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Influence of forest fires on climate change studies in the central boreal forest of Canada

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Abstract

This brief paper indicates that forest fires may have short and longer term effects on runoff and thus, can influence trend studies on the response of watersheds to climate change. Twenty-two watersheds at the Experimental Lakes Area in northwestern Ontario were studied to view the impacts of climatic variability and forest fires on runoff. A roughly 30 year database demonstrated few trends in climatological variables and even fewer trends in runoff data at the 5% significance level. Daily maximum temperature increased by 0.053 °C per year, while precipitation in the months of February and March showed significant decreases. Total snow showed a significant decrease over a 30 year period at the 8% significance level. The Mann Kendall test for trend was applied to the runoff indices of 19 watersheds and it was revealed that only six exhibited trends. Of these, five had been burned during the test period. Virtually all burned watersheds showed initial increases in runoff, however, long term runoff trended lower in the burned watersheds, while the one watershed that was not burned showed an increasing trend. Forest fires alter the age distribution of trees with subsequent impacts on water yields in the short and longer term.

Keywords: Surface runoff; Forest fires; Climate change; Boreal forest; Evapotranspiration

1. Introduction

The central boreal forest region of Canada resides in the boreal shield east of Winnipeg, Manitoba and west of the Great Lakes, Ontario. It contains a number of *boreal soft-water lakes*, which are home to a variety of freshwater fish species. Maintaining the ecological and biological health of these lakes has become an important mandate for the public, and of primary importance to various governing agencies. Our ability to preserve fish habitat requires an understanding of the response of these lakes and the surrounding watersheds to natural (such as forest fires) and unnatural (anthropogenically induced climate change) disturbances. How these disturbances affect runoff is important as runoff transports nutrients and sediments (Beaty, 1994; Bayley et al., 1992) to the streams and lakes, thus affecting fish habitat.

Forest fire impacts on runoff in the Canadian central boreal forest has not been researched

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extensively in the past. When vegetation is destroyed by a forest fire, changes can occur to the runoff generation and erosion processes within the watershed. These changes are generally attributed to reduced transpiration and interception related losses, decreases in infiltration, and if applicable, more and earlier snowmelt runoff generation. Studies of other forested regions have shown that runoff and erosion rates after wildfires can increase by as much as two or three orders of magnitude (Benavides-Solorio and MacDonald, 2001).

Studies of the impacts of climate change and forest fires for the Canadian central boreal forest have mostly arisen from work conducted at the Experimental Lakes Area (ELA). The ELA is a research site in northwestern Ontario that was established by the Freshwater Institute of the Department of Fisheries and Oceans of Canada (see Fig. 1). The area encompasses 200 km^2 of the Precambrian shield and contains approximately 1000 boreal lakes.

Originally established to study biological activity leading to eutrophication, 58 small lakes were chosen and set aside by a joint Provincial–Federal government agreement for aquatic research, and an intensive environmental monitoring campaign of these lakes and the surrounding region was initiated (Johnson and Vallentyne, 1971) in 1968. In the last 30 years, research at the ELA has expanded to include ecosystem-scale experimental investigations and long-term monitoring of ecosystem processes including physical, chemical, and biological processes. This has produced numerous studies, reports, thesis and journal papers on a variety of topics including water and chemical budgets, sediment yield, and the impacts of forest fires and possible climate change (Bayley et al., 1992; Beaty, 1994; Newbury and Beaty, 1977, 1980; Schindler et al., 1976, 1990, 1996).

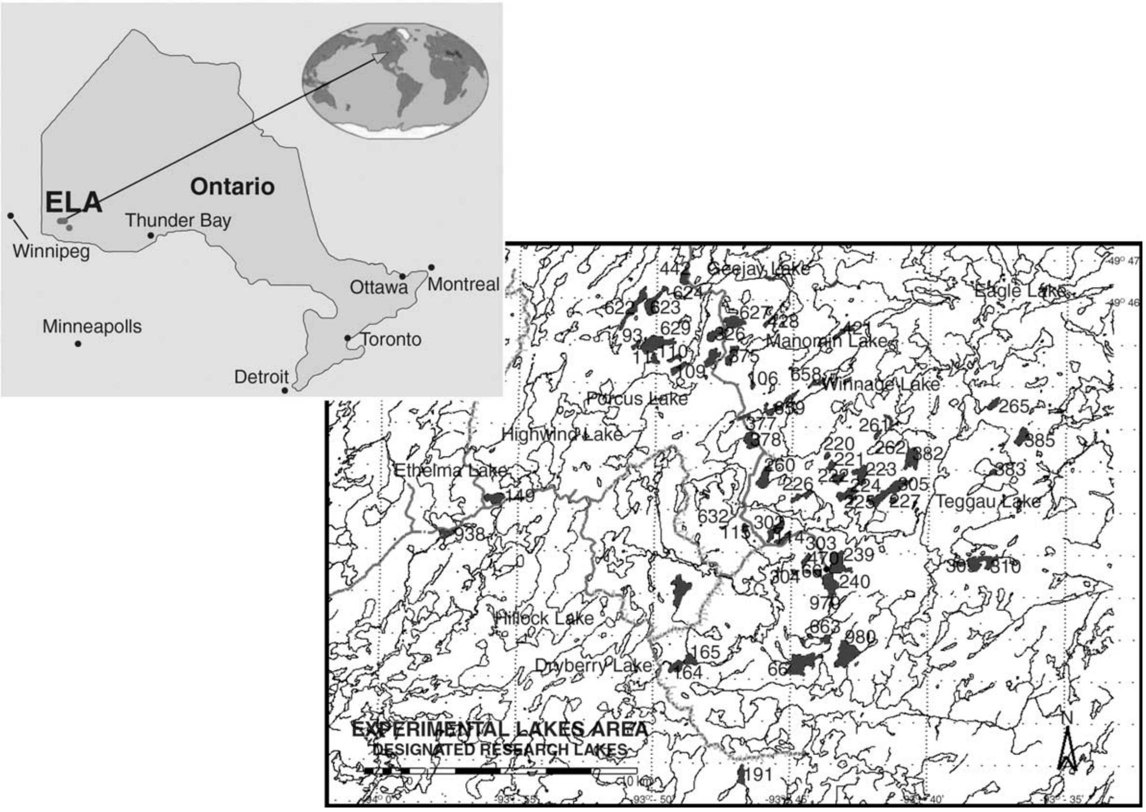

Fig. 1. Map of the experimental lakes area.

The area may be classified as boreal sub-climax forest populated by jack pine, black spruce, trembling aspen and white birch, and can also include bogs, fens and is dominated by sphagnum. This region receives relatively little rainfall but runoff yields are *relatively* high due to low evapotranspiration levels in cool, short summers (Sala et al., 2001). A cold temperate continental climate produces six months of below freezing temperatures and roughly a third of the precipitation falling at the ELA is snowfall. Summer rainfall generally occurs during thunderstorm events which are most frequent between the months of June and August. Long-term hydrological monitoring involves a meteorological station and numerous hydrometric gauges scattered throughout the region.

1.1. Previous climate and fire impact studies at the ELA

Because the boreal lakes in the region are perceived to have a heightened sensitivity to climate change (Schindler et al., 1996), a handful of studies have been conducted to examine the impacts of climate change on yield for this area using the ELA database. Schindler et al. (1990) examined trends in the data from 1969 or 1971 (depending on the type of data) through to 1988. They found that the mean annual air temperature at the ELA site increased by about 2 °C which caused a corresponding increase in the surface temperature of lakes in the area. The incidence of years with precipitation below the long-term average increased, evaporation levels increased, and the volume of runoff from terrestrial basins decreased. The average duration of the ice-free season increased by about 20 days and is believed to be due to increasing air temperatures in the spring.

Schindler et al. (1996) added two more years to their analysis to conduct the same study on data from 1970 to 1990. The increase in mean annual air temperature during this period was similar to the 1990 study but quoted as 1.6 °C over the 21 year study period with a linear trend of 0.08 °C/yr. Precipitation was observed again to decrease at a rate of 10.5 mm/yr and annual evaporation increased at a rate of 8.8 mm/yr. These trends were deduced from simple straight line fits to the data. The average ice free season was shown to increase by about 15 days, again believed to be due to higher than average spring temperatures causing an early ice off date.

Schindler et al. (1996) also stated that runoff represented 40–50% of precipitation in the early 1970s but declined to 15–30% by the late 1980s, turning perennial streams into ephemeral streams. Burned watersheds seemed to show higher yields then unburned ones, but the effect of fires was considered small in comparison to the long term declines of stream-flow.

When the ELA was first established, the area was covered in mature forest, and no forest fires had occurred within recent memory. In June of 1974, a forest fire burned over 50% of the watershed draining into Rawson Lake (Lake 239). Another, more extensive forest fire burned virtually 100% of the watershed, in June of 1980 (Beaty and Lyng, 1989). Some areas that burned in both of the fires had complete removal of vegetation, particularly those at higher elevations.

Recovery rates for runoff vary between watersheds and depend on vegetation and soil type. It should be noted that the region consists of Pleistocene deposits overlaying granitic Precambrian bedrock with an overburden of generally less than 1 m in depth. However, in valley bottoms and low lying areas, Pleistocene deposits can range from 2 to 15 m deep. Typical profiles contain surface materials of sandy loams, underlain by clay. Beaty (1994) estimated a regeneration period of approximately five years for this area. Bayley et al. (1992) did report that areas affected by the 1974 fire in the Rawson Lake watershed re-vegetated rapidly with small jackpine, black spruce, poplar birch, balsam poplar and shrub vegetation. On the whole, vegetation became very dense after only three years. After the 1980 fire, boggy areas of the Rawson Lake watershed that were burned for a second time did regenerate quite rapidly while other areas regenerated very slowly with little or no plant cover after 2 years. Species present in the regenerating vegetation in areas burned for a second time in the 1980 fire included black spruce and surface sphagnum.

Bayley et al. (1992) examined water yield from three terrestrial dominated catchments in the area that were affected by both fires in 1974 and 1980. Their results did not conclusively show that the fires increased water yield due to what they believed to be confounding effects of lower precipitation and higher evapotranspiration. They did compare water yields and results seemed to show that yield after the fires actually decreased. Blais et al. (1998) claim that climatic change seems to have had a greater effect on erosion and sediment accumulation than logging or fire at the ELA. They state this because the observed decline in sedimentation rates of lake core samples seemed unrelated to land use history and was attributed instead to overall decline in runoff since 1980.

1.2. Research objectives

As noted earlier, Bayley et al. (1992) were unable to conclusively show the effects of forest fires on yield and attributed this to the confounding effects of other climatological parameters. Climate change would be expected to reduce runoff in the long term but forest fires are expected to increase runoff (at least in the short-term). The observations made in the studies of fire and climate change impacts prompts several questions regarding the impact of these phenomena when acting separately and concurrently. Specifically,

1. Are the trends in climatological and hydrometric data that were identified in previous studies continuing unabated to this day; and have any new trends developed?
2. Are there statistically discernable short and long term impacts of forest fires when climate change is occurring?

   In addition, some of the hydrometric gauges drain watersheds in which a large percentage of the drainage area is a waterbody. The waterbody may mitigate or magnify the effects of forest fires or climatic change, and hence, brings about a third question:
3. Are lake dominated watersheds more sensitive to the impacts of forest fires and climate change then those watersheds that do not drain large bodies of water?

The purpose of this paper is to answer these questions by conducting a series of appropriate statistical tests using the most up-to-date database. It should be noted that the ELA database is now 34 years old and this research will provide the most recent trend study for the purposes of inferring the implications of climatic change. In reality, the length of the database is too short for a conclusive climate change analysis but the sensitivity of this unique region to climatic fluctuations is considered high; hence the interest in continuously updating this analysis as new data is generated.

2. Methodology

To answer the questions brought forth in Section 1.2, statistical tests for trend are required for application to the hydrometric and climatological data. In addition, homogeneity tests are helpful in determining the impacts of forest fires. The data to be tested include annual total precipitation volumes (TP), annual snow volumes (S), annual rain volumes (R), annual average temperature (T), annual average maximum temperature (T_X), annual average minimum temperature (T_N), Ice-On date, Ice-Off date, the duration of ice on Rawson Lake (also known as Lake 239 and will henceforth be abbreviated as 239), and pan evaporation levels (E). All climatological data sets start in 1970 and end in 1999. In addition, monthly values of all parameters (except for those related to ice) will also be tested to help infer seasonal trends.

Flow data are available for a number of watersheds in the study area. The watersheds used were selected based on the number of years of recorded stream-flow data. Table 1 details characteristics of the watersheds used in this work including information on drainage area and the number of years of record. A seasonal runoff index was prepared for each catchment in which water runoff volumes during the ice free season were normalized with respect to the precipitation that fell in that period and the area of the catchment. Therefore, the runoff index is defined as Runoff index = (Volume of runoff/Catchment area)/(Precipitation). As flow data in frozen areas were often estimated or missing, a seasonal runoff index was computed from May 1 to October 31, which roughly coincides with the snow free period in the region. An annual runoff index was also computed such that the volume of runoff was only summed from May 1 to October 31, but the precipitation was summed from the previous November 1 to October 31. This would

Table 1
Discharge data sets used in analysis

Watershed*	Drainage area (ha)	Terrestrial drainage (excluding lake surface and tributary watersheds) (ha)	Fire year (% burned)	Data period (series length)
114NE	5.73	5.73		84–97(14)
114	57.7	45.6		72–94(23)
223	259.96	135.21		75–97(23)
224	97.48	41.09		75–97(23)
225	30.47	26.48		75–92(18)
226	97.17	81.08	79(34%)	72–94(23)
227	34.4	29.4		70–97(28)
230	8.89	7.22	74(100%)	71–80(10)
239	170.28	170.28	74(100%), 80(100%)	71–97(27)
239NE	10.58	10.58	74(100%), 80(100%)	71–97(27)
239NW	56.38	56.38	74(71%), 80(100%)	70–97(28)
239	391.49	337.21	74(71%), 80(100%)	70–97(28)
240	721.18	117.12	74(37%), 80(100%)	69–97(28)
261	47.58	42.01		71–78(8)
265	71	57.9	78	71–78(8)
302UT	7.2	7.2		86–97(12)
302	102.51	78.81		81–97(17)
303	54.14	44.67	80(100%)	70–97(28)
373	83	55		90–97(8)
382	205	167.9	78(8%)	87–97(11)
470	167.71	36.59	80(100%)	69–97(28)
661	125	43.59	80(100%)	83–97(14)

*NE: northeast sub-basin; NW: northwest sub-basin; E: east sub-basin; UT: upslope sub-basin. If no letters exist beside the lake number, then this signifies the entire watershed and all its sub-basins.

take into account the snowpack that would have accumulated over the winter. It should also be noted that a severe windstorm affected the area in 1973 causing a major blow-down of many trees in the region. Therefore, 1973 will be excluded in all homogeneity tests.

2.1. Statistical tests

Randomness in a data set is a fundamental assumption in frequency and statistical analysis that is often taken for granted. Also, normalcy in the data is often erroneously assumed prompting the use of inappropriate tests. The Runs Test will be used to test for randomness in annual precipitation volumes, average annual temperature, and flow volumes for all the watersheds.

Initial attempts were made to fit a variety of distributions to some of the data. Annual precipitation volumes, mean annual temperature, annual flow volumes and peak flows for the Lake 240 watershed (all watersheds will now be addressed by number only), and the annual runoff/precipitation index for 240 were fitted with five distributions, namely the Normal, Log-Normal, Gumbel, Log Pearson Type III and the Generalized Extreme Value distributions. The Kolmogorov–Smirnov goodness of fit test indicated that only one of the data sets was best represented by the normal distribution. Therefore, only nonparametric statistical tests are chosen to test the data for the impacts of forest fires and climatic trends.

The test selected to detect significant trends in the data is the Mann Kendall non-parametric test (Mann, 1945; Kendall, 1975). It has been shown to be an effective tool for identifying trends in hydrologic variables (Burn, 1994). The Mann Kendall test is illustrated in Appendix A. It provides a z value when a data series has 11 or more data points. The method of Hirsch et al. (1982), also shown in Appendix A, is used to obtain a robust estimate of the slope β of the trend. Note that a negative value of z indicates a decreasing trend and hence produces a negative value of β.

To determine the impacts of forest fires, a homogeneity test will be applied to the seasonal runoff indices of a *Fire-Affected* group of watersheds, and a *Basis of Comparison* (BOC) group. The Fire-Affected group are watersheds that were all completely burned in the same fire and the BOC group of watersheds were unaffected by the fire. In addition, groups would be formed on whether or not they lie within the regeneration period, or outside of the fire regeneration periods. The post-fire regeneration period was decided as 5 years. The Mann Whitney U (Mann and Whitney, 1947) non-parametric test for homogeneity is selected as the most suitable test and is shown in Appendix A.

To address the third question of Section 1.2, an additional study is undertaken where terrestrially dominated watersheds are distinguished from lake dominated watersheds, with the latter being characterized as draining a large body of water consisting of more than 10% of the total drainage area. The Mann Whitney U homogeneity test will be applied to a Fire-Affected group that drains large bodies of water (*Lake Dominated Watersheds*) and a Fire-Affected group that does not drain large bodies of water (*Terrestrial Watersheds*).

3. Results

3.1. Data suitability and trend tests

The Runs Test demonstrated that all annual data that was tested were random at the 5% significance level. The trend tests were then applied to the data mentioned in Section 2.0 and the results for annual climatological data are shown in Table 2. Table 2 also shows tests on monthly data that were significant at the 10% significance level in a two-tailed test. Trends in the seasonal runoff index that were significant at the 10% level are shown in Table 3 along with the approximate P-values, and the results for the corresponding annual index. The table also indicates whether or not the watershed experienced a forest fire. Figs. 2–4 show some of the climatological data that exhibited trends.

Table 2
Annual and monthly trend results in climatological data

Data set	z	β	P-value
Total precipitation (TP)	−0.321	−0.9	0.74
Snow (S)	−1.713	−1.875	0.08
Rain (R)	0.642	1.533	0.52
Average daily temperature (T)	1.891	0.045	0.06
Daily maximum temperature (T_X)	2.034	0.053	0.04
Daily minimum temperature (T_N)	1.641	0.04	0.1
Annual total pan evaporation values (PE)	1.445	3.064	0.14
Number of ice-free days for lake 239	1.428	0.366	0.16
Ice-on date for lake 239	0.763	0.059	0.44
Ice-off date for lake 239	−1.623	−0.31	0.1
January T_X	1.855	0.151	0.06
February T_X	1.641	0.126	0.1
February TP	−2.783	−0.941	0.006
February S	−2.658	−0.895	0.008
March R	−1.98	−0.608	0.04
September T_X	1.659	0.071	0.1
September PE	1.748	0.686	0.06

In the trend analysis of the annual and seasonal runoff index, the occurrences of forest fires, wind storms and the sizes of internal water bodies were ignored. Note from Table 3 that the z values do not change very much between the seasonal index and the annual index (with the annual index statistic generally being slightly smaller).

3.2. Impact of forest fires

Table 4 shows the homogeneity tests that were conducted on watersheds that were burned in the 1980 fire and Fig. 5 shows the data used. The impact of the 1974 fire was not studied as the fire occurred too soon after the database began and therefore, there was not enough data for a statistical test. Table 5 lists the results of these tests and Table 4 shows the average runoff index for the group.

Of the 22 watersheds, 16 contain water bodies (specifically lakes) that are 10% or more of the total drainage area. These watersheds are termed *Lake Watersheds* in order to distinguish them from Terrestrial Watersheds that do not drain relatively large water bodies. Both types of watersheds were affected by the 1980 fire. The groups are listed in Table 6 and the homogeneity test results are shown in Table 7. The 240 watershed was originally included

Table 3
Significant trends in watershed seasonal and annual runoff index

Watershed	z	β	P-value	Burned?
239	−1.751, −1.835	−0.0085, −0.0035	0.08, 0.07	Y
239	−1.679, −1.442	−0.0059, −0.0023	0.10, 0.15	Y
240	−2.153, −1.640	−0.0088, −0.0027	0.04, 0.10	Y
302UT	1.713, 1.713	0.0153, 0.0231	0.08, 0.08	N
470	−2.035, −1.600	−0.0077, −0.0050	0.04, 0.11	Y
303	2.001, −2.085	−0.0096, −0.0069	0.04, 0.04	Y

Statistic for seasonal index value is shown first, followed by the statistic value for the annual index.

in the analysis as part of groups II and IV but as Lake 239 and 470 drain into Lake 240, it was felt that those values may bias the results and therefore, 240 is excluded in this second homogeneity test.

4. Discussion

4.1. Trend tests as an indication of climate change

Table 2 and Fig. 2 show that there were significant trends in snow volumes which dramatically decreased over the 30 year period at roughly a rate of 1.9 mm/yr. There was no significant trend in total precipitation or total rainfall. Daily average temperature however did see an increasing trend at the 6% significance level. An increasing trend of $\beta = 0.045$ °C/yr was observed which is in contrast to earlier reports of 0.08 °C/yr. If a linear trendline were applied as done in the case of Schindler et al. (1996), then the average temperature would be increasing at a rate of 0.048 °C/yr which is very close to the value of β mentioned above. The most significant increase in temperature data was in daily maximum temperature, which increased at a rate of 0.053 °C/yr at the 5% significance level. Total pan evaporation values also increased by approximately 3 mm/yr at the 14% significance level, no doubt in response to increasing temperature. The number of ice

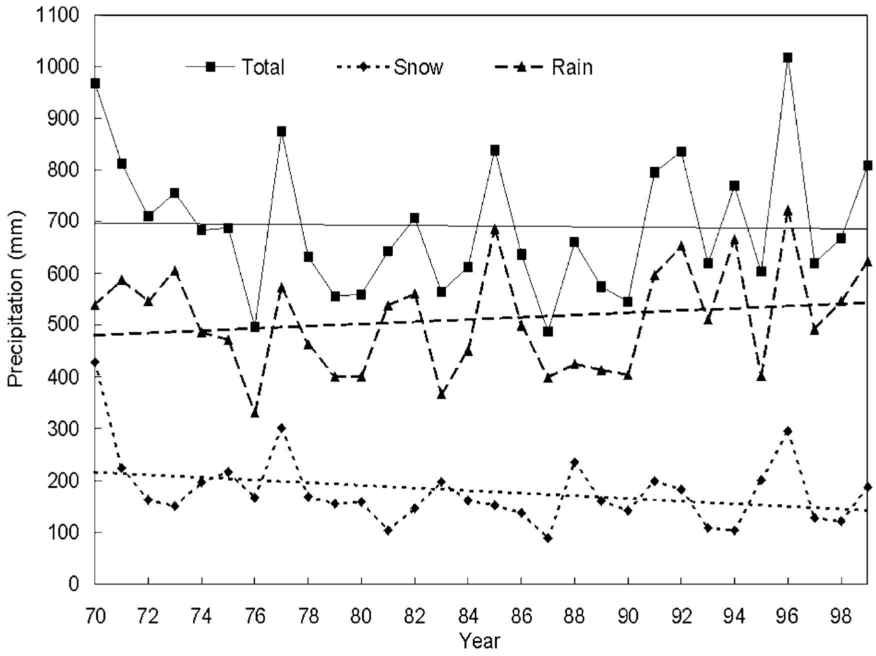

Fig. 2. Trends in precipitation data.

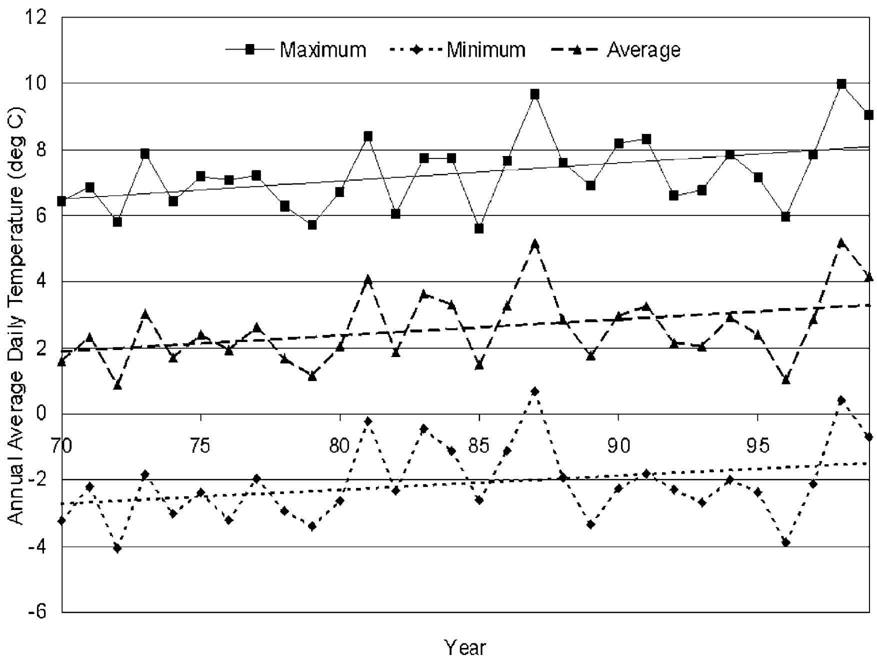

Fig. 3. Trends in temperature data.

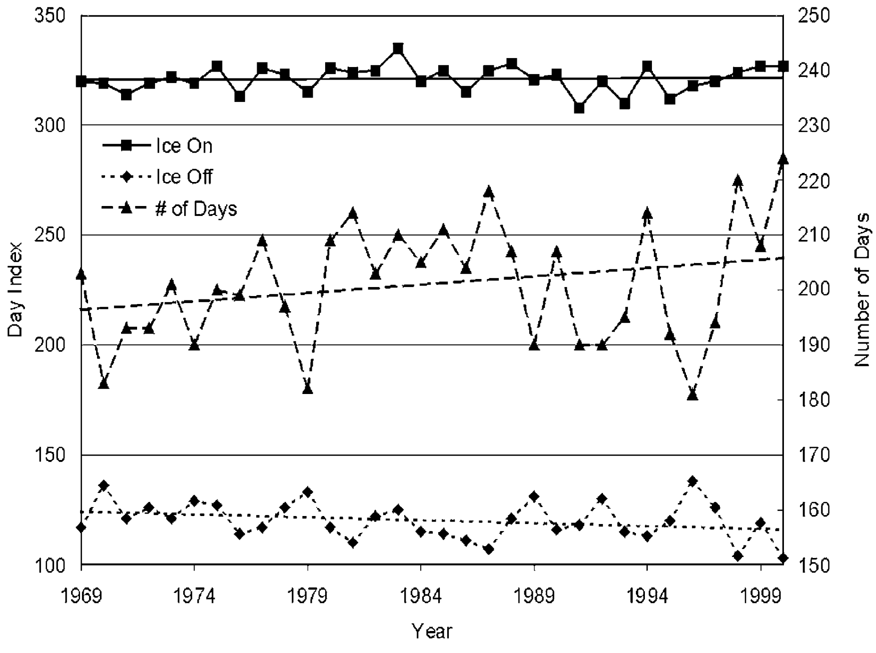

Fig. 4. Trends in ice formation and depletion data.

Table 4
Watersheds used in 1980 fire impact test

	Pre-fire window			1980 Fire window			Post-fire window		
BOC	I	227	70–79	III	225	81–86	V	382	87–97
		265	72–77		223	81–86		223	87–97
		225	78, 79		302	81–86		302	87–97
		261	71–72		224	81–86		224	87–97
		114	71–72		227	83, 84		227	87–97
	Average = 0.31			Average = 0.19			Average = 0.23		
Affected	II	470	70–79	IV	239W	81–86	VI	470	87–97
		303	72–79		240	81–86		303	87–97
		240	71–72		303	81–86		240	87–97
		239	71–72		470	81–86		239	87–97
					661	83, 84		661	87–97
	Average = 0.35			Average = 0.29			Average = 0.22		

free days increased at a rate of 0.37 day/yr which implies an effective increase of 11 days as opposed to 20 in the entire period. Again the ice-on date did not change appreciably but the increase in the number of ice free days was caused by an earlier ice-off date. The increase in temperature as shown from the monthly trend results (only those that were significant were shown) is due predominately to higher spring temperatures. There is a significant increase in maximum September temperatures but this did not impact the ice on date. The higher September temperatures likely contribute to the significant increase in pan evaporation levels in that month. February also showed a very significant decrease in snow and this huge decrease contributed to the significant overall decrease in snow over the year and for the general decrease in total precipitation (although it was not considered significant). It also

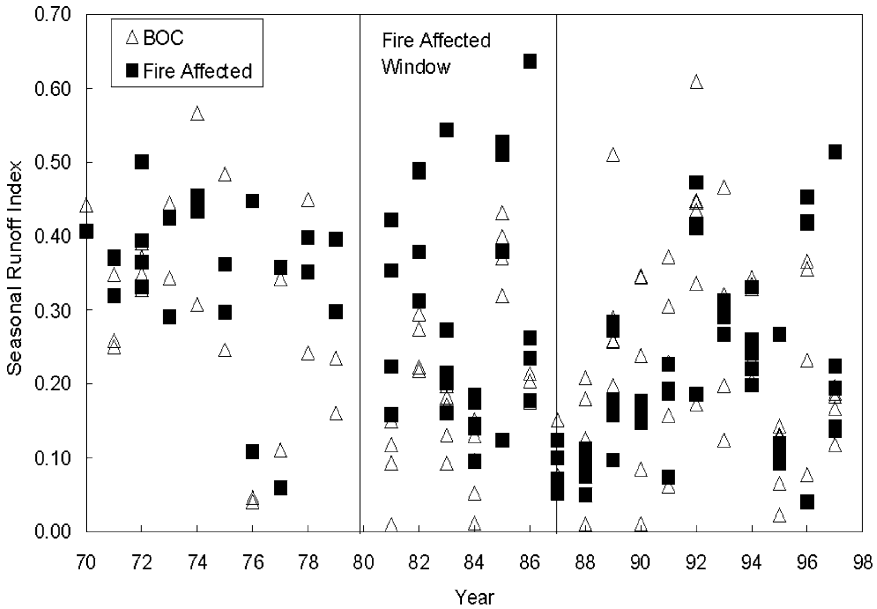

Fig. 5. Data used in 1980 fire homogeneity test.

Table 5
Homogeneity test results for 1980 fire

Test	z_U	P-value
I vs. II ($m = n = 22$)	1.48	0.14
III vs. IV ($m = n = 26$)	2.75	0.06
V vs. VI ($m = n = 55$)	−0.4	0.68

probably led to an earlier ice off date. March however showed a significant decrease in rain and therefore, producing an overall drop in precipitation during the spring period. Lower albedos due to a decrease in snowpack in the spring may have also contributed to an earlier ice off date.

With regard to the seasonal runoff index, only those watersheds (of the 18 that were analysed) that exhibited trends at the 10% significance level in two-tailed tests (and only those data series that were 11 data points or longer were tested) are shown in Table 3. The table shows that of the watersheds that exhibited significant trends, were burned by more than 50% (excluding 661 as its burn did not occur in its monitoring period) during the respective monitoring period, and had 11 or more data points, five showed decreasing trends. The other watershed to show a significant trend (302UT), which was not burnt in the period, was the only one to exhibit a significantly increasing water yield. Of the 12 watersheds that did not show *significant* trends, six had slightly decreasing trends (114, 223, 239NE, 239NW, 382, 227) two showed no trend (224, 225), and four showed positive trends (114NE, 226, 302, 661). Of the seven slightly decreasing trends, watersheds 239NE, and 239NW were completely burned during the monitoring period,

Table 6
Terrestrial vs. lake dominated watersheds in fire impact test

	Non-fire window			Fire window		
Terra	I	239	72, 86–96	III	239	81–85
		239NE	72, 86–96		239NE	81–85
		239NW	72, 86–96		239NW	81–85
	Average = 0.26			Average = 0.30		
Lake	II	239	72, 86–96	IV	239	81–85
		303	72, 86–96		303	81–85
		470	72, 86–96		470	81–85
	Average = 0.23			Average = 0.29		

Table 7
Homogeneity test results for Table 6 tests

Test	z_U	P-value
I vs. II ($m = n = 36$)	1.16	0.25
III vs. IV ($m = n = 15$)	−0.27	0.79
I vs. III ($m = 36, n = 15$)	0.89	0.37
II vs. IV ($m = 36, n = 15$)	1.3	0.19

and watersheds 265 and 382 were slightly burned. Watershed 114NE, which is a sub-basin of watershed 114 was subjected to a logging experiment in 1974, and parts of 114 and all of 114NE were scarified in July of 1979. Both of these practices completely cleared the area. Of the positive trends, watershed 661 was completely burned but the data series used in the test began 3 years after the fire.

All of the watersheds have a sizeable body of water draining to the outlet with the exception of 114NE, 239E, 239NE, 239NW, and 302UT. Watersheds 302UT and 114NE were not burned during their monitoring periods and showed positive trends, while watersheds 239E, 239NE and 239NW were burned and showed negative trends.

What the data seem to be indicating is that forest fires contribute to long term decreasing trends in runoff. Forest fires are assumed to increase yield in at least the short term, but the evidence seems to demonstrate that while the forest regenerates relatively quickly in the short term, the losses due to young stands are greater than in mature stands. Wildfires will consume forest canopies and ground litter leading to a decrease in canopy interception, decreases in evapotranspiration and thus an increase in net precipitation, base-flow and surface runoff velocities (Moody and Martin, 2001). Water repellent soils can develop as a result of a fire as volatised organic matter condenses as a hydrophobic coating on soil particles, thus resulting in reduced infiltration (Letey, 2001; Debano et al., 1998). Consequences to runoff have been studied extensively in a variety of forested watersheds (Pierson et al., 2001) but runoff recovery to pre-fire levels is generally expected to be within five years (Wright and Bailey, 1982).

The effects of competing vegetation on regrowth is difficult to estimate. Conrad et al. (1997) noted that shrubs and vegetation sprouting immediately after a fire can reduce the amount of soil moisture available for regenerating conifers. They also note that transpiration and water use is affected by several independent factors that co-vary. Conrad et al.'s (1997) study also noted that certain species of competing shrubs had high leaf area index values, leading to high transpiration rates that were equal to or higher than 15–20 years old closed canopy stands. In addition, lower albedos as a result of burned vegetation can increase ground heating and high soil heat fluxes, thus contributing to higher evapotranspiration levels. Cornish and Vertessy (2001) note that changes in evapotranspiration levels have been reported as forests age. They noted that initial increases were observed in water yield for a variety of catchments with varying tree species in the event of logging but this was followed by declines in water yield as regeneration was established. Reductions in water yield due to regenerating forests have been observed and predicted in a handful of studies including Kuczera (1987), Bren and Papworth (1991) and Legesse et al. (2003). Thus, characteristics of any stream-flow changes related to forest water use should be evaluated and thus, should be considered as it may affect aquatic habitat (Cornish and Vertessy, 2001).

Wood production is limited by the length of the growing season (as well as moisture and mineral supplies) where a longer and warmer growing season may enhance forest production. While the boreal region is relatively dry, moisture is not limiting due to the short summers but any increases in moisture stress could be detrimental (Van Kooten and Arthur, 1989). The expected increase in fire frequency and intensity and the possible increase in moisture stress may offset any expected increases in growth resulting from climate warming (Van Kooten and Arthur, 1988). Van Kooten and Arthur (1988) showed that climate warming should favour biomass production as climatic warming accelerates the cycling of nitrogen, phosphorus and other nutrients. CO_2 induced climate change should result in a greater incidence of supra-optimal temperatures for photosynthesis related gain of wood production (20 °C). Sala et al. (2001) showed that losses to transpiration increases as succession proceeded after a fire with one coniferous species recruiting into another species stand.

While the database is too short to show that climatic variables are non-stationary, a drier climate may lead to more forest fires. Forest fire increases can lead to decreases in vegetation maturity (Matheussen et al., 2000), thus leading to greater increases in water use by regenerating vegetation, and thus overall decreasing trends.

4.2. Homogeneity tests as an indication of fire impacts

The homogeneity test results shown in Table 5 for the watersheds shown in Table 4 indicate that when comparing the BOC group to the Fire-Affected group in the pre-fire period, there is no significant difference in the runoff index, although, the fire-affected group showed slightly higher runoff (about 13% relative to the BOC group). This difference changed in the fire window, with the Fire-Affected group being much higher than the BOC group at the 6% significance level, attesting to the well believed notion that fire will increase yield (it increased by about 53%). In the post-fire window however, the BOC group was slightly higher than the fire group (4%). This is in contrast to the observation that the BOC group was lower than the Fire-Affected group prior to the fire. Although the difference was not significant, it possibly indicates that the regeneration of vegetation is leading to higher increases of water consumption.

When watersheds were further subdivided into Terrestrial and Lake watersheds, Table 6 results indicated that in fact there is no significant difference in runoff between the Terrestrial group and the Lake group outside of the fire window (I vs. II) or within the fire window (III vs. IV). The Terrestrial group had a higher average yield than the Lake group outside of the fire window (I vs. II: 12% relative to the Terrestrial group), but was only marginally higher in the window (III vs. IV: 3% relative to the Terrestrial group). When comparing the differences between Terrestrial groups inside and outside of the window, average yield was higher by 15% in the fire window (I vs. III). Average yield in the fire window for the Lake group was higher by 26% (II vs. IV). Table 7 indicates that there are no significant differences in flow series between any of the periods tested. The homogeneity tests of Table 6 seem to indicate that there may not be a lake-induced effect but the inclusion of 239 in the Lake Group may also cause bias in the results as it includes flows from 239E, 239NW and 239NE.

However, with such a small data set, 239 was left in the analysis and 240 excluded.

5. Conclusions

This paper attempted to answer three questions arising from previous climate trend studies in a sensitive area of the central boreal forest of Canada. New data are continuously being collected and questions arose as to whether trends previously observed were continuing unabated; whether forest fires were impacting these trends; and whether watersheds that drain significantly large bodies of water could be affecting the results. Many annual and monthly climatological variables over a 30 year period were tested for trends but only snow volumes, ice off dates, and temperatures showed significant trends. Snow volumes decreased dramatically at a rate of 1.9 mm/yr at the 8% significance level. There was however, no significant trend in total precipitation or total rainfall. Daily average temperature increased by 0.045 °C/yr at the 6% significance level with the most significant increase occurring in daily maximum temperature, which increased at a rate of 0.053 °C/yr at the 5% significance level. There was a significant increase of 11 ice-free days due primarily to an earlier ice off date. Trends observed in this paper are not as strong as those observed in previous studies, and several climatological parameters are returning to earlier values.

Of the 18 watersheds that were tested for trend, few showed significant trends and those that had been burned during the study period. Watersheds that were burned seem to cause a decreasing trend in runoff as opposed to those that were not burned and this may be due to overall increases in evapotranspiration from emerging vegetation. This study shows that flow trends seem to be exacerbated by forest fires and that while increases in yield exist, the replacement of old forests by new young forests after a fire impacts the yield more significantly than climate change alone. A lack of data hindered a conclusive answer to the third question regarding lake dominated watersheds. When conducting trend tests on watersheds as a function of climate change, one must consider the impacts of land cover changes due to forest fires as a possible cause of decreasing flow trends.

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Appendix A

Mann Kendall Test for Trend (as described in Boulet, 1988)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{A1}$$

where the x_j are the sequential data values and n is the length of the data set.

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{A2}$$

The theoretical mean and variance of the test statistic, under the null hypothesis of no trend in the series, are given as

$$E[S] = 0 \tag{A3}$$

$$\operatorname{Var}[S] = \frac{n(n-1)(2n+5) - \sum t(t-1)(2t+5)}{18} \tag{A4}$$

where t is the extent of any tie (i.e. the number of data points involved in a tie) and the summation is over all ties. For sample sizes larger than ten, the statistic is very nearly normally distributed if a continuity correction is applied, giving

$$S' = S - \operatorname{sgn}(S) \tag{A5}$$

where S' is the corrected test statistic value. Assuming the corrected test statistic follows the normal distribution, a z value associated with the trend statistic can be calculated as

$$z = \frac{S'}{(\mathrm{Var}[S])^{1/2}} \tag{A6}$$

where z is a standard normal value.

A non-parametric estimate for the magnitude of the slope following Hirsch et al. (1982) is:

$$\beta = \mathrm{Median}\left(\frac{x_j - x_k}{j - k}\right) \forall k < j \tag{A7}$$

where β is a robust estimate of the slope.

Mann Whitney U Test for Homogeneity (as shown in Devore, 1982)

Combine samples and rank them in ascending order. The sum of ranks of group 1 is R_1 while the sum of ranks for group 2 is referred to as R_2. The size of group 1 is m and the size of group 2 is n. The null hypothesis under this test is:

H_o: the two groups have identical distributions.
H_1: the two groups have different distribution.

The test statistic is

$$U = mn + \frac{m(m+1)}{2} - R_1$$

If the null hypothesis is true, then the distribution of U has a mean μ_U and μ_U is given as

$$\mu_U = \frac{mn}{2}$$

$$\sigma_U = \sqrt{\frac{mn(m+n+1)}{12}}$$

If both m and n are greater than 8, then the distribution U is approximately normal, and a z scale test statistic of the following form can be used.

$$z = \frac{U - \frac{mn}{2}}{\sqrt{\frac{mn(m+n+1)}{12}}}$$

We reject the null hypothesis at the α significance level if the computed value is less than $-z\alpha_{/2}$ or greater than $-z\alpha_{/2}$.

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