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The Virginia Hills Fire of 1998 and the opportunity to evaluate the impact of fire on water quality in upland stands on the Boreal Plain

The Virginia Hills Fire: A once-in-a-lifetime opportunity to evaluate the impact of natural versus forestry-related disturbance on water quality, contaminants and biodiversity in surface waters on the Boreal Plain.

by

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ABSTRACT

Prior to 1998, there were no sites on the Boreal Plain where effects of forest fire and forestry practices on surface waters could be evaluated for watersheds with comparable vegetation. The 1998 Virginia Hills fire offered an unprecedented opportunity to evaluate the impact of fire on abiotic and biotic water quality parameters. Two streams, one with > 90% of its watershed burnt in 1998 and another outside the fire's range, were intensively studied for water quality in 1983. This pre-burn database, along with a survey that included additional burnt (2) and reference (1) stream watersheds, and a willingness of industrial partners to harvest comparable stream reaches, provided the opportunity to link forest harvesting and natural disturbance effects on surface waters with detailed forest management plans. This project received one year of funding to focus on the effect of fire on surface water quality in five streams up to 16 months following the fire. Total phosphorus export almost doubled after the fire, and this increase was in the particulate fraction. Further, nitrate export more than doubled after the fire. Many water quality parameters including dissolved organic carbon, colour and dominant cations remained similar to non-disturbed conditions in these upland-dominated watersheds. While this forest fire enhanced particulate phosphorus and nitrate export from the watershed, forest harvesting in another site on the Boreal Plain enhanced phosphorus but not nitrate export.

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INTRODUCTION

Warm and dry winter conditions in western Canada in 1997-98 and the predominance of older forest stands led to large-scale spring and summer wildfires in north-central Alberta in 1998. Over 350,000 ha of western boreal forest were burnt by more than 50 discrete fires. The largest fire occurred between May and early June, 1998, in the Virginia Hills north of Whitecourt, Alberta. The Virginia Hills fire accounted for the loss of more than 170,000 ha of upland timber.

Phosphorus is the nutrient considered to control the level of primary production most often in fresh waters (Schindler et al. 1980). Two studies have reported stream export of phosphorus and to a lesser extent nitrogen, from forested watersheds on the Boreal Plain (Munn and Prepas 1986; Cooke and Prepas 1998). The earlier study focused on two streams in the Virginia Hills northwest of the city of Edmonton, while the second focused on two forested and two agricultural watersheds in the Athabasca region due north of Edmonton. Combined, these studies demonstrated that removal of the forest canopy through watershed disturbance can affect hydrological budgets and expose soils to erosion, resulting in the potential for increased export of nutrients to surface waters (Gresswell 1999). In forested watersheds, the relative proportion of dissolved to total phosphorus export averaged 34 and 43%, respectively. In the agricultural streams, dissolved phosphorus export expanded to 82% of total phosphorus. The type of agricultural activity in the watershed influenced inorganic nitrogen speciation. Overall, total phosphorus export was five-fold higher and inorganic nitrogen was 30-fold higher from the agricultural watersheds. Forest harvesting, which affected on average < 20% of watersheds in the TROLS lake program, also on the Boreal Plain, enhanced phosphorus but not nitrogen export (Prepas et al. 2000, in press). In the TROLS lakes, enhanced phosphorus but not nitrogen concentrations paralleled changes in biotic indicators including cyanobacterial biomass and cyanotoxin concentration (Prepas et al. 2000, in press). The TROLS program similarly demonstrated that timber harvesting can influence the export of nutrients for Boreal Plain watersheds, but left many unanswered questions concerning how forest harvest and fire differ in their impact on aquatic systems.

Recent studies of the impact of fire disturbance on aquatic ecosystems have focused on lakes on the Boreal Shield in Quebec (Carignan et al. 2000), or lakes and streams in the Boreal Subarctic region of Alberta (McEachern et al. 2000). The effect of fire on the aquatic ecosystems on the Boreal Plain is poorly understood, particularly among upland watersheds destined for timber harvesting. Carignan et al. (2000) compared the impact of fire versus forest harvesting on water quality, finding significant differences in the chemical and biological signals from the two types of disturbances. Major fires across Canada in 1995 burnt extensive areas of the Boreal Shield and the Boreal Plain. While the fires on the Boreal Shield burnt largely upland regions undergoing extensive forest harvesting, fires in Alberta burnt primarily wetland-dominated regions with little merchantable timber. A review of lakes in undisturbed watersheds on the Boreal Plain suggests that lakes with substantive wetlands in their watersheds may respond differently to watershed disturbance than those, which are primarily upland-dominated, as wetlands can act as either a sink or source of nutrients (Prepas et al. 2000, in prep.). As forest harvesting shifts toward natural disturbance based models, it is imperative to understand how natural disturbances affect the water quality of forested watersheds.

The 1998 Virginia Hills fire provided a rare opportunity to study the impact of an upland-dominated fire on stream water quality on the Boreal Plain of Alberta. A previous study in this region provided unparalleled pre-disturbance data for two watersheds, one of which was severely burnt in 1998. The present report presents the chemical and physical changes in streams between 1998 and 1999, with watersheds burnt in the Virginia Hills fire, and compares the data collected to the pre-disturbance data from 1983.

The hypotheses being tested are that large scale fire on upland areas of the Boreal Plain would: 1) increase total phosphorus export from the disturbed watershed, 2) elevate nitrogen export from the disturbed watershed, and 3) have no detectable impact on dissolved organic carbon export.

MATERIALS AND METHODS

Study Area

The streams are located in the Virginia Hills region of central Alberta (Figure 1). Underlying the streams is sedimentary bedrock (shale, sandstone and mudstone) of the Paskapoo formation (Paleocene), overlain by 3 to 5 m of glacial till. Watershed soils are primarily clay or sandy-clay loam, and soils along the streams are high in organic content (Munn and Prepas 1986). The vegetation of the area is mixed-wood boreal forest dominated by white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and balsam poplar (*Populus balsimifera*). Shrub species along the streams include willows (*Salix* spp.), wild rose (*Rosa acicularis*), river alder (*Alnus tenufolia*), and various berries (Munn and Prepas 1986).

Five streams were selected in this region based on historic data, compatibility with previously selected streams, and/or amount of burn from the 1998 fire. Two of the streams (Two Creek and Sakwatamau River) were intensively studied in 1983 (Munn and Prepas 1986). The 1998 fire did not affect the Two Creek watershed while 92% of Sakwatamau River watershed above the historic sampling site was burnt. In 1998, a second burnt watershed was sampled (unnamed Goose River tributary, 100% burnt). Late in 1998, a second reference basin (Chickadee Creek) and a third burnt watershed (Freeman River, 91% burnt) were added to the sampling protocol. All five streams have well-defined channels.

The 25-year average precipitation for this region is 586 $mm \cdot yr^{-1}$ (31% as snow). Precipitation (all numbers are for water years – November 1 to October 31) for 1983 was 7% below this average (542 mm), whereas for 1998 and 1999, precipitation was 25% and 12% below the average (434 and 516 mm, respectively). The average long-term evaporation rate for this region is 525 $mm \cdot yr^{-1}$. Runoff for the permanently gauged stream in this region (Sakwatamau River) for 1983, 1998 and 1999 was 145, 53 and 115 $mm \cdot yr^{-1}$, respectively. Precipitation data from the Whitecourt airport weather station and discharge data from the Sakwatamau River gauging station were obtained from Environment Canada (Monitoring Operations Division, Water Survey of Canada).

Sampling and chemistry

Between July and October 1998, streams were routinely sampled twice weekly and more frequently during storm events. Most sampling was done via helicopter due to the remote location of the sampling sites. This protocol was sustained in 1999 between May and October. Grab samples were collected in the middle of each stream at mid-depth with acid washed 2-L Nalgene polyethylene containers. Each site had an automated ISCO sampler set to collect water every four hours to capture storm events. Water samples were stored on ice in the field and refrigerated at 4°C in the laboratory prior to analysis. Stage height was measured weekly with a staff gauge installed at the beginning of the open-water season. Stream discharge measurements were obtained weekly by measuring current velocity and water depth at 0.5-m intervals across each stream channel with a Gurley pygmy current meter. A continuous water level recorder was installed at each site.

Water samples were analyzed in the limnology laboratories at the University of Alberta and the Meanook Biological Research Station. Freshly collected (grab) samples were analyzed for phosphorus (total, total dissolved), nitrogen (ammonium, nitrite+nitrate, particulate, total), carbon (dissolved organic, dissolved inorganic, particulate), and colour. Grab samples from the spring and fall were analyzed for major ions (sodium, potassium, calcium, magnesium, sulfate, chloride). ISCO samples were analyzed for the same suite of nutrients as the grab samples with the exception of ammonium-N and nitrite+nitrate-N, since these parameters are less stable and require immediate analysis.

Water samples for total phosphorus and total dissolved phosphorus were analyzed with the modified (Prepas and Rigler 1982) potassium persulfate method (Menzel and Corwin 1965). Ammonium-N (NH_4^+-N) and nitrite+nitrate-N (NO_3-N) were analyzed with a Technicon autoanalyzer (Stainton et al. 1977; Solórzano 1969). Total dissolved nitrogen and total nitrogen samples were photocombusted in an ultraviolet digester and analyzed as ammonia. Particulate nitrogen and particulate carbon were combusted at 700°C and analyzed on a Control Equipment Corporation 440 Elemental Analyzer. Colour of pre-filtered water was measured at 440 nm with a Milton Roy 1001 spectrophotometer (Cuthbert and del Giorgio 1992). Sulfate and chloride were analyzed on a Dionex 2000i/SP ion chromatograph fitted with an AS4A-Sc high capacity anion exchange column. Major cations were acidified to pH < 2 with concentrated nitric acid and analyzed on a Perkin Elmer 3300 atomic absorption spectrometer (sodium and potassium by atomic emission; calcium and magnesium by atomic absorption). Dissolved carbon samples were filtered through pre-combusted Whatman GF/C filters then measured at 850°C from acidified (pH < 2), sparged subsamples on an Ionics Corporation 1505 programmable carbon analyzer with a platinum catalyst.

Drainage basin areas were estimated from Geographic Information System (GIS) databases provided by the participating companies and compared against 1:50,000 topographic maps. Channel slope was estimated from 1:50,000 topographic maps. Percent disturbance was interpolated from GIS data provided by the participating company for each stream (Table 1).

Table 1: Study streams, drainage basin area, channel slopes and % disturbance in the watershed

Stream	**Drainage basin area (km^2)**	**Channel slopes (%)**	**Disturbance (%)**
Reference			
Chickadee Creek	163	0.70	0
Two Creek	132	0.55	0
Burnt			
Freeman River	444	0.36	91
Sakwatamau River	242	0.49	92
Goose Tributary	151	0.97	10

Total nutrient load was calculated as the sum of the product of nutrient concentration and estimated discharge over each sampling interval (Munn and Prepas 1986; Cooke and Prepas 1998). Nutrient export coefficients were calculated by dividing the total nutrient load (kg) by the watershed area above the sampling site (km^2). Rating equations were generated to extrapolate Environment Canada discharge data from the gauging station on the Sakwatamau River to the sampling sites in the other watersheds. This allowed for the daily calculation of nutrient loading. The relationships between staff height (cm) and instantaneous stream discharge ($m^3 \cdot s^{-1}$) allowed us to predict flow from water height for each stream.

Our analysis currently focuses on data collected in 1983 and 1999 from Two Creek and Sakwatamau River, because these data are complete and allow comparison of a burnt and a non-burnt lake. We also compare data collected from Chickadee Creek, Freeman River and Goose Tributary with 1999 data from Two Creek and Sakwatamau River to further document difference between burnt and reference systems after the fire. Data were also collected in the year 2000, but not currently included in this report. The 2000 data will be combined with those presented in this report and submitted as a primary publication. We also describe how the study streams fit within a context of other published data from the Boreal forest.

Statistical analyses were performed with SPSS version 8.0. For 1999, mean export coefficients in the two stream groups (reference and burnt) were compared with *t*-tests, even though sample sizes were small (df = 3). Inclusion of the 2000 data will allow more powerful statistical analysis (Prepas et al. 2000, in press).

RESULTS

Flow

An initial study of Two Creek and Sakwatamau River was carried out in a year (1983) when flow was similar to the 25-year mean for 1973 – 1997 (163,128 and 163,293 dam^3, respectively) and concentrated in the summer months. The Virginia Hills fire of 1998 occurred during an extraordinarily dry summer, with only a brief peak in precipitation and runoff in early July. During 1983, total flow (163,128 dam^3) was one-third the long-term average. In the following year, 1999, annual runoff was between 1983 and 1998 levels (129,859 dam^3) and 20% below the long-term mean, but with peak flow concentrated in the spring. Thus, both seasonal patterns and total flow varied annually (Figure 2).

Changes in export of total phosphorus following fire in upland areas

Prior to disturbance, export of total phosphorus was 68% higher from Two Creek compared to Sakwatamau River (Table 2a). In 1999, following the fire, both streams had lower export rates due to the dry condition, particularly in the summer. However, the 1999:1983 ratio of total phosphorus export was twice as high (0.8 compared with 0.4) from the burnt watershed of the Sakwatamau River compared to Two Creek (Table 2a). These results suggest a doubling in total phosphorus export with severe fire. While the fraction of particulate phosphorus remained constant (75%) in the pre- and post-treatment year for Two Creek, it increased from 60 to 73% in the burnt long-term stream, Sakwatamau River (Table 2a,b). In the dry months following the 1998 fire (25 July to 21 October), total phosphorus loading was 2.4 times higher from the burnt watershed than from the reference watershed, or five times the 1983 ratio for the two streams. Thus, phosphorus export in the long-term burnt stream was consistently higher post-treatment relative to the reference stream and pre-treatment data.

Table 2: Total phosphorus (TP), particulate phosphorus (PP) and total dissolved phosphorus (TDP) export coefficients (open water) for Two Creek and Sakwatamau River for 1983 and 1999

Stream	**1983**	**1999**	**1999:1983**
a)		**TP export coefficient ($kg \cdot km^{-2}$)**	
Two Creek (reference)	12.6	4.6	0.4
Sakwatamau River (burnt)	7.5	5.9	0.8
b)		**PP export coefficient ($kg \cdot km^{-2}$)**	
Two Creek (reference)	9.4	2.8	0.3
Sakwatamau River (burnt)	5.6	4.3	0.8
c)		**TDP export coefficient ($kg \cdot km^{-2}$)**	
Two Creek (reference)	3.2	1.8	0.6
Sakwatamau River (burnt)	1.9	1.6	0.8

When phosphorus export coefficients were compared for 1999 among the five streams, TP export was 66% higher (P = 0.05) in the burnt than the reference streams (Table 3). All of the increase in total phosphorus export appears to be in the particulate rather than the dissolved fraction; dissolved phosphorus is essentially indistinguishable between the two stream types (P = 0.8), while particulate phosphorus was three-fold higher (P = 0.05) in the burnt streams compared with the reference streams. Increased total phosphorus export rates for 1999 for the burnt streams was associated with peak runoff, suggesting soil loss rather than ash deposition as the source of phosphorus.

Table 3: Mean total phosphorus (TP), dissolved phosphorus (DP), and particulate phosphorus (PP) export for the three burnt and two reference streams monitored in 1999 in the Virginia Hills, Alberta

Treatment	**TP export coefficient ($kg \cdot km^{-2}$)**	**DP export coefficient ($kg \cdot km^{-2}$)**	**PP export coefficient ($kg \cdot km^{-2}$)**
Reference Streams	4.0	1.3	2.7
Burnt Streams	6.6	1.1	5.5

These results are similar to other recent studies on the Boreal Plain and Boreal Shield, where the watershed has been disturbed. Total phosphorus concentration increased, approximating a 1:1 ratio with the amount of vegetation removed in the watershed (in our before (1983) and after study (1999), the ratio was 2.1; 1999 burnt compared with reference stream export, 1.7) (McEachern et al. 2000; Carignan et al. 2000; P.A. Chambers, National Water Research Institute, Saskatoon, SK, unpublished data for streams in wetland-dominated basins in the Fort McMurray area). In our study, the increase in phosphorus export was largely in the particulate fraction, while on the subarctic Boreal Plain, the increase was mostly in the dissolved form (McEachern et al. 2000). However, this form of phosphorus increase was not consistent with other studies.

Fire typically causes an increase in runoff (Gresswell 1999), which was observed in our streams. In 1983, the ratio of water export in Two Creek and Sakwatamau River was 1.7. In 1999, that ratio was 2.0. Thus, in 1999, less than a third of the increase in TP export (1.2 versus 1.7) is likely associated with increased runoff.

Nitrogen losses following fire

There is no evidence of an increase in total nitrogen export following fire. Rather, total nitrogen export was lower (45 kg· km^{-2}) from the burnt, as compared to reference watersheds (Table 4). The ratios of total nitrogen export from Two Creek and Sakwatamau River in 1983 (pre-fire) and 1999 (post-fire) were virtually identical (1.19 and 1.20, respectively). Thus, total nitrogen export remained stable with the fire.

Table 4: Mean total nitrogen (TN), nitrate (NO_3) and ammonium (NH_4) export in the three burnt and two reference streams monitored in 1999 in the Virginia Hills, Alberta

Treatment	**TN export coefficient (kg· km^{-2})**	**NO_3 export coefficient (kg· km^{-2})**	**NH_4 export coefficient (kg· km^{-2})**
Reference Streams	64	0.62	0.95
Burnt Streams	45	1.79	1.22

In contrast, inorganic nitrogen export coefficients were higher in the burnt, versus the reference streams. Inorganic nitrogen is a relatively small proportion (< 5%) of the total nitrogen pool at any point in these streams, with approximately equal amounts of ammonium- and nitrate-nitrogen. Although export coefficients for ammonium were higher in the burnt compared with the reference streams, the differences were modest (28%), while nitrate export was three-fold higher in the burnt streams (Table 4).

In the two streams monitored in 1983, nitrate export coefficients differed by < 5% in the pre-treatment year, while the treated watershed exported 2.3 times more nitrate in 1999 (post-fire) and twice the nitrate during the arid 1998 (post-fire) open-water period. Although these increases in nitrate represent minuscule losses from terrestrial ecosystems, they are substantive inputs to aquatic systems. Further, these increases are relatively large compared to those reported elsewhere on both the Precambrian Shield and Boreal Subarctic (e.g., Lamontagne et al. 2000; McEachern et al. 2000). Minshall et al. (1997) also noted that of all the parameters they studied, only nitrate increased in burnt streams.

Carbon and colour

In contrast to the Boreal Subarctic (McEachern et al. 2000) and suggestions on the Boreal Shield (Carignan et al. 2000), there is no evidence of an increase in dissolved organic carbon or colour with fire in the upland-dominated Boreal Plain. Although water in the Sakwatamau River at our sample site is more coloured (pre-treatment: 69 $mg \cdot L^{-1}$ Pt) than Two Creek (pre-treatment: 47 $mg \cdot L^{-1}$ Pt), they both changed the same amount (two-fold) between 1983 (wet summer) and 1999 (relatively dry summer). Similarly, there was no evidence of increase loading of dissolved organic carbon or colour in our burnt streams relative to our reference streams (Table 5).

Table 5: Dissolved organic carbon (DOC) and colour for Two Creek (reference) and Sakwatamau River (burnt) for 1983 and 1999

Stream	**DOC ($mg \cdot L^{-1}$)**	**Colour ($mg \cdot L^{-1}$ Pt)**	
	1999	**1983**	**1999**
Two Creek (reference)	11	47	97
Sakwatamau River (burnt)	17	69	146

Colour is associated with wetlands connected to lakes (Prepas et al. 2000, in prep.) on the Boreal Plain and remains relatively unchanged with this severe watershed disturbance. This lack of impact of disturbance on dissolved organic carbon and colour is likely related to the virtual absence of wetlands (< 4% by area) in the chosen watersheds.

Cations

In contrast to studies elsewhere (e.g., Boreal Shield, Carignan et al. 2000), export of cations remained unchanged less than a year following the fire in these calcium bicarbonate dominated streams (Figure 3). Further, dominant ion concentrations remain stable, increasing slightly during the arid periods (data not shown). There is no evidence of increased export of cations from the burnt watershed. Rather, dominant cations were relatively low in Sakwatamau River relative to Two Creek following the fire (Figure 3).

MANAGEMENT APPLICATIONS

The current study, in combination with others from the Boreal Plain, suggests that phosphorus export will increase with the amount of watershed disturbed in these relatively large (> 100 km^2) watersheds. Phosphorus and nitrogen, two limiting nutrients in fresh water, demonstrate increased export following fire, thus the primary producing community (including algae, cyanobacteria and rooted plants) will likely respond with increased biomass. However, community shifts following fires in upland sites are more difficult to predict. In contrast, current harvesting practices, even at low levels, appear to influence export of phosphorus, but not nitrate (TROS study, Prepas et al. 2000, in press). Increased phosphorus in the absence of nitrogen can help shift phytoplankton communities towards cyanobacterial and cyanotoxic domination. This study will form the basis of a long-term review of the signature of fire on aquatic systems, including toxic substances and how forestry practices can most closely link with the appropriate nutrient signature on receiving waters.

With our industrial partners (Millar Western, Blue Ridge Lumber, Alberta Plywood, Vanderwell, and Louisiana Pacific), we will evaluate a set of harvesting patterns to compare with the effects of the Virginia Hills and related fires. Harvesting patterns being considered include clear cut with and without buffer, variable amounts of leave areas within the watershed, select tree removal, and within both aspen- and conifer-dominated systems. We will focus our attention on export of phosphorus and nitrogen following disturbance.

Further, in cooperation with Alberta Health and Wellness and Environment Canada, we had the opportunity to evaluate the impact of the fire and subsequent logging on contaminants, including mercury and chlorinated organics. Two months following the fire, there was no clear evidence of increased dioxins, furans, PCBs or PAHs in sediment and/or biotic samples collected in the zone of likely impact from the fire (Chen et al. 1999; Gabos et al. 1999, 2000 in press; Ikonomou et al. 1999). However, a potential signal was observed for mercury in stream water and sediment samples from burnt (Sakwatamau and Feeman rivers) and non-burnt (Little Smoky River) sites, suggesting that erosion of soil material following forest fire may affect the flux of mercury to surface waters (Alberta Health, 1999 unpublished data). These results are being followed up with a study of mercury in biota from Virginia Hills lakes with burnt and non-burnt watersheds and a whole-lake experiment that will incorporate pre- and post-logging treatment to evaluate the effect of timer harvesting on mercury in aquatic biota.

CONCLUSIONS

Both total phosphorus and nitrate export increased immediately, and the year following, the burn of upland-dominated sites in central Alberta. These results contrast with the impact of logging on similar terrain – in the logged watersheds, total phosphorus export increased similarly, given the degree of disturbance to the burnt watersheds. In contrast to sites in the subarctic Boreal Plain (McEachern et al. 2000), the majority of the total phosphorus increase following fire was in the particulate fraction. Also, nitrate export did not change detectably in the logged lakes (Prepas et al. 2000, in press), while it increased in this study. The differences in export of nitrate under logged and burnt conditions have direct implications for aquatic biota. The predicted response in lakes in logged watersheds on the Boreal Plain would be an increase in cyanobacteria (some of which can fix atmospheric nitrogen; Prepas et al. 2000, in press), while in burnt watersheds, phytoplankton communities are predicted to have a more stable and unchanged composition but increased biomass.

While phosphorus is the limiting nutrient in the trophic status of aquatic systems, nitrogen also plays an important role in stream and lake productivity, particularly in sedimentary locations such as the Boreal Plain of western Canada. Thus, it is clear that forest fires can alter the chemistry and biology of aquatic systems. Soil disturbance associated with forest fire and timber harvesting may also increase the export of soil-bound pollutants such as mercury, which bioaccumulates in aquatic systems. Based on the results from this study and the TROLS lake study, as well as a parallel study on the Boreal Shield, we conclude that fire and forest harvesting have divergent effects on water chemistry, with potentially substantial consequences on biodiversity in fresh waters.

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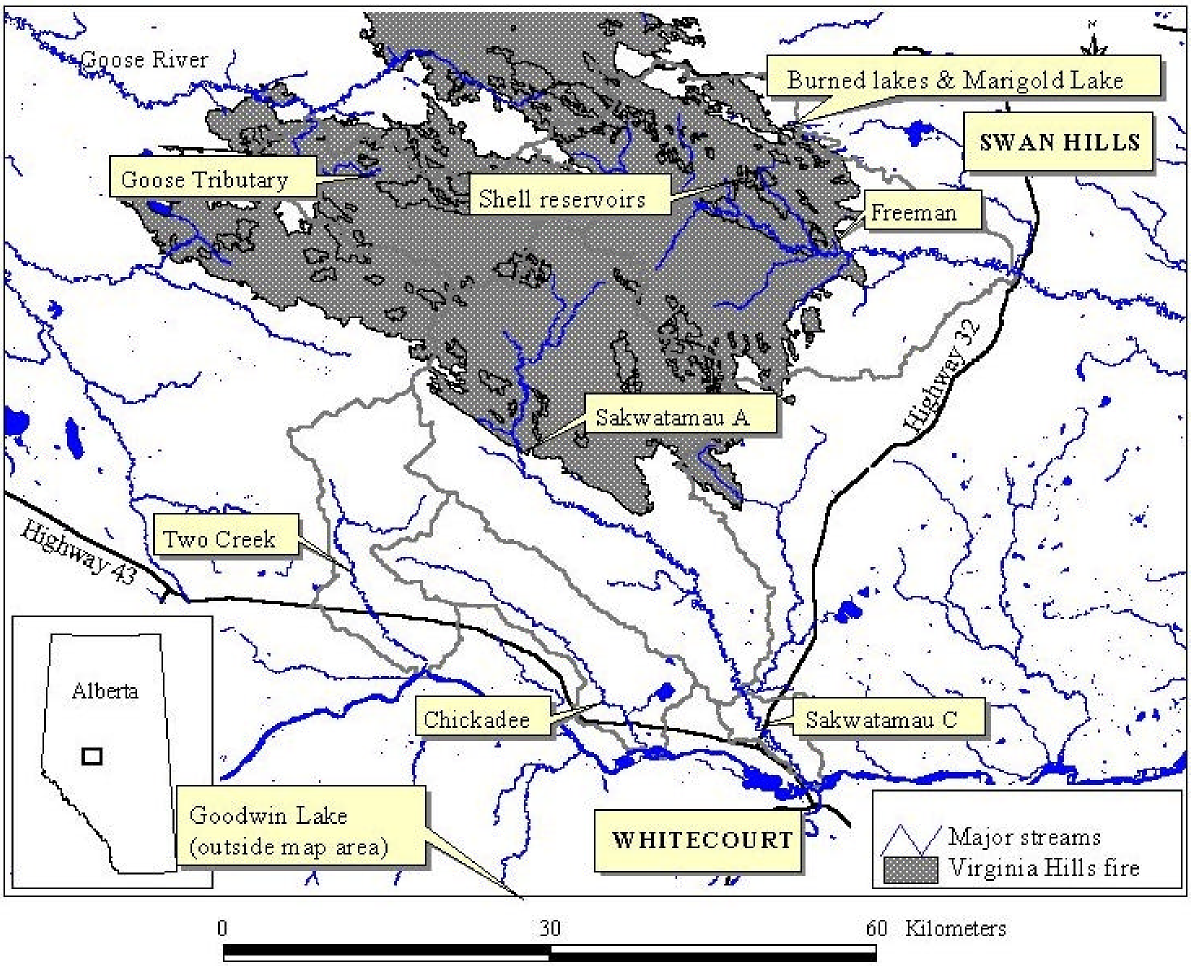

Figure 1: The Virginia Hills study area.

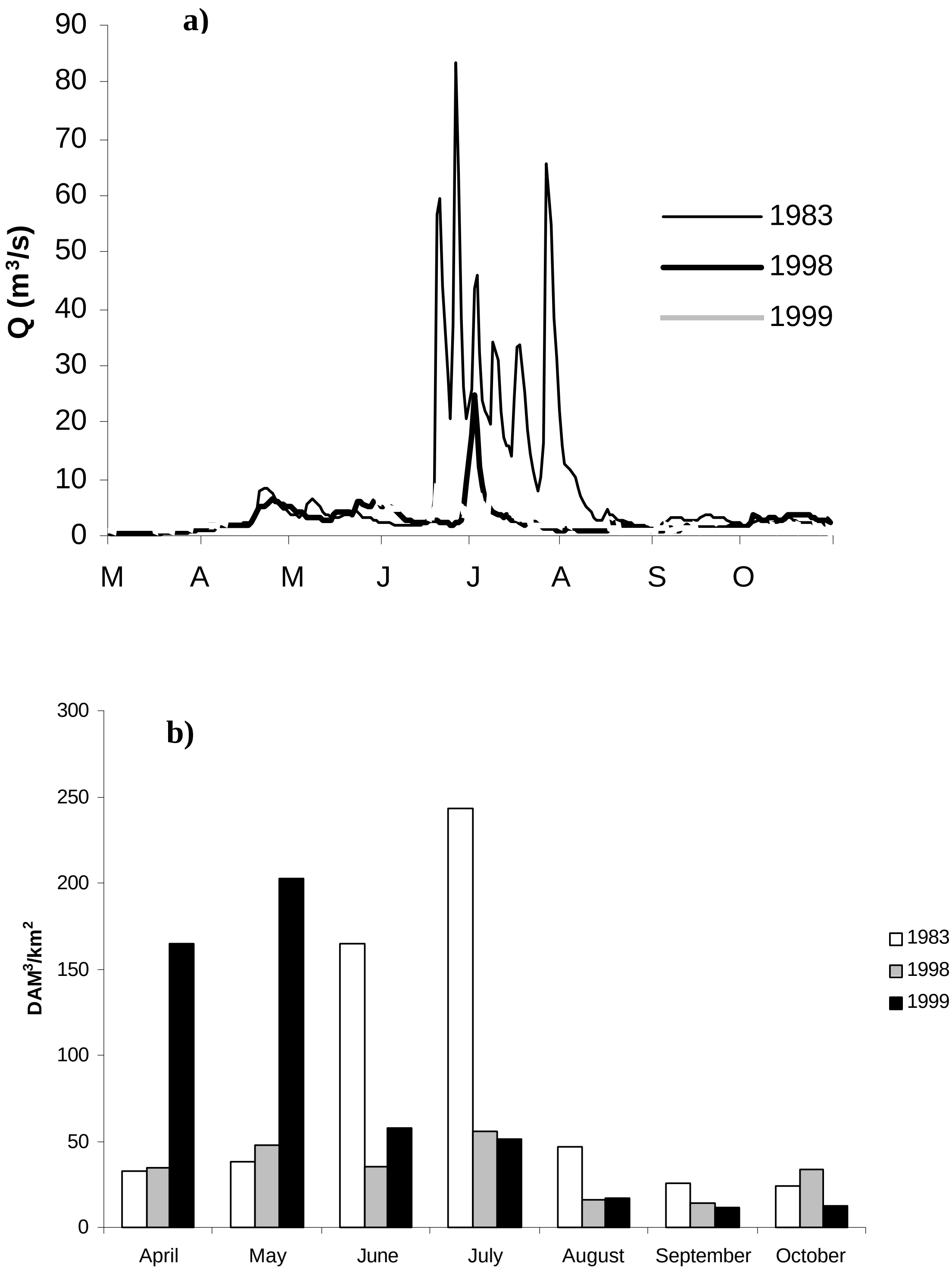

Figure 2: Sakwatamau River at Environment Canada gauged station a) hydrograph and b) total discharge from March to October, for 1983, 1998 and 1999.

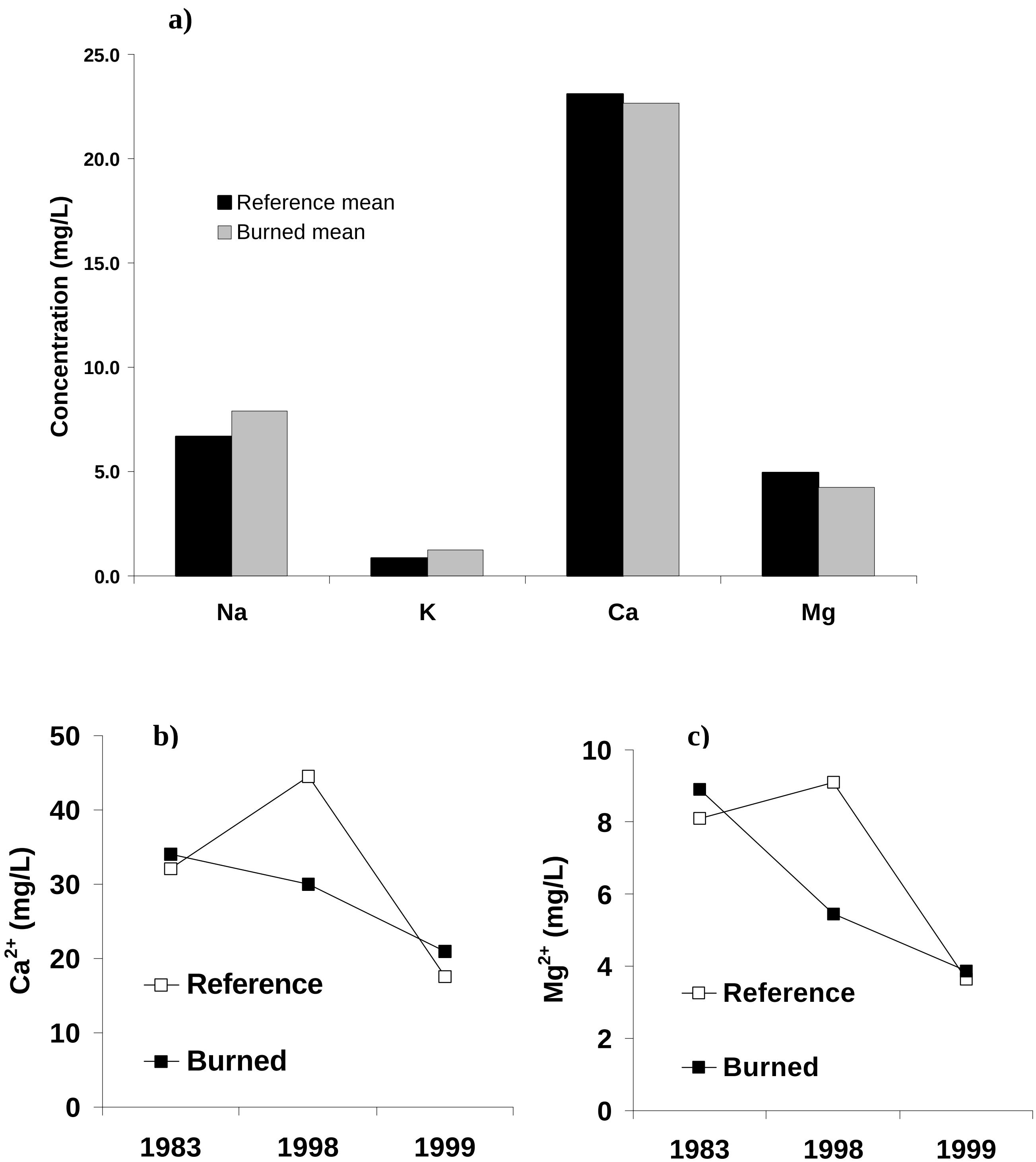

Figure 3: Mean cation concentrations for the streams monitored in the Virginia Hills: a) sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) concentrations for three burnt and two reference streams for 1999, and b) calcium and c) magnesium concentrations for 1983, 1998 and 1999 in the long-term reference (Two Creek) and burnt (Sakwatamau) streams.