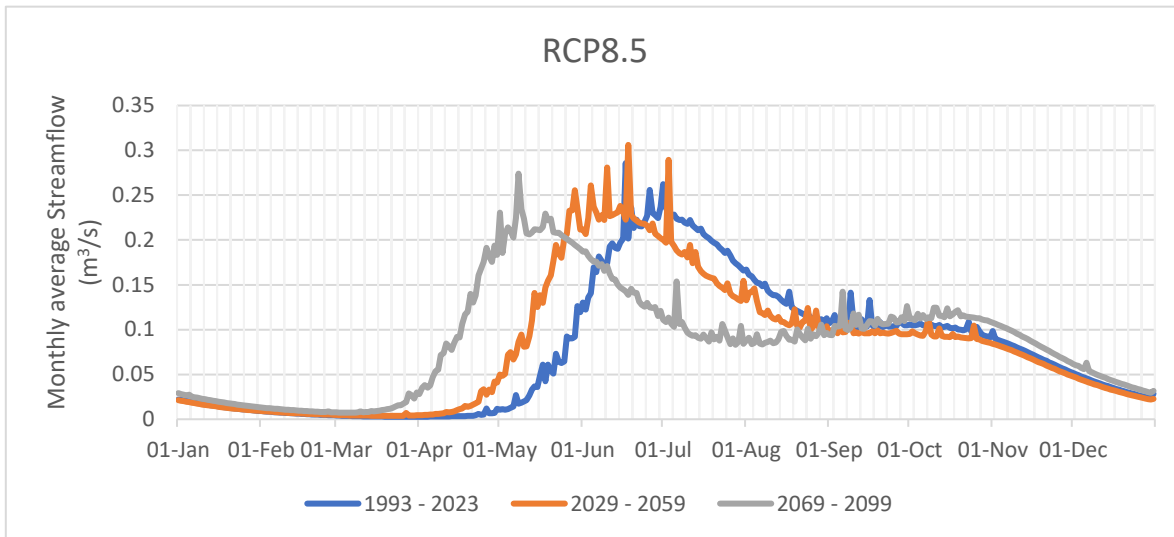


Figure 41 Monthly average Streamflow ( $m^3/s$ ) in different periods (1993 – 2023, 2029 – 2059, 2069 – 2099) in Umiujaq under RCP8.5

The graphs show that climate change would modify the river's mean hydrograph, moving its peak flow to an earlier moment during the year. Specifically, the higher the concentration of Green House Gases, the sooner the peak streamflow would happen. This relates to the faster melting of snow evaluated in the previous section. In the worst-case scenario (RCP8.5), the peak streamflow will move to April and which could result in lower water availability during the summer (Figure 41).

However, when analysing the total year streamflow in the different climate change scenarios, the overall streamflow could be higher with the increase of temperature. By the end of the century, in the RCP8.5, there would be even a second peak due to an increase of precipitation. This behaviour would indicate more available water, but at the same time, higher risks of flooding.

### 4.3. WEAP

As mentioned in the Section 3.5 Water Evaluation And Planning system (WEAP), results of the worst-case climate change scenario (RCP8.5) were analyzed in WEAP to evaluate how the change in streamflow could affect the water availability in Umiujaq. The model was run with the data and assumptions presented in the same Section.

First, the Accumulated Thawing Degree Days (ATDD) and Accumulated Freezing Degree Days (AFDD) are used to estimate the new dates when the river would be melted and frozen under RCP8.5 and, therefore, when it would be available to be pumped. It is assumed that in 2022 the river melted on June 15 and got frozen on October 15. The ATDD for June 15<sup>th</sup> was 451.2 °C, and the AFDD was 14.4 °C. Table 13 presents the dates when the river would have those ATDD and AFDD values for selected years during the period 2029 – 2059 and, consequently, when it would be expected to be melted and frozen.

<b>YEAR</b>	<b>Day ATDD &gt; 451 °C</b>	<b>Day AFDD &gt; 14.4 °C</b>
<b>2022</b>	15-Jun	15-Oct
<b>2029</b>	03-Jun	23-Oct
<b>2034</b>	22-Jun	27-Oct
<b>2039</b>	05-Jun	18-Oct
<b>2044</b>	09-Jun	01-Oct
<b>2049</b>	29-May	25-Oct
<b>2054</b>	28-May	26-Oct
<b>2059</b>	08-Jun	13-Oct

*Table 13 Days when Umiujaq river would be expected to be melted and frozen for selected years (2029 – 2059) under RCP8.5*

The increase in temperature due to climate change would result in an earlier melting of the river (9 days on average) and later freezing (4 days on average for this period). One positive effect of these new dates is that the community could pump water for more days and would have, in theory, better water availability. However, the population is expected to grow (4.1% per year) and, thus, the water demand. Therefore, the extra water available would not compensate for the increased demand for water.

The unmet demand during 2029 and 2059 is presented in Figure 42. The graph shows that from the beginning of the evaluation period, 2029, there is an unmet demand of 500 m<sup>3</sup> or more than six days without water (considering a population of 700 people with a consumption per capita of 108 L/p/day). This situation aligns with the current reality where the community is facing difficulties in

satisfying the population's demand for yearly water with storage of 16,000 m<sup>2</sup>. In other words, the Umiujaq community requires a solution for their water demand as soon as possible. Similarly, the storage volume is presented in the Figure 43 for selected years. With a growth population of 4.1%, by 2059 the population would be 2337, and the storage would be empty from December to June.

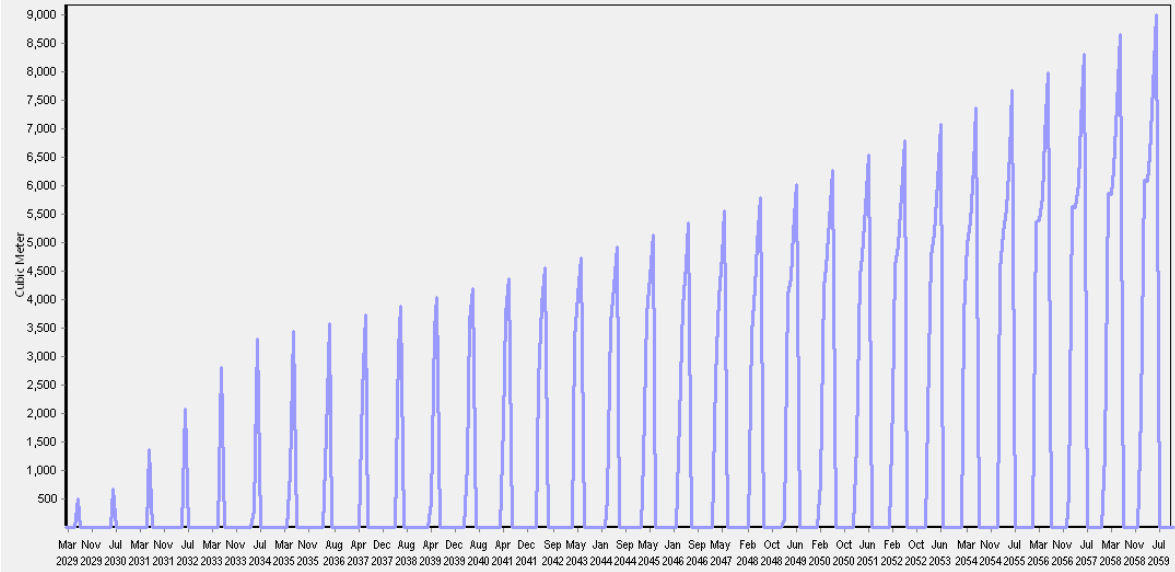


Figure 42 Unmet water demand (m<sup>3</sup>) in Umiujaq under climate change scenario RCP 8.5 (2029 - 2059)

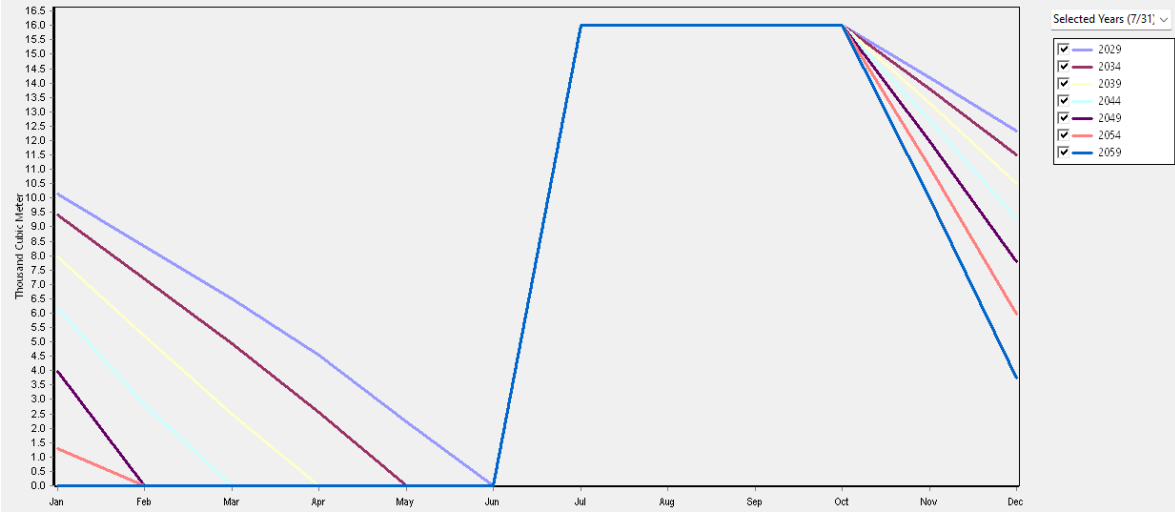


Figure 43 Storage volume (thousand m<sup>3</sup>) in selected years under RCP8.5

For the long-term period (2069 – 2099), the melting day would be even earlier, with an average of 39 more available water days than in 2022. The freezing day would oscillate during the period but

would not change considerably compared with 2022 (3 more days on average). Table 14 presents the values for the mentioned period (2069 – 2099).

YEAR	Day ATDD > 451 °C	Day AFDD > 14.4 °C
2069	10-May	30-Oct
2074	18-May	05-Oct
2079	20-May	14-Oct
2084	30-Apr	21-Oct
2089	13-May	08-Oct
2094	28-Apr	31-Oct
2099	21-Apr	22-Oct

Table 14 Days when Umiujaq river would be expected to be melted and frozen for selected years (2069 – 2099) under RCP8.5

Nevertheless, the extra water that could be pumped and stored in the reservoir would not significantly impact meeting the community's water demand. For reference, the unmet water demand (m<sup>3</sup>) in Umiujaq for 2069 – 2099 is shown in Figure 44. From the beginning of the period, there would be a total unmet water demand near 37.600 m<sup>3</sup>, equivalent to almost 100 days of water for the 3492 people living in the town by that year.

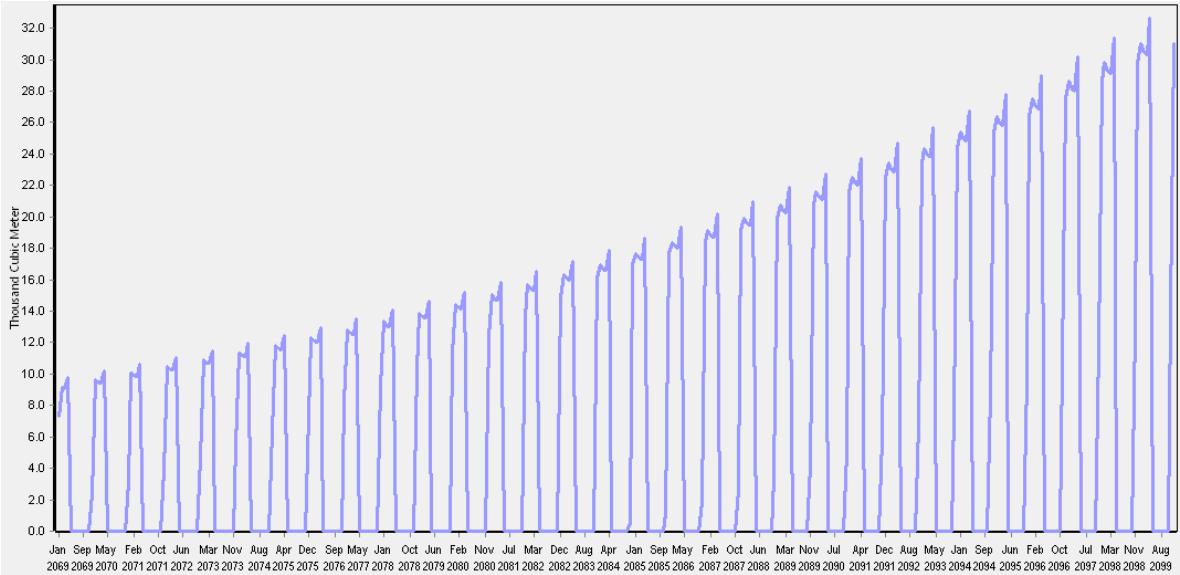


Figure 44 Unmet water demand (m<sup>3</sup>) in Umiujaq under climate change scenario RCP 8.5 (2069 - 2099)

#### 4.3.1. Suggested strategies

Climate change adaptation is “the process of adjustment to actual or expected climate and its effects, to either lessen or avoid harm or exploit beneficial opportunities” (IPCC, 2014). Understanding what makes human systems vulnerable or resilient to climate change is necessary for informing policies, programs, and actions for adapting (Ford et al., 2018).

As previously presented so far, Umiujaq is a small Northern community that would be affected by climate change in different ways. Below are two possible strategies that the community could use as an alternative to alleviate part of the consequences of global warming related to water availability. However, other severe impacts (flooding, snow content reduction, diet altered due to changing ecosystems and migration patterns, etc.) are not as easy to alleviate, which shows the importance of continuing efforts to reduce greenhouse gas emissions to stop or mitigate climate change.

##### 4.3.1.1. Bigger reservoir

The current reservoir has a capacity of 16,000 m<sup>3</sup>, which can supply water for 269 days with an average consumption of 108 litres per day and a population of 550 people. As mentioned before, the community already has water availability issues due to the storage volume. As a first strategy, another reservoir is proposed to be built in the community and have more capacity to supply water while the river is frozen. A reservoir with the same characteristics as the current one is proposed (capacity = 16,000 m<sup>3</sup>). However, a specific study would be required to analyze available land, funding, soil properties, etc.

The unmet demand (m<sup>3</sup>) with the extra reservoir is presented in Figure 45. This strategy would allow meeting the water demand of the new population at least until 2044 when would be an unmet demand of 570 m<sup>3</sup>. Compared with Figure 42, an improvement in water availability of at least 15

years is visible. This analysis also assumes that the water consumption would maintain constant throughout the evaluation period and yearly growth in the population of 4.1%.

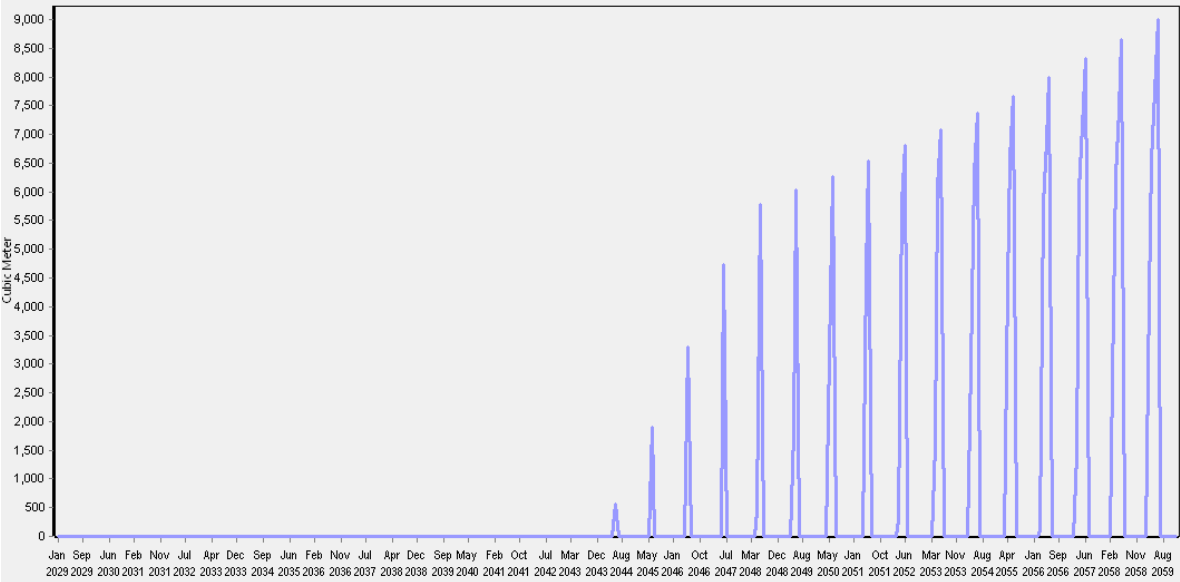


Figure 45 Unmet water demand (m<sup>3</sup>) in Umiujaq under climate change scenario RCP 8.5 (2029 - 2059) with an extra reservoir of 16,000 m<sup>3</sup>

However, the strategy would not have a significant impact after 2045. The water demand would continue growing, and the extra reservoir would not meet the necessity. In that sense, a bigger reservoir or another one could be suggested as a strategy. However, the investment costs and operation and maintenance would be difficult for this solution. Consequently, as an alternative, another water source is proposed.

**4.3.1.2. Other water source**

As presented in the numeral 4.2.4 Streamflow variation, climate change would bring a sooner peak flow that could affect the community’s water supply capacity. Therefore, it is imperative to analyze alternatives, other than a more extensive reservoir supplied with the same body of water. In this sense, groundwater is evaluated as a different water source option.

Presently, water supplies for northern Canadian communities come mainly from surface water such as rivers and lakes. While these water sources are usually abundant, their quality is variable, they

are vulnerable to contamination, and they are unreliable, as they often either freeze or dry up in winter. In contrast, groundwater is generally of better quality, less vulnerable to contamination, and usually requires minimal treatment. However, because groundwater is currently stored as ground ice in permafrost, access to groundwater is limited for most northern communities (Lemieux, Fortier, Murray, et al., 2020).

Nevertheless, due to permafrost degradation, the increased availability of and its exploitation as a source of drinking water could potentially improve water quality and security of water supply for northern communities. Even in Nunavik, groundwater is already being used (fully or marginally) in the communities of Kuujuaq, Salluit and Whapmagoostui-Kuujuarapik. Expected climate change, with predicted permafrost thaw and increases in temperature and precipitation, should enhance groundwater availability and may contribute to a more secure source of water for northern communities and development projects (Lemieux et al., 2016).

Cochand et al. (2020) studied the groundwater system in the watershed at Umiujaq, finding dynamic recharge and high renewal rates. Jasmin et al. (2020) measured significant flow rates in the upper and lower aquifer using the finite volume point dilution method. Additionally, this source meets the Canadian quality standards for drinking water. And mainly, Lemieux et al. (2020) presented results that suggested that groundwater is available in the Tasipik Valley (near Umiujaq) as a source of drinking water, being rapidly recharged during spring and fall.

Furthermore, as a positive consequence of climate change, Young et al. (2020) found that the groundwater recharge in this region would increase. First, they provided qualitative evidence that the vegetated area has increased since the 1950s in the zone. Then, Young et al. analyzed that the primary mechanism for increased recharge appears to be greater snow entrapment under taller vegetation, occurring as both a result of capture during precipitation events, and the accumulation

of blowing snow from areas with shorter, more immature forms of land cover. Finally, they suggested that with continued maturation of the landscape, the potential for greater groundwater recharge increases due to increased snow entrapment beneath taller vegetation.

On the other hand, climate change would also negatively impact groundwater as an option for the Umiujaq community. It has been found that the vulnerability of these types of hydrogeological aquifer systems is expected to increase due to rapid recharge dynamics associated with the gradual loss of the confining effect of permafrost. Moreover, the impact of permafrost degradation on groundwater quality and availability is still poorly documented (Cochand et al., 2019).

In summary, the literature review on groundwater in Northern Communities, specifically Umiujaq, suggests that groundwater holds promise as a viable alternative water source, potentially offering increased reliability and better quality compared to other sources. However, to ascertain the feasibility and potential benefits of groundwater utilization, conducting a comprehensive hydrogeological study specific to the region is imperative. Such a study would provide a deeper understanding of the local aquifer system, groundwater availability, recharge rates, water quality parameters, and sustainable extraction practices. By undertaking a thorough hydrogeological investigation, decision-makers and stakeholders can make informed choices regarding the development and management of groundwater resources in Umiujaq, ensuring a sustainable and reliable water supply for the community.

Finally, it is crucial to acknowledge that in both strategies (expanding reservoir capacity and utilizing groundwater), careful consideration must be given to the capacity of the water treatment plant. Despite the availability of a larger reservoir or increased groundwater resources, the existing plant may become a bottleneck in meeting the water demands associated with population growth and potential variations in streamflow resulting from climate change. Consequently, it becomes

imperative to enhance the capacity of the water treatment plant to accommodate these factors adequately. This proactive approach ensures that the water supply system remains capable of meeting the evolving needs of the community while maintaining water quality standards in the face of changing conditions.

## 5. Conclusion and recommendations

Climate change is a reality that we are facing today. The scientific consensus is overwhelming: the planet is getting warmer and humans are behind it. While mitigation remains an important aspect of dealing with climate change, current scientific predictions suggest that even if we stopped all greenhouse gas emissions today, global average temperatures could rise by as much as 2°C during this century. Therefore, it is essential that Umiujaq is well prepared to meet the current and predicted impacts associated with a changing climate. Furthermore, considering that the Northern regions are warming much faster than the rest of the planet.

Due to the limited quantity and quality of data in Umiujaq, a hydrological *Grande Riviere de la Baleine* model was developed, calibrated and validated using SWAT and SWAT—CUP. The model had an excellent performance compared to the observed data. The parameters that had a major influence on the model were the snow ones. This aligns with what is mentioned in the literature due to the watershed's location. Then the model was transposed to the Umiujaq watershed. This transposition was supported in the special proximity of the watersheds, and in the fact that the snow parameters were the most influenced in the models. It was found that Climate Change will modify the hydrological regime of this watershed, and its reservoir will need to be managed accordingly. Based on the Climate Change projections used in this research, the hydrological impact of global warming will produce an earlier arrival of the spring peak of streamflow by about 4 weeks. Temperatures will rise earlier, which will directly impact the timing of snowmelt.

After analyzing the community's current and future water demand, it has been noted that the community is facing significant challenges in providing a reliable water supply throughout the year. This predicament is anticipated to worsen with the projected population growth. Enhancing the situation is the expected increase in temperatures resulting from climate change, which will bring about a positive consequence of an earlier melting of the river and a delayed freezing period. This

extended timeframe for river access could potentially provide more opportunities to extract water, thus allowing for an increased window of time for water pumping activities. However, despite this favorable outcome, it remains evident that even with the additional water availability, it would still be insufficient to meet the escalating water demand of the community. Therefore, alternative strategies and solutions need to be explored to ensure a sustainable water supply and address the imminent water scarcity concerns.

The analysis considered two strategies: increasing reservoir capacity and exploring alternative water sources. While a larger reservoir was found to provide short-term relief, it was determined that it would not suffice to meet long-term water demands. On the other hand, upon review of the literature, the investigation determined that groundwater is indeed a promising alternative water source in light of the anticipated impacts of climate change in the region. The analysis of various studies and findings consistently pointed towards groundwater as a viable option. However, further research and investigation are necessary to thoroughly assess the feasibility and sustainability of groundwater utilization in the context of the specific hydrogeological conditions in the area. These additional studies will provide crucial insights to inform decision-making processes and ensure the long-term reliability and adequacy of the water supply in Umiujaq.

In addition to addressing the technical aspects, it is essential to recognize that future impacts, adaptation, and vulnerability research in the northern region should be grounded in strong community engagement and partnerships. Such research should prioritize respect for northern culture and incorporate guidance from local and traditional knowledge. Collaborating closely with the community will ensure that the research aligns with the needs and priorities of the residents. By integrating traditional knowledge and local perspectives, the research outcomes will be more relevant, accurate, and culturally sensitive. This inclusive approach will foster a comprehensive

understanding of the region's water resources, their vulnerability to climate change, and the most appropriate adaptation strategies.

It is important to acknowledge the limitations of this research and methodology. Firstly, the hydrological model developed for Umiujaq was based on data and calibration from the Kuujjuaraapik watershed. With more comprehensive and specific data available for Umiujaq, the reliability and accuracy of the results would be enhanced. Secondly, certain assumptions were made regarding Umiujaq, such as the specific size of the reservoir and the timing of river melt and freeze events in different years, as well as water consumption trends. These assumptions could be further validated and refined to improve the precision of the calculations. Thirdly, as highlighted in the literature review, hydrological models inherently possess uncertainties arising from input and calibration data, model structure, and parameters. Additionally, uncertainties can emerge from the model's initial and boundary conditions. Lastly, climate change models also come with limitations due to the complex nature of the variables included and uncertainties surrounding future greenhouse gas concentrations. Being mindful of these limitations is essential in interpreting and utilizing the research findings effectively.

Finally, it is important to consider future research and work in order to expand upon the findings of this study, as it enables a deeper understanding of the impacts of climate change on northern communities. Here are some potential future research directions:

1. Long-term Monitoring: Establishing a long-term monitoring program in Umiujaq to continuously collect hydrological data, including streamflow, groundwater levels, precipitation, and temperature, to enhance the accuracy and reliability of the hydrological model and improve understanding of long-term trends and variability.

2. **Multi-Model Ensemble:** Conducting a multi-model ensemble approach by running climate change scenarios using different climate models to assess the range of possible future outcomes and reduce uncertainties associated with climate projections. When downscaled data from the Sixth Assessment Report of the IPCC is available to Canada, this information could be used to update the models with the new Shared Socioeconomic Pathways (SSP) proposed by IPCC.
3. **Integration of Socio-economic Factors:** Incorporating socio-economic factors such as population growth, land-use changes, and water demand projections into the hydrological model to obtain a more comprehensive understanding of the interactions between climate change and human activities on water resources.
4. **Community Engagement and Adaptation Strategies:** Engaging with the local community to co-develop adaptation strategies that address the specific challenges and needs of the community in the face of climate change impacts on water resources. This collaboration would ensure the relevance and effectiveness of adaptation measures, promoting community resilience and well-being.
5. **Other Northern Communities:** The methodology presented and developed in this research holds potential for application in other northern communities within Nunavik or Nunavut. However, it is important to note that specific analyses should be conducted for each community, considering key factors such as data availability from the watershed and the community itself. Each region possesses unique hydrological characteristics and data limitations, requiring a tailored approach for accurate assessment.
6. **Lastly,** Stephanie Guilherme's research group is currently investigating water quality trends in the watershed. Leveraging their data and results in conjunction with the hydrological

model developed in this study would enable a comprehensive evaluation of how climate change may impact the water quality of the community.

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## Appendix

### Appendix A: Python code for visualize and open climate data (NetCDF)

```
import netCDF4
import numpy as np
import netCDF4 as nc
import pandas as pd
from netCDF4 import Dataset

fn = r"C:\Users\mario\OneDrive - Universidad Nacional de
Colombia\UOttawa\Umiujaq\Data\Climate data\Umiujaq\Umiujaq85pcp.nc"
ds = nc.Dataset(fn)
pcp = ds.variables['pr'][:]
tme = ds.variables['time'][:]
lat = ds.variables['lat'][:]
lon = ds.variables['lon'][:]

# With num2date verify start date and end date
# Creating an empty Pandas DataFrame covering the whole range of data
start_date = '1989/12/22'
end_date = '2100/11/24'
date_range = pd.date_range(start= start_date,
                           end = end_date,
                           freq='D')

df = pd.DataFrame(0.0, columns=['Precipitation'], index=date_range)

# Defining the lat, lon for the location of interest
lat_umi = 56.543889
lon_umi = -76.543056

# Squared difference between the specified lat,lon and the lat,lon of the
netCDF
sq_diff_lat = (lat - lat_umi)**2
sq_diff_lon = (lon - lon_umi)**2

#Identify the index of the min value for lat and lon
min_index_lat = sq_diff_lat.argmin()
min_index_lon = sq_diff_lon.argmin()

# Reading pcp in each day
for t_index in np.arange(0, len(date_range)):
    df.loc[date_range[t_index]]['Precipitation'] = pcp[t_index,
min_index_lat, min_index_lon]

#print(df)
df.to_csv('pcp_Umi_85.csv')
```