

Hydrological Regime Responses to Climate Change for the 2020s and 2050s Periods in the Elbow River Watershed in Southern Alberta, Canada

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Abstract The Elbow River watershed, located in southern Alberta, drains approximately 1,235 km² area, and supplies the Glenmore Reservoir that provides water to nearly half of Calgary, a fast growing city of 1.1 million inhabitants. The watershed is characterized by a complex hydrological regime and is typical of snow dominated basins, with a spring freshet driven by snow melt and rainfall in late spring and early summer. This context creates favorable conditions for springtime flooding, which resulted in extensive damage in 2005 and 2013. Therefore, understanding how future climate changes might influence the watershed hydrological regime is critical. This research was conducted to investigate the hydrological regime responses of the watershed to climate change for the period of 2020s (2011–2040) and 2050s (2041–2070), relative to 1961–1990. The physically-based, distributed MIKE SHE/MIKE 11 model was used to simulate hydrological processes based on a warmer and drier (CCSRNIES A1FI) climate scenario. Results reveal that the average annual overland flow, baseflow, and river flow will decrease over the next 60 years and that this decrease combined with a drastic increase in evapotranspiration might increase water scarcity. Peak flows will increase in the winter and early-mid spring while decreasing in the summer and early fall. This enhances the risk of flooding in the spring, especially in the month of April which exhibits a significant increase in rainfall coinciding with the highest increase in spring freshet.

Keywords Hydrological modeling · MIKE SHE/MIKE 11 · Elbow River watershed · Alberta · Climate change · Flood

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1 Introduction

The Elbow River watershed, located in southern Alberta, drains approximately 1,235 km² (Fig. 1) area. It belongs to the Canada's Western Prairie Provinces (WPP), which lie in the rain shadow regions of the Rocky Mountains and are the driest of southern Canada (Schindler and Donahue 2006). This area has experienced several severe droughts in the 20th century. In one of the worst events in the 1930s, referred to as the “dirty thirties”, 7.3 million hectares of agricultural land were damaged and 250,000 people left the Canadian prairies (Gan 2000).

The Elbow River watershed is one of the regions in the WPP that is most affected by climate change. Valeo et al. (2007) performed statistical analysis on historical temperature data in the watershed and found that the annual average temperature has increased by 0.056 °C/yr between 1965 and 2004 in the west part of the watershed and by 0.007 °C/yr between 1885 and 2004 in the east part. Future projected data (provided by Alberta Environment and Sustainable Resource Development) for the CCSRNIESA1FI climate model project that the temperature may increase by approximately 4 °C by 2050, relative to 1990, in the watershed. This considerable change can lead to extreme hydrological events in the future, such as droughts (Schindler and Donahue 2006) and floods (Valeo et al. 2007).

Chen et al. (2006) investigated future climate trends and river water resources availability based on historical climate, streamflow, and population data of the Calgary region. They indicated that Calgary might face significant water supply

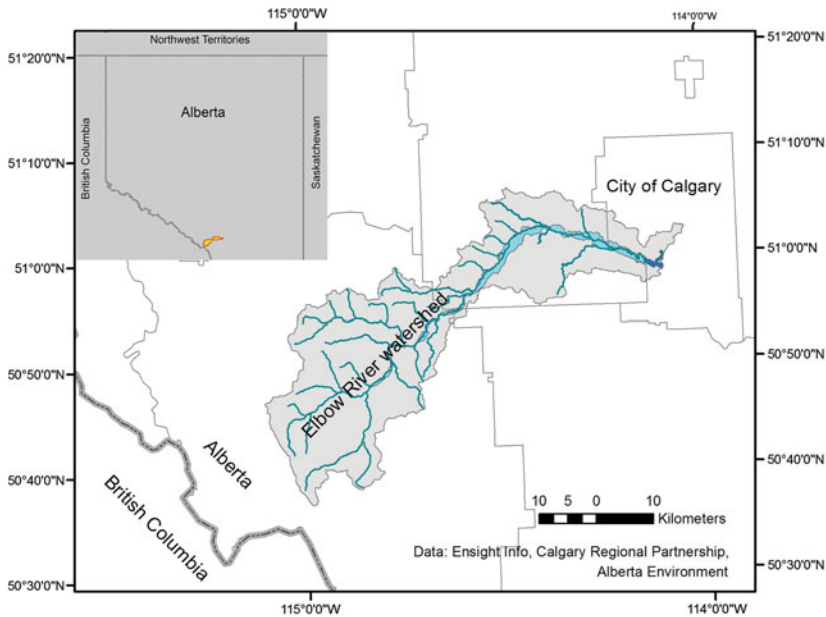


Fig. 1 Location of the Elbow River watershed

challenges in the future. For this city to maintain a sustainable water supply, it will require water conservation efforts to reduce the per-capita water consumption to less than 50 % of the current level by 2064. Even then, in the hot and dry projected periods, water demand could exceed the supply allotments (Chen et al. 2006). As a result, the Province of Alberta has stopped accepting new applications for the allocation of water since August 2006 in the Bow River basin of which the Elbow River is an important multi-use tributary (Pernitsky and Guy 2010).

Flooding is the other great stress endured in the Elbow River. In June 2013, the Elbow River was flowing through Calgary at 12 times the regular rate causing \$400 million of damages, and the evacuation of 110,000 people (City of Calgary 2013). Two other floods of less magnitude occurred in 1995 and 2005. These floods happened in the month of June, which coincided with Albertans experiencing the driest years in climate history (Valeo et al. 2007). This is an indication of how climate change can alter the frequency and severity of extreme and contrasting events in a watershed, which depend not only on the magnitude of the change but also on the watershed characteristics, and its vulnerability to climate change. To better understand the vulnerability of the Elbow River watershed to climate change, its main characteristics are presented in the next section.

1.1 Characteristics of the Elbow River Watershed

The Elbow River originates at Elbow Lake at an elevation of 2,095 m above sea level and flows 120 km eastward through the alpine, subalpine, boreal foothill, and aspen parkland before joining the Bow River at 1,033 m above sea level in downtown Calgary (Beers and Sosiak 1993). In terms of land-use (Fig. 2), the watershed is comprised of urban area (5.9 %), agricultural land (16.7 %), rangeland/parkland (6.2 %), evergreen forest (34 %), deciduous forest (10 %), and clear-cut (1.8 %), (Wijesekara et al. 2012).

1.1.1 Meteorological Characteristics of the Watershed

Climate data (obtained from the Alberta Environment and Sustainable Resource Development (AESRD)) indicate that the average annual air temperature is 2.5 °C in the watershed. The warmest month is July with an average temperature of 13.2 °C, while the coldest month is January with an average temperature of -9 °C. The average total annual precipitation is 690 mm, of which almost 67 % falls between the months of April–September. The month of June is the wettest month with an average precipitation of 99.6 mm. The average annual potential evaporation is 552.5 mm, with the highest rate of evaporation (101 mm) recorded in July.

There is a significant difference in climate between the eastern and western portions of the watershed, since it lies between almost 2,100 m difference in elevation (Appendix A.1). To take this difference into consideration, the watershed

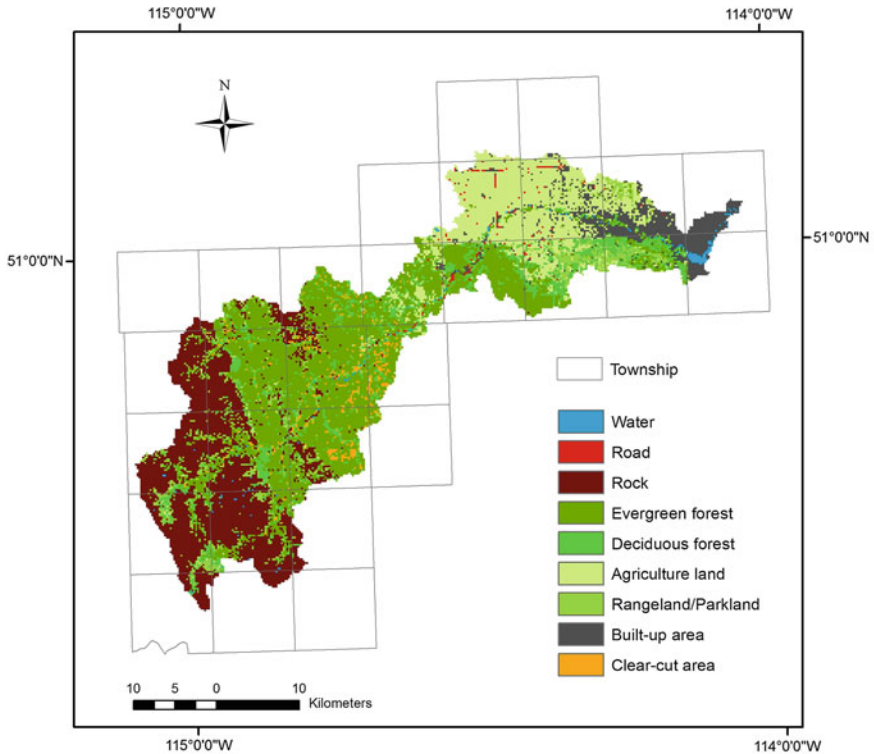


Fig. 2 Land-use map of the Elbow River watershed for the year 2010 (*Data source* Geocomputing Laboratory, University of Calgary)

was delineated into two sub-catchments (based on a digital elevation model): the west sub-catchment which is upstream of the 05BJ004 station (Bragg Creek), and the east sub-catchment which is downstream of that station (Fig. 3).

To estimate the average precipitation for the eastern and western sub-catchments, two precipitation gauges were selected for each sub-catchment in different locations; since precipitation varies spatially, it was necessary to use the data from gauges located at different locations. For the eastern sub-catchment, the temperature index station is Calgary, and the precipitation index stations are 3031875 and 3031090 (Fig. 3). For the western sub-catchment, the temperature index station is Nakiska, and the precipitation index stations are 305LRKB and 353602 (Fig. 3).

In the east sub-catchment, the annual average temperature is 4.1 °C at the Calgary station while in the western sub-catchment the annual average temperature is -1.9 °C at the Nakiska station. From April to September, precipitation reaches 399 mm in the eastern sub-catchment and 332 mm in the western sub-catchment (Figs. 4 and 5). However, the western sub-catchment gets significantly higher precipitation (272 mm) than the eastern sub-catchment (98 mm) between the months of October and March.

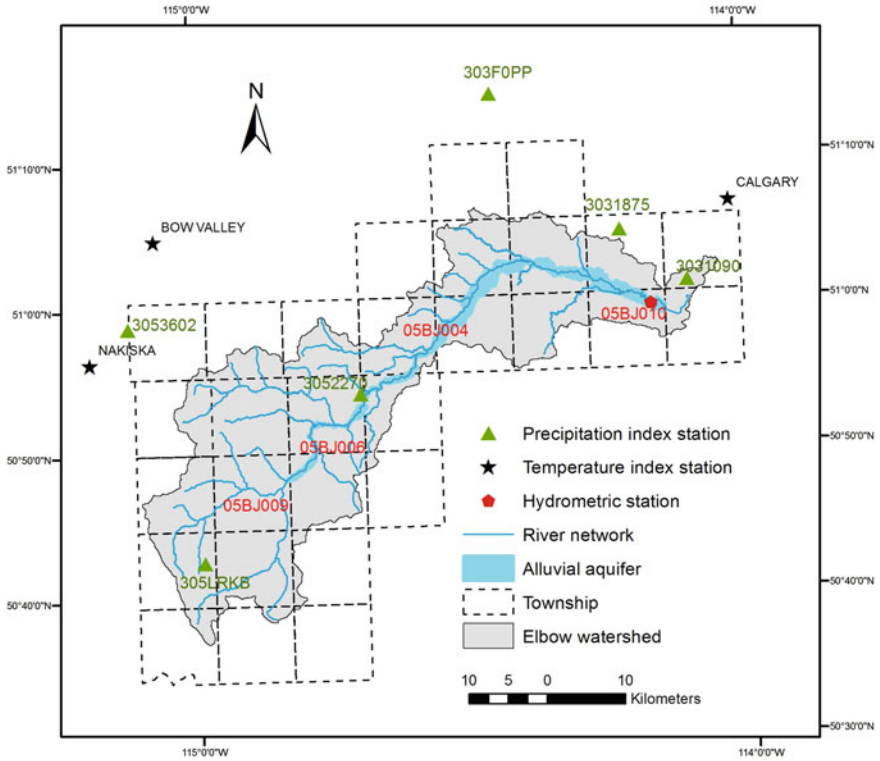


Fig. 3 Location of the climate index and hydrometric stations in the Elbow River watershed (*Data source* Alberta Environment and Sustainable Resource Development)

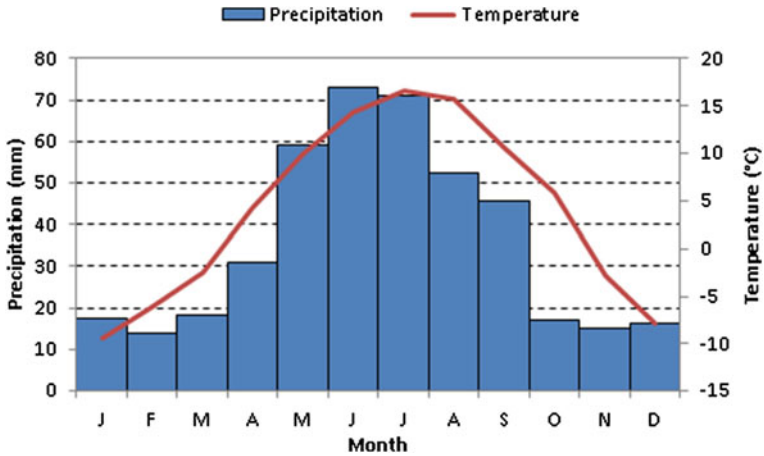


Fig. 4 Average monthly precipitation and temperature distribution in the eastern sub-catchment of the Elbow River watershed

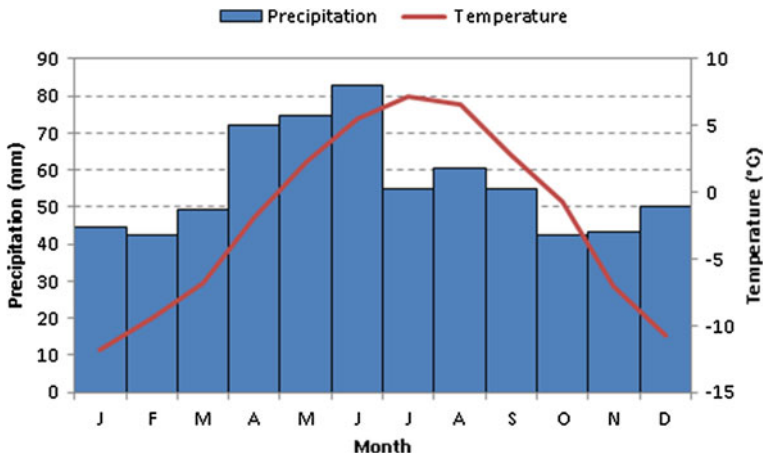


Fig. 5 Average monthly precipitation and temperature distribution in the western sub-catchment of the Elbow River watershed

1.1.2 River Regime

Four hydrometric stations, 05BJ009, 05BJ006, 05BJ004, and 05BJ010 (Fig. 3), measure discharge rates along the river. From west to east, the 05BJ009 and 05BJ006 stations cover 129 and 437 km² drainage areas in the front ranges of the Rocky Mountains in the western sub-catchment. The average annual discharge is 3.33 and 6.44 m³/s at these stations respectively. The volume of water flowing down the river increases at the 05BJ004 station with the average annual discharge of 8.13 m³/s. This station represents the outlet of the western sub-catchment and measures discharge rates of 791 km² drainage area upstream of the hamlet of Bragg Creek. The river flows to the lowlands areas in the eastern sub-catchment and drains a cumulative area of almost 1,200 km² at the 05BJ010 station upstream of the outlet of the watershed. The average annual discharge rate at this hydrometric station, which can be considered as the river flow volume discharging into the Glenmore reservoir, is 10 m³/s.

The discharge rates differ, especially for peak flows, from month to month, and year to year. Figure 6 displays a typical average daily hydrograph of the Elbow River based on 72 year average daily discharge in the watershed. Generally, the flow of the river starts rising between the 100th and the 130th days from the beginning of the year, and reaches its peak flow between the 150th and the 180th days and then gradually starts decreasing between the 181st and the 210th days. In fact, overland flow and through flow are the major contributors to the river flow in the days between rising and falling limbs of the hydrograph and the baseflow is the main contributor in the remaining of the days during a year. In terms of monthly discharge variability (Fig. 7), the high flow period occurs in May, June, and July.

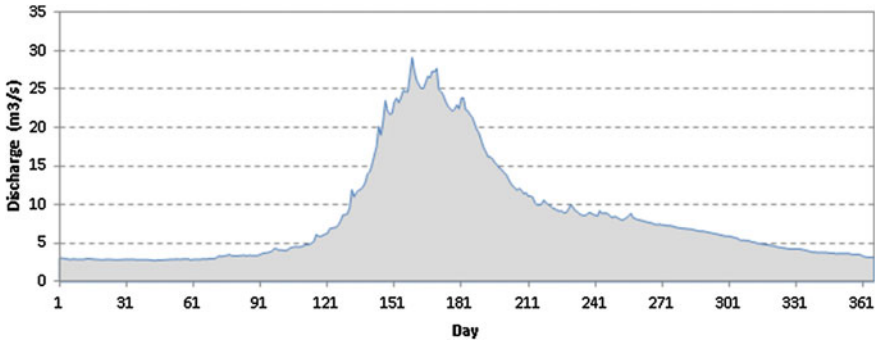


Fig. 6 Average daily hydrograph in the watershed (*Data source* Alberta Environment and Sustainable Resource Development)

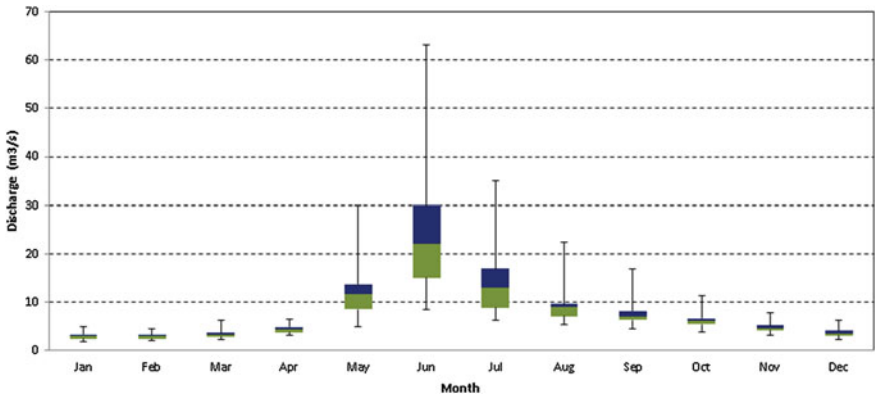


Fig. 7 Box plot of average monthly discharge illustrating the minimum, the 25 percentile, the median, the 75 percentile, and the maximum discharge values

The average peak flow for these months are 30, 63.1 and 35 m³/s while the low flow are 4.83, 8.51 and 6.27 m³/s for the period of 1978–2011, respectively.

The historical variability in low flow and high flow were investigated to understand the vulnerability of the watershed to droughts and floods. Daily historical low flow, peak flow, and instantaneous discharge are available for the periods of 1978–2011, 1935–2011, and 1950–2011, respectively. A trend analysis of the streamflow exhibits a moderate (0.30 m³s⁻¹y⁻¹) and slight (0.11 m³s⁻¹y⁻¹) increase in the instantaneous discharge and peak flow for the periods of 1950–2011 and 1935–2011, respectively (Fig. 8). In addition, low flow increases slightly (0.01 m³s⁻¹y⁻¹) for the period of 1978–2011 (Fig. 9). An increasing trend in both low flow and high flow is a clear indication of increasing risk of droughts and floods in the past decades in the watershed, which might be associated with climate and/or land-use changes in the watershed.

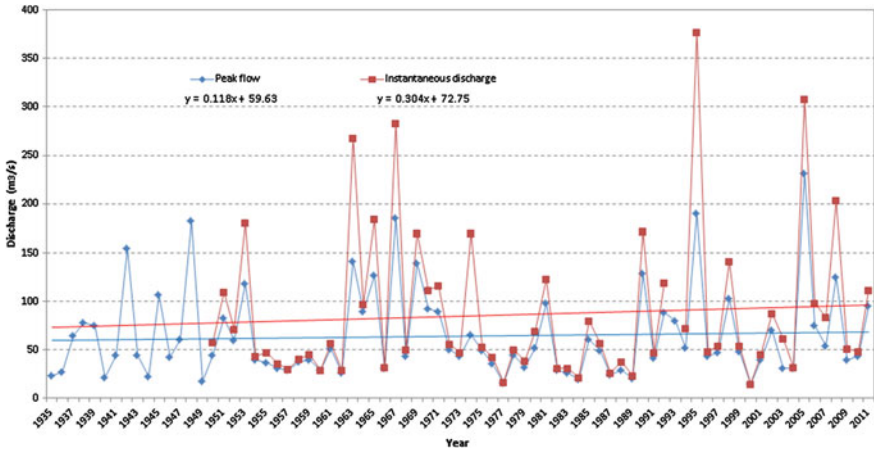


Fig. 8 Peak flow and instantaneous discharge series in the watershed (Data source Alberta Environment and Sustainable Resource Development)

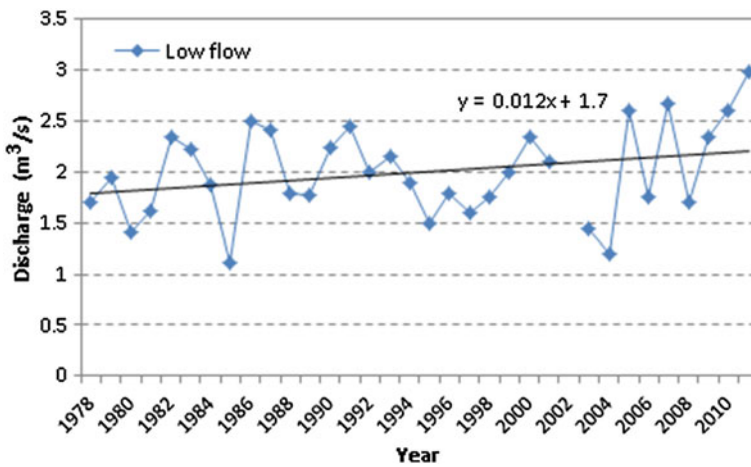


Fig. 9 Low flow discharge series in the watershed (Data source Alberta Environment and Sustainable Resource Development)

The highest peak flows of the watershed that have been recorded in history (at the 05BJ004 station) occurred in 1879 (Waterline 2011) and in 2013 with discharge values of 980 and 959 m^3/s , respectively. Other high peak flows of lesser magnitude are 836 m^3/s in 1932 and 489 m^3/s in 1929 while the recurrence of 20 and 100 year of flood events are 340 and 758 m^3/s , respectively (Waterline 2011). It is not possible to directly relate the flood events (such as the recent ones of 1995, 2005,

and 2013) to climate change. However, the observed trends in increased peak flows and temperature (which results in increased snow melting) are affirmative signs of increasing vulnerability to floods of higher magnitudes and frequencies.

1.1.3 Geomorphological Characteristics of the Watershed

The geomorphological characteristics of the watershed can influence the flow regime, especially during flooding. For example, the time of concentration, which describes the speed and intensity of the watershed response to storms, changes with the different morphological characteristics. The geomorphological characteristics of the Elbow River watershed, namely the stream patterns, shape, drainage density, stream order, and topography vary considerably from west to east (Fig. 10). The western sub-catchment mostly lies in the highland areas with less recession time of overland flow. The stream patterns of the western sub-catchment are similar to trellis patterns that are characterized by long main streams intercepted by numerous shorter right-angle tributaries. Trellis patterns are commonly found in regions of folded or tilted strata. However, the stream pattern of the eastern sub-catchment is dendritic, which is characterized by gentle regional slope, and relatively uniform lithology (Mejía and Niemann 2008).

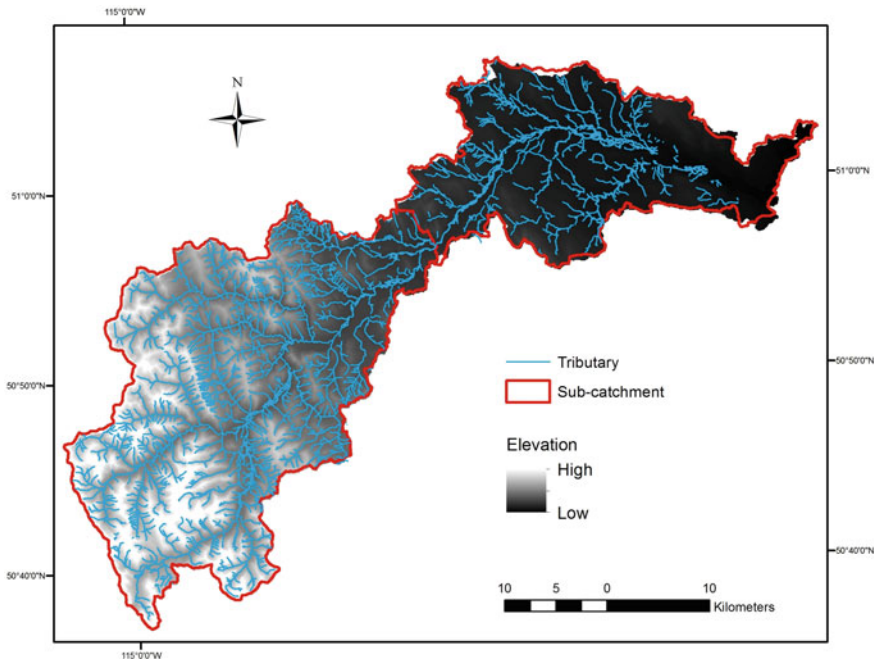


Fig. 10 Geomorphological characteristics of the Elbow River watershed (*Data source Alberta Environment and Sustainable Resource Development*)

These physical characteristics in the western sub-catchment along with the orographic precipitation and snowmelt are the major factors explaining that about 80–90 % of streamflow originates upstream of the station 05BJ004.

1.1.4 Geological and Hydrogeological Characteristics of the Watershed

The surficial geology of the Elbow River watershed is dominated by glacial deposits and recent alluvial deposits (Manwell et al. 2006). The watershed contains the following aquifers (Waterline 2011): Unconsolidated Glacial Overburden aquifers, Elbow River alluvial aquifer, Porcupine Hills Formation aquifers (multiple aquifers with depth), Coalspur Formation aquifer, Brazeau Formation aquifer, and the karstic Paleozoic carbonate aquifer(s).

The alluvial aquifer plays an important role in the hydrological regime of the watershed since it is generally very permeable and hydraulically connected to the Elbow River. The aquifer lies along the Elbow River for approximately 5 % of the watershed (61 km²) which extends from the near headwaters in the west to the Glenmore reservoir in the east (Waterline 2011).

The hydraulic conductivity of the aquifer is on the order of $1 \times 10^{-3} \text{ m s}^{-1}$ (Manwell et al. 2006; Meyboom 1961), and the direction of groundwater flow is generally from the west to the east along the axis of the watershed (Waterline 2011). Discharge from groundwater to river flow, between August and April, is approximately 40 % of the total annual streamflow (Beers and Sosiak 1993).

Different geological settings and the alluvial aquifer along the river create complex interactions between surface water and groundwater. This complexity can be enhanced when there are different climate conditions in the watershed. Furthermore, the watershed is typical of snow dominated basins, with a spring freshet driven by snow melt and rainfall in late spring and early summer. Along with the morphological characteristics of the basin, this creates favorable conditions for springtime flooding, which resulted in extensive damage in 2005 and 2013. Therefore, understanding how future climate change might influence the hydrological regime of the Elbow River watershed is of critical importance. The objective of this study is to investigate the hydrological regime responses to climate change for the period of 2020s (2011–2040) and 2050s (2041–2070), relative to 1961–1990.

2 Methodology

MIKE SHE/MIKE 11, a physically-based, distributed model, capable of simulating the entire processes occurring in the land phase of the hydrologic cycle (DHI 2009), was used to simulate the hydrological processes in the watershed.

Most of the equations in the MIKE SHE/MIKE 11 model are based on the interchangeable types of mechanical energy (kinetic energy, potential energy, and

pressure energy) for moving a water particle along a streamline. MIKE SHE quantified overland flows using the two-dimensional Saint-Venant equation, unsaturated zone flows using the two-layer water balance method, saturated zone flows using the Darcy equation, and evapotranspiration using Kristensen and Jensen method. MIKE 11 is a fully dynamic and one-dimensional hydraulic model that simulates flows, rivers, channels, and other surface water bodies based on the complete dynamic wave formulation of the Saint Venant equations (Singh 1995).

The methodological framework used in this study is illustrated on Fig. 11. The coupled MIKE SHE/MIKE 11 model requires a large amount of data. Some of these data, such as the physical characteristics of the surface/subsurface (Appendix B.1), were provided by earlier research (Wijesekara et al. 2014). Land-use maps of the years 1985, 1992, 1996, 2001, and 2006 were generated from Landsat Thematic Mapper imagery at the spatial resolution of 30 m (Hasbani et al. 2011). Climate data were provided by the Alberta Environment and Sustainable Resource Development (AESRD). The observed temperature data are from the period 1961–1990, acquired at an hourly basis for three index stations: Calgary, Nakiska, and Bow valley. The observed precipitation data were acquired for the same period of time (1961–1990), on a daily basis at six index stations: 3031090, 3031875, 303FOPP, 3052270, 353602, and 305LRKB.

Future climate data were selected for the warmer and drier climate scenario (A1FI), and were projected for the period of 2011–2040 (2020s) and 2041–2070 (2050s) relative to the baseline period of 1961–1990 using the CCSRNIES model (Barrow and Yu 2005). These data include precipitation and temperature which have been downscaled using the delta method. The delta method is widely used in hydrological studies of climate change (Hay et al. 2000; Snover et al. 2003; Buytaert et al. 2009; Xu et al. 2009; Buytaert et al. 2010). This method applies change values, obtained from simulation of baseline and future, to perturb the historical daily climate data (1961–1990). The perturbed precipitation and temperature data were generated for the mentioned index climate stations (Golder Associates 2010).

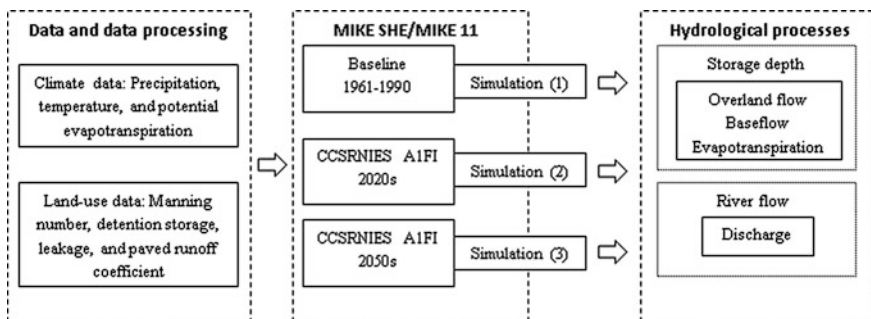


Fig. 11 Methodological framework

The index-based precipitation data were used for configuring the MIKE SHE model. However, the index-based temperature data were converted into township-based temperature (the MIKE SHE model performed better based on township-based temperature rather than index-based temperature during the calibration process as revealed in previous studies (DHI Water and Environment 2010; Wijesekara et al. 2014)).

A programming code was developed in Matlab to interpolate the temperature data using the following procedure. First, Thiessen polygons were created to identify the area of influence for the temperature index stations. Second, a digital elevation model was used along with an elevation lapse rate to interpolate temperature at the resolution of 80 m. The orographic correction factor that was selected is 0.75 °C/100 m, a value that was recommended in previous studies (DHI Water and Environment 2010; Wijesekara et al. 2014). Finally, the interpolated temperature data were split into 29 townships (each 6 by 6 square mile) and employed for configuring the MIKE SHE model.

Potential evapotranspiration (PET) is the other primary climate dataset required in MIKE SHE. It must be estimated using the available projected data (temperature) for the future periods. A literature review was conducted to identify models that could be used for calculating future PET in the watershed. The following criteria were considered for the selection of a model: (a) it must be based on air temperature for calculating PET, (b) it must have been applied in the study area or in a similar climate, and (c) it must be widely used (accepted). Based on these criteria, the following models were chosen: (a) the Hargreaves-Samani (Hargreaves and Allen 2003), (b) the Thornthwaite (Sentelhas et al. 2010), and (c) the Blaney-Criddle models (Espadafor et al. 2011). These models were compared using PET rates provided by AESRD for the period of 1961–2005. These rates have been calculated using the Priestley-Taylor model (Priestley and Taylor 1972) used by Alberta Agriculture and Food for the Elbow River watershed. The performances of the models were evaluated using linear regression analysis, Root Mean Square Error (RMSE), and Mean Bias Error (MBE). The Hargreaves model showed the best performance and was selected for calculating PET. This model was calibrated for the period 1961–1990 and validated for the period 1991–2005.

In addition to the baseline (1961–1990) and future (2020s and 2050s) climate data, four land-use parameters, namely, the Manning number, detention storage, paved runoff coefficient, and leakage coefficient were also used to setup the model. The parameters were extracted from the land-use map of 1985 and were assumed constant for all simulations. The parameters were defined for each land-use class using specific values. The values of the Manning number were derived from the literature whereas the values of the detention storage were determined through calibration (Appendix C.1). A value of 1 (100 % of overland flow) and 1e-013 (minimum value for infiltration) was assigned to built-up areas for paved runoff and leakage coefficient, respectively.

The water balance of the watershed was determined in the MIKE SHE model, since it is an important indicator to assess the responses of hydrological processes to climate change (Hendriks 2010). The water balance corresponds to the amount of

water that is taken into or released for storage within the watershed. The hydrological processes such as evapotranspiration (ET), baseflow, and surface flow were used as the major water balance components for estimating the storage depth in the watershed. They were simulated for the entire watershed and for the western and eastern sub-catchments on an average monthly and annual basis for the 2020s, 2050s, and the baseline period. Apart from the water balance assessment, the daily absolute value of discharge at hydrometric stations in m³/s was obtained through the coupling of MIKE SHE and MIKE 11. For the purpose of this study, only discharge values for station 0BJ010 were evaluated since this hydrometric station is located near the watershed outlet and represents most of the drainage area.

The model was calibrated and validated using a rigorous procedure described in detail in Wijesekara et al. (2014). The calibration was conducted for the period of 1981–1991 with the land-use map of 1985. Four time periods (1991–1995, 1995–2000, 2000–2005, and 2005–2008) were used for validation with their corresponding land-use maps (1992, 1996, 2001, and 2006). The goodness-of-fit was evaluated by comparing observed data and simulated data of total snow storage and stream flow.

3 Results

In this section, results from the simulation of hydrological processes and streamflow in response to climate changes are presented.

3.1 Simulation of Hydrological Processes

Table 1 and Fig. 12 illustrate the average annual storage depth and percentage of change of overland flow, baseflow, and evapotranspiration (ET) for the periods 2020s and 2050s, relative to the baseline. The average annual overland flow decreases by 10.5 % in the 2020s and by 10.6 % in the 2050s. These decreases correspond to the changes in the projected climate variables namely, temperature and precipitation (Table 2). In the 2020s, the considerable decrease in overland flow is primarily associated with the average annual precipitation that reveals a 4.7 %

Table 1 Average annual storage depth and percentage of change (relative to the baseline) for overland flow (OL), baseflow (BF) and evapotranspiration (ET)

Hydrological processes	Average annual storage depth (mm)		
	Baseline	2020 s	2050 s
OL	141.24	126.43	126.27
BF	86.43	80.46	83.34
ET	415.47	411.55	444.28

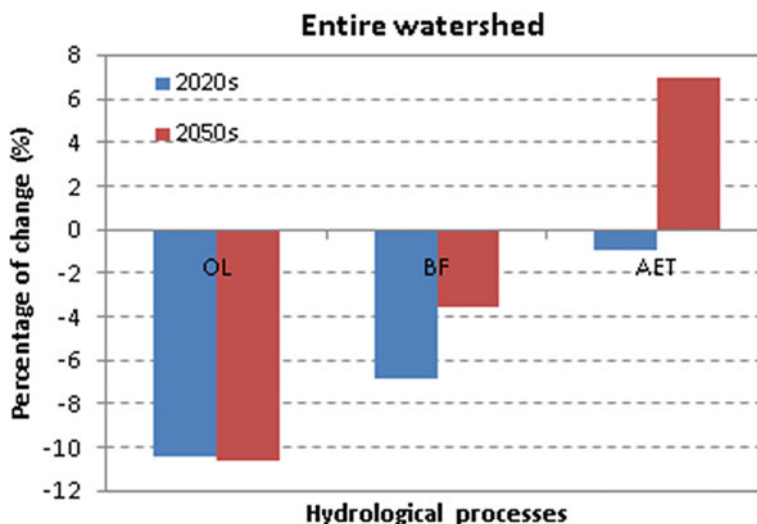


Fig. 12 Percentage of change in overland flow (OL), baseflow (BF) and evapotranspiration (ET) relative to the baseline for the entire watershed

Table 2 Projected average annual precipitation and temperature

Climate variable	Baseline	2020s	2050s
Precipitation (mm)	689.64	657.26	689.60
Temperature (°C)	2.53	2.93	6.63

decline, and to the average annual temperature, which increases by 0.4 °C. The decline in average annual overland flow in the 2050s is almost the same as in the 2020s. However, the average annual precipitation in the 2050s remains stable relative to the baseline. Therefore, the decline in the average annual overland flow in the 2050s is mainly linked with the 4.1 °C projected changes in the average annual temperature.

The average annual baseflow decreases by 6.9 % in the 2020s, which is related to the 4.7 % decrease in precipitation and 0.4 °C increase in the average annual temperature. In the 2050s, the percentage of decrease in baseflow (3.6 %) is mainly due to the 4.1 °C increase in the temperature (that results in increased evaporation loss from surface and subsurface), while the precipitation is invariable relative to the baseline.

In response to the changes in precipitation and temperature, the average annual ET declines by 0.9 % in the 2020s, but increases by 6.9 % in the 2050s. This increase occurs when there is a 4.1 °C increase in temperature and constant precipitation relative to the baseline period. This indicates that ET is more associated with the projected temperature changes than the projected precipitation changes compared to overland flow and baseflow in the 2050s.

The impact of climate change on the hydrological processes is more important in the eastern sub-catchment than the western sub-catchment, except for ET in the 2050s (Figs. 13 and 14). In the 2020s, overland flow and baseflow decrease in the western and eastern sub-catchments. They significantly drop in the eastern sub-catchment by 20.7 and 12.9 %, respectively, while the decline in overland flow

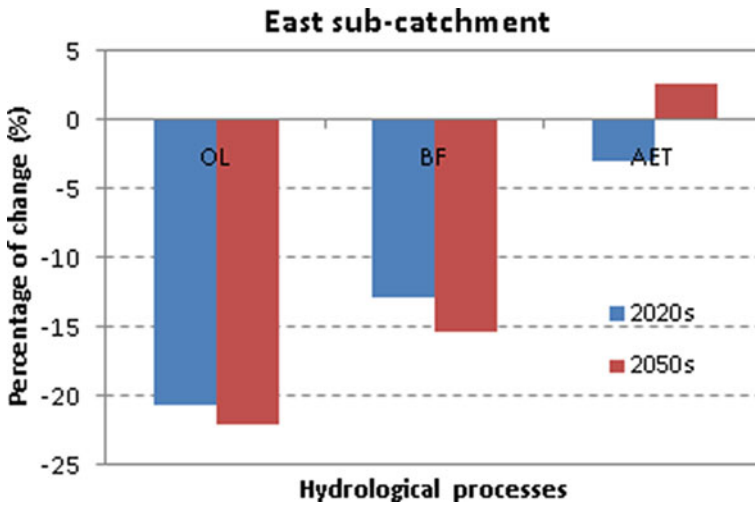


Fig. 13 Percentage of change in overland flow (OL), baseflow (BF) and evapotranspiration (ET) in the eastern sub-catchment

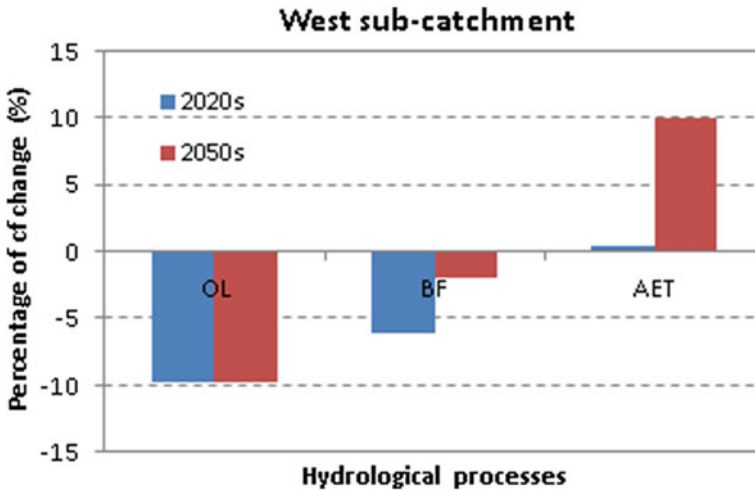


Fig. 14 Percentage of change in overland flow (OL), baseflow (BF) and evapotranspiration (ET) in the western sub-catchment

(9.7 %) and baseflow (6 %) is modest in the western sub-catchment, compared to the eastern sub-catchment. Although, the impact of climate changes is more perceptible in the eastern sub-catchment, these changes are offset by the western sub-catchment. In the 2050s, the significant rise in temperature (Table 2) results in even larger percentage decreases in the surface flow (22.1 %) and baseflow (15.3 %) in the eastern sub-catchment compared to the surface flow (9.8 %) and baseflow (2.0 %) in the western sub-catchment. This is mainly due to more evaporation and loss of soil water as a result of the rise in temperature. However, it is less noticeable in the western sub-catchment, especially in the period of time when only the highland areas receive either runoff or infiltration from melted snow.

In terms of ET, a significant drop in precipitation in the 2020s (Table 2) decreases the available water for evaporation from ponded water and soil (these are the main factors in the Kristensen and Jensen method used in MIKE SHE to calculate ET). In response to these changes, ET decreases by 3 % in the eastern sub-catchment, but it slightly increases (0.4 %) in the western sub-catchment due to sublimation and snow melting (caused by a slight rise in temperature) in the summer and fall which only occurs in the western sub-catchment. In the 2050s, ET increases in both the west (9.9 %) and east (2.5 %) sub-catchments due to a significant increase in temperature by 4.1 °C.

Table 3 and Fig. 15 present how the seasonal distribution of the projected temperature and precipitation change compared to the baseline. In the 2020s, the average monthly temperature increases for every month (0.1–1.5 °C), with the exception of January and February that experience a decrease of –1.3 and –0.6°C, respectively. The significant increase of temperature occurs in the spring and summer (0.4–1.5 °C) with the highest rise occurring in April (1.5 °C). Contrary to

Table 3 Average monthly projected temperature and precipitation

Month	Temperature (°C)			Changes in temperature (°C)		Precipitation (mm)			Changes in precipitation (%)	
	Baseline	2020s	2050s	2020s	2050s	Baseline	2020s	2050s	2020s	2050s
J	-9.05	-10.37	-5.37	-1.32	3.68	36.96	34.03	40.98	-7.93	10.88
F	-6.24	-6.81	-1.78	-0.58	4.46	34.23	32.04	38.37	-6.41	12.09
M	-3.07	-2.69	1.44	0.38	4.51	44.05	43.31	52.72	-1.68	19.68
A	2.66	4.15	7.79	1.48	5.13	68.49	73.31	81.49	7.03	18.98
M	7.60	8.55	10.45	0.95	2.84	83.16	73.98	77.66	-11.03	-6.61
J	11.32	11.71	14.42	0.39	3.10	99.63	81.19	90.44	-18.51	-9.23
J	13.20	14.07	17.54	0.87	4.34	75.60	74.96	78.11	-0.85	3.33
A	12.53	13.57	16.78	1.04	4.25	73.61	74.65	62.98	1.40	-14.45
S	8.05	8.12	10.81	0.07	2.76	63.04	59.71	56.50	-5.28	-10.39
O	3.97	4.09	7.25	0.12	3.29	37.27	36.97	33.63	-0.79	-9.75
N	-3.38	-2.79	0.99	0.59	4.37	35.05	36.00	34.35	2.69	-2.02
D	-7.67	-6.90	-1.19	0.77	6.48	38.55	37.12	42.38	-3.73	9.91

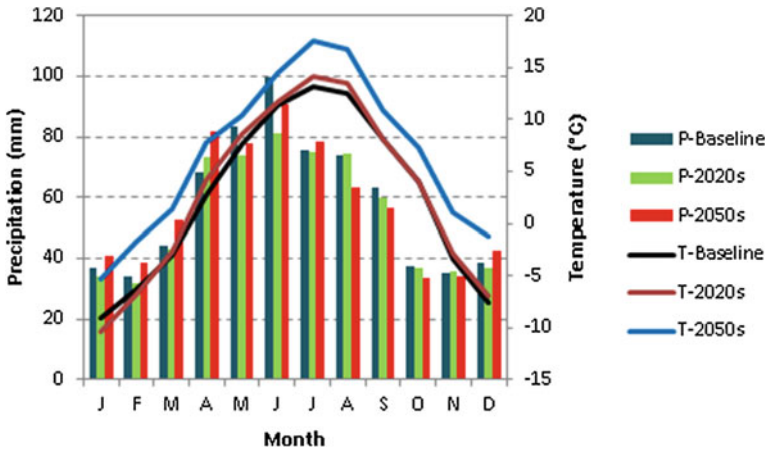


Fig. 15 Monthly average projected temperature and precipitation

the temperature, the average monthly precipitation decreases (0.8–18.5 %) for all the months, except in April, August, and November. In the 2050s, the average monthly temperature increases in every month (2.8–6.5 °C), while precipitation increases considerably in the winter and early and mid-spring.

In response to the seasonal distribution changes, overland flow significantly increases in the mid- and late spring in the 2020s and in the winter, and early and mid-spring in the 2050s (Fig. 16). This is mainly due to snow melt and a higher rain/snow ratio caused by higher temperatures. In addition, during this period of time, a unit of rainfall generally produces more overland flow when it falls on wet soils in early spring compared to the summer where rains often fall on very dry soils and generates less overland flow relative to the intensity of the events. The highest increase in overland flow occurs for both the 2020s and 2050s in the month of April

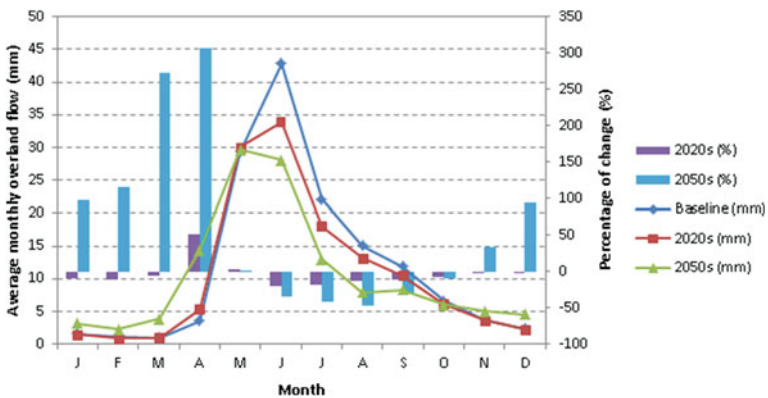


Fig. 16 Monthly average overland flow and percentage of change relative to the baseline

since snow starts melting usually in this month, and a significant increase in temperature amplifies sublimation and melting snow packs. In the 2050s, the precipitation in April is another factor that can increase the intensity of overland flow. April is the second wettest month in the 2050s with the average monthly precipitation of 81.4 mm after the month of June (99.4 mm). However, the average monthly temperature in this month is considerably lower than the month of June, and consequently, there is less water loss due to evaporation. Therefore, a large portion of water storage is available for either runoff on the surface or for infiltration into the soil. The lowest drop in overland flow occurs in June (20.9 %) in the 2020s and in August (46.9 %) in the 2050s, as the highest decline in precipitation (18.5 and 14.4 %, respectively) happens during these months. In both the 2020s and 2050s, overland flow declines in the summer as a result of an earlier and less intense snowmelt and an increase in evaporation during the summer period.

In the 2020s, baseflow decreases for every month, except in April and May in which case there is a slight increase (0.24 mm) relative to the baseline (Fig. 17). Baseflow during these months is mainly driven by the spring time snowmelt due to the considerable increase in temperature. In addition, the rising of temperature in early spring increases the period of time available for infiltration, and eventually increases the baseflow. The highest rise in baseflow occurs in April due to the highest increase in precipitation and temperature which ultimately leads to an increase in snow melting. In the 2050s, baseflow increases in winter and spring which is associated with more snow melting as a result of the increase in temperature; it decreases in the summer and fall due to an increase in temperature (and an increase in evaporation from unsaturated zone), and a decrease in precipitation.

In the 2020s, ET decreases in the summer and early fall (1.5–4.8 %) (Fig. 18), due to an increase in temperature and a reduction in soil water which result in less available water to the roots and a drop in transpiration. The lowest decrease in ET (14.9 %) happens in January in relation with the lowest decline in precipitation. However, the highest increase in ET (11.23 %) occurs in April, which is associated with the highest rise in precipitation (7.9 %), and additional available water to the

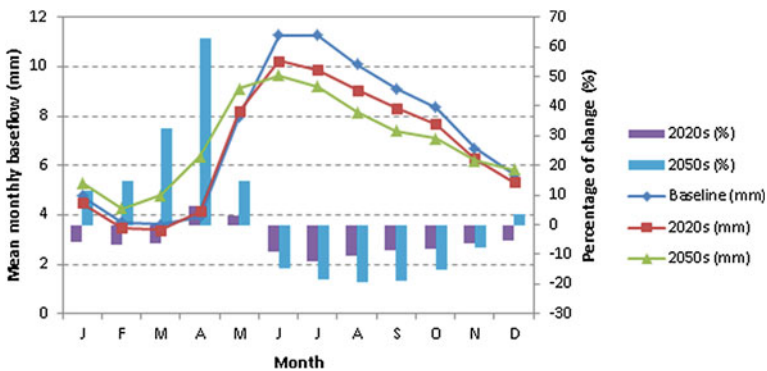


Fig. 17 Monthly average baseflow and percentage of change relative to the baseline

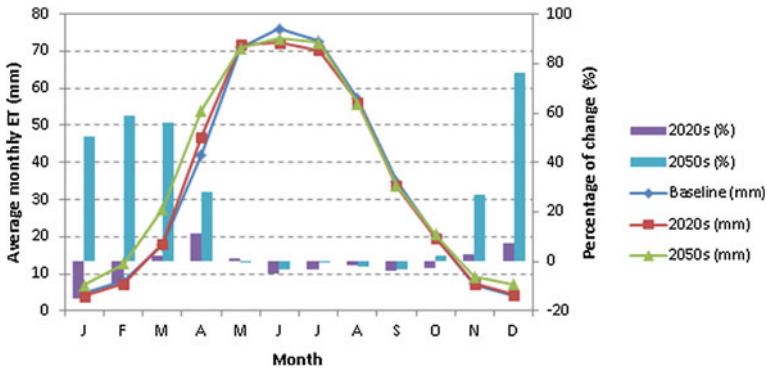


Fig. 18 Monthly average evapotranspiration and percentage of change relative to the baseline

roots due to a significant sublimation and snow melting during this month. The lowest decrease in ET (14.9 %) happens in January due to the lowest decline in precipitation. In the 2050s, evapotranspiration increases significantly in the winter and early spring due to snow melting as a result of an increase in temperature during this period.

3.2 Simulation of Streamflow

Simulations of 30 year average daily hydrograph for the 2020s, 2050s, and the baseline are shown in Fig. 19. Streamflow simulation reveals that the average annual stream flow decreases by 8.47 and 7.29 % in the 2020s and 2050s, respectively.

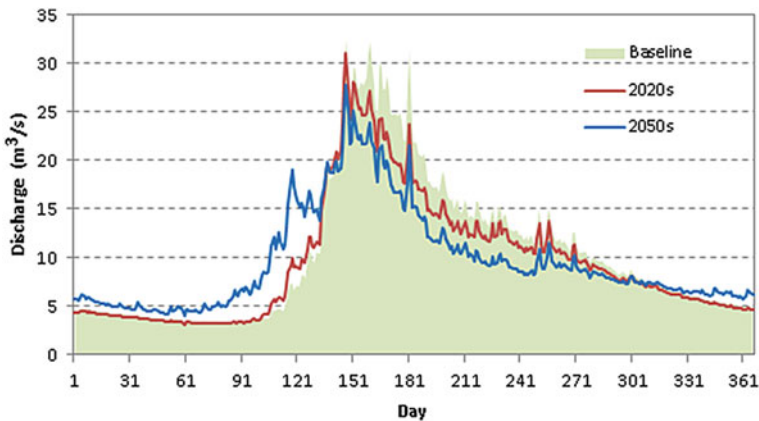


Fig. 19 Simulated 30 year average daily hydrograph for the 2020, 2050s, and the baseline

In the 2020s, both high flow and low flow decrease by 3.5 and 10.7 % whereas in the 2050s, the high flow increases by 1.4 % and low flow decreases by 7 %.

The streamflow declines for both the 2020s and 2050s in the summer and early fall, and increases in the 2050s in winter and early-mid spring (Fig. 20). There is a shift in peak river flow from late spring-early fall to the middle of spring-summer in the 2050s which indicates the possibility of spring flood in association with snow melt and at an earlier date. The highest rise in discharge occurs in the month of April. A rise in temperature in April increases rain-on-snow and eventually rainfall on a melting snowpack provides more infiltration and overland flow. Furthermore, the high flow season becomes much shorter. Historically, river discharge exceeds 10 m³/s during 5 months (from May to September) of a year; however, it only lasts three months (May, June, and July) in the 2050s. The predicted average monthly winter temperature stays below 0 °C for only 3 months (December, January and February), while historically, five months of a year were below 0 °C. This results in a large shift away from winter snowfall to rainfall that will cause more river flow during the winter months in return of lower flows during the spring and summer months. Rising temperature above 0 °C in winter, increases the sublimation of snow packs before the melting occurs, which results in a reduction of water storage in winter and of contribution to river flow in summer.

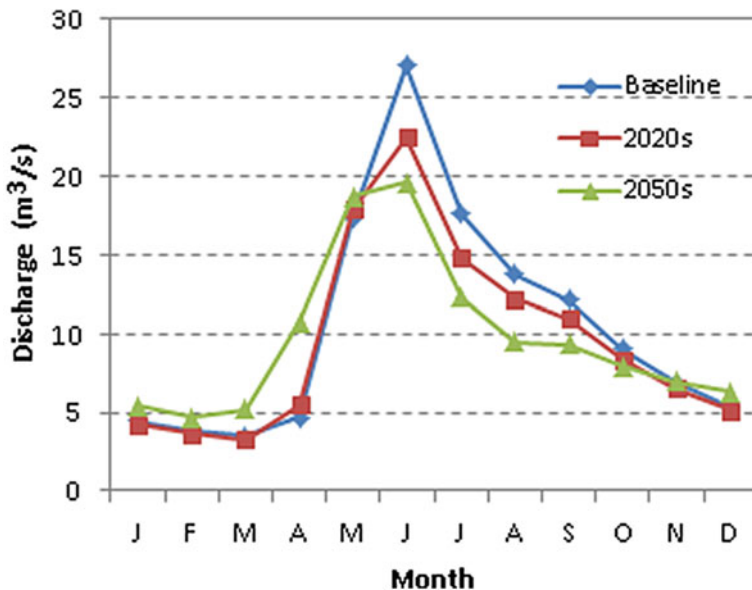


Fig. 20 Average monthly discharge flow

4 Conclusions

- This study reveals that the climate changes projected for the 2020s and 2050s might induce significant modifications on the Elbow River watershed hydrological regime. These changes are more noticeable in the eastern sub-catchment compared to the western sub-catchment. However, the induced changes in the eastern sub-catchment are offset by the western sub-catchment which almost governs the hydrology of the entire watershed due to its characteristics.
- The average annual overland flow, baseflow, and river flow will decrease over the next 60 years, while evapotranspiration will considerably increase, resulting in water scarcity. The situation might become critical due to projected increase in water supply demands.
- An increase in temperature during winter and spring (especially in April) will drive most of the changes affecting the hydrological processes and river flow. It will induce an important increase in the proportion of rainfall. Furthermore, the increase in number of months having a temperature above 0 °C will enhance the sublimation of snow packs before the melting occurs, which will result in an increase in winter and spring runoff and a reduction in the volume of water stored in the snowpack relative to the baseline period.
- Overall, climate change in the watershed will lead to an increase in overland flow, baseflow, evapotranspiration, and river flow in the winter-spring season as a result of an earlier and intense snowmelt, and a decrease in the summer-fall due to less intense snowmelt and an increase in evaporation. This implies a smaller difference in average monthly discharge between these two periods (summer-fall and winter-spring).
- The shift in peak river flow from late spring-early fall to the middle of spring-summer (which is mainly associated with earlier spring melt) will enhance the risk of flooding, especially in the lowlands in the eastern sub-catchment. The risk of flooding will increase in the month of April, which exhibits a significant increase in rainfall coinciding with the highest increase in spring freshet. This might even increase the risk of flooding in the following months (May and June), since the soil moisture reaches field capacity in early spring (March–April), and water released by snowmelt in May and June primarily contributes to runoff. This situation, in May and June, would be intensified once all the rainfall becomes runoff due to soil moisture field capacity.
- All the significant changes, such as the graduated shift from snow to rain, the snowpack reduction, along with the changes in hydrological processes will influence the timing and frequency of low and high discharge in the Elbow River, and eventually will affect the operation strategy of the Glenmore reservoir. The future modifications of the Elbow River watershed will not only be related to the hydrological regime, but will also cause important modifications in the watershed ecology.

Work is currently in progress to incorporate four additional climate change scenarios to cover the range of possible future climate conditions, along with projected land-use changes to fully evaluate the impact of future climate change and land-use changes on the hydrology of the watershed.

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Appendix A

See Table 4.

Table 4 Physiography of east and west sub-catchments of the Elbow River watershed

Sub-catchment	Min-elevation (m)	Max-elevation (m)	Mean elevation (m)	Area (km ²)
West	1301.07	3208.38	1938.60	791.3
East	1039.78	1495.70	1209.06	443.7

Appendix B

See Table 5.

Appendix C

See Table 6.

Table 5 Datasets and parameters used for the setup of MIKE SHE in the Elbow River watershed

Data	Description
Topography	A digital elevation model was obtained from GeoBase at the spatial resolution of 80 m and was re-sampled at 200 m
Root depth (RD) and leaf area index (LAI)	These data were obtained from the literature. Root depth values are based on average depths of actual root zone of the vegetation, and leaf area index values vary between 0 and 7 in different seasons
Manning number	These data were obtained from the literature for each land-use class.
Detention storage	Detention storage values were obtained based on the sensitivity analysis and calibration for each land-use class
Channel flow	Water level data were obtained from field survey and LiDAR generated cross sections located across the Elbow River and its branches
Soil hydraulic properties	Soil hydraulic values were acquired based on physical properties of different soil classes. A soil classification map was obtained from the Agricultural Region of Alberta Soil Inventory Database and the Canadian Soil Information Service Data sources
Land-use maps	The land-use maps of 1985 indicate other years were generated from Landsat Thematic Mapper imagery at 30 m resolution

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Table 6 The assigned values for the manning number and detention storage parameters

Parameter	Assigned value
Manning number	Water: 25.04, road: 76.9, rock: 40.0, evergreen: 10.0, deciduous: 10.0, agriculture land: 28.57, rangeland/parkland: 33.33, built-up area: 90.9, clear-cut area: 90.9
Detention storage	Water: 0 mm; road: 5 mm; rock: 10 mm; evergreen: 20 mm; deciduous: 20 mm; agriculture land: 20 mm; rangeland/parkland: 20 mm; built-up area: 0 mm; clear-cut area: 0 mm

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