Trends of hydroclimatic variables and outflow in the Athabasca River basin

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ABSTRACT Our study focuses on assessing trends of hydroclimatic variables and their impact on the runoff regime in the Athabasca River basin in two periods (from the beginning of monitoring until 2011 and 1971–2011). Applied methods included the Mann-Kendall statistical test, linear regression, multiplicative decomposition of data series, the Indicators of Hydrologic Alteration, and the Range of Variability Approach. Temperature records indicated a strong regional warming trend, which influenced decreased snowfall and a declining trend in spring runoff. Our results indicate that between 1971 and 2011 median discharge values decreased by > 20% on the lower and middle courses of the Athabasca River. Although on the upper course the median long-term minimum discharge increased due to the melting of mountain glaciers, on the middle and lower courses a significant decrease occurred. The discharge variability has also increased. All factors and changes are important because they affect the Athabasca-Peace delta's ecosystem and socioeconomic activities on the lower course.

KEY WORDS trend – climate warming – runoff variability – precipitation variability – low flows – Athabasca River

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1. Introduction

During the 20th century warming has been recorded throughout western Canada. Mean annual air temperatures have increased, as have annual precipitation amounts, particularly in southern Canada (Zhang et al. 2000). Besides warming, the Pacific decadal oscillation, the North Atlantic oscillation, the North Pacific index, and Atlantic multidecadal oscillation have had an effect on changes in hydroclimatic factors (Stewart, Cayan, Dettinger 2005; Burn 2008; Brabets, Walvoord 2009; Yu et al. 2020). In some cases, the Pacific decadal oscillation have a demonstrably larger effect on runoff changes than long-term global climate change (Chen, Grasby 2009; St. Jacques, Sauchyn, Zhao 2010; Haines 2012). During its cold phase, greater snowfall, lower mean temperatures, and greater discharges have all been recorded. During its warm phase, the opposite is the case (Haines 2012; Rood, Stupple, Gill 2015).

Many studies have demonstrated a historical decrease in mean annual discharges and mean summer discharges. Rood et al. (2005) reported a decrease in mean annual discharges on the upper courses of rivers with headwaters in the Rocky Mountains. On the upper Athabasca River (*AR* near Jasper station) a decrease in discharges from July to September of about 0.2% per year was recorded for the period 1914–2005. In contrast, in winter and spring a slight increase in mean values was recorded (Rood et al. 2008) and is still expected to increase in the future (Eum, Dibike, Prowse 2017). A significant decrease in discharges between 1958 and 2009 on the lower course was determined (Peters et al. 2013). Using the Mann-Kendall test, Bawden et al. (2014) have reported at the 10% significance level a strong declining trend in annual runoff, particularly a decline during the warm season (March–November) since the second half of the 20th century. In comparison with the surrounding watersheds of western Canada, the decreasing trend was also higher.

Several hypotheses have been developed to explain the causes. Since the 1980s significant regional warming has occurred in the prairie regions of Alberta, which has unquestionably influenced runoff decline in the summer months on the middle and lower Athabasca River (Schindler, Donahue 2006; Peters et al. 2013). Growing water consumption has also influenced decreasing runoff on the lower course. Squires, Westbrook, Dubé (2009) report a decrease in both water quantity and quality in the river.

Other factors influence runoff changes in the catchment. During the last century glaciers in headwater areas have retreated significantly; between 1985 and 2005 glaciers in Alberta have melted 25.4 ± 4.1% faster than other glaciers in the Rocky Mountains (Bolch, Menounos, Wheate 2010) and is supposed that because of the undergoing glacier melting, the Columbia Icefield will detach from the outlet ice tongues in the future and some of them (also the Athabasca glacier) could

Fig. 1 – Retreat of the Athabasca Glacier, Columbia Icefield. Photo: M. Matoušková (2008)

Fig. 2 – Front line of the Athabasca Glacier in 2008. Photo: M. Matoušková

ultimately decay (Rippin et al. 2020). The Athabasca Glacier (Fig. 1), which is one of the largest outlet ice tongues of the Columbia Icefield and supplies a large amount of meltwater to the headwaters of the Athabasca, has lost about half its volume and the front line retreated by more than 1.5 km in the past 125 years, see Figure 2 (Riebeek 2010). Together with increasing temperature, snowfall has decreased, and changes in evapotranspiration have occurred. These changes have affected the seasonal distribution of annual runoff, as well as runoff totals (Abarca et al. 2007). Especially the prairie's regions at the middle course are very sensitive to climate warming because of the air temperature and evaporation increase, which has strong impact on available water resources.

In relation to the predicted emission scenarios, it is expected continual decrease in snow water equivalent over the entire basin with largest decreases of up to 50% in March and April which is expected to have huge implications on soil-moisture content and hydrologic regime of the river (Dibike, Eum, Prowse 2018).

Decrease of runoff in winter could severely endanger biota on the lower Athabasca, specifically in the wetland's ecosystem of the Peace-Athabasca Delta (Prowse et al. 2006; Wolfe et al. 2012; Remmer et al. 2018), which is protected under the Ramsar Convention and is also a UNESCO World Heritage Site (Environment Canada 2013a). Decreases in minimum flows, which typically occur in winter months when the river freezes, can cause freezing of stream reaches throughout the profile due to the large branching of the stream and thus significantly affect winter habitat and the ability of fish populations to migrate for food (Andrishak, Hicks 2010). Peters et al. (2022) alerted the need of the development of an environmental flow framework for the downstream the Peace-Athabasca Delta and therefore performed a novel analysis approach that should be considered in water management plans and decision making for this basin. In the Peace-Athabasca Delta area increasing temperatures have been reported for 1960–2005, with the largest increase of nearly 1 °C per decade occurring in the winter months, along with a decrease in annual snowfall of 12 to 41 cm per decade (Ghaderpour, Vujadinovic, Hassan 2021; Timoney 2009). An increase in water temperature causes reduce in number of fish due to lack of reproduction and a decrease in dissolved oxygen in the water, which can cause higher fish mortality (Cott et al. 2008). Temperature increase has a major impact on precipitation phase and results in an increase in liquid and decrease in solid precipitation. This shift has a consequence in the decrease of the amount of snowpack, which is important part of the spring runoff, and overbank flooding, which is essential to the ecological health of the Peace-Athabasca Delta (Prowse et al. 2002). Overbank flooding is essential for isolated small lakes, which are at higher elevation than the river and are replenished by period flooding. Because of the flat topography, lakes are very sensitive to small changes in water level, which may cause their disappearance. They are prime habitat for muskrats, waterfowl, and other wildlife and also the most productive areas of the delta (Andrishak, Hicks 2010).

Runoff began being monitored in the 20th century, particularly in the second half of the 20th century. It is impossible to rely on runoff predictions and subsequent management plans for permitting water withdrawal. Researchers have called attention to the long-lasting droughts that have occurred in the past and that currently might pose a significant problem, particularly due to regional warming (Monk, Peters, Baird 2012; Rood et al. 2008; Schindler, Donahue 2006). Some predictions have suggested that evapotranspiration will increase faster than precipitation (Schindler, Donahue 2006). This would lead to less water being available in the future. For the population, this means in particular a lack of drinking water and water for irrigation in agriculture and industrial use (e.g., tar sands). A changing climate can cause increased frequency and severity of droughts, floods, forest fires and storms (Government of Alberta 2022).

The main aim of our study is to assess trends of selected hydroclimatic variables and outflow in the upper-, middle-, and lower course of the Athabasca River. The main attention of our study was to focus on climatic and gauging stations with long term year-round monitoring and with complete data series. The novelty of our study is in the comparative trend analysis of selected hydroclimatic variables and use of long-term year-round monitoring data which represent a variety of conditions across the whole catchment. The Athabasca River basin is very sensitive to climate warming but also growing water consumption on the lower course has a negative ecological impact on the unique wetland's ecosystem of the Peace-Athabasca Delta.

2. Methodology

2.1. Methods and data sources

The Athabasca River basin was divided into three parts—the upper, middle, and lower course (Fig. 3). Based on long-term data series, long-term trends were evaluated, focusing also on the winter period, which is important because flows are lowest during this period. The chosen stations and their basic characteristics are given in Table 1. For the analysis, data from the Water Survey of Canada was used, including mean daily discharge (Q_d) and mean, minimum, maximum, and median monthly (Q_m) and annual (Q_{an}) discharge values (Environment Canada, *HYDAT* archive; Water Survey of Canada 2013). Precipitation data (P) was analyzed separately as snowfall (S) and rainfall (R) using monthly and annual precipitation total time series data from the Environment Canada database. For temperatures, data series of mean, minimum, and maximum monthly (T_m) and annual (T_{an}) temperatures available from the Environment Canada database were used. Precipitation and temperature time series data were chosen so that there were no data gaps exceeding three years. The chosen period ends in 2011/2012, because after 2012 the availability of climate data has changed, only total precipitation

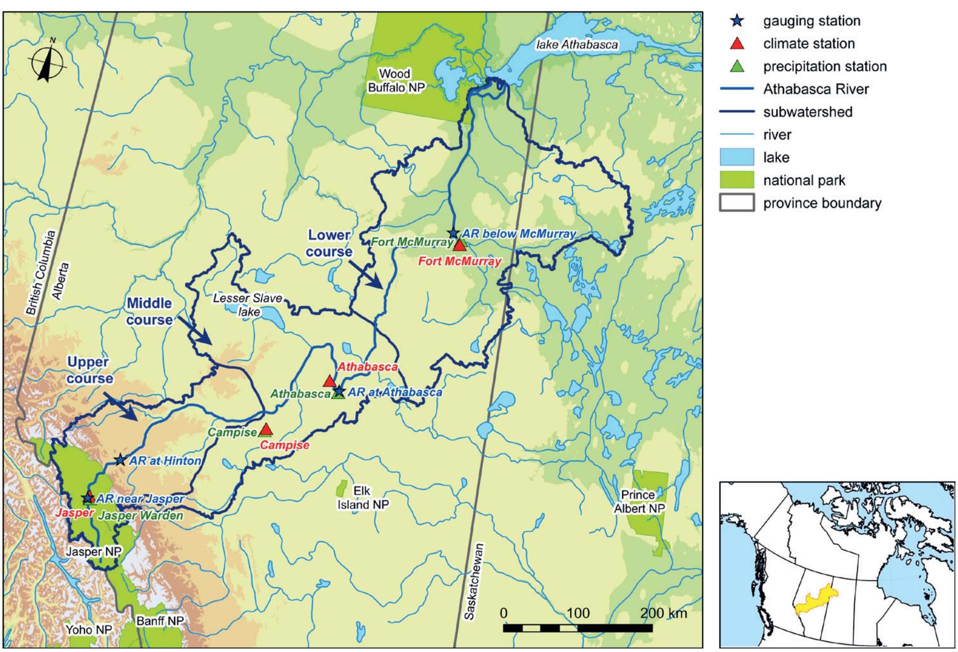


Fig. 3 – Study area. The sections of the basin and the locations of the selected gauging stations, climate stations and precipitation stations, more in Table 1; created by *ArcGIS* software.

Table 1 – Selected stations in the Athabasca River basin, their location and study period

	Station ID	Latitude (°N)	Longitude (°W)	Altitude (m a.s. l.)	Data period (number of missing years)
Q					
Athabasca River (*AR*) near Jasper	07AA002	52.91	118.06	1,059	1977–2012 (0)
AR at Hinton	07AD002	53.42	117.57	954	1961–2012 (0)
AR at Athabasca	07BE001	54.72	113.29	516	1959–2012 (0)
AR below McMurray	07DA001	56.78	111.40	237	1958–2012 (4)
P					
Jasper Warden	3053536	52.93	118.03	1,020	1937–2007 (5)
Campise	3061200	54.13	114.68	671	1911–2011 (13)
Athabasca	3060L20	54.72	113.28	515	1920–2010 (13)
Fort McMurray	3062693	56.65	111.22	369	1922–2007 (1)
T					
Jasper	3053536	52.93	118.03	1,020	1941–2012 (2)
Campise	3061200	54.13	114.68	671	1913–2012 (11)
Athabasca	3060L20	54.82	113.53	626	1939–2010 (12)
Fort McMurray	3062696	56.65	111.22	369	1917–2011 (4)

Note: Discharge (Q): Upper course – Athabasca River (*AR*) near Jasper, *AR* at Hinton; Middle course – *AR* at Athabasca; Lower course – *AR* below McMurray. Precipitation (P): Upper course – Jasper Warden; Middle course – Campise, Athabasca; Lower course – Fort McMurray. Temperature (T): Upper course – Jasper; Middle course – Campise, Athabasca; Lower course – Fort McMurray.
Data source: Environment Canada 2013b, Environment Canada 2013c, Water Survey of Canada 2013.

data were available, not precipitation and snowfall separately. For one climate station Athabasca (3060L20) no climate data were available since 2013 and another climate station Campise (3061200) changed the location. When selecting discharge time series data, emphasis was placed on continuity and comparability between gauging stations in each part of the basin.

Statistical tests for determining the homogeneity of time series were used to conduct a more detailed analysis of changes in runoff and to find any inhomogeneities in each time series. To test the homogeneity of Q_m and Q_{an} data, the Pettitt test was applied (Mann-Whitney-Pettitt test; Pettitt 1979) using AnClim software. For each times series the Pettitt test determined the probable change point. The null hypothesis (that the series is homogenous) was rejected if the level of significance p was less than 0.05. In a further step, change points suggested by the Pettitt test were used to conduct a Mann-Whitney test using *SPSS* software. If the Pettitt test suggested two years of change, the Kruskal-Wallis test was applied. For all tests the level of significance was 0.05.

Linear regression was used to analyze trends in Q_{an}, S_{an}, R_{an}, and T_{an} time series; for seasonal, nonparametric annual and monthly data the Mann-Kendall (*M-K*) test (Mann 1945, Kendall 1975, Yue et al. 2002) was applied using Excel (Grimvall, Libiseller 2003). The results of the *M-K* test are expressed in *MK-S* values, which express the direction and magnitude of trends, and in *p*-values (*p*-v), which determine the significance level (the closer to zero, the greater the significance; Libiseller 2004; Kisi, Ay 2014). The significance level can be selected (the most frequent levels are 0.01 and 0.05); the null hypothesis is rejected if the significance level is higher than the set values (Gocic, Trajkovic 2013).

Q_m was further analyzed using multiplicative decomposition of time series. To analyze time series, the series are decomposed into three systematic components – the trend component, the seasonal component, and the cyclical component – and one irregular component (Cipra 1986). With this method it is possible to analyze long-term tendencies of relevant indicators (in this case discharge) using the trend component. The time series for discharges were decomposed using multiplicative decomposition, as discharge is a variable that changes over time. This decomposition can be expressed as:

$$y_t = T_t \times Sz_t \times C_t \times \varepsilon_t \ , \quad (1)$$

where *T* is the Trend Component, *Sz* is the Seasonal Component, *C* is the Cyclical Component, and *ε* the Irregular Component.

Before decomposing the time series, they were standardized to contain the same number of days in each month. Discharge values were adjusted using a coefficient equal to the number of days in the given month divided by the number of days in the average month (Myšáková 2009).

The Indicators of Hydrologic Alteration (*IHA*, version 7.1.0.10; The Nature Conservancy 2009) software was used to evaluate changes in the runoff regime between two periods. This analysis comprises 33 hydrological parameters, arranged into five different groups (according to magnitude, duration, amplitude, frequency, and timing). To assess runoff changes in relation to increased water withdrawal, nonparametric *RVA* analysis (*The Range of Variability Approach*) was applied (Richter et al. 1996, 1997, 1998). The *RVA* method is based on assessing two periods: "before change" (period 1) and "after change" (period 2), and a degree of change, *D*, expressed as a percentage. The hydrological alteration is calculated as:

Hydrologic alterations = (Observed frequency – Expected frequency) / Expected frequency.

According to Richter et al. (1998) three categories of change based on magnitude can be established: low (0–33%), middle (34–67%), and high (68–100%). Taking into account continuous daily discharge time series and the increased interference with the hydrological regime, the periods of 1971–1990 and 1991–2011 were selected.

2.2. Characteristics of the study area

The study area is in the Canadian provinces of Alberta and Saskatchewan (Fig. 3). The Athabasca River is the southernmost tributary of the Mackenzie River with a length of 1,231 km (Statistics Canada 2005) and a watershed area of approximately 156,000 km² near Old Fort before it flows into Lake Athabasca (Dibike et al. 2019). The study area is formed by the mainstream of the Athabasca River (*AR*) from *AR* near Jasper station to *AR* below McMurray station (Table 1).

The Athabasca River originates in the Rocky Mountains in Jasper National Park, in an unnamed lake within the Columbia Icefield between Mt. Columbia, Snow Dome and the Winston Churchill Range at an elevation about 1,600 m (5,200 ft). The river then flows through foothill regions, prairies, boreal forests to the north-east, where it flows into Lake Athabasca.

The Athabasca River catchment was selected because of very good example of a river with a complex rainfall-runoff regime, large impact of regional climate warming and different hydroclimate processes on the upper, middle, and lower course. The main sources of water contributing to the mean annual discharge of the Athabasca River are seasonal snow cover, rainfall, and glacial meltwater.

Mean annual precipitation is highest in the upper basin – more than 1,000 mm in the Rocky Mountains and 500 mm in their foothills (SLCWG 2010). Temperature fluctuations during the year are the smallest in the upper parts from the whole catchment. The average temperatures at Jasper climate station for 1941–2010 were −10.8 °C in January and +14.8 °C in July (Environment Canada 2013b). Besides precipitation and snow cover, glaciers are important sources of water on the upper Athabasca River. The long-term average discharge (Q_{avg}; 1971–2012) at *AR* near Jasper station is 85.25 $m^3.s^{-1}$ and at *AR* at Hinton 169.4 $m^3.s^{-1}$. Specific runoff q_{an} at *AR* near Jasper is 21.86 $l.s^{-1}.km^{-2}$ and at *AR* at Hinton is 17.21 $l.s^{-1}.km^{-2}$ (Water Survey of Canada 2013).The Q_{avg} (1971–2012) at *AR* at Athabasca station is 419.99 $m^3.s^{-1}$. Specific runoff q_{an} for *AR* at Athabasca is 5.58 $l.s^{-1}.km^{-2}$ (Water Survey of Canada 2013).

The lowest precipitation, about 400 mm, can be found in the lower course (SLCWG 2010). The greatest temperature fluctuations throughout the year can be found here; at Fort McMurray station between 1941 and 2010 the mean January temperature was −19.9 °C and the mean July temperature +16.7 °C (Environment Canada 2013b). The Q_{avg} (1971–2012) at *AR* below McMurray is 613.13 $m^3.s^{-1}$. Specific runoff q_{an} at *AR* below McMurray is 4.60 $l.s^{-1}.km^{-2}$ (Water Survey of Canada 2013).

3. Results

3.1. Analysis of annual hydroclimatic time series

On the upper course warming is clear from the linear regression of both T_{an} values and extremes (T_{anMax}, T_{anMin}) recorded at Jasper station (Fig. 4). T_{avg} rose from +2.3 °C for period 1941–1970 to +3.0 °C for 1971–2012. The results of the *M-K* test (Table 2) also indicate warming. An increasing trend is significant (p-v < 0.05) for the entire studied period (1941–2012) as well as for the period 1971–2011, which has caused the constant retreating of glaciers in headwater areas. Change in P_{avg} at Jasper Warden station was not so marked, but it did grow from 435.4 mm (1941–1970) to 454.6 mm (1971–2007). However, if we look separately at R_{an} and

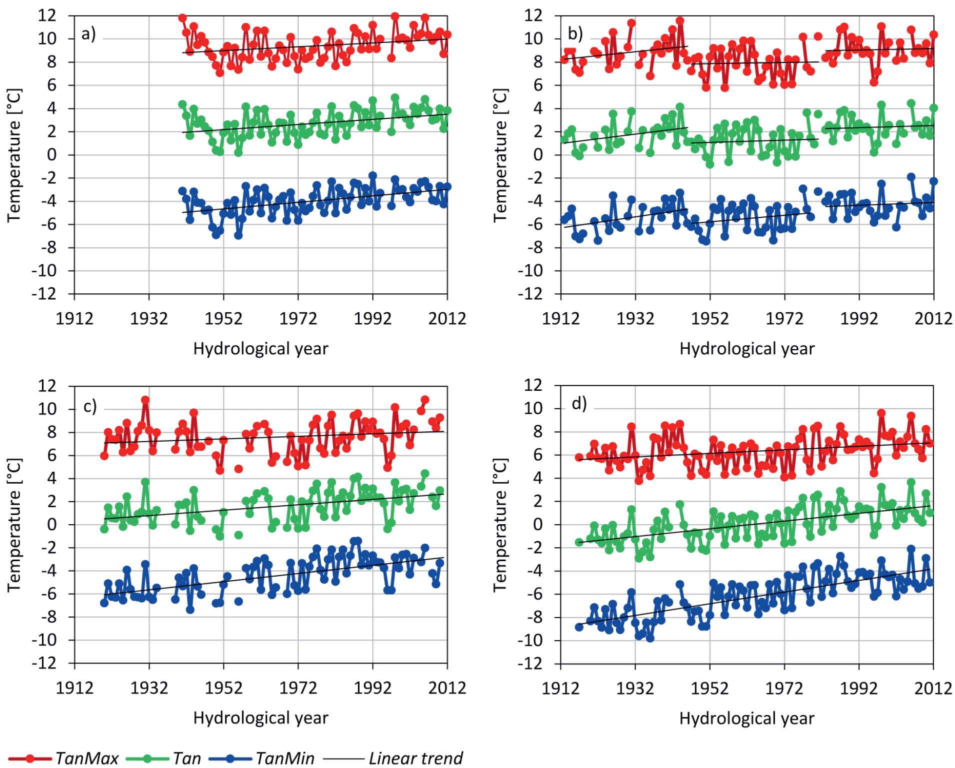


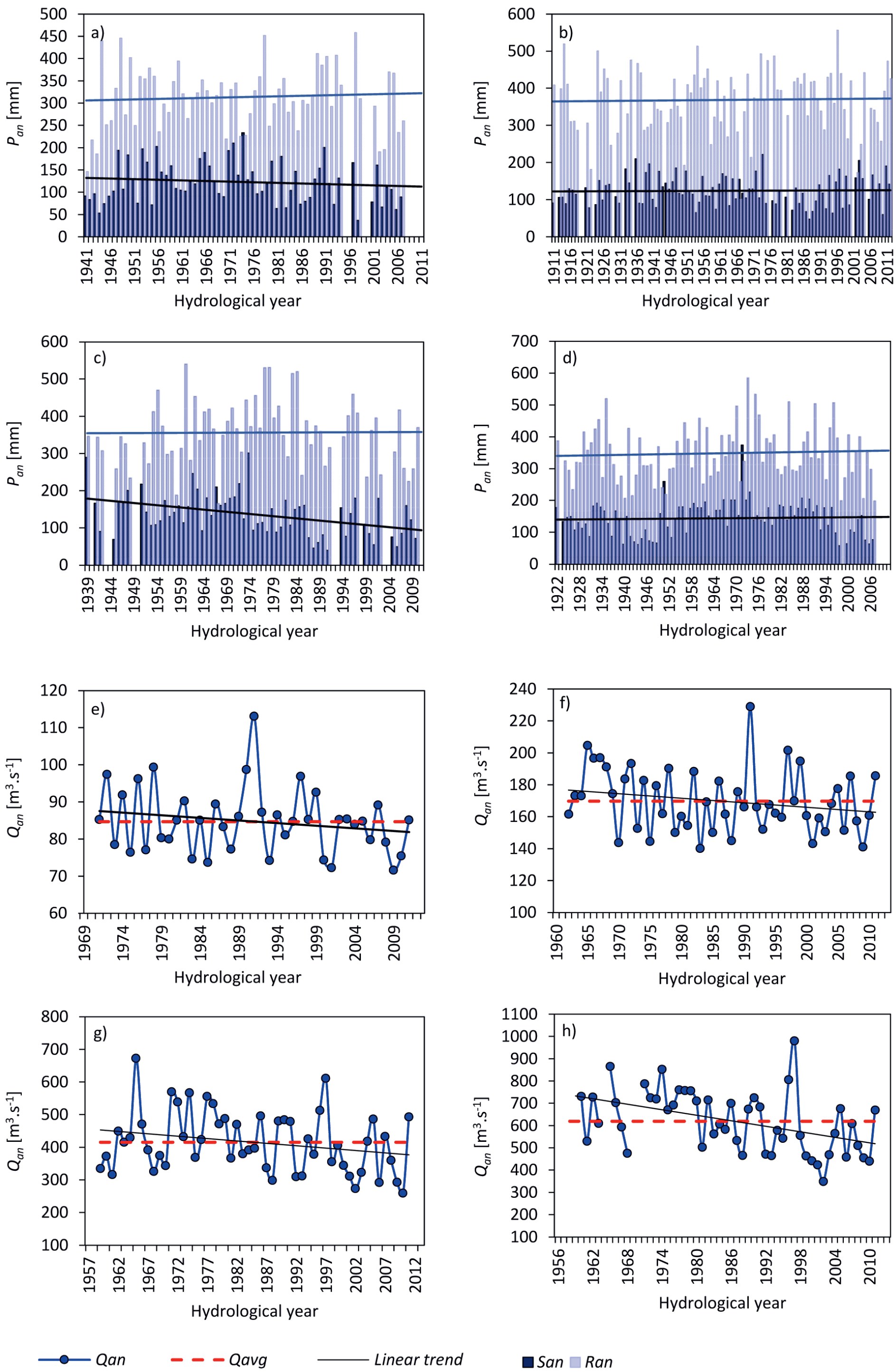
Fig. 4 – Linear trends of temperature (*Tan* = mean annual temperature, *TanMax* = maximum annual temperature, *TanMin* = minimal annual temperature) for: a – Jasper climate station (1941–2011), b – Campise climate station (1913–2012), c – Athabasca climate station (1920-2011), Fort McMurray climate station (1917–2011); Hydrological year begins on 1.11. and ends on 31.10. Data source: Environment Canada 2013b.

Table 2 – Results of the Mann-Kendall (*M-K*) trend test

Station name										
	Mean		Maximum		Minimum		Max-Min		Median	
Qan	MK-S	p-value	MK-S	p-value	MK-S	p-value	MK-S	p-value	MK-S	p-value
AR near Jasper	−1.258	0.208	−1.326	0.185	1.709	0.087	−1.303	0.193	−0.067	0.946
AR at Hinton	−0.584	0.559	−1.617	0.106	2.224	0.026	−1.617	0.106	0.562	0.574
AR at Athabasca	*−3.167*	*0.002*	−2.123	0.034	*−3.000*	*0.003*	−2.067	0.039	*−3.325*	*0.001*
AR below McMurray	*−4.066*	*0.000*	*−2.562*	*0.010*	*−2.752*	*0.006*	−2.370	0.018	*−3.617*	*0.000*
	Rainfall		Snowfall		Rainfall (from 1971)		Snowfall (from 1971)			
Pan	MK-S	p-value	MK-S	p-value	MK-S	p-value	MK-S	p-value		
Jasper Warden	0.608	0.543	−0.574	0.566	0.217	0.828	−2.200	0.028		
Campise	0.510	0.610	1.040	0.298	−1.308	0.191	1.099	0.272		
Athabasca	1.165	0.244	−2.239	0.025	−2.201	0.028	−2.116	0.034		
Fort McMurray	0.477	0.633	0.506	0.613	−1.452	0.147	*−3.174*	*0.002*		
	Mean		Maximum		Minimum		Mean (from 1971)			
Tan	MK-S	p-value	MK-S	p-value	MK-S	p-value	MK-S	p-value		
Jasper	*3.199*	*0.001*	2.474	0.013	*4.086*	*0.000*	*3.006*	*0.003*		
Campise	*2.644*	*0.008*	1.095	0.273	*3.916*	*0.000*	1.858	0.063		
Athabasca	*4.190*	*0.000*	2.171	0.030	*5.542*	*0.000*	1.697	0.090		
Fort McMurray	*6.085*	*0.000*	*3.143*	*0.002*	*7.638*	*0.000*	1.168	0.243		

Note: Analyzed parameters: Mean annual temperature (T_a), annual precipitation amount (P_a), mean annual discharges (Q_a); Q_a for period 1971–2011; T_a, P_a (R_a = annual rainfall amount, S_a = annual snowfall amount) for the entire studied period and for 1971–2011 (or 1971–2007 for P_a (R_a, S_a) at Jasper Warden and Fort McMurray Station); grey background *p*-value < 0.05, bold lettering *p*-value < 0.01, *MK-S* = the direction and magnitude of trends, *p*-value determine the significance level (the closer to zero, the greater the significance), Discharge (*Q*): Upper course – Athabasca River (*AR*) near Jasper, *AR* at Hinton; Middle course – *AR* at Athabasca; Lower course – *AR* below McMurray. Precipitation (P): Upper course – Jasper Warden; Middle course – Campise, Athabasca; Lower course – Fort McMurray. Temperature (*T*): Upper course – Jasper; Middle course – Campise, Athabasca; Lower course – Fort McMurray.
Data source: Environment Canada 2013b, Environment Canada 2013c, Water Survey of Canada 2013.

Fig. 5 – Linear regression of: a – annual snowfall (S_{an}), annual rainfall (R_{an}) at Jasper Warden precipitation station (1939–2007) – upper course; b – S_{an}, R_{an} at Campise precipitation station (1911–2011) – middle course; c – S_{an}, R_{an} at Athabasca precipitation station (1919–2011) – middle course; d – S_{an}, R_{an} at Fort McMurray precipitation station (1922–2007) – lower course; e – annual mean discharge (Q_{an}), long-term (1971–2012) average discharge (Q_{avg}) at *AR* near Jasper station (1971–2011) – upper course; f – Q_{an} and Q_{avg} at *AR* at Hinton (1962–2011) – upper course; g – Q_{an}, Q_{avg} at *AR* at Athabasca (1959–2011) – middle course; h – Q_{an}, Q_{avg} at *AR* below McMurray (1958–2011) – lower course. Hydrological year begins on 1.11. and ends on 31.10. Data source: Environment Canada 2013c, Water Survey of Canada 2013.


a)
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S_{an}, we can observe a slight decrease in snowfall and a slight increase in rainfall (Fig. 5), which is closely related to increasing temperatures and has a fundamental effect on spring runoff. The results of the *M-K* test (Table 2) show that S_{avg} has decreased especially in the more recent period (1971–2007).

Using linear regression on Q_{an} values demonstrates a clear, slight decreasing trend (Fig. 5). The next downstream station, *AR* at Hinton, indicated only a significant decrease in Q_{anMin}, which occurred in the winter (Table 2).

Data from climate stations of middle course, Campise and Athabasca, were analyzed (see Table 1) for the period 1913–2012 and 1939–2010 respectively. When divided data set to three periods, related to the Pacific decadal oscillation phase, it is obvious that the changes can be related to the warm and cold phases of the Pacific decadal oscillation (Fig. 4). At both sites from the middle course (Campise and Athabasca station), the mean air temperature was 0.5–1.2 °C lower during cold phase than in warm phase of the Pacific decadal oscillation. The *M-K* test confirms an increasing trend in T_{an} from the beginning of the studied period for both sites; however, as opposed to the upper course, for the period 1971–2011 the increasing trend was not significant (Table 2).

At the lower-elevation Athabasca station from the middle course, S_{an} decreased, as demonstrated by the linear regression curve (Fig. 5) as well as *M-K* test results (Table 2). Since 1971, both precipitation phase (S_{an} and R_{an}) has also decreased significantly at Athabasca station.

The results of the *M-K* test for Q_{an} at *AR* at Athabasca station indicate a significant decreasing trend since 1959, which is confirmed by the linear regression curve (Fig. 5). Here the decrease in median discharge is very significant, as is the decrease in Q_{anMin}.

There was a very significant change in mean annual air temperatures on the lower course at Fort McMurray station (Fig. 4). Here, T_{an} increased from −0.67 °C for 1922–1970 to +1.02 °C for 1971–2011. The increase in T_{anMin} was even more significant, the change was more than 2.4 °C between these two periods. The results of the *M-K* test (Table 2) confirm the extremity (p-v < 0.001, *MK-S* 6.085). However, when applying the *M-K* test to the 1971–2011 period, there is no significant increase in air temperature.

Regarding to the precipitation amount changes at Fort McMurray station, there was a significant decrease in S_{an} in the most recent period (1971–2007; Table 2), like the decrease on the upper course and on the middle course at Athabasca station.

The outcome of the *M-K* test indicates a large decrease in discharge (Table 2). These findings correspond with the outcome of the linear regression of Q_{an} at *AR* station below McMurray, which indicates a large decreasing trend (Fig. 5). Since this is the lower course, besides increasing temperatures and decreasing snowfall, flow is also affected by water withdrawal.

It is possible to record a significant increase in air temperature in the whole river catchment, however, in the last period since 1971 there has been no noticeable continuation of the trend, on the middle and lower course. Together with the increase in air temperatures, it is also possible to record a decrease in snowfall, which is most noticeable on the lower course. With these changes, a decrease in the runoff from the middle course downstream is also evident.

3.2. Monthly hydroclimatic times series variability

Based on the outcome of the *M-K* test, there was a clear increase in T_m at the upstream Jasper station over the entire studied period (1941–2012) for 4 months (Fig. 6a). If we look at monthly extremes, similar trends are in T_{mMin}, which are more significant than the trends in T_{mMax}. In the most recent period (1971–2011) as well there was an increasing trend in T_m during 2 months in summer and in January (Fig. 6b).

The *M-K* test indicated a significant decreasing trend in precipitation during December and February on the upper course for the most recent period (1971–2007). A decreasing trend in S_m was detected during February for the entire studied period (Fig. 6d). Since 1971 a decrease in S_m in December and September was observed, which is related to increasing temperatures on the upper course.

The outcome of time series analyses indicates more significant changes in Q_m trends in the first half of the 1990s at *AR* near Jasper station (Fig. 6a). In addition, it is perceptible that there were more significant changes at the beginning of the studied period than there were in the early 21st century.

When comparing ten-year periods and the average discharge during the monitored period at individual stations (Fig. 8), changes during the summer months especially could be observed. On the upper course (*AR* near Jasper, *AR* at Hinton, Figs. 6a, b) can be registered a decline during the spring and summer months, with the largest decline during August. In the period 2001–2010, the average discharge in August decreased, compared to periods 1971–2010 and 1961–2010, by 14 and 17%, respectively. During the winter months, there was an increase in flows, the most significant increase was recorded during February and March at the station *AR* at Hinton (4 to 8%, Fig. 8b) and in January at the station *AR* near Jasper (4%, Fig. 8a).

Significant decreases in Q_m at *AR* near Jasper station and at *AR* at Hinton station were detected using the *M-K* test in August (Fig. 6e), when median values also decreased. This corresponds to the increase of temperature and decrease of snowfall in upper parts of the catchment during this time of the year. At the *AR* at Hinton station an increasing trend was detected in Q_{mMin} in spring (Fig. 6f) and in Q_m in winter months (Fig. 6e). A significant increasing trend in Q_{mMax} was also observed in January at both stations on the upper course. The increasing difference

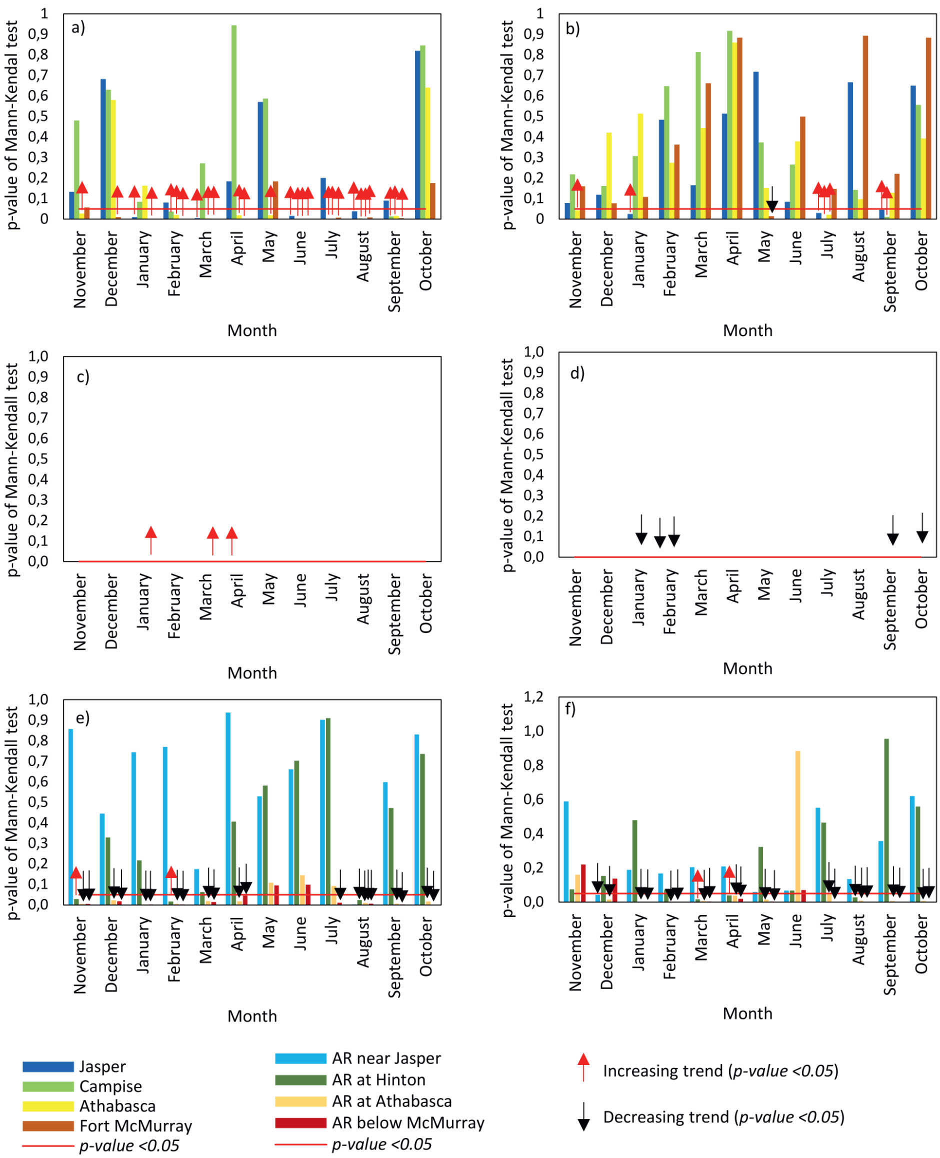

Fig. 6 – *P-values* of the Mann-Kendall (*M-K*) trend test results for*:* a – mean monthly temperatures (T_m); b – T_m (from 1971); c – monthly rainfall amounts (R_m); d – monthly snowfall amounts (S_m); e – mean monthly discharges (Q_m); f – minimal monthly discharges (Q_{mMin}); red arrow indicates increasing trend, black arrow indicates decreasing trend, if *p-value* < 0.05, colors indicates different sites. Discharge: Upper course – *AR* near Jasper, *AR* at Hinton; Middle course – *AR* at Athabasca; Lower course: *AR* below McMurray. Temperature: Upper course – Jasper; Middle course – Campise, Athabasca; Lower course – Fort McMurray. Precipitation: Upper course – Jasper Warden; Middle course – Campise, Athabasca; Lower course – Fort McMurray. Data source: Water Survey of Canada 2013.

in Q_{mMax} and Q_{mMin} during the winter (December–February) is also significant and influences the runoff regime.

At both middle course climate stations (Campise, Athabasca) a significant increasing trend in T_m in the summer (June–August) has been observed since measurements began (since 1913 at Campise and 1939 at Athabasca observed; Fig. 6a). This trend influences increased potential evapotranspiration in the area (Eum, Dibike, Prowse 2017). Since 1971 there has not been such great warming (Fig. 6b). On the middle course (Athabasca station), there was a significant decrease in P_m in winter months since the beginning of the studied period (1920–2010), with mainly snowfall being affected (Fig. 6d). Since 1971 this trend continued only in February and was observed as a new phenomenon in July. At Campise station R_m increased during April from the beginning of the studied period (Fig. 6c) as well as after 1971.

On the middle course, higher variability in discharge is more noticeable than on the upper course (Fig. 8c). Discharges during 1961–1970 were lower than in the following period, but the lowest discharges have occurred in the last decade (2001–2010). There was no increase in discharge at this station during any month, as it was the case at the upper course. Compared to the average values (1961–2010), there has been a decrease of 14–24% at *AR* at Athabasca in the last decade (Fig. 8c), with the highest decrease during August.

On the graph analyzing Q_m time series data (Fig. 7c) at *AR* at Athabasca station, besides fluctuation, a clear decreasing trend is also present. Overall, the decrease in Q_m is significant at the Athabasca station for most of the year, with the most significant decrease in August.

At Fort McMurray station on the lower course the *M-K* test detected the largest increasing trends in T_m, T_{mMin}, and T_{mMax} in the entire basin from the beginning of the studied period (1917–2011). When T_m data from only 1971–2011 is analyzed, no increasing trend is observed. Although from the beginning of the studied period (1922–2007) at Fort McMurray station the *M-K* test did not detect any trend in P_m and indicated an increase in R_m (January and March), since beginning in 1971 a decrease in both R_m (November–January, March, October) and S_m (January, February) was observed. Decreases in precipitation have occurred primarily during the cold season, which have a fundamental impact on spring runoff.

On the lower course, the situation of decreasing discharges is similar to middle course (Fig. 8c, d). Compared to the average values (1961–2010), there has been a decrease of discharges by 14–25% at *AR* below McMurray (Fig. 8d), with the highest decline during July.

On the graph analyzing the Q_m time series (Fig. 7), it can be observed that 1981 is the local minimum and 1998 the maximum. The *M-K* test detected significant decreasing trends of Q_m for 1971–2011 at *AR* below McMurray station. Q_m decreased almost throughout the entire year, with the largest decreasing trend in October (*M-K* Stat 3.28, p-v 0.001).

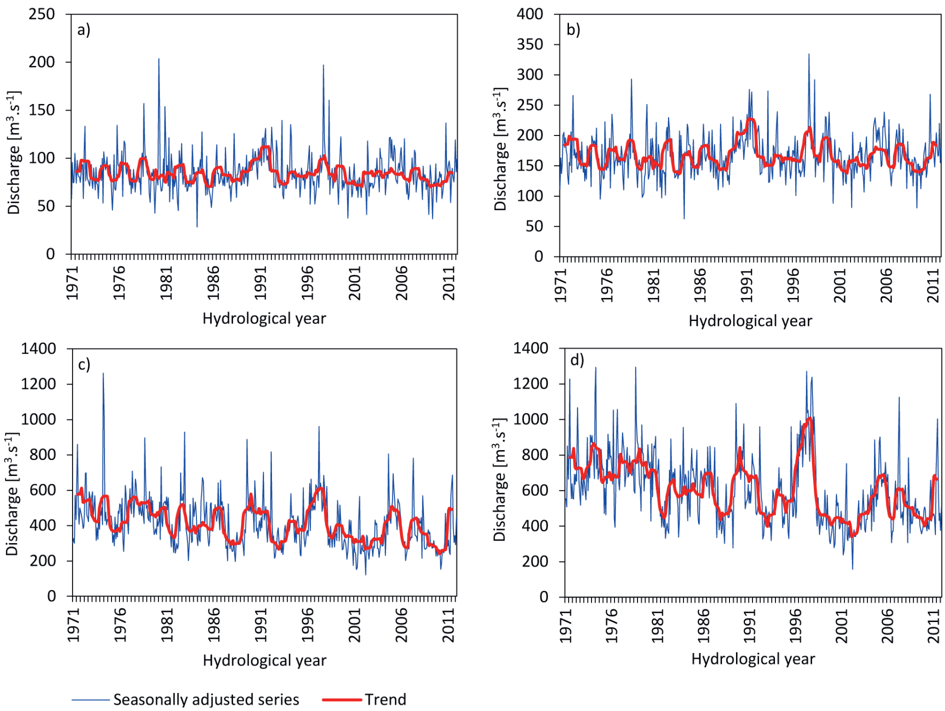

Fig. 7 – The outcome of time series analyses for 1971–2011 at: a – *AR* near Jasper – upper course; b – *AR* at Hinton – upper course; c – *AR* at Athabasca – middle course; d – *AR* below McMurray – lower course; blue line represents seasonally adjusted time series and red line represents the trend component. Hydrological year begins on 1. 11. and ends on 31. 10. Data source: Water Survey of Canada 2013.

The air temperature (T_m) has increased significantly across the catchment throughout the entire year since the beginning of the monitoring. However, the air temperature increase has slowed and appear for a smaller part of the year since 1971. With increasing temperatures, there was a significant decrease in snowfall mainly in winter and autumn months. Runoff (Q_m) decreased significantly, with only less affected in spring and beginning of summer. The decreasing trend in runoff is most distinctive on middle and lower course. Important change is registered for minimum monthly discharges, which decreased significantly mainly on the middle and lower course.

3.3. Hydrological alteration of daily time series

The results of the *IHA* analysis (Table 3) indicate a change in median discharges in the studied period, with increases (around 10%) predominately observed during winter and spring months on the upper course. Decreases in median discharge of more than 10% were observed only at *AR* at Hinton station during May. The number of reversals, which during the second period rose by 32% at *AR* near Jasper station, is also important. The results of *RVA* analysis show changes in the expected discharges. The greatest changes occurring at *AR* near Jasper station were in October (64%) and at 7-day and 30-day minimum discharges (76%). While the change in discharge in October is still of middle magnitude and decreased, the minimum discharges are of high magnitude of change when comparing two periods "before change" (period 1: 1971–1990) and "after change" (period 2: 1991–2011). At this station, the minimum discharges have increased in the second period. In Figure 9 there is no decrease in 90-day minimum discharges and even though there was greater annual variability during the second period (1991–2011), the median and the 75th percentile increased at both stations. At *AR* at Hinton station the 25th

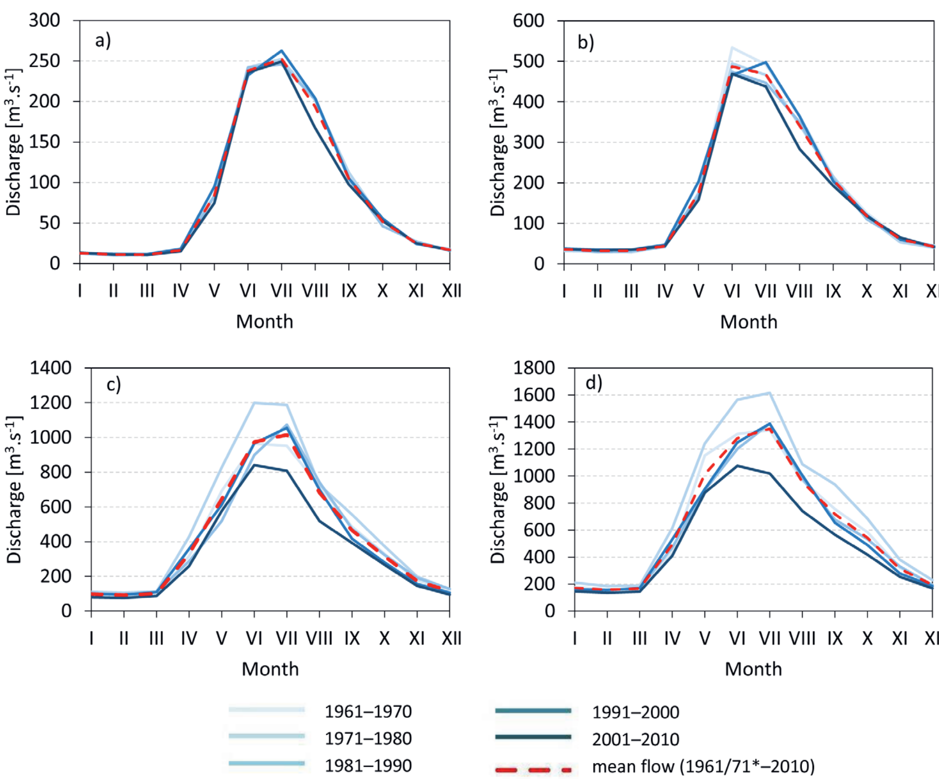

Fig. 8 – Changes of runoff in the Athabasca River basin in 10-year periods between 1961–2010; a – *AR* near Jasper – upper course; b – *AR* at Hinton – upper course; c – *AR* at Athabasca – middle course; d – *AR* below McMurray – lower course. **AR* near Jasper includes period 1971–2010. Data source: Water Survey of Canada, 2013.

Table 3 – Results of the Indicators of Hydrologic Alteration (*IHA*) analysis for daily median discharges (Q_d) for 1. period: 1971–1990, and 2. period: 1991–2011

		AR near Jasper		AR at Hinton		AR at Athabasca		AR below McMurray	
	Unit	1. period	2. period	1. period	2. period	1. period	2. period	1. period	2. period
Group 1									
November	$m^3.s^{-1}$	23.5	23.7	53.9	59.4	195.8	133↓	340.5	234↓
December	$m^3.s^{-1}$	15.5	17.0	39.7	42.5	121.0	97.0	201.0	165.0
January	$m^3.s^{-1}$	12.7	12.3	34.1	38.0	111.5	85.3↓	193.5	150↓
February	$m^3.s^{-1}$	11.0	11.4	31.0	34.0	100.1	79.15↓	172.0	133↓
March	$m^3.s^{-1}$	10.2	11.1	31.8	35.3	108.5	83.5↓	179.5	134↓
April	$m^3.s^{-1}$	13.0	13.4	37.5	39.8	299.3	212.5↓	459.3	270↓
May	$m^3.s^{-1}$	58.9	55.2	130.0	116.0	544.5	536.0	983.5	778↓
June	$m^3.s^{-1}$	228.0	224.5	464.5	451.5	912.0	859.5	1,355.0	1120.0
July	$m^3.s^{-1}$	236.5	239.0	439.0	447.0	1020.0	868.0	1,305.0	1090.0
August	$m^3.s^{-1}$	192.5	182.0	336.5	310.0	633.5	585.0	970.0	762↓
September	$m^3.s^{-1}$	91.9	91.9	200.3	182.0	453.0	348↓	769.8	503.5↓
October	$m^3.s^{-1}$	45.4	43.1	111.5	103.0	350.0	233↓	605.5	381↓
Group 2									
1-day minimum	$m^3.s^{-1}$	8.3	9.0	22.4	25.2	87.0	65↓	150.0	120.0
3-day minimum	$m^3.s^{-1}$	8.4	9.4	24.0	27.0	91.4	67.17↓	153.8	120.7↓
7-day minimum	$m^3.s^{-1}$	8.7	9.7	24.6	28.3	93.4	68.69↓	157.1	122.1↓
30-day minimum	$m^3.s^{-1}$	9.7	10.3	28.6	31.6	96.6	74.25↓	166.8	126↓
90-day minimum	$m^3.s^{-1}$	10.9	11.3	32.2	34.7	108.6	79.36↓	180.0	139.8↓
1-day maximum	$m^3.s^{-1}$	423.5	370.0	796.5	680.0	2,260.0	1,640↓	2,615.0	1,960↓
3-day maximum	$m^3.s^{-1}$	397.3	350.3	721.7	652.3	2,142.0	1,600↓	2,470.0	1,883↓
7-day maximum	$m^3.s^{-1}$	354.5	317.0	688.1	598.0	1,812.0	1,490.0	2,230.0	1,807.0
30-day maximum	$m^3.s^{-1}$	283.5	278.9	527.9	519.5	1,369.0	1,150.0	1,821.0	1,331↓
90-day maximum	$m^3.s^{-1}$	228.7	225.3	427.2	418.9	1,090.0	876.2	1,411.0	1,056↓
Base flow index		0.101	0.118	0.145	0.170	0.198	0.187	0.221	0.227
Group 3									
Date of minimum		76.0	57↓	27.5	27.0	5.0	35↑	9.0	54↑
Date of maximum		174.5	180.0	173.5	181.0	187.5	179.0	192.0	180.0
Group 4									
Low pulse count		3.0	4↑	3.5	4.0	2.0	2.0	2.0	1↓
Low pulse duration	days	31.8	7.5↓	9.3	4.5↓	49.3	62↑	53.0	114↑
High pulse count		5.0	5.0	3.5	3.0	3.5	4.0	3.0	3.0
High pulse duration	days	6.3	6.0	5.3	10↑	9.0	9.0	15.5	12.5
Group 5									
Rise rate	$m.s^{-1}.d^{-1}$	2.7	1.5↓	3.9	2.6↓	9.5	5.6↓	13.5	9↓
Fall rate	$m.s^{-1}.d^{-1}$	−1.7	−1.5	−3.7	−4.0	−10.0	−8↓	−13.8	−10↓
Number of reversals		84.0	111↑	100.0	100.0	69.5	84↑	59.5	72↑

Note: Grey background > 20% change, Upper course – Athabasca River (*AR*) near Jasper, *AR* at Hinton; Middle course – *AR* at Athabasca; Lower course – *AR* below McMurray
Data source: Water Survey of Canada, 2013; created by IHA Software 2009.

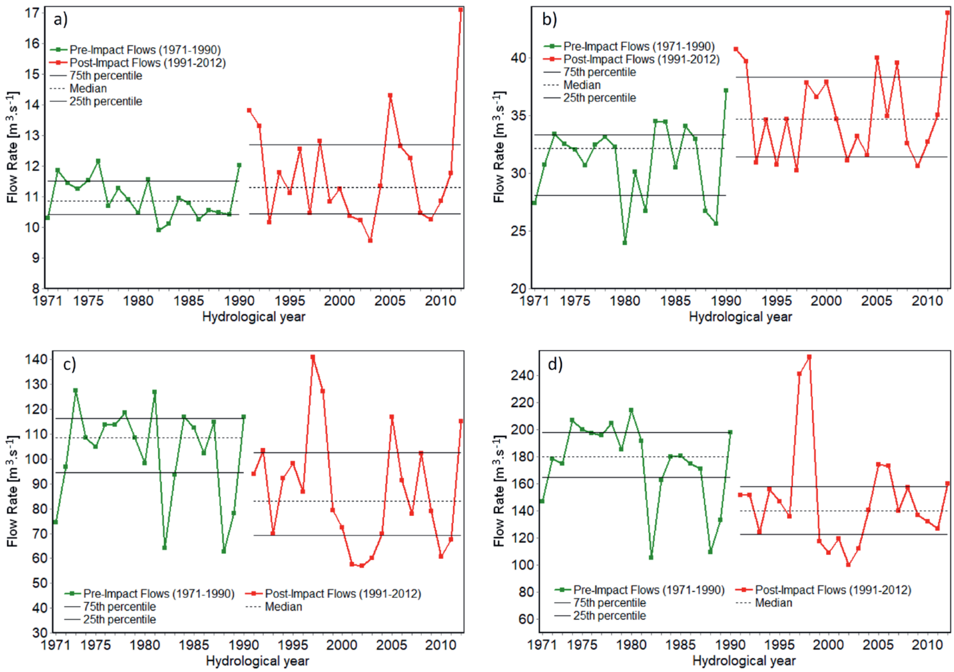

Fig. 9 – Results of the Indicators of Hydrologic Alteration (*IHA*) analysis for 90-day minimum annual discharge for two periods. 1. period (1971–1990) is displayed as green lines and 2. period (1991–2011) is displayed as red lines, solid lines represent 25th and 75th percentile discharges for whole period, dashed lines represent median discharge for whole period. Sites: a – *AR* near Jasper – upper course; b – *AR* at Hinton – upper course; c – *AR* at Athabasca – middle course; d – *AR* below McMurray – lower course. Data source: Water Survey of Canada 2013, created by IHA Software 2009.

percentile discharge (counted for each period separately and means that the value at which 25% of the discharges during this period lie below that value) increased as well, which indicates a long-term increase.

At *AR* at Athabasca station on the middle course of the river there was a decrease in median discharges between 1971–1990 and 1991–2011 throughout the entire year; the greatest decreases (> 20%) were observed in the cold season. The number of reversals at *AR* at Athabasca station increased by 20%. The decrease in m-day minimum and maximum discharges here was significant; median 90-day minimum discharges declined by 26.9%; Fig. 9 indicates that, as opposed to the upper course, there is a significant decrease in the median, as well as the 25th and 75th percentiles. The *RVA* analysis also resulted in high rates of change. For most of the year mid-sized changes in expected discharges occurred (34–67%) and were always associated with a decline. For 1-day, 3-day, and 7-day minimums these changes were even 100%, which means, that no values of discharge in the second period "after change" hit the target range, which spans the 25th to 75th percentiles of the pre-impact indicator values.

On the lower course (*AR* below McMurray) the situation is similar to the middle course. For more than half of the year there was a decrease in median discharges between 1971–1990 and 1991–2011 of more than 20%; a decrease of about 20% was observed in median m-day minimal and maximum discharges. The duration of periods of decreased discharge at *AR* below McMuray station is also significant; it more than doubled in the second period (from 53 days in the first period to 114 in the second). Just like at *AR* near Jasper station and *AR* at Athabasca station, here (at *AR* below McMurray) there was an increase in number of reversals in the second period (by 21%). The *RVA* analysis also resulted in high variability in m-daily minimal discharge values (88 and 100%). In Fig. 9 there is a clear, significant decrease in 90-day 25th percentile, median, and 75th percentile minimum discharges during the second period.

The results of daily discharges in the whole catchment showed increased variability after 1991 when comparing with previous period (1971–1990). Radical changes were visible especially for the minimum flows – both short-lasting and longer-lasting. While there was an increase in minimal discharges at the upper course station, at the middle and lower course stations there was a significant decrease in low flows.

4. Discussion

The results of the analyses indicate significant changes have occurred in the entire basin. The influence of the Pacific decadal oscillation has impact on temperatures, precipitation and discharges as was reported in previous Athabasca River basin studies (Haines 2012; Rood, Stupple, Gill 2015) and other Canadian river basins studies (Burn 2008; Brabets, Walvoord 2009) by higher precipitation, lower mean temperatures, and greater runoff during the cold phase and in contrast lower Q_{an} during the warm phase. Based on that significant connection with the Pacific decadal oscillation was obvious only at Campise station for temperature. Rather long-term warming is occurring in whole catchment, as has been reported in earlier studies (Schindler, Donahue 2006; Peters et al. 2013; Ghaderpour, Vujadinovic, Hassan 2021), with T_{anMin} and T_{mMin} increasing the most. These results correspond with the overall changes in the Canada's climate, which indicates increasing of summer days and hot days and decreasing of frost days and ice days since the second half of the 20th century (Vincent et al. 2018; Newton, Farjad, Orwin 2021). During the past century (from 1913 or 1939 for middle and from 1917 for lower course until 2011), warming has most significantly occurred on the middle and lower courses; however, when analyzing the shorter data series beginning in 1971 no significant increasing trend was detected. In contrast to earlier studies (Peters et al. 2013; Bawden et al. 2014), a significant increasing trend in T_{an} was detected on the upper Athabasca River for the last period (1971–2011), which has affected the constant glacial retreat.

Even though a slight increase in precipitation totals is predicted for Canada's western prairie provinces in 21st century (Schindler, Donahue 2006), our results indicate precipitation decreases since 1971. This finding corresponds with the findings of Bawden et al. (2014), who analyzed warm season data (March–October) for the second half of the 20th century and Ghaderpour, Vujadinovic, Hassan (2021) who found out that the annual precipitation of 91% of the region has been decreasing by 1.56 mm per year since 1960. Only at the middle course Campise station did we observe an increase in rainfall during April, both from the start of observations (1911) and when using data starting in 1971. A significant decrease in precipitation was recorded at the middle course Athabasca station. Since 1971 there has been a significant decrease in snowfall in all parts of the basin (except at Campise station). This is consistent with studies by Vincent et al. (2018) and Newton et al. (2021), who found that the southern provinces of Canada in particular have seen a decline in the number of days with snowfall and a shift from snow to rain since the second half of the 20th century. Rainfall decreased only at the middle course Athabasca station. The most significant decreasing trends can be observed since 1971 on the lower course of the river from October to January.

Our results show that Q_m and median discharges have decreased during most months at all observed stations in the Athabasca River basin, an increase of Q_m and median discharges was significant only on the upper course during November and February during the studied period (1971–2011). As opposed to Haines's (2012) findings, who analyzed 1971–2005 period, the *M-K* test did not confirm a decrease in Q_{an} at *AR* near Jasper station. This may be due to the different length of data series. In total, mainly decreasing trends were recorded (for 1971–2011), not only on the lower course as studies by Peters et al. (2013) and Monk, Peters, Baird (2012) report, but also on the middle course, where over the course of the century T_{an} increased, evapotranspiration increased as expected, and snowfall decreased. These findings of upper and middle course streamflow changes support the conclusion that precipitation and temperature are two of the main factors of the streamflow fluctuation for Athabasca River basin. Together with declining snowfall, and the associated decrease in snow cover depth, spring runoff has decreased, which corresponds with the conclusions of Peters et al. (2022), who registered flow decrease at spring break up on the lower course since 1974. The decrease in Q_{mMin} on the lower and middle courses during nearly the entire year, as indicated by *M-K* test results, is important. The decrease of minimum discharges forms a barrier in the Peace Athabasca delta for biota migration. The impossibility of migration can cause their death in many cases (Wolfe et al., 2012). By comparing 1971–1990 with 1991–2010 using *IHA*, a decline in short-term and long-term minimum and maximum discharges on the middle and lower courses was observed, similar to the study by Monk, Peters, Baird (2012) focused on the Peace-Athabasca Delta in which lower-course data from the 1958–2009 and 1974–2009 periods were compared. Along with a decrease in minimum and maximum discharges, discharge variability has increased. These factors are some of the most important ones affecting the delta's ecosystem (Andrishak, Hicks 2010). Because on the upper course minimum discharges registered an increase during the second period, the decrease of minimum discharges started in the area between the upper and middle courses.

5. Conclusion

Significant decreases in discharge on the middle and lower Athabasca River have been proved and these changes have negative effects on natural environment and water sources in the Athabasca catchment. Besides Q_{an}, Q_{m}, and median discharge, significant decreases in Q_{anMin} have occurred in winter months. The socioeconomic activities concentrated in this part of the basin can expect to be strongly affected by these changes. As a result of declining snowfall, and the associated decrease in snow cover depth, spring runoff has decreased. Due to warming, which in the past century was very significant in the prairie regions of Western Canada, potential evapotranspiration has increased, which is yet co-acting factor of declining discharges. Significant warming has occurred also on the upper course, where glaciers are rapidly retreating, which has and will have an even greater impact in the future on the total supply of meltwater and the hydrological regime of the upper course. Temperature increases in prairies regions influenced the runoff decline in the warm period on the middle course. The decrease of low streamflow's during nearly the entire year can be critical for wetland ecosystems and biota migration on the lower course. Significant impact has decrease in precipitation amounts, especially in snow precipitation in the period 1971–2011. In recent years the climate has also become more unpredictable, and it is therefore important to select a suitable system for water resource management and land management in different parts of the studied basin. Based on our results, it would be possible to further establish future projections for changes in hydro-climatic conditions in the catchment in relation to different emission scenarios. It would be interesting to assess the changes in potential evapotranspiration and link the hydro-climatic changes with the effect on water quality in the area. The results of the study may help in developing appropriate water management strategies in this vulnerable ecosystem.

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