



Review

# An Overview of Climate Change Induced Hydrological Variations in Canada for Irrigation Strategies

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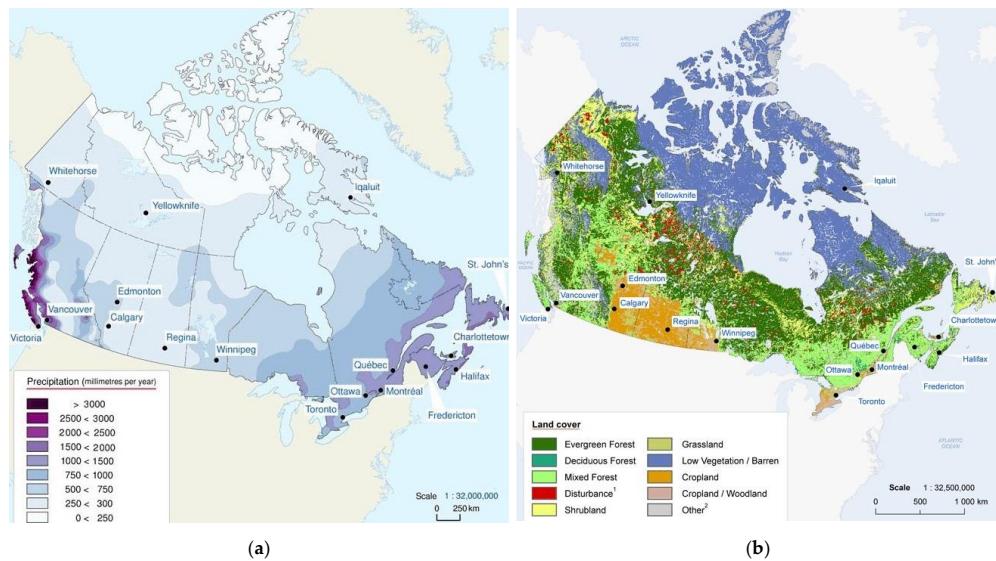
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## 1. Introduction

Canada is geographically the second-largest country in the world, expanding over 9.98 million km<sup>2</sup>. Its substantial area is, however, occupied by freshwater, i.e., 0.89 million km<sup>2</sup>. Situated on the North American continent, Canada is located between latitude 42° to 83° N and longitude 53° to 141° W. The country is bordered by the Atlantic Ocean in the east and the Pacific Ocean in the west [1–3]. Canada is a vast country, as wide as it is long, with the longest coastline (202,080 km), yet it has the lowest population density of 3.8 persons/km<sup>2</sup>. Hydrological diversity prevails, including precipitation and land use across 10 provinces in Canada, as shown in Figure 1 [2].



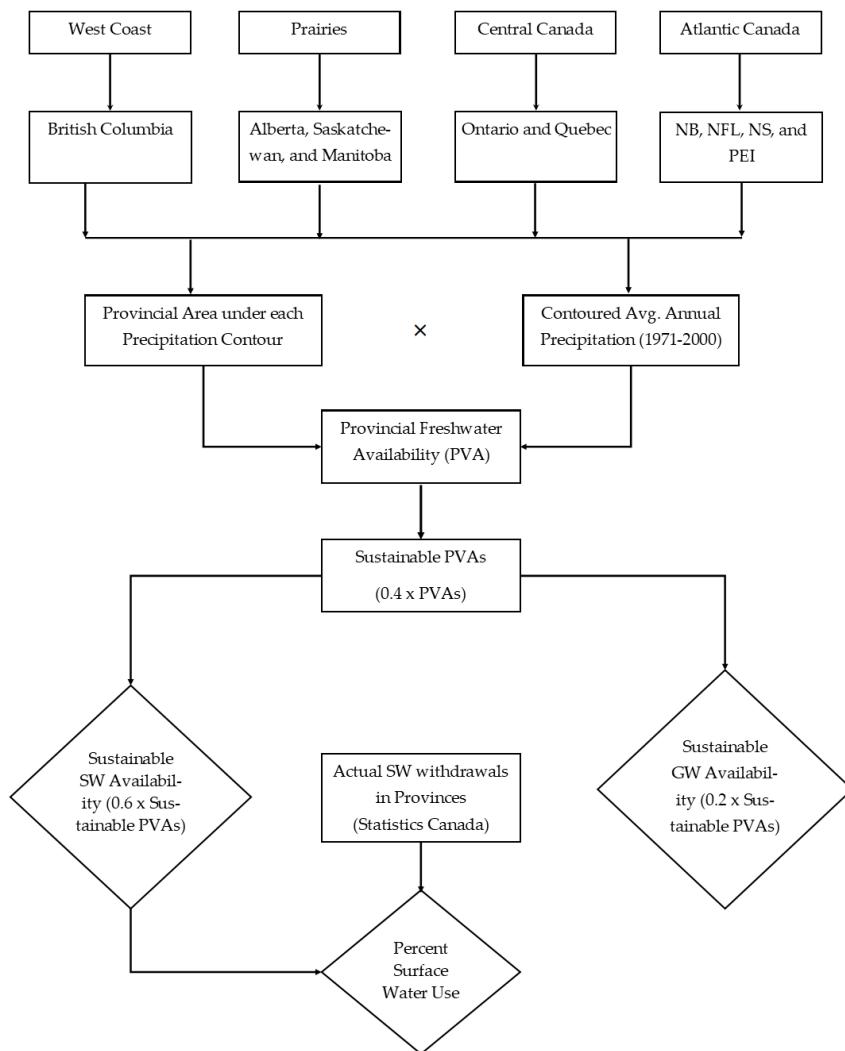
**Figure 1.** Spatial distribution of average annual precipitation (a) and land-use diversity (b) in Canada [2].

Canada is impacted by climate change in terms of warming, changing precipitation patterns, streamflow patterns, etc. An overview of all the changes has been made to propose some irrigation strategies. The novelty of the article is that it integrates information scattered in government reports and scientific publications to understand climate change impacts on Canadian hydrological regimes better and find some sustainable irrigation strategies. Specific research questions explored under the study are: what are the patterns of warming, precipitation, and stream flows in Canada under the changing climate? What are freshwater availability, withdrawals, and its sustainability implications in different regions? What irrigation strategies can be adopted for sustainable agriculture under the changing climate?

## 2. Materials and Methods

The paper integrates information scattered across governmental reports and scientific publications. Governmental websites were used to extract pertinent information, and Google scholar was majorly used to search relevant scientific publications. Initially, around 150 publications were short-listed and reviewed. However, almost one-third of those could not provide added information and were, therefore, excluded. Only information for which more than one authentic source was available has been presented.

Delineation of climate change impacts was segregated into temperature, precipitation patterns, streamflow patterns, and appropriate irrigation strategies thereof. The analysis was spatially segregated into the West Coast (British Columbia), Prairies (Alberta, Saskatchewan, and Manitoba), Central Canada (Ontario and Quebec), and Atlantic Canada (Nova Scotia, New Brunswick, Prince Edward Island, Newfoundland, and Labrador) on a broader scale. However, provincial results were also included. Freshwater availability in provinces was calculated from their weighted average annual precipitations for the latest climate norm available, i.e., 1971–2000, as shown in Figure 1a to serve as benchmarks. Hydrological variations that occurred thereafter have been presented and discussed region-wise. Contoured precipitations within provincial boundaries were multiplied with their respective areas and added together to estimate freshwater availabilities. Sustainable availability/withdrawals were taken as 40% of the total water availability as an established norm. Rational techniques were used to approximate surface water and groundwater as 60% and 20% of sustainable water availability in each province, which in turn, were counterchecked from publications. A flow chart of the input data, steps, and assumptions for computation of sustainable surface water availability, withdrawals, and percent surface water use is given in Figure 2.

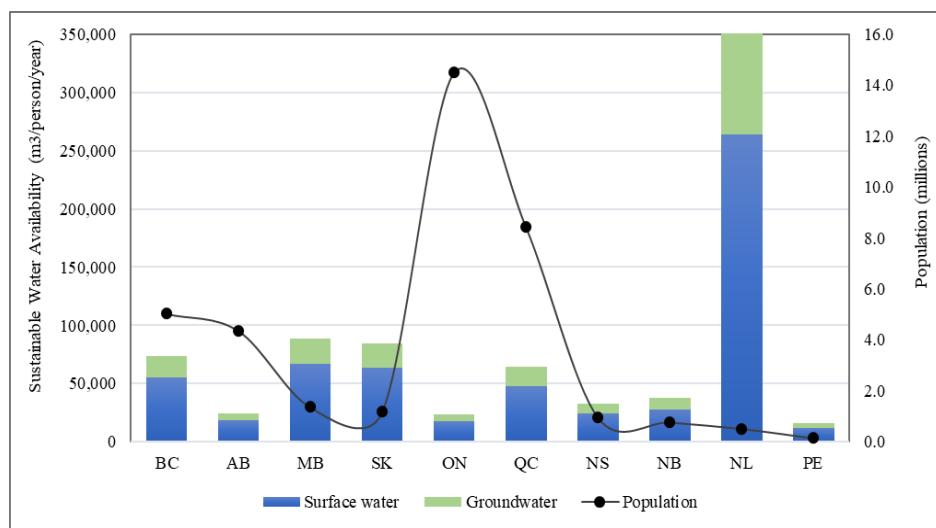


**Figure 2.** Logical flow diagram of sustainable surface water availability and use computations (NB: New Brunswick, NFL: Newfoundland and Labrador, PEI: Prince Edward Island, PVA: Provincial water availability, SW: Surface water, and GW: Groundwater).

It is important to mention that all analysis was in quantitative terms, and water quality aspects were not considered, which indirectly can affect water availabilities. Actual water withdrawals for different uses were ascertained from Statistics Canada for all the provinces. The information was graphically presented to better grasp regional variations and discussed in comparison to the sustainable limits.

### 3. Results and Discussion

Canada is rich in freshwater resources with precipitation, rivers, lakes, and groundwater and has around 20% of the world's freshwater resources [4]. However, it is not uniformly distributed as 60% of the streamflow is in the north, while 84% of the population lives in the south. Most of the provinces and territories recognize 'domestic uses' as the highest priority users [5]. Total renewable freshwater during 1971–2013 averaged  $3478 \text{ km}^3/\text{year}$ , which gives a per capita water availability of  $104,000 \text{ m}^3/\text{person/year}$  [6–8]. The provincial distribution of freshwater availability is shown in Figure 3. Water availability was computed from weighted average annual precipitations in respective provinces as shown in Figures 1 and 2, whereas the sustainable limit was taken as 40% of the available water. The distribution of sustainable water into surface and groundwater was approximated as 60% and 20%, respectively, excluding 20% losses.



**Figure 3.** Provincial distribution of freshwater availability [2].

There are 25 drainage basins and 167 sub-watersheds altogether [4]. The Pacific Coastal regions of Canada produced the maximum amounting to 1500 mm/year, followed by Atlantic Maritime provinces, which produced 850 mm, whereas the Prairies produced the least, i.e., 50 mm average for the Missouri, Assiniboine–Red, North Saskatchewan, and South Saskatchewan regions. However, the freshwater resources are under stress at several places due to population concentrations and climate change [4]. Industrial and miscellaneous water withdrawals are greater than residential withdrawals (Figure 4). Water withdrawals (million cubic meters per year) as well as per capita water consumption (liters/person/year) pertain to the year 2017.

Canada is one of the countries highly affected by climate change. It is facing a multitude of climatic changes, including warming, sea-level rise, changing precipitation patterns, seasonal shifts, thawing permafrost, accelerated snow and ice melt leading to extra exposure to solar radiation, etc. [9,10]. The water balance across the Arctic region (Alaska, Finland, Greenland, Iceland, Northern Canada, Norway, Russia, and Sweden) has been disturbed particularly due to diminishing snow and ice melt contributions and reducing precipitation during winter [11–13]. Water supply and water quality issues are emerging in different parts of Canada. The different impacts of climate change faced by Canada are elaborated in the subsequent sections.

### 3.1. Temperature

In the last 100 years, the average annual temperature has increased by 1.6 °C against the global average of 0.6 °C, which is a higher rate of warming than most other regions of the world. The temperature increase is particularly evident during winter and spring and is likely to further change in the future [14]. The warming is not uniform, though, as northern Canada is warming faster [15].

The rise in temperature in Canada has a lot of spatial and temporal variations. The most pronounced change has been warming winters (1.5–3 °C), particularly in western and southern Canada, whereas the northeastern parts of Canada indicate minimal changes. Temperature rise in spring is evident in most of Canada except some northern parts. The summers do exhibit temperature rise throughout Canada (0.5–2 °C). The autumns have gotten warm in all northern Canada [16].

Temperature rise in Canada has several impacts on different sectors. However, the urban population is severely affected. The amplitude of impact signifies 82% of the Canadian population is urban [17]. The urban heat island (UHI) effect is impacting Canadian population centers harshly in terms of increased summertime energy demands, degradation of urban air quality, and enhanced water demands [18].

There is a direct relationship between the number of greenhouse emissions and temperature rise. Under a high global emission scenario, the mean annual temperature in Canada concerning the recent past (1986 to 2005) is projected to increase by 1.8 to 6.3 °C by the end of the century. During the same period, summer temperatures in Canada are projected to increase by 1.4 to 5.4 °C. Mean winter temperature is projected to increase by 2.4 to 8.2 °C [19].

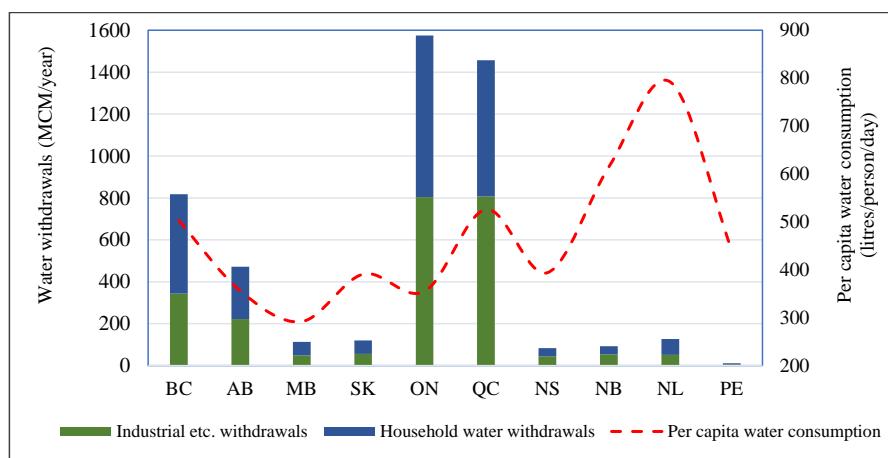
The impact of a further rise in temperature may increase heat-related illnesses and deaths in the elderly and sick people. It will increase cooling demand leading to increased electricity costs, and may increase the risk of food and water contamination. In a broader context, it can increase forest and agricultural pests and diseases, droughts, and wildfires. Particularly, northern Canada is likely to be impacted most [20].

### 3.2. Precipitation Patterns

Precipitation patterns bear a lot of spatial, temporal, and type variation in Canada [21]. The average annual precipitation is 535 mm, which varies from 3000 mm/year near the Pacific coast to less than 500 mm in Prairies. The southern parts receive about 70% of precipitation as rainfall, whereas in the northern parts, the snowfall and rainfall contributions are equal [22]. On a broader scale, Canada can be divided into four climatic zones, namely, Atlantic, Central, Prairies, and West Coast.

The average annual precipitation in the Prairies is around 454 mm, ranges from 800 to 1000 mm in the Atlantic region, from 883 and 1199 mm in the Central and West Coast, respectively. The Prairies and Central regions receive convective precipitation; it is frontal in the Atlantic region and orographic in the West Coast region [23].

The precipitation along the West Coast (British Columbia) is the highest and sharply decreases as we move away from the coast inland, presumably because of the rain shadow effects of the West Coast Mountains [24]. In northeastern British Columbia (BC), major precipitation occurs during summer as rainfall, whereas in the lower mainland of southwestern BC, it is winter rainfall [25,26].



**Figure 4.** Province-wise water withdrawals for different uses [25,26].

The Prairies are drier due to their location under the shadow of the Rocky Mountains and being away from moisture sources; the Southern parts are the driest. The rainfall and snowfall contributions here are 70% and 30%, respectively. Since it is rainfed, rainfall distribution is critical for crops. More than 50% of the precipitation events here are less than 5 mm making 23% of the total, while 25 mm or more events were 2.5%, yet contribute 19% of the total precipitation [27].

The precipitation is also high along the east coast and Atlantic Canada ranging from 1000 to 1500 mm/year. The wettest regions are along the east coast and receive decreased precipitation westward at the rate of 40 mm/100 km [28]. In most of Atlantic Canada,

precipitation is evenly distributed throughout the year, e.g., on Prince Edward Island, the average monthly precipitation is 80–120 mm, and the rainfall to snowfall ratio is 1:2.5 [29].

Northern Canada and the high Arctic regions are the driest. The annual precipitation ranges from 400 mm in their southern parts to less than 200 mm in the high Arctic islands. The underlying reasons are cold air and lack of large moisture sources. Most of the precipitation in Arctic Canada falls during late summer and early autumn [28]. There is considerable inter-annual variability in precipitation as well [24].

The last 65 years' trend reveals that precipitation has been gradually increasing in Canada since the 1950s. The observations at most of the meteorological observatories showed significant variations, through peaks of precipitation increases and decreases reflecting intense and frequent events. Several studies testified to the increasing precipitation trend and its spatial variability in the 20th century [25,26]. Zhang et al. [30] reported that precipitation in Canada increased up to 35% with inter-annual and spatial variability. Vinnikov et al. [31] found a linearly increasing precipitation trend in Southern Canada, whereas Groisman and Easterling [32] found a similar trend for eastern and northern Canada.

A statistically significant increase in snowfall has been detected in northern Canada; conversely, southwestern Canada indicated a significant decline in snowfall [33,34]. The southwestern and southeastern parts showed a significant decrease in snowfall in winter; nonetheless, the rest of Canada did have more precipitation, particularly in the winter, spring, and fall months [16,25]. The annual precipitation increased from 5% to 35% in southern Canada during the 20th century [30]. It can, therefore, be concluded that the climate became gradually wetter in southern Canada throughout the 20th century and in the entire of Canada, particularly after the 1950s.

The correlation between increased precipitation during the 20th century and precipitation extremes is less conclusive. Several studies, including Mekis and Vincent [33], Vincent and Mekis [34], and Zhang et al. [22], reported that the linearly increasing trend of precipitation in the 20th century was mostly contributed by small to moderate precipitation events [30]. Akinremi et al. [35] examined daily events of different classes of intensity over the Prairies and found increased precipitation in terms of more frequent lighter events. Trends of seasonal and regional changes were observed in long-term analysis of the extreme events [36]. Groisman et al. [37], however, concluded that the probability of daily precipitation exceeding 25 mm increased by about 20%, which is 4-times the increase in the mean values. Since Canada is a vast country and its climate greatly varies from the northwest to southeast, the precipitation extreme analysis needs to be done on a regional basis.

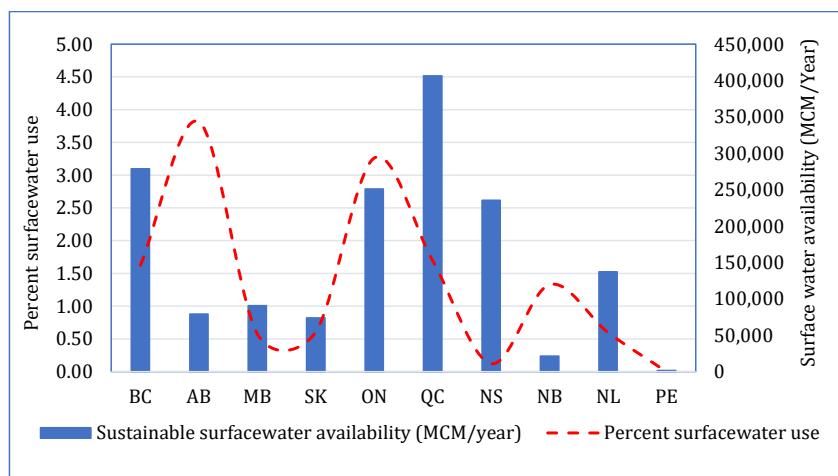
Tan et al. [38] conducted an annual maximum daily precipitation (AMP) analysis for six regions of Canada, including Arctic Maritime, Atlantic Maritime, Boreal Regions, Pacific Maritime, Prairies, and Taiga Regions for the period 1930 to 2010. They found that 5, 21, 45, and 50 stations in the respective regions of the Prairies, Pacific Maritime, Boreal, and Taiga indicated change points in AMP. The Atlantic Maritime region indicated increasing change points during 1990–2000, whereas, in the other five regions, increasing and decreasing change points were equal. They concluded that the AMP had increased in the Pacific Maritime, central Boreal, and the Atlantic Maritime regions and decreased in Prairies, Boreal regions, eastern Ontario, western Quebec, and northwestern Canada. The change points occurred in different regions during the period 1960–1980 [38].

Global atmospheric concentrations of Greenhouse Gases (GHG) are and will continue to increase in the 21st century, continuing climate change at the regional level [39]. It is, therefore, anticipated that total precipitation, as well as intensity and frequency of extreme events, will increase. Numerous studies analyzing the output of Global Climate Models (GCMs) project intense and frequent daily and multi-day precipitation events for most Canadian regions [40,41]. Similarly, Diffenbaugh et al. [42] and Tebaldi et al. [43] found that the precipitation intensity is likely to increase in the 21st century, particularly in northern Canada. Following the observed trends of the 20th century, North America, including Canada, is likely to receive more heatwaves, declined cold extremes and frost

days, and elongated growing season, and some projections show increased snowpack along the Arctic Rim [44].

### 3.3. Streamflow Patterns

The changing precipitation patterns in Canada would have impacted the streamflow patterns, as those are directly related. Around the world number of perennial streams have been converted into ephemeral waterways along with several other changes in hydrological dynamics and water cycle [45,46]. In Canada, the gross area of drainage basins is hydrological divides; however, the effective drainage area is what contributes to streamflow every year or every other year [47]. There are 25 drainage basins in Canada with present surface water withdrawal for all kinds of uses in all the provinces far below the sustainable limits of 40%, as depicted in Figure 5. Sustainable surface water availabilities (in million cubic meters per year) were computed from weighted average precipitation for each province of the latest climate normal, i.e., 1971–2000, as shown in Figure 1a as explained in the Materials and Methods section (Figure 2). Surface water uses were computed from Statistics Canada data and provincial surface and groundwater dependencies [5].



**Figure 5.** Province-wise surface water withdrawal [2,25].

However, it is very difficult to conclude prospective streamflow patterns (annual mean flow and streamflow extremes) under the impact of climate change [22,48,49] due to multiple reasons, including man-made interventions, data scarcity, complex hydrology, local warming, and lack of streamflow gauging. The situation in the major climatic regions and drainage basins is depicted in the subsequent sections.

#### 3.3.1. West Coast

The West Coast regions majorly include BC. It is the third most populous province with a population of over 5 million. Most of the winter precipitation is orographic, as the moisture-laden winds of the North Pacific Ocean encounter the mountains [50].

The precipitation includes both snow and rainfall, which feed most of the watersheds' streams together. Most of the streams in the coastal southern BC are hybrid, whose water supplies depend upon the receding snowpack, temperature, and summer precipitation. The streams experience two peaks in a year, i.e., during winter (November–March) and in spring (April–May) due to rainfall and snowmelt, respectively [51,52].

Watersheds of the area are experiencing climatic changes, mostly in terms of reduced water supplies. The annual mean streamflow in BC significantly decreased during the last 50 years due to a rise in the spring temperatures [22]. It suffered from a streamflow drought situation, below-average runoff over more than a month [53], in 2014 and 2015 due to very low snowfall during winters and accelerated melting due to high temperatures.

Even the snow water equivalent (SWE) for the area reduced by 6% during the second half of the 20th century [54].

Pike et al. [55] showed that the winters have become milder and wetter during the last century, whereas summers have gotten warmer and drier. The average temperatures of the coastal mountains increased by 1.4 °C in the 20th century and are anticipated to continue, due to which the total winter precipitation would increase by 6% by 2050. Despite the anticipated increase in winter precipitation, the streamflow droughts during the summers have become a major water management challenge [56,57].

### 3.3.2. Prairies

The climate of Canadian Prairies is semi-arid to sub-humid. The rainfall–snowfall proportion is 70% to 30% of 454 mm of annual precipitation [35]. Most of the runoff is generated from the rapid snowmelt that takes place during spring, i.e., March and April, whereas snowpack mostly accumulates and redistributes in winter [58,59]. Snowmelt is driven primarily by solar radiation in March or April. However, most of the snowfall ranging from 30% to 75% is either lost due to sublimation or is transported [60,61]. The transported snow contributes in terms of developing ponds. As such, the snow is mostly redistributed to the depressions [62].

The interplay of snowpack in terms of sublimation and transportation to generate streamflow is quite variable in the Prairies. If the blowing wind, responsible for snow transport, gets a longer downward distance, most of the snow sublimates and vice versa [60]. Canopy and vegetation cover also play a part in this process; less sublimation occurs in taller crops and vice versa. Low streamflow during summer may be attributed to high soil infiltration and storage rates due to de-frozen soils, rapid plant growth, and high evapotranspiration rates thereof [63,64].

In northern Alberta, the Athabasca River Basin (ARB) is a lifeline for the communities. Water resources are under tremendous pressure due to rising population, industrialization, and climate change [65–68]. The source of water for the basin is glacier melt and spring freshets, in which the spring flows are much higher than in winter.

Integrated hydrological modeling was conducted for ARB to simulate the impacts of climate change on monthly, seasonal, and annual water (blue and green) at different spatial scales. The results indicated increased streamflow made a major contribution to the boreal lower regions. The annual streamflow in the future can increase up to 16–54% and can cause flooding problems due to precipitation extremes. The biomass is also likely to increase, which would increase green water flow from 9% to 22% [69]. As the coastal watersheds of BC reflect a decline in streamflow, in contrast, some of the Prairies' basins depict otherwise.

Water security in the Saskatchewan River Basin (Sask RB) is at stake as the current and prospective flow regimes of the river are changing due to climate change and human regulations [70]. In Saskatchewan, seasonal rainfall is equal to seasonal evaporation except in overly wet or cool years, particularly in the eastern and northern regions. Inter-river water diversion is already redistributing water from the South Saskatchewan River to the Qu'Appelle River to be used in the Regina and Moose Jaw regions [71]. More than 56% of water withdrawal in Saskatchewan is used by agriculture [72]. This water is used to irrigate 40,000 ha of land. The irrigated area can, however, be increased up to 200,000 ha, subject to the availability of water.

The Agriculture Ministry has proposed to bring more area under irrigation and increase it to 160,000 ha [73]. In addition, the basin is experiencing both severe floods and droughts [74]. The prospective rise in annual average and seasonal temperatures and changes in precipitation regimes thereof [75] would further affect the streamflow patterns.

Therefore, integrated modeling which could integrate agricultural water demand, impacts of climate change, and economic benefits of policy decisions is required. The conventional hydrological models cannot simulate such complex systems [76]. The hydrological modeling by Hassanzadeh et al. [77] revealed that an increase in the irrigated

area would significantly increase evapotranspiration (ET) leading to intense competition between hydropower and agriculture. Climate change and increasing water demands need careful planning and an integrated approach for sustainable water management in the region.

### 3.3.3. Central Canada

The provinces of Ontario and Quebec are categorized as Central Canada. It occupies 2,265,154 km<sup>2</sup> in area, where 60% population of Canada (21.6 million) resides. The climate is continental, with long and cold winters and short, hot-humid summers [22].

The Ottawa River drainage basin is the 12th largest in Canada, draining an area of 146,300 km<sup>2</sup> in the provinces of Ontario and Quebec. It makes up 11% of the Saint Lawrence River drainage area. The streamflow pattern in the Ottawa River basin does witness flooding in spring, while flows remain consistent rest of the year [78]. The Ottawa river basin along with its major tributary, i.e., the Rideau River basin, have lower annual amplitudes and thus show less seasonality and remain less affected by climate change. Ehsanzadeh et al. [79] reported that summer flows are increasing in central Canada, which, however, is not the case for its eastern regions. In the southeastern regions, maritime influences generate streamflow peaks in summer or fall [80]. However, early flood preparedness will be required for better water resources management, particularly in its northwestern regions.

Adamowski and Bocci [49] reported a significant increase in streamflow throughout the year in western Quebec and southern Ontario [49]. Similarly, Burn and Hag Elnur [48] indicated increased flooding in southern Quebec. However, a reduction in streamflow was observed for rivers of eastern regions. Assani et al. [81] reported an increase in intensity and frequency of heavy floods in Quebec, which is also supported by the findings of McBean and Motiee [82] using General Circulation Models (GCMs) for the year 2050. Therefore, the impacts of climate change on the streamflow patterns of the region are quite diverse.

### 3.3.4. Atlantic Canada

The area is rich in freshwater resources with relatively high precipitation, lakes, and rivers. There are 1792 lakes in the region [83]. The largest lake, namely Grand Lake, and the largest river, i.e., Saint John River, are both located in New Brunswick [84]. Stream flows of the region are quite high, which generally decreases from west to east, i.e., 60 cm/annum in the western parts to 120 cm along the Atlantic coast [84,85]. According to Hodgkins et al. [86], the summer flows (August to October) showed a declining trend in the period 1983–2003 as compared to those during 1961–1982, along with early springs.

It has also been reported that the minimum daily flow of the year shifted later in the year as analyzed during the period 1970–2005. Similarly, at most of the gauging sites, a decrease in the minimum and maximum flows was reported over the same time. Although a lot of seasonal variabilities were found, no overall trend was found in the variability of annual runoff [87].

No specific trend can be found for the entire Atlantic Canada in terms of storm surges; however, there is strong evidence of storm surges above 90 cm for Charlottetown, PE, during the period 1940–1980. Warmer climate and reduced ice in the Gulf of St. Lawrence are responsible for this event. Similarly, the Atlantic Provinces are more prone to sea-level rise as several harbors have experienced average rise rates of between 22 and 32 cm/century, which is the highest in Canada [88]. Bhatti et al. [89] investigated rainfall intensity trends in Prince Edward Island and found it increased by 1.15 to 2.24 mm/hr, on average, in central and western parts, respectively, in 2004–17 compared to 1970s.

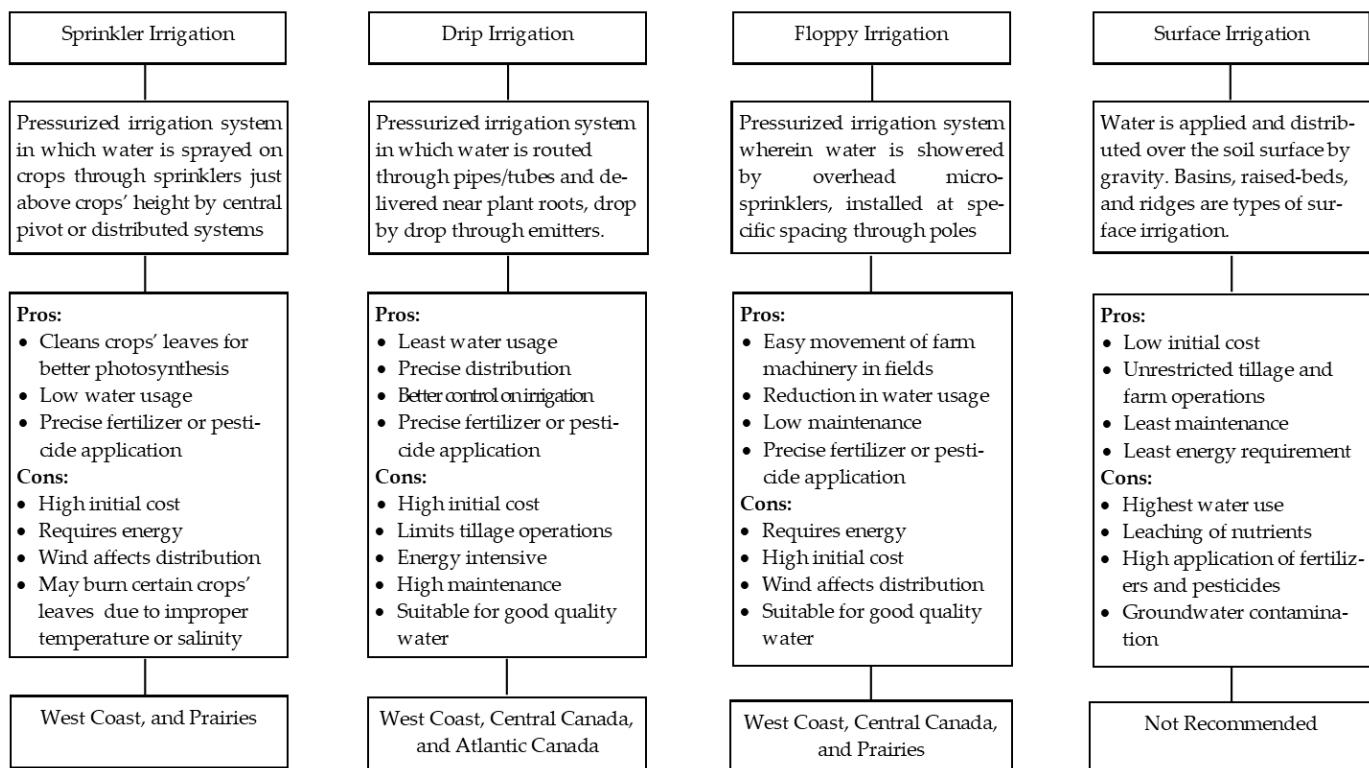
Atlantic Canada is, therefore, likely to be affected by climate change somewhat differently. The temperature rise may be gentler than the rest of Canada; however, the severity of precipitation events, flooding, and more escapade of fresh water to the sea are the major water management challenges for the region.

#### 4. Irrigation Strategies

Irrigation water withdrawals in Canada are negligible (Figure 3). One crop is mostly grown in a year during the summer, for which antecedent soil moisture and rainfalls are enough to meet crop water requirements. However, warming summers and temporal unevenness of rainfall have given rise to supplemental irrigation requirements at different places. Supplemental irrigation is an efficient practice to mitigate water stress and improve yields [90]. For instance, the largest potato production in Canada on Prince Edward Island was found to reduce 4–21% due to climatic extremes. Supplemental irrigation during dry months was proposed for sustainable production there [91]. Similarly, other crops' production can be boosted by providing supplemental irrigation at crucial stages of growth. Supplemental irrigation is neither required in every season nor throughout the crop's growth period; rather, it is a backup to fill any gap between available and required soil moisture due to delayed rainfalls and hot weather. The philosophy of supplemental irrigation is the reverse to conventional irrigation, in which the principal source of moisture for the crops is irrigation, and highly variable precipitation is taken as supplementary. It is not likely to affect regional hydrological balances, as withdrawals for supplemental irrigation are relatively small, and the existing water withdrawals are much below sustainable limits in most of Canada, as shown in Figure 4. It is, however, pertinent to mention that agricultural water use has significantly increased in the last decade. Approximately  $2.95 \text{ km}^3$  of water was used for agricultural irrigation in 2018, whereas in 2012 it was  $1.7 \text{ km}^3$  and  $0.84 \text{ km}^3$  in 2010 [92].

Though the availability of water is not a limitation for the requisite supplemental irrigation, rising energy demand thereof is. Notaro et al. [93] studied the water–energy nexus in the European context and found that energy intensity for the provision of water there ranges from  $0.25$  to  $4.5 \text{ kWh/m}^3$ . Energy demands could exponentially rise depending on the quality of water sources, e.g., desalination will require an additional  $15 \text{ kWh/m}^3$ . This impacts GHG emissions as presently, each kWh of energy produces on average  $0.49 \text{ kgCO}_2\text{eq}$ . Therefore, sustainability of agriculture through supplemental irrigation as required may have indirect environmental impacts in terms of increased GHG emission. However, ensuring efficiency in water supply systems through the elimination of leakages, usage of energy-efficient pumps ( $\eta = 0.75$  and above), and using renewable energy sources, such as photovoltaic power, can mitigate such likely impacts [93].

Provision of supplemental irrigation by the least efficient surface irrigation is not a good idea. This is even though the availability of water is mostly not a limitation in most of the regions in Canada. Drip irrigation systems for orchards and sprinkler or floppy irrigation systems for high-value crops are recommended. An increase in production is likely to outweigh costs as supplemental irrigation not only increases yield but also stabilizes production. The International Centre for Research in Dry Areas (ICARDA) found a 30–400% increase in wheat yields by providing supplemental irrigation in Syria. Though yield increase by supplemental irrigation is significantly higher in dry areas, where moisture is the single most limitation for productivity [94], supplemental irrigation would substantially increase crops' yields in Canada. This is a good adaptation to climate change in which rising temperatures are increasing crop water requirements and keeping up with the pace of rising food demands. A schematic of irrigation strategies with their benefits, performance, and weaknesses for different regions is given in Figure 6.



**Figure 6.** Schematic of irrigation strategies for different regions with merits and demerits.

## 5. Conclusions

Spatial and temporal distribution of warming is non-uniform in Canada with winters: 1.5–3 °C; summers: 0.5–2 °C and is more pronounced on southern and western parts. It is causing several hydrological changes, most importantly, accelerated loss of arctic ice (12.8%/decade) and BC glaciers (40–70 gigatons/year), sea-level rise, particularly on the east coast (38 cm/century), more storm surges, increasing precipitation (from under 500 mm to around 600 mm per year), but unevenly distributed (+35% to –10%) with a simultaneous increase in rainfall intensity, frequent and early flooding, etc. The precipitation trends are likely to continue in the 21st century. Annual streamflow patterns mostly exhibit stability, with changed temporal distribution, due to the complex interplay of different hydrological components. Surface water withdrawals in all the provinces were found to be well under the sustainable limits, i.e., 40% of the water availability. However, several hydraulic structures and drainage infrastructure of cities would need re-designing against the backdrop of rising rainfall intensity for efficiently disposing of peak loads. Furthermore, warming is increasing energy and water requirements; efficient systems can mitigate its carbon footprints, as presently each m<sup>3</sup> of supplied water causes GHG emission of 0.12 to 2.2 kgCO<sub>2</sub>eq. Supplemental irrigation would be required to fulfill rising crop water requirements due to rising temperatures in rainfed and prairies regions. Water availability is mostly not a concern; however, raised energy demand for pumping and distribution is. Adopting high-efficiency drip systems for orchards, and sprinklers or floppy systems for high-value crops, transition and up-gradation to water and energy-efficient supply systems, such as those having good quality sources, leak-proof distribution, and powered by renewable energy sources, can ensure sustainable agriculture. Massive investment in clean energy development, regional monitoring, and adapted water management would be required to combat the impacts of climate change to provide sustainable water and agriculture in Canada.

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B.A., and A.A.F.; data curation, A.Z.B., F.A., and Q.L.; writing—original draft preparation, A.Z.B. and A.A.F.; writing—review and editing; N.K., Q.L., W.P., and B.A.; supervision, A.A.F.; project administration, A.A.F. and F.A.; funding acquisition, A.A.F. All authors have read and agreed to the published version of the manuscript.

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