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Streamflow input to Lake Athabasca, Canada

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Abstract

The 271 000 km^2 Lake Athabasca drainage in Northern Canada encompasses ecologically-rich and sensitive ecosystems, intensive agricultural lands, vast forests, glacier-clad mountains, and abundant oil reserves in the form of tar-sands. In this study, streamflow variability and trends in eight rivers feeding the 7800 km^2 Lake Athabasca are investigated over the period 1960–2010. Hydrological regimes and trends are established using a robust regime shift detection method and the Mann-Kendall (MK) test, respectively. Results show that the Athabasca River, which provides ~ 57 % of the total annual lake inflow of 34.06 km^3 yr^{-1}, experiences marked declines in recent decades impacting lake levels and its ecosystem. The Fond du Lac River, which contributes ~ 30 % of total Lake Athabasca inflow, has an increasing trend of 0.021 km^3 yr^{-1} over 1970–2010 according to the MK test, equating to a 0.86 km^3 discharge increase from Fond du Lac River to the lake. From 1960 to 2010 there has been approximately a 21.2 % reduction of average discharge equivalent to a 7.22 km^3 recession in the Lake Athabasca causing lake levels to drop. The lake level has a trend of −0.008 m yr^{-1} which is equivalent to a 0.39 m decline in the lake level over 1960–2010. The total lake inflow trend over 1977–2010 is −0.207 km^3 yr^{-1} or a reduction of 25.67 km^3 by 2100 by linear extrapolation. This may imply a further reduction of 2 m to 3 m in lake level that is in the range of a 5200-yr historical minimum inferred from proxy data in nearby sediment cores.

1 Introduction

Lake Athabasca, straddling the provinces of Alberta and Saskatchewan, forms the third largest lake (by area) in Northern Canada. It receives direct runoff from a large catchment area spanning 271 000 km^2 including the Athabasca, Fond du Lac, and other small river catchments. Lake Athabasca forms a large, natural reservoir of freshwater in the upper reaches of the 1.8 × 10^6 km^2 Mackenzie River Basin thus influencing the timing and amount of pan-Arctic river discharge (e.g. McClelland et al., 2006). It is the site of the ecologically-sensitive Peace-Athabasca Delta (PAD) that depends on spring flood events for freshwater recharge (Peters et al., 2006; Smith and Pavelsky, 2009; Wolfe et al., 2008a,b). The Athabasca River, the longest river entirely within Alberta, is especially important for societal needs and economic development such as for domestic water consumption and for irrigation of agricultural lands. This waterway is also important for the oil sands industry near Fort McMurray, Alberta, as bitumen extraction requires significant amounts of water that are currently being sourced from the river itself. Thus the cumulative impacts of industrial and other anthropogenic activities in addition to climate change are affecting the lake's water balance and surrounding ecosystem (Schindler and Donahue, 2006).

Previous studies on streamflow variability and trends in the Lake Athabasca watershed have focused on the Athabasca River itself. Summer streamflow in the headwaters of the Athabasca River declined by about 0.2 % per year over the 20th century reducing riparian groundwater recharge and imposing water deficit stress on floodplain forests (Rood et al., 2008). Further downstream, May to August streamflow declined by 33.3 % from 1970 to 2003 on the Athabasca River near Fort McMurray in response to receding Rocky Mountain glaciers and lower snowpack levels (Schindler and Donahue, 2006). Abdul Aziz and Burn (2006) found strong increasing trends in the December to April flows as well as in the annual minimum flow in the Athabasca River system. They also reported weak decreasing trends in the early summer and late fall flows as well as in the annual mean flow for the Athabasca River. Woo and Thorne (2003) reported increasing variability in annual streamflow of the Athabasca River near Fort McMurray in the late 20th century. Recent sediment cores extracted from a pond adjacent to Lake Athabasca place the recent hydrological variability of the Athabasca River into a 5200-yr context (Wolfe et al., 2011). Their proxy record in water levels of Lake Athabasca show drops between 2–4 m below the 20th century mean in the mid-Holocene that may reoccur by 2100 with continued climate change.

Despite some of these recent advances in our knowledge of the hydrology of the Lake Athabasca Basin, little information exists on total streamflow input to Lake Athabasca. Previous studies have focused on the Athabasca River itself but have not investigated lake inflows from other main contributors such as the Fond du Lac River and other small rivers that collectively contribute ∼ 43 % of its total input. In the current research, we investigate quantitative changes through analysis of hydrological regime variability and trends across the Lake Athabasca Basin using an observational dataset of streamflow. The total streamflow input to Lake Athabasca and the contribution of different tributaries from 1960 to 2010 are also examined. Furthermore, the reasons and periods of decline in lake level as well as the prospects for the future are investigated and compared with the results found from the nearby sediment studies. In the next sections, the study area and data are introduced. Next, the methodology and hydrological regime variability and trend detection tools are explained. The results follow and the paper ends with a discussion of the implications of our work.

2 Study Site

The Lake Athabasca Basin is located between 52° 10′ N and 60° 10′ N and 100° W and 120° W covering an area of 271 000 km^2 in the Canadian provinces of Saskatchewan and Alberta as well as the Northwest Territories (Fig. 1). The catchment elevation varies between 3747 m at Mount Columbia and 205 m near the lake shore. The Athabasca River drains from the Rocky Mountains in Jasper National Park. Elsewhere the landscape in the lower Lake Athabasca Basin is mainly covered by ponds, agricultural lands, and black spruce forests. The basin has over 1000 lakes and ponds that support many First Nations communities. The Athabasca River is especially important for the tar-sands industry as oil extraction requires significant amounts of water that are currently being extracted from the river itself. The future oil sands operations may extend over 140 000 km^2 or 20 % of Alberta given projected developments (Jordaan et al., 2009).

The Fond du Lac River flows from Wollaston Lake to Black Lake and there are twenty-eight rapids or falls along the river. Up to 86 % of the Athabasca-Fond du Lac rivers drainage area has been gauged at least 20 yr in the last few decades. The two largest rivers by contributing area are the Athabasca River (~ 150 000 km^2) and the Fond du Lac River (~ 50 000 km^2). There are also a number of smaller rivers draining into Lake Athabasca, mainly on its southern shore including the MacFarlane, Douglas, Grease, Otherside, Richardson and William Rivers. The lower reaches of the Athabasca River begin at Fort McMurray, where the river is joined by the Clearwater River. During ice-jam floods, the Peace River may overflow into Lake Athabasca and act as a hydraulic barrier to lake outflow when the river level is higher than the lake level. Lake Athabasca covers an area of 7800 km^2 and its mean depth is about 20 m (Peters and Buttle, 2010). The lake basin has long, cold winters and relatively short summers. No less than 50 % of the total lake inflow occurs over May–August (Muzik, 1991). Mean annual air temperature at the nearby Fort Chipewyan meteorological station is –1.9 °C and 59 % of the annual precipitation occurs during May–September (Wolfe et al., 2008b).

3 Data and Methods

3.1 Data sources

A list of the 14 gauges on the rivers and lake shore for measuring the lake level used in the present study along with their identification numbers and geographical information are summarized in Table 1. The source of the data is the Water Survey of Canada. Daily streamflow data (in $\text{m}^3\,\text{s}^{-1}$) are extracted and compiled to form annual time series. Streamflow variability between two immediate gauges on the Athabasca River, so called hereafter “gauge contribution”, is determined by subtracting the annual streamflow from an upstream gauge from that of the nearest downstream gauge. This helps identifying the contributions of individual reaches within the Athabasca River drainage to streamflow variability and trends across the basin. For simplicity, the total streamflow for the smaller rivers (Douglas, Grease, MacFarlane, Otherside, Richardson and William Rivers) are combined to create a single annual discharge time series for the regime shift and trend analyses. The gauge on the Fond du Lac River was moved just upstream from its original location in 1963, so the records from the two gauges are spliced to form one time series of annual discharge for 1960 to 2010 while accounting for the change in contributing area (e.g. Déry et al., 2012). Five of the gauges are on the main stem of the Athabasca River, listed from the largest to the smallest gauged area in the table. Data span the period of record up to 2010. Annual discharge are in units of $\mathrm{km}^3\,\mathrm{yr}^{-1}$ and after initial analyses (e.g. cross correlations) reconstructed to obtain the period 1960–2010 for all the 13 gauges as the records do not cover all the same periods. Three Athabasca, Stony Rapids, and MacFarlane gauges' time series are used for reconstructing the missing data for gauges on the Athabasca River and small rivers. The Fond du Lac River is used to reconstruct missing data on the Grease and MacFarlane Rivers, as there is a significant correlation between overlapping records. For the other smaller rivers (Otherside, Douglas, William, and Richardson Rivers), they correlate significantly with the MacFarlane River more so than with the Fond du Lac River (significant correlation level, $\rho \geq 0.67$). Therefore, these rivers are reconstructed using the time series recorded at MacFarlane with nearly complete data. To evaluate the level of the Lake Athabasca, records of lake level near Crackingstone Point (07MC003) is implemented.

3.2 Methodology

The regime detection method of Rodionov (2004) that detects significant shifts in the mean level of streamflow variations is applied in this study (http://www.beringclimate.noaa.gov/). Model outputs are lines of zero slopes representing the different regimes detected. Two factors are needed to be considered in regime shift detection: the significance level and the length of the regimes compared. The significance level (in this study $p \leq 0.1$) is a threshold at which the null hypothesis is rejected by the two-tailed

Student t-test. The null hypothesis is defined so that the means of the two regimes are equal. If the significance level is low the shift should be greater to be detected. In the method used in this study a cut-off length constraint is 12 yr. If the regime length is less than the cut-off length, the probability of detection declines although the longer regimes are detected. Equal-weighed arithmetic means of the regimes are considered for different regime changes in the hydrometric gauges of the study area. We have attempted to relate the regime shifts and the trend results by conducting trend analyses on the separate "regimes" identified in the regime shift analysis. The reason we have combined the regimes and trends is that, if the only change actually occurring in the data comes from the regime shifts, then the trends identified are simply artifacts of the regime shifts and not real trends. Trend analysis on the separate regimes would then be acceptable to extrapolate the trends into the future.

The non-parametric Mann-Kendall (MK) statistical test developed by Mann (1945) and Kendall (1975) has been widely used to detect trends in different environmental time series such as river discharge, rainfall, air temperature, and water quality (e.g. Burn et al., 2004; Déry et al., 2005; Abdul Aziz and Burn, 2006). The advantage of using this method for trend detection is that it is powerful in the case of non-normally distributed time series and relatively insensitive to outliers. The MK test is applied in this study to assess the significance of sub-basins' trends in the Athabasca River (i.e. areas between gauges) and existing trends in the Lake Athabasca input. The null hypothesis test is conducted on different, common lengths detected and a set of the rejected hypotheses (significant trends) are obtained. Trend detection analysis is carried out for four different analysis periods, 13, 34, 41 and 51 yr in duration, with each analysis period ending in the year 2010. The former analysis period links the detected regimes to the trends found in the study area. The analysis periods represent a trade-off between greater accuracy of the lake inflow time series versus greater power for the statistical tests for a longer record length. The serial correlation in the data sets is a factor that can impact the results of the MK test (von Storch, 1995). This results in the incorrect rejection of the null hypothesis of no trend, whereas the null hypothesis is actually true. One of the pre-whitening methods was proposed by Hamed and Rao (1998) in which an empirical relation is used to compute the effective sample size to remove the effect of the serial correlation. Another procedure used to account for autoregressive parameter, ρ with small sample size (say $n = 7$) is based on the assumption that the first approximation of the biased estimate of ρ is inversely proportional to sample size. This is one of the pre-whitening approaches that is used to remove the red noise component from time series prior to applying the regime shift detection procedure (Orcutt and Winokur, 1969; Rodionov, 2004). Since the conventional pre-whitening methods in removal of the serial correlation component from time series reduces the magnitude of the existing trend, we have applied the trend-free pre-whitening (TFPW) procedure in this study introduced by Yue et al. (2002). The TFPW method includes the following steps:

- Estimation of the trend slope based on Theil (1950a,b,c) and Sen (1968).
- Computation of the lag-one serial correlation coefficient of the detrended series and removal of the AR(1).
- Combining the identified trend and the residuals.
- Conducting the MK test.

In this approach, the removal of a trend component from a time series prior to pre-whitening removes the effect of the trend on the serial correlation and does not significantly influence the true lag-one autoregressive, AR(1).

4 Results

In the following paragraphs the detected regime shifts and trends both for the recorded data at the gauges and sub-basin contribution of the gauged drainage areas are discussed in detail. Results for the Athabasca River itself are first examined where possible discharge trends in some reaches may be compensated by changes elsewhere in the basin. Thereafter the streamflow variability and trends in the Fond du Lac River and other lake tributaries, as well as total inflow to Lake Athabasca, are analyzed.

4.1 Relative contributions of Lake Athabasca river inflow

The Athabasca and Fond du Lac rivers contribute 86.5 % of the annual Athabasca Lake inflow whereas the other smaller rivers account for 13.5 % total lake inflow (Table 1). Figure 2 illustrates the temporal evolution of the relative contribution of the main reaches in Lake Athabasca inflow. The annual flow during 1988–2010 in the Athabasca River has declined which might be because the McMurray gauge has experienced the minimum contribution into the lake inflow in 1995–1997 and 2001–2005. The recorded time series at this gauge has the higher variability (standard deviation of 4.3 $\mathrm{km^3\,yr^{-1}}$ shown in Table 1) in the study period and the coefficient of variation, CV, is 0.21. In contrast, the contribution of annual flow rate along the Fond du Lac River has increased during the period 1977–2010, which has partially compensated the hydrological regime shift in other parts of the Lake Athabasca Basin.

4.2 Athabasca River Basin

Glacier runoff from the Columbia Icefield and other mountain glaciers as well as seasonal snow-melt from the mountain headwaters are important components of the annual water availability in the lake drainage basin (Marshall et al., 2011). The total contribution from the headwaters of the Athabasca River as recorded at Jasper amount to 8.1 % of the total lake inflow (Table 1) over 1960–2010. The MK test reveals a clear decreasing trend of 0.005 $\mathrm{km^3\,yr^{-1}}$ detected for the entire study period at Jasper while no regime shift is detected at the gauge (Fig. 3). The contribution of the headwaters in the Rocky Mountains to the lake inflow has thus declined 0.27 $\mathrm{km^3}$ over 1960–2010 (Table 2).

Athabasca River discharge data at Hinton show no regime shift and for the contributing area between Hinton and Jasper, there is a slight regime drop in 1979 from

$2.8\,\text{km}^3\,\text{yr}^{-1}$ to $2.6\,\text{km}^3\,\text{yr}^{-1}$. In addition, the trend for discharge data as measured at Hinton is $-0.011\,\text{km}^3\,\text{yr}^{-1}$ equivalent to a $0.57\,\text{km}^3$ decline over 1960–2010 while the area between the Hinton and Jasper gauges shows no significant trend. Athabasca River discharge data at Windfall and for the contributing area between Windfall and Hinton exhibit significant trends of $-0.033\,\text{km}^3\,\text{yr}^{-1}$ and $-0.022\,\text{km}^3\,\text{yr}^{-1}$, respectively with corresponding mono-regimes of $7.4\,\text{km}^3\,\text{yr}^{-1}$ and $2.04\,\text{km}^3\,\text{yr}^{-1}$. Streamflow in the Athabasca River at the Windfall gauge has thus declined $1.67\,\text{km}^3$ over 1960–2010. The contribution of the drainage area between Windfall and Hinton gauges has decreased by $1.11\,\text{km}^3$ over the study period. Elsewhere on the Athabasca River, a regime drop of $2.9\,\text{km}^3\,\text{yr}^{-1}$ in 1998 is detected at the Athabasca gauge (Fig. 4, upper panel). Similarly, the contribution from the Athabasca drainage area between this gauge and the upstream gauge at Windfall (Athabasca minus Windfall time series) experiences a downward regime shift in 1998 (Fig. 4, lower panel). At the Athabasca gauge, there is one significant decreasing trend detected over 51 yr. The trend rate is $-0.070\,\text{km}^3\,\text{yr}^{-1}$ equating to a $3.55\,\text{km}^3$ volume loss in the Lake Athabasca input. Trend analysis in the period of 1998–2010 demonstrates a relation between the regime change in 1998 and stronger trend afterward. The contribution of the drainage area between Athabasca and Windfall gauges has decreased $2.06\,\text{km}^3$ over the study period.

The most downstream gauge on the Athabasca River in this study is located near Fort McMurray (see Fig. 1) and is thus a good indicator of the total contribution of the Athabasca River to Lake Athabasca inflow. There is a large downward regime shift of $5.4\,\text{km}^3\,\text{yr}^{-1}$ over 1998–2010 at the McMurray gauge on the Athabasca River (Fig. 5, upper panel). The gauge records and the contribution of the Athabasca River between the McMurray and Athabasca gauges (Fig. 5, lower panel) show decreasing trends of $-0.145\,\text{km}^3\,\text{yr}^{-1}$ and $-0.056\,\text{km}^3\,\text{yr}^{-1}$ equivalent to a $7.38\,\text{km}^3$ reduction in flows on the Athabasca River at the McMurray gauge with a contribution of $2.85\,\text{km}^3$ for the area between the McMurray and Athabasca gauges to that trend over 1960–2010 (Table 2). Unlike the drainage area between the Athabasca and Windfall gauges, the time series of discharge difference between McMurray and Athabasca representing the contribution of the area between these two gauges shows no regime shift.

4.3 Fond du Lac River Basin and other tributaries

After the Athabasca River, the Fond du Lac River has the highest contribution to total annual Lake Athabasca inflow at 29.6 % (Table 1). No regime shift is detected in Fond du Lac River and the detected trends for different analysis periods are not significant even though there is a slight increase over 1970–2010 (Fig. 6). Trends and equivalent discharges in the small rivers including MacFarlane, Douglas, Grease, Otherside, Richardson and William rivers discharging to Lake Athabasca are summarized in Table 2. Similar to the Fond du Lac River, no regime shift or significant trends are found in the analysis of small rivers' time series. The MK test for the combined time series of the small tributaries shows that there are two increasing trends for periods of 1970–2010 and 1977–2010, but none of them are significant (Fig. 7). Together with the Fond du Lac River, other small rivers have increased lake input by ~ 0.59 km^3 over 1977–2010, partially offsetting declines along the Athabasca River. There is a slight regime shift in the overall Lake Athabasca input detected in 1998 (Fig. 8) and a significant trend of $-0.142\,\text{km}^3\,\text{yr}^{-1}$ from 1960 to 2010 according to the MK test. Over this 51-yr period, total lake input has thus declined by 7.22 km^3.

5 Discussion

5.1 Regime shifts and trends in the Lake Athabasca Basin

Streamflow for the different gauges along the Athabasca River shows a decreasing regime shift at downstream gauges from Athabasca to McMurray and no regime shift for the upstream reaches between the Jasper and Windfall gauges during the analysis period. The average contribution from the glacier sources in the Athabasca River discharge is 0.8 % over 2000–2007 (Marshall et al., 2011). The contribution of the drainage areas in between two immediate gauges in the Athabasca River does not indicate any regime shift, except for the area in between the Athabasca and Windfall gauges. The regime shift for the area between Hinton and Jasper is relatively small in magnitude to call it as streamflow regime change. The largest downward shift for the gauge record belongs to the McMurray gauge. The other rivers (e.g. the Fond du Lac River and combination of the small rivers) experience no regime change during the last five decades.

To assess the streamflow regime change in relation to climate variability, we compared the regimes detected in the Athabasca River with those of the Pacific Decadal Oscillation (PDO) index as one of the important climate indicators affecting the snowmelt rate and consequently the streamflow variability. The regime change in the Athabasca River at McMurray and Athabasca gauges as well as the lake input are detected in 1998, two decades after the regime change in PDO in 1977 (Rodionov, 2004). A study by Burn (2008) showed that trends in streamflow correlate to temperature changes in the spring and to some extent to one or more climate indices representing the fact that there is a possibility of climate change impact on the observed trends. To verify this in the study area we conducted a correlation analysis and found significant correlations between mean and maximum air temperatures at the Fort McMurray meteorological station and total Lake Athabasca inflow as well as gauge record at Jasper. This supports the idea that part of the streamflow changes is due to climate change in the study area.

The magnitude of the trends varies markedly across the basin (Table 2). All gauge records indicate a modest decreasing trend in the headwaters of the Athabasca River and a strong decreasing trend at the McMurray gauge over the last decades. The contribution from the gauges decreases and other tributaries with outlets to Lake Athabasca have an increasing trend during 1960–2010, attenuating downward shifts and decreasing trends along downstream reaches of the Athabasca River. Over the last 51 yr, the volume of lake inflow has declined 7.22 km^3, which accounts for about 21.2 % of annual average inflow in that period. The relative changes are −26.9 % and

−37.9 % at the Athabasca and McMurray gauges. The analyses of variability of the Lake Athabasca inflow and detected trends and regime changes over 1960–2010 are assessed without consideration of their driving mechanisms.

5.2 Potential implications to water levels of Lake Athabasca

Wolfe et al. (2011) report up to 2–4 m historical declines in Lake Athabasca levels in their 5200-yr proxy data based on sediment cores compared to present day conditions. Lake Athabasca has a surface area of about 7800 km^2, implying this change in water level corresponds to a 15.6 km^3 to 31.2 km^3 change in lake volume. The MK trend detection method on the annual discharge data for the Athabasca River at McMurray yields a trend of $-0.145\,\text{km}^3\,\text{yr}^{-1}$, equivalent to a loss of 7.38 km^3 in volume or a decline of about of 0.95 m in Lake Athabasca water level over 1960–2010. This matches our rough estimate of lake level changes from streamflow trends. The lake level data recorded near Crackingstone Point is investigated in order to evaluate the possible regime and trend change. Figure 9 illustrates the level time series of the Lake Athabasca over 1960–2010 with trends detected over the analysis periods. The trend rate over 1960–2010 is $-0.008\,\text{m}\,\text{yr}^{-1}$ which is equivalent to a 0.39 m recession in the lake level. In addition, the lake average level has changed from 209.66 m over 1942–1967 to 208.89 m in 1972–1989 (Muzik, 1991). Since there is a lack of quality in the available data before 1960 for all the gauges recording streamflow in the Lake Athabasca Basin, we have conducted our analysis afterward. Taking into account the findings from Muzik (1991) it is expected that the lake level has dropped by ∼ 0.9 m over 1942–2010. The total lake inflow trend over 1977–2010 is $-0.207\,\text{km}^3\,\text{yr}^{-1}$ equating to a reduction of 25.67 km^3 by 2100 if the linear trend persists. Only 6 % of the total lake inflow has greater uncertainty due to the reconstruction of the time series for gauges on the smaller rivers and 94 % of the total lake inflow has been calculated solely based on the observed data over 1977–2010. This leads to a possible 2–3 m further decline in the lake level considering the lake surface area. On the other hand, the in-situ lake level data indicate a 1.61 m recession in the lake level obtained extrapolating the linear trend applied to the level data at the Crackingstone Point. The possible reasons for discrepancies between the two values are the diminishing outflow over time and/or the vertical water fluxes which are compensating for the decrease in streamflow input. The streamflow decline observed on the Athabasca River at McMurray is attenuated in part by an upward trend in discharge for the Fond du Lac River of about 0.59 km^3, equivalent to a few centimeters rise in lake level over the last 51 yr.

The highlands of the Athabasca River (e.g. near Jasper) are fed both with abundant snow-melt and seasonal glacier ablation from high elevations of the Rocky Mountains, which intensifies in the summer and results in high flows then (Woo and Thorne, 2003). Projections of future changes in Rocky Mountain rivers suggest that the predicted summer flows in 2005–2055 may decline considerably, while winter and early spring flows may increase, resulting in $\sim$ 3–9 % decline in the annual discharge (Shepherd et al., 2010). Generally under warming scenarios winter flows will increase, the spring freshet dates will advance, but peak flows will decline (Woo et al., 2008). Climatic changes, land cover/use changes, and enhanced water extractions for various societal and commercial needs including the tar-sands development near Fort McMurray, which is projected to increase by 200 % by 2015 (Pavelsky and Smith, 2008), may continue to decline Lake Athabasca inflow rates. Ignoring changes in vertical water fluxes over the lake (e.g. precipitation, evaporation, and infiltration) and in lake outflow, the monotonic, decreasing trend in total lake inflow obtained in this study suggests that by 2100 the lake level may drop by 2 m to 3 m which is within the range of 2–4 m of the 5200 yr historical minimum inferred from a sediment proxy record of the lake's level (Wolfe et al., 2011) and would exacerbate water shortages in the area.

6 Conclusions

Water extractions for potable water and domestic use in communities, irrigation for agriculture, and industrial tar-sands projects in the Athabasca drainage in combination with discharge declines due to climate variability and change may affect the Lake

Athabasca's ecosystem. In the present study, the 1960–2010 variability and trends of streamflow and lake inputs irrespective of causal factors are investigated using the Mann-Kendall test and regime shift detection method. The results show that there are significant trends in the principal rivers discharging into Lake Athabasca and strong shifts in downstream reaches of the Athabasca River. During the last 51 yr of the study period, there have been 7.22 km^3 reductions in total streamflow input equating less than 1 m decline in lake levels. Although rising air temperatures during the last decades may initially enhance the peak waters in highly glacierized watersheds such as the Athasbaca River at Jasper and possibly influence the overall lake inflow, we found a decreasing trend of 0.005 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ at this gauge. A previous analysis of streamflow trends in glacier-fed basins of British Columbia, Canada, suggests that should the current warming rate continue, glaciers will recede and summer flows will decrease even more (Stahl and Moore, 2006). An increase in the flow rate in the Fond du Lac River, the second largest contributor to total lake inflow, has partially offset recent lake level reductions; however this trend is relatively smaller in magnitude than the overall downward trend of total lake inflow. Prospects for the future of the Lake Athabasca Basin may include more water extractions for industry (Pavelsky and Smith, 2008), and more variability of the winter and summer flows and decreased annual inflow to the lake (Shepherd et al., 2010). Important changes in the flora and fauna of the basin, especially in the ecologically-sensitive Peace-Athabasca Delta, are thus expected to happen in the near future.

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Table 1. List of hydrometric gauges in the study area and corresponding discharge statistics. Discharge difference between two immediate gauges on the Athabasca River, combined gauge area for small rivers, and total lake inflow information over 1960–2010 are also provided.

Code	River	Hydrometric station	Lat. (° N)	Lon. (° W)	Area (km^2)	Mean ($km^3\,yr^{-1}$)	St Dev. ($km^3\,yr^{-1}$)	CV (–)	Contribution (%)
07DA001	Athabasca	Below McMurray	56.8	111.4	132 585	19.5	4.1	0.21	56.9
07BE001	Athabasca	Athabasca	54.7	113.3	74 602.3	13.2	3.1	0.23	38.5
07AE001	Athabasca	Windfall	54.2	116.1	19 600	7.4	1.2	0.16	22.0
07AD002	Athabasca	Hinton	53.4	117.6	9764.8	5.4	0.7	0.12	16.0
07AA002	Athabasca	Jasper	52.9	118.1	3872.7	2.7	0.3	0.10	8.1
07LE002	Fond Du Lac	Outlet Black Lake	59.1	105.5	50 700	10.0	1.5	0.15	29.6
07LE001	Fond Du Lac	Stony Rapids	59.3	105.8	51 800	–	–	–	–
07MA003	MacFarlane	Outlet Davy Lake	59.0	108.2	9120	1.70	0.30	0.15	5.1
07LE003	Douglas	Near Cluff Lake	58.3	109.8	1690	0.30	0.10	0.19	0.9
07MB001	Grease	Below Fontaine Lake	59.5	106.4	6150	0.88	0.21	0.24	2.6
07LE004	Otherside	Outlet Mercredi Lake	58.9	107.5	2700	0.54	0.09	0.17	1.6
07DD002	Richardson	Mouth	58.4	111.2	2730.9	0.50	0.04	0.08	1.5
07MA004	William	Above Carswell River	58.8	109.0	4030	0.63	0.11	0.17	1.9
	Athabasca	McMurray minus Athabasca			57 982.7	6.34	2.16	0.34	18.4
	Athabasca	Athabasca minus Windfall			55 002.3	5.73	2.20	0.38	16.5
	Athabasca	Windfall minus Hinton			9835.2	2.04	0.71	0.35	5.9
	Athabasca	Hinton minus Jasper			5892.1	2.68	0.40	0.15	8.0
	Combined	All small tributaries			17 300.9	4.57	0.70	0.15	13.5
	Total	Lake Athabasca inflow			271 000	34.06	5.17	0.15	100.0
07MC003	Lake level (m)	Crackingstone Point	59.4	108.9	271 000	208.78	0.38	0.00	–

Table 2. Total discharge variability in the different tributaries across the Lake Athabasca Basin and detected trends for four different, common analysis periods, 13, 34, 41 and 51 yr in duration with associated discharge changes in comparison to the long-term average. Note that bold values denote significant trends (p-value ≤ 0.1) and that Lake Athabasca level trends and change are in units of m yr^{-1} and m, respectively.

No.	Station	Period of record	Trend 1 1960–2010 (km^3 yr^{-1})	Trend 2 1970–2010 (km^3 yr^{-1})	Trend 3 1977–2010 (km^3 yr^{-1})	Trend 4 1998–2010 (km^3 yr^{-1})	Change 1960–2010 (km^3)	Change 1960–2010 (%)
1	Below McMurray	1957–2010	**−0.145**	**−0.229**	**−0.216**	0.005	−7.38	−37.9
2	Athabasca	1913–2010	**−0.070**	**−0.124**	**−0.138**	−0.165	−3.55	−26.9
3	Windfall	1960–2010	**−0.033**	**−0.033**	**−0.039**	−0.063	−1.67	−22.6
4	Hinton	1961–2010	**−0.011**	−0.004	−0.005	−0.037	−0.57	−10.6
5	Jasper	1970–2010	**−0.005**	−0.004	−0.004	−0.022	−0.27	−10.2
6	Fond Du Lac (Lake)	1946–2010	−0.002	0.021	−0.006	−0.084	−0.10	−1.0
7	MacFarlane	1967–2010	−0.002	0.002	0.003	−0.004	−0.10	−6.0
8	Douglas	1975–2010	−0.001	0.000	0.000	−0.003	−0.03	−11.3
9	Grease	1973–1995	0.000	0.003	0.000	−0.011	0.00	0.0
10	Otherside	1976–1995	0.000	0.001	0.001	−0.001	−0.01	−2.6
11	Richardson	1970–2010	0.000	0.000	0.001	**0.007**	0.00	0.0
12	William	1976–1995	−0.001	0.000	0.000	−0.001	−0.05	−7.8
13	McMurray-Athabasca	1957–2010	**−0.056**	**−0.092**	−0.061	**0.222**	−2.85	−45.0
14	Athabasca-Windfall	1960–2010	**−0.040**	**−0.098**	**−0.108**	−0.058	−2.06	−35.9
15	Windfall-Hinton	1961–2010	**−0.022**	**−0.026**	**−0.032**	−0.04	−1.11	−54.2
16	Hinton-Jasper	1970–2010	−0.006	0.000	0.000	−0.012	−0.29	−10.9
17	Combined 7–12	1976–1995	−0.003	0.008	0.005	−0.012	−0.13	−2.8
18	Lake Athabasca inflow	1976–1995	**−0.142**	**−0.188**	**−0.207**	−0.084	−7.22	−21.2
19	Lake Athabasca level	1960–2010	**−0.008**	**−0.006**	−0.009	−0.014	−0.39	−0.2

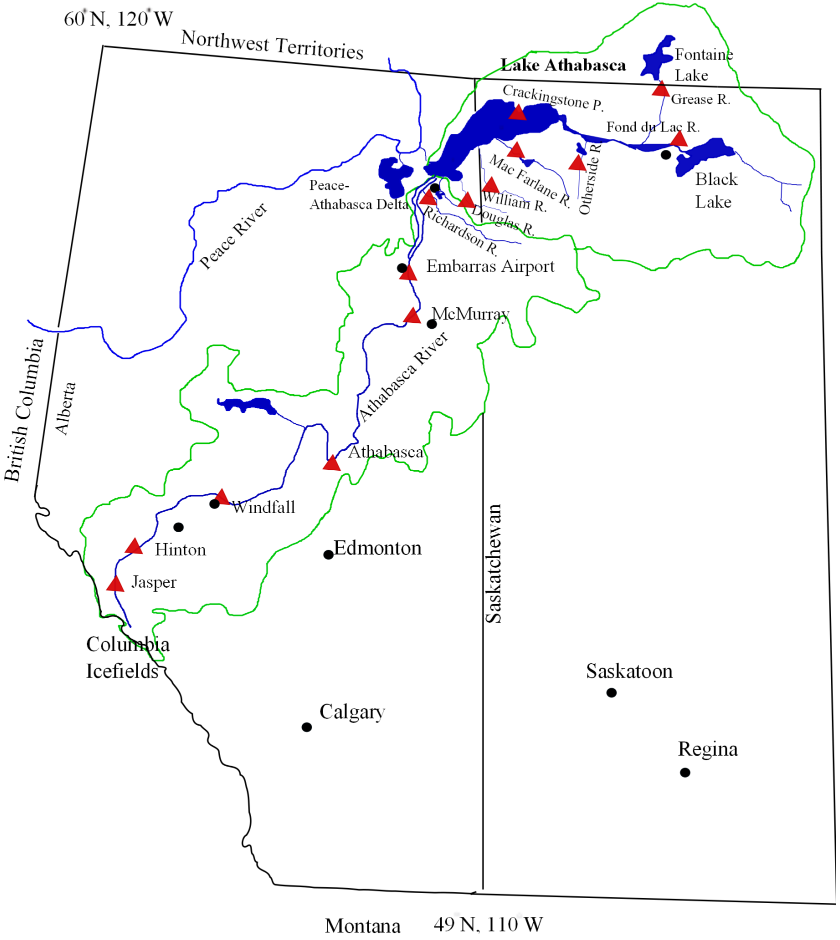

Fig. 1. Map of the Athabasca and Fond du Lac River basins and location of monitoring stations in the Lake Athabasca Basin.

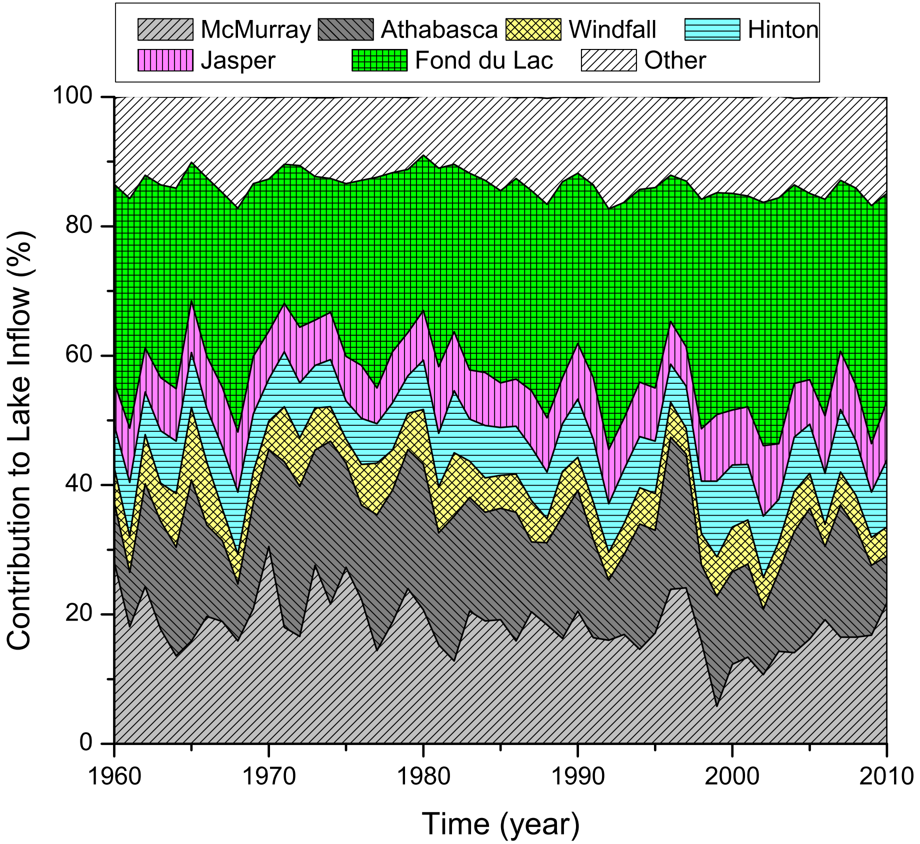

Fig. 2. Percentage of the annual contribution into Lake Athabasca inflow and hydrological regime variability in the Lake Athabasca Basin over 1960–2010. There is a decline along the Athabasca River and a slight increase along the Fond du Lac River and other combined small rivers.

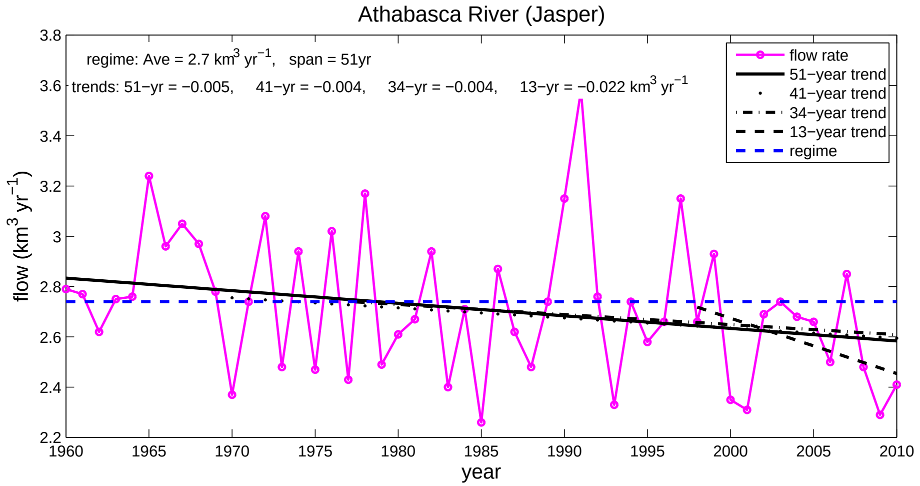

Fig. 3. Trends detected for four different analysis periods, 13, 34, 41 and 51 yr in duration, in the Athabasca River at Jasper.

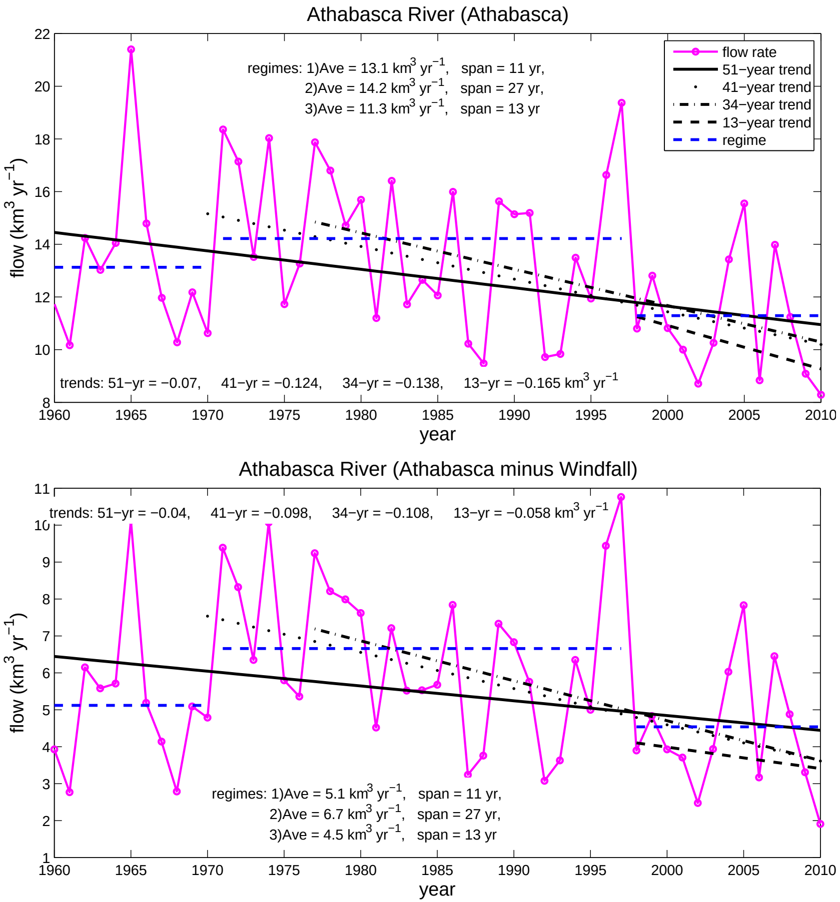

Fig. 4. Regime shifts and detected trends for four different analysis periods in the Athabasca River near Athabasca (upper panel) and contribution of the Athabasca River between Athabasca and Windfall gauges (lower panel).

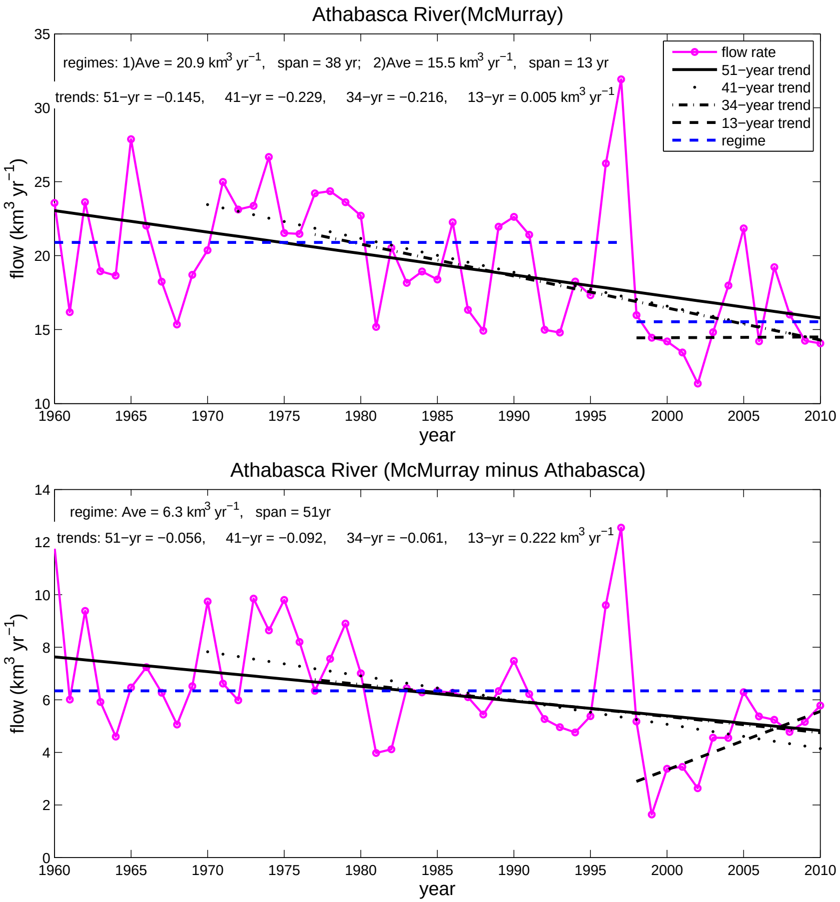

Fig. 5. Regime shifts and the detected trends for four different analysis periods for the Athabasca River at McMurray (upper panel) and the reach of the Athabasca River between the McMurray and Athabasca gauges (lower panel).

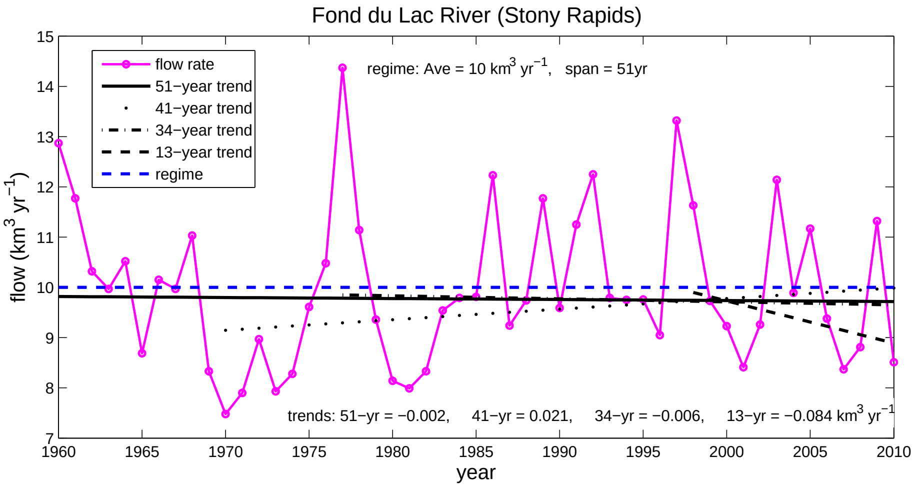

Fig. 6. Detected trends for four different analysis periods in Fond du Lac River.

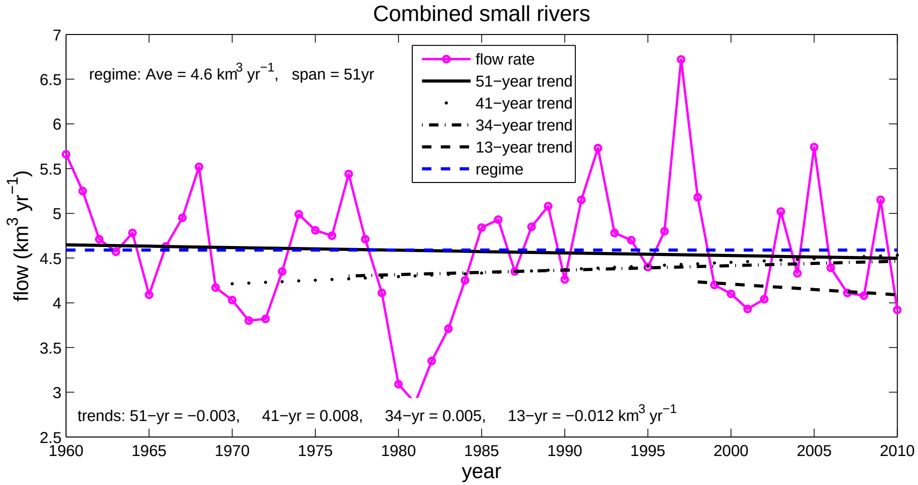

Fig. 7. Input flow rate to the Lake Athabasca from other small rivers and the detected trends for four different analysis periods.

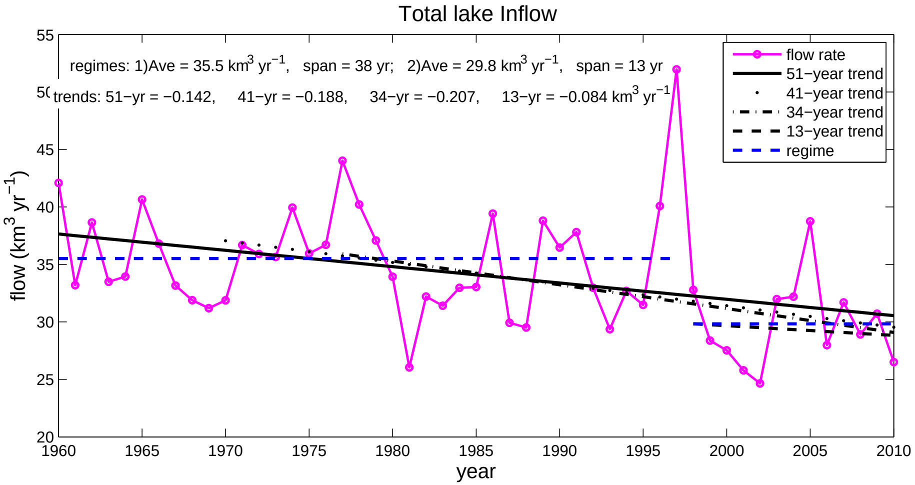

Fig. 8. Input flow rate to the Lake Athabasca and the significant detected trends for four different analysis periods.

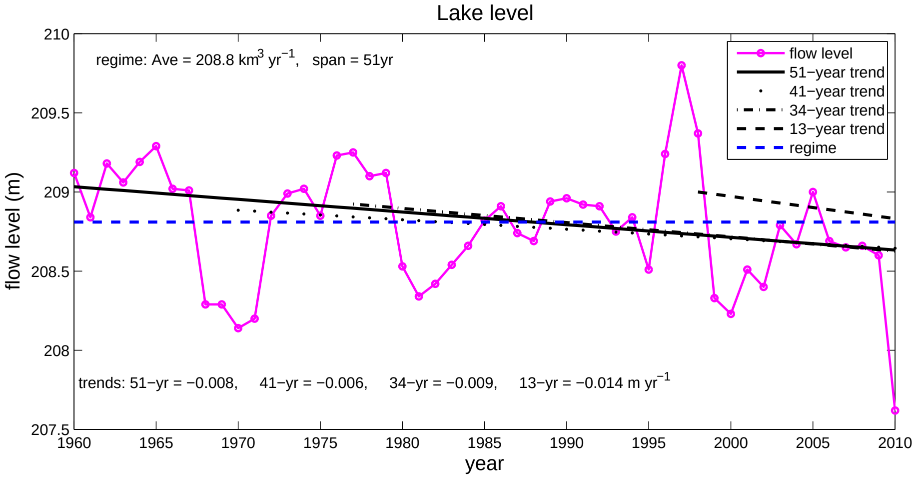

Fig. 9. Level of the Lake Athabasca near Crackingstone Point and the detected trends.