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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 89% of its watershed burned 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 burned (*n* = 2) and reference (*n* = 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. Previously, 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, and a final report was submitted to SFMN in November 2000 (Prepas et al. 2000). Data collection following the Virginia Hills fire was given another year of funding for the sampling year 2000. This final report is for the second, full year post-fire evaluation in the study site. In 1999, total phosphorus export almost doubled after the fire, and this increase was in the particulate fraction. In 2000, total phosphorus export increased even more. Further, inorganic nitrogen export was 2.5 times higher and particulate carbon export was nearly 4 times higher from burned compared with reference watersheds. From 1999 through 2000, many water quality parameters in burned watersheds, including dissolved organic carbon, colour, and dominant cations remained similar to non-disturbed conditions in these upland-dominated watersheds. Whereas this fire enhanced particulate phosphorus and inorganic nitrogen export from the watershed, forest harvesting in another site on the Boreal Plain enhanced phosphorus but not nitrate export. The impact of forest fire on water quality on the Boreal Plain more than two years after the fire was greater than the first full year after the fire.

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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 burned 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 western 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 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 the two forested watersheds, the relative proportion of dissolved to total phosphorus export averaged 34 and 43%, respectively. In the agricultural streams, dissolved phosphorus export comprised 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. 2001a). In the TROLS lakes, enhanced phosphorus but not nitrogen concentrations paralleled changes in biotic indicators including cyanobacterial biomass and cyanotoxin concentration (Prepas et al. 2001a). 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 effects of fire on aquatic ecosystems on the Boreal Plain are 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 burned extensive areas of the Boreal Shield and the Boreal Plain. While the fires on the Boreal Shield burned largely upland regions undergoing extensive forest harvesting, fires in Alberta burned 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, that are primarily upland-dominated, as wetlands can act as either a sink or source of nutrients (Prepas et al. 2001b). 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 fire in the Virginia Hills 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 burned in 1998. In 2000, a final report was submitted to SFMN on the impacts of the 1998 fire on streams in the Virginia Hills up to the 1999 sampling year. The present final report adds one more year of data to this study. This report presents the chemical and physical changes in streams between 1998 and 2000, with watersheds burned 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, 3) have no detectable impact on dissolved organic carbon export, and 4) have a long-term (> 2yr) impact on surface water quality.

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 89% of Sakwatamau River watershed above the historic sampling site was burned. In 1998, a second burned watershed was sampled (unnamed Goose River tributary, 84% burned). Late in 1998, a second reference basin (Chickadee Creek) and a third burned watershed (Freeman River, 77% burned) 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, 1999, and 2000, precipitation was 25, 12, and 13% below the average (434, 516, and 509 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, 1999, and 2000 was 145, 53, 115, and 110 $mm \cdot yr^{-1}$, 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 and 2000 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: Mean drainage basin areas, channel slopes, and % disturbance in the watershed for the three reference streams (Chickadee and Two Creek) and the three burned streams (Freeman River, Sakwatamau River, and Goose Tributary).

Stream	**Drainage basin area (km^2)**	**Channel slopes (%)**	**Disturbance (%)**
Reference Streams	148	0.63	0
Burned Streams	281	0.61	83

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, 1999, and 2000 from Two Creek and Sakwatamau River, because these data are complete and allow comparison of a burned and a non-burned stream. We also compared data collected from Chickadee Creek, Freeman River and Goose Tributary with 1999 and 2000 data from Two Creek and Sakwatamau River to further document differences between burned and reference systems after the fire. We describe how the study streams fit within a context of other published data from the Boreal forest.

Statistical analyses were performed with SigmaPlot. For 2000, mean export coefficients in the two stream groups (reference and burned) were compared with *t*-tests, even though sample sizes were small (df = 3).

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. In 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. In comparison, flow was concentrated in the summer months in 2000. 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 burned watershed of the Sakwatamau River compared to Two Creek (Table 2a). These results suggest a doubling in total phosphorus export with severe fire. The 2000:1983 ratio of total phosphorus export was 3.8 times higher (1.5 compared to 0.4) from the burned watershed compared to Two Creek. In the dry months following the 1998 fire (25 July to 21 October), total phosphorus loading was 2.4 times higher from the burned watershed than from the reference watershed, or five times the 1983 ratio for the two streams. Thus, phosphorus export in the long-term burned stream was consistently higher post-treatment relative to the reference stream and pre-treatment data. Further, phosphorus export shows no sign of decline in 2.5 years following the fire. If anything, export is highest with summer storms.

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, 1999, and 2000.

Stream	**1983**	**1999**	**2000**	**1999:1983**	**2000:1983**
a)			**TP export coefficient ($kg \cdot km^{-2}$)**		
Two Creek (reference)	12.6	4.6	5.2	0.4	0.4
Sakwatamau River (burned)	7.5	5.9	11.4	0.8	1.5
b)			**PP export coefficient ($kg \cdot km^{-2}$)**		
Two Creek (reference)	9.4	2.8	2.3	0.3	0.2
Sakwatamau River (burned)	5.6	4.3	8.6	0.8	1.5
c)			**TDP export coefficient ($kg \cdot km^{-2}$)**		
Two Creek (reference)	3.2	1.8	2.9	0.6	0.9
Sakwatamau River (burned)	1.9	1.6	2.8	0.8	1.5

Similar to the long-term study streams above, mean TP export from the burned watersheds was 3.4 times higher (P = 0.02) than from reference watersheds in 2000 (Table 3).

All of the increase in total phosphorus export appears to be in the particulate rather than the dissolved fraction. Dissolved phosphorus export is essentially indistinguishable between the two stream types (P = 0.3), while particulate phosphorus export was five times higher (P = 0.04) in the burned streams compared with the reference streams.

Table 3: Mean total phosphorus (TP), particulate phosphorus (PP), and total dissolved phosphorus (TDP) export coefficients (open water) for the three burned and two reference streams monitored in 2000 in the Virginia Hills, Alberta.

Treatment	**TP export coefficient (kg· km^{-2})**	**PP export coefficient (kg· km^{-2})**	**TDP export coefficient (kg· km^{-2})**
Reference Streams	4.0	1.8	2.2
Burned Streams	13.6	9.4	4.2

These results are similar in overall nutrient impact 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 (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 ratio of total phosphorus export for 1999 (after burn) compared to 1983 (before burn) was 2.1. In 1999, the ratio for burned compared with reference stream export was 1.7, and in 2000, the ratio was 3.4. 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).

Fire typically causes an increase in runoff (Gresswell 1999), as was seen in our streams. However, the increase in runoff did not fully account for the increased total phosphorus export observed. The 2000:1983 water export ratio was 0.49 in Two Creek (reference) and 0.91 in Sakwatamau River (burned). This represents a nearly 2-fold increase in water export in the burned stream relative to reference stream. However, the 2000:1983 total phosphorus export ratio was 0.41 and 1.52 in the same two streams, a 3.6-fold increase. Thus, less than half of the increase in total phosphorus export after fire can be explained by an increase in water export.

Nitrogen losses following fire

There is no evidence of a detectable increase in total nitrogen export following fire (P = 0.5, Table 4). The ratios of total nitrogen export from Two Creek and Sakwatamau River in 1983 (pre-fire), 1999 (post-fire), and 2000 were similar (1.19, 1.20, and 1.05, 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 burned and two reference streams monitored in 2000 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	60.1	1.29	0.41
Burned Streams	77.2	2.96	1.37

In contrast, inorganic nitrogen export coefficients were higher in the burned, 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 nitrate and ammonium. In 1999, inorganic nitrogen export was twice as high in burned compared with reference watersheds, and by 2000, inorganic nitrogen export was 2.5 times higher in burned watersheds. In 2000, the export coefficient for nitrate was 2.3 times higher in burned compared with reference watersheds, and ammonium export was 3.3 times higher in burned watersheds (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). In 2000, the nitrate export coefficient for Sakwatamau River was only 23% higher than for Two Creek, but the ammonium export was twice as high. Thus, in 2000, ammonium export from burned watersheds was higher than in previous years.

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 our burned streams relative to our reference streams (Table 5). However, particulate carbon export was nearly 4 times higher from burned compared with reference watersheds. Colour is associated with wetlands connected to lakes (Prepas et al. 2001b) 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.

Table 5: Mean dissolved organic carbon (DOC) and particulate carbon (PC) export and mean colour in the three burned and two reference streams monitored in 2000 in the Virginia Hills, Alberta.

Stream	**DOC ($kg \cdot km^{-2}$)**	**PC ($kg \cdot km^{-2}$)**	**Colour ($mg \cdot L^{-1}$ Pt)**
Reference streams	1,997	89	135
Burned streams	2,473	335	130

Cations

In contrast to studies elsewhere (e.g., Boreal Shield, Carignan et al. 2000), export of cations remained unchanged 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 burned 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. 2001a). Increased phosphorus in the absence of nitrogen can help shift phytoplankton communities towards cyanobacterial and cyanotoxin 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, 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 aspen- versus conifer-dominated systems. We will focus our attention on export of phosphorus and nitrogen following disturbance. The Virginia Hills study will allow us to follow and in a related study, model the long-term and dynamic effects of fire on aquatic systems.

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, 2001; Ikonomou et al. 1999). However, a potential signal was observed for mercury in stream water and sediment samples from burned (Sakwatamau and Feeman rivers) and non-burned (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 burned and non-burned watersheds and a whole-lake experiment that will incorporate pre- and post-logging treatment to evaluate the effect of timber harvesting on mercury in aquatic biota.

CONCLUSIONS

Both total phosphorus and inorganic nitrogen 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 burned 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. 2001a), whereas it increased in this study. The differences in export of nitrate under logged and burned 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. 2001a), while in burned watersheds, phytoplankton communities are predicted to have a more stable and unchanged composition but increased biomass.

Whereas 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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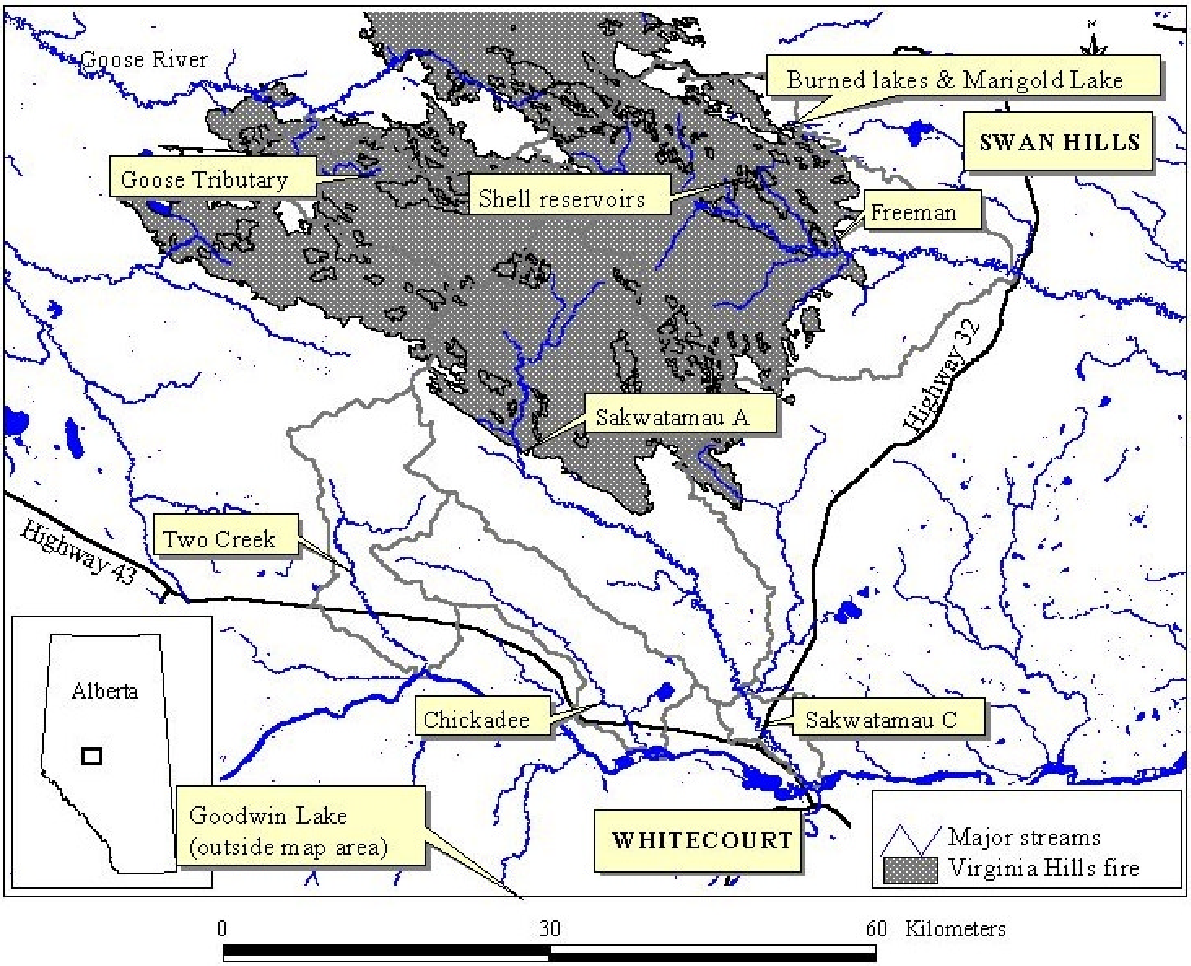

Figure 1: The Virginia Hills study area.

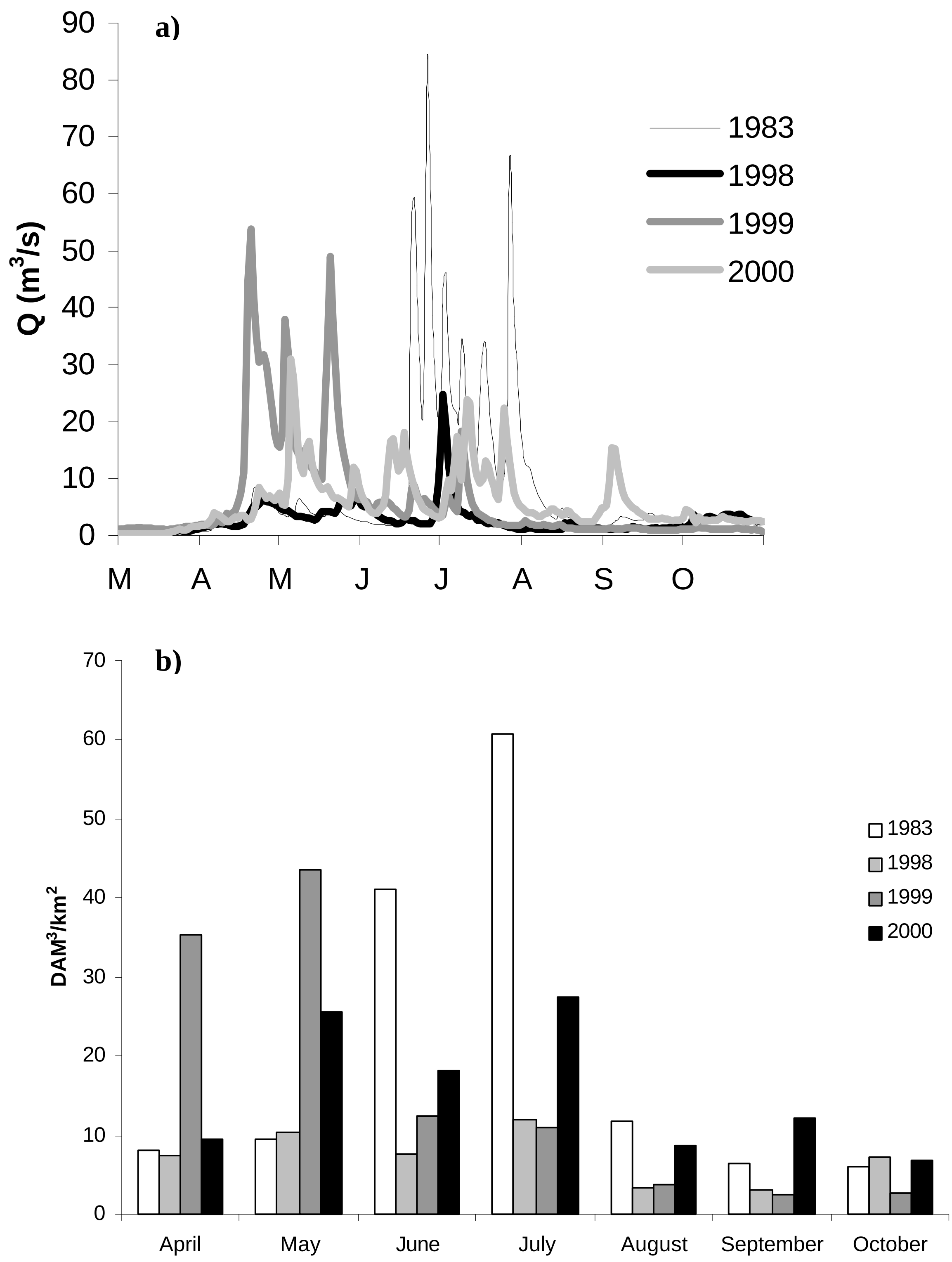

Figure 2: Sakwatamau River at Environment Canada gauged station a) hydrograph and b) total discharge from March to October for 1983, 1998, 1999, and 2000.

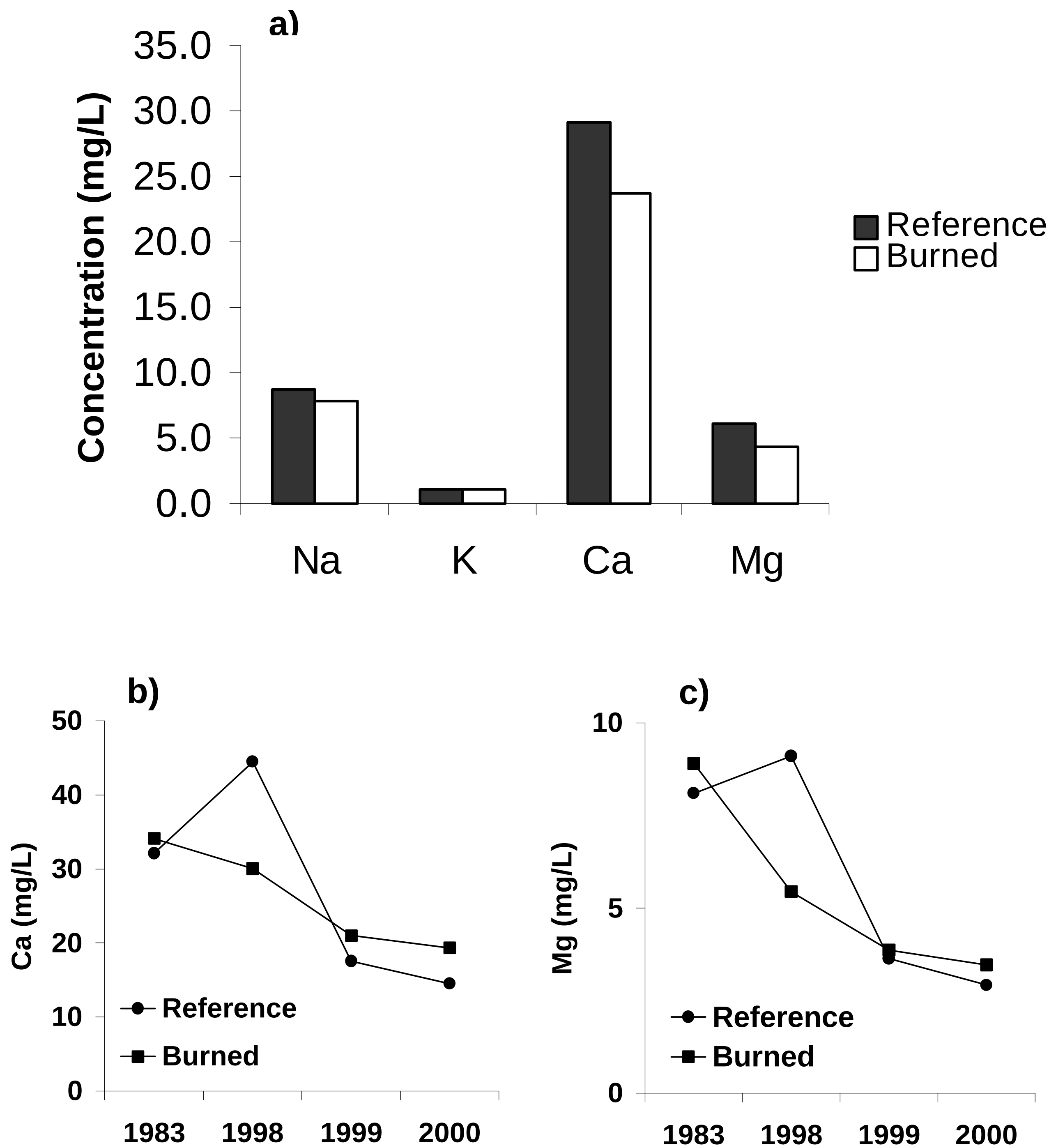

Figure 3: Mean (April to August) cation concentrations a) for the three burned and two reference streams monitored in the Virginia Hills in 2000 and b) calcium and c) magnesium concentrations for the long-term reference (Two Creek) and burned (Sakwatamau) streams monitored in the Virginia Hills for 1993, 1998, 1999, and 2000.