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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

Modeling water quality and watershed disturbance on the Boreal Plain

by

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EXECUTIVE SUMMARY

Wildfires are the most important natural disturbance in forests of the Boreal Plain. Although the processes are not well understood, wildfires are thought to have profound effects on water yield and nutrient export in the potentially phosphorus-rich streams on the Boreal Plain. Prior to the 1998 Virginia Hills fire, few opportunities existed to evaluate the impact of fire on water quality in the Boreal Plain. As one of the streams whose watershed was burned in the 1998 Virginia Hills fire was the subject of a previous study, this offered an unprecedented opportunity to evaluate the impact of fire on water quality and quantity. Our study indicates that during peakflow, water and phosphorus exports increased after 89% of an upland watershed was burned (database from 1998 to 2000) in comparison to a pre-burn database (1983). Higher discharge enhances loading of phosphorus-rich particulates from the watershed and/or stream channel, which appear to account for these changes. This is the final report for the second, full year post-fire evaluation in the study area. This study was published in the invited collection of nine publications in the Journal of Environmental Engineering and Science (2003) under the special editorship of D.W. Smith and E.E. Prepas.

INTRODUCTION AND OBJECTIVES

The Boreal Plain ecozone is the western subregion of the Canadian Boreal Forest. This region has a relatively dry climate (300 mm in northern Alberta to 625 mm in southwestern Manitoba) along with cold winters and short, warm summers. Vegetation consists of mixed-wood forest in a low-relief area (mean watershed slope <4%; Prepas et al. 2003a) on phosphorus-rich soils underlain with soft sedimentary bedrock. Of the natural disturbances that occur in this region, wildfires are the most important (Prepas et al. 2003a; Smith et al. 2003a) as they have been hypothesised to have significant effects on water yield and nutrient export in the potentially phosphorus-rich streams. Further, watershed - surface water relationships differ between upland- (generally <25% wetland) and lowland- (>25% wetland) dominated watersheds (Prepas et al. 2001a). Undisturbed wetlands in upland watersheds tend to be rich fens that sequester inorganic phosphorus as calcium and magnesium phosphates while wetlands in lowland watersheds tend to be bogs that release phosphorus (Prepas et al. 2001a).

In comparative studies, Carignan et al. (2000) found that following fire on the eastern Boreal Shield, some upland-dominated watersheds had enhanced phosphorus export for at least three years while phosphorus export was little changed in others (Bayley et al. 1992). As well streams in lowland bog-dominated watersheds on the Boreal Shield, Boreal Subarctic and Boreal Plain exported 2- to 7-fold more phosphorus following fire than their forested counterparts

(Bayley et al. 1992; McEachern et al. 2000; P.A. Chambers, NHRI, Saskatoon, SK, unpublished data). In the Boreal Subarctic, enhanced phosphorus export was observed for minimally 25 years following intense wildfire (McEachern et al. 2000).

It has also been shown that in forested regions, in general (Omernik 1977) and on the Boreal Plain (Munn and Prepas 1986; Cooke and Prepas 1998), erosion of watershed soils and stream banks exert the strongest influence on phosphorus export rates in upland-dominated watersheds. The majority of soils on the Boreal Plain have been formed on alkaline parent materials (e.g., fine grained and calcium-rich Orthic Gray Luvisols; Whitson et al. 2003). Infiltration may be impeded in these soils and rapid increase in overland flow during storm events can flush particulates that have accumulated in the organic and till layers of the forest floor (Munn and Prepas 1986). Thus, export of phosphorus is linked closely to precipitation and associated discharge patterns on the Boreal Plain. In addition, higher discharge rates should be associated with tree removal by wildfire (Hibbert 1965) and higher sediment loads from the burned watersheds and in-channel erosion processes (Prepas et al. 2003a).

The 1998 fire in the Virginia Hills provided a rare opportunity to study the impact of wildfire on stream water quality and nutrient export from an upland-dominated watershed on the Boreal Plain. This fire burned intensely, and accounted for the loss of more than 170 000 ha of upland timber. A previous study in 1983 on seasonal patterns of phosphorus export in this region provided unparalleled pre-disturbance data for two watersheds, Sakwatamau River and Two Creek (Munn 1984; Munn and Prepas 1986). In the Virginia Hills fire approximately 89% of the forested Sakwatamau River watershed was burned upstream of the sampling site (Sakwatamau A) while Two Creek remained undisturbed.

The objective of this study was to compare water and phosphorus export between pre- and post-disturbance in the burned (Sakwatamau A) and the reference (Two Creek) watersheds. We hypothesed that large scale fire in upland areas of the Boreal Plain would: 1) increase water and phosphorus yields after the fire, 2) increase flow to the stream channel during storm events, bringing particulates from the watershed and channel banks, and 3) have long-term impact before phosphorus export levels recover to pre-disturbance levels.

MATERIALS AND METHODS

STUDY AREA

The study watersheds, Sakwatamau A (burned) and Two Creek (reference), are located in the Virginia Hills region of the Swans Hills in central Alberta (Figure 1). Sedimentary bedrock such as shale, sandstone and mudstone of the Paskapoo formation (Paleocene) underlie the streambeds (Knapik and Lindsay 1983), which is overlain by three to five metres of glacial till. The watershed soils are mineral-rich Luvisols while soils along the streams are Organics and Gleysols (Knapik and Lindsay 1983). Vegetation in the Sakwatamau A and Two Creek watersheds is composed of 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).

In 1983 Sakwatamau A and Two Creek watersheds were intensively studied (Munn and Prepas 1986). These data provided the study with unparalleled pre-disturbance data. The Virginia Hills fire in 1998 did not affect the Two Creek watershed while 89% of Sakwatamau River watershed was burned above the 1983 sampling site.

Both Sakwatamau A and Two Creek watersheds have well defined channels that drain into the Athabasca River (Figure1). Sakwatamau A is classified as a fourth order stream while Two Creek is third order. Channel slopes are very shallow for both Sakwatamau A and Two Creek (Table 1). The elevations for sampling sites at both the reference and burned watersheds are very similar, i.e., Sakwatamau A at 1227 m and Two Creek at 1100 m. The drainage basin area (DBA) for Sakwatamau A is almost two times that of Two Creek. Prior to the disturbance, drainage densities (0.37 and 0.43 per km, respectively) and water chemistry (both alkaline with moderate colour) were similar for Sakwatamau A and Two Creek.

Data for precipitation, air temperature, evaporation and discharge patterns for the Sakwatamau C site (Figure 1) were obtained from Environment Canada (Canadian Climate Centre, Data Management Division, Downsview, ON). Mean annual precipitation has historically (1972 to 1997) been recorded as 584 mm water per year (30% as snow). The mean annual precipitation for 1983 was 550 mm and 452, 506 and 548 mm, respectively for 1998, 1999 and 2000. Historical mean monthly air temperature ranged from -23.5 to 2.3°C in winter and from 0.1 to 17.5°C from April to October. The average long-term (1972 to 1997) evaporation rate for the region was 525 mm per year. Stream flow was typically monitored from

March to October and runoff for the permanently gauged stream site in this region (Sakwatamau C, DBA = 1127 km^2) for 1983, 1998, 1999, and 2000 was 145, 53, 115, and 110 mm per year, respectively.

Water samples were collected, flow monitored and data analyzed as outlined in Prepas et al. (2003a).

Table 1: Mean drainage basin areas, channel slopes, and percent disturbance in the watershed for the Two Creek (reference) and Sakwatamau A (burned) streams

Stream	**Drainage basin area (km^2)**	**Channel slopes (%)**	**Disturbance (%)**
Reference	129	0.45	0
Burned	247	0.34	89

RESULTS

At a permanently gauged site on the Sakwatamau (Sakwatamau C), the May through July period was characterized by peakflow associated with summer storms, whereas from August through October, baseflow was dominant (Figure 2). Stormflow was higher in the pre-fire year (1983) than for the post-fire years; peak discharge was measured in 1983. Dry conditions that contributed to the Virginia Hills fire are reflected in the hydrograph for 1998, when the only detectable stormflow event occurred in early July 1998. In addition, the total volume of water exported from Sakwatamau C in 1998 was only 59 249 dam^3, which represents only 36, 46 and 48% of the volume exported in 1983, 1999 and 2000, respectively. Peakflow periods were spread out through the open-water season in 2000, whereas they occurred earlier in the season in 1999. This year was also remarkable in that snowmelt in March and April 1999 was a stronger contributor to annual runoff (34%) than in the other study years (6 to 17%; Figure 2) due to high snowfall (Figure 3). However, the early May stormflow peak in 1999 can be attributed to heavy rains (37 mm) in early May.

In the study streams, peak water export was also reported in the summer storm season (May through July) and minimum export reported during the baseflow season (August through October). Over three-quarters of the flow from May through October was recorded in the summer storm season. In the pre-fire year, the burned stream exported 25 960 dam^3 of water during May through July, or 21% of the volume exported from Sakwatamau C in the same time period. In 1999 and 2000, the total water volume exported from May through July was 36 and 42%, respectively, of that exported from Sakwatamau C, higher than the expected proportion of 21%. The reference stream exported 23% of that exported from Sakwatamau during May through July 1983. In 1999 and 2000, water export from the reference watershed was 18 and 19% of that from Sakwatamau C, which did not differ from the expected proportion of 20% for this stream. Thus, seasonal patterns in water yield in the two study streams were similar to those seen at the permanently gauged site. However, only in the burned watershed after the fire, water export relative to the permanently gauged site appeared higher than expected.

Water export per unit area from the burned watershed during the summer storm season was only half that of the reference stream during the pre-fire year, whereas it was similar after the fire. Runoff in the region tended to decline between 1983 and the post-fire years (Prepas unpublished data). However, the trend in the burned stream was opposite; runoff increased after fire relative to 1983. Thus, the response in discharge from the burned stream was different than the reference stream under the same regional precipitation regime (Figure 3). The difference in water export between the pre- and post-fire years within each watershed was detectable when the two study streams were compared. In the burned stream, there was a slight increase in water export for the May through July period and in the reference stream there was a strong decrease, despite a trend for rainfall to increase each year after the fire. No difference was detectable when within-watershed changes in water export were compared in the same manner for the baseflow period. Therefore, it appears that during the summer storm season, precipitation as a proportion of runoff was higher in the burned compared to the reference watershed.

The phosphorus composition of the water in the two streams was similar during baseflow periods; the burned to reference total dissolved phosphorus and particulate phosphorus flow weighted mean concentrations ratios were within 20% of unity during all study years. Burned to reference ratios of total dissolved phosphorus and particulate phosphorus export during baseflow were similar to the drainage basin ratio of the two basins (~two) during all study years, with the exception of the period immediately after fire in 1998 when ratios of both fractions increased. Before fire, the flow weighted mean concentrations and export ratios during peakflow were similar between the two watersheds (within 13% of unity), despite the larger size of the burned watershed. The burned to reference particulate phosphorus flow weighted mean concentration ratios were higher after fire (≤ 2.8), whereas the total dissolved phosphorus ratios were not. The burned to reference particulate phosphorus export ratios increased more dramatically after fire (≤ 6.7) and again, the total dissolved phosphorus export ratios varied little from unity. Effects of fire on phosphorus export appeared to be associated with mechanisms related to export of the particulate phosphorus fraction during storm flows and were more dramatic in year two than year one.

Before the fire, the contribution of particulate phosphorus to total phosphorus export did not differ between the two streams during peakflow and baseflow. Therefore, data from the reference stream for all study years were pooled with pre-fire data from the burned stream to obtain an expected proportion for the peakflow and baseflow seasons. After the fire, particulate phosphorus comprised a higher than expected proportion of total phosphorus export in the burned stream during peakflow. During baseflow after the fire, there was no difference between the expected and observed contribution of particulate phosphorus to total phosphorus export in the burned stream. By 2000, particulate phosphorus accounted for only 42% of total phosphorus exported during the storm season in the reference stream, whereas it accounted for almost twice as much in the burned stream (79%). The contributions of particulate phosphorus to total phosphorus export were identical in the two streams during the baseflow period of 2000. The same patterns were observed when the particulate phosphorus proportion of the total phosphorus flow weighted mean concentrations was compared in an identical manner for the peakflow or baseflow periods. Thus, as a proportion of total phosphorus export and flow weighted mean concentrations, particulate phosphorus became more dominant after fire in the burned stream during the summer storm season.

In both streams, there were positive linear relationships between the log of total dissolved phosphorus and log of discharge, which could explain about 46% of the variation in total dissolved phosphorus concentration. In the burned stream, the slopes did not differ between the pre- and post-fire periods. In the reference stream, the total dissolved phosphorus *versus* the discharge slope was steeper after than before fire. The slope for the pooled burned stream data was steeper than the pre-fire line in the reference stream, but shallower than the post-fire line in the reference stream. Although there was no relationship between particulate phosphorus concentration and discharge in either stream at low discharge ($<1.5\ m^3 \cdot s^{-1}$), there was a positive relationship at discharge rates exceeding $1.5\ m^3 \cdot s^{-1}$, which explained 43 and 56% of the variation in particulate phosphorus concentration in the burned and reference streams, respectively. There was no difference between the slopes of the pre- and post-fire particulate phosphorus *versus* discharge line in either the burned or reference stream. The slopes of the particulate phosphorus *versus* discharge lines did not differ between streams, but points tended to cluster toward the high end of the graph in the burned stream after fire. The slope of the particulate phosphorus-discharge regression was five times steeper than the total dissolved phosphorus-discharge regression line in the burned stream and four to six times steeper than the total dissolved phosphorus-discharge regression lines in the reference stream. In both streams, the particulate phosphorus fraction of stream total phosphorus concentration increased at high discharge rates, whereas total dissolved phosphorus concentrations were similarly related across the observed discharge range.

KEY FINDINGS AND DELIVERABLES

The current study suggests that water and phosphorus exports increase during peakflow after a fire in a Boreal Plain upland watersheds. Changes in water export associated with fire cannot be attributed to regional precipitation patterns, because the maximum storm-season precipitation among the study years occurred in 1983 and parallel changes did not occur in the reference stream. Discharge increase after fire could be due to enhanced overland flow, that is, reduced interception of water by vegetation and reduced soil infiltration rates (Stark 1977; Beschta 1990; Whitson et al. 2003).

Although there does not appear to be a trend toward pre-fire conditions, the long-term effects of the Virginia Hills fire on water yield in the burned watershed (Sakwatamau A) remain to be seen. Vegetation recovery at the site has been slow. As of spring 2002, there was evidence of herbaceous and shrub growth, but tree recolonization was limited.

Particulate phosphorus export in the burned watershed was nearly seven times that in the reference watershed by 2000 and it remained a dominant fraction of total phosphorus export after the fire. This was not purely an artifact of more water moving through the burned watershed, since the burned to reference stream particulate phosphorus export ratio was more than two times the particulate phosphorus flow weighted mean concentrations ratio. In addition, in-stream primary production was probably a minor contributor to high particulate phosphorus exports after fire. During low flow periods, when one would expect planktonic producers to take advantage of the higher light conditions after tree removal, particulate phosphorus flow weighted mean concentrations were not higher. Instead one or a combination of enhanced overland flow or in-stream erosion due to higher bankfull flow discharges associated with forest removal (Verry 2000) probably contributed phosphorus-rich particulates to the sediment load. Field observations support the operation of both mechanisms in the burned stream. Channel erosion appears to have increased since 1998, with widespread stream bank slumping and formation of new channels in the streambed.

In the reference stream, discharge appeared to be lower in post-fire years than in 1983, thus there was likely particulate phosphorus accumulation in the watershed and little opportunity for flushing. Conversely, as a disturbed landscape, the burned watershed had higher particulate phosphorus mobility during periods of high discharge. Similar to water export, there does not appear to be a trend toward pre-fire conditions in particulate phosphorus export patterns after more than two years post-fire. Most of the higher total phosphorus export in the burned watershed can be attributed to higher particulate phosphorus export during storm events, due to discharge-driven erosion of watershed soils and/or stream sides.

Thus, forest fires can alter the chemistry and biology of aquatic systems. Based on the results from this study and the TROLS lake study (Prepas et al. 2001b), as well as a parallel studies on the Boreal Shield, we conclude that fire and forest harvesting (Prepas et al. 2003b) have divergent effects on water chemistry, with potentially substantial consequences on biodiversity in fresh waters.

RESEARCH CONTRIBUTIONS IN ADVANCEMENT OF FIELD

1. This study supports the hypothesis that wildfires have profound effects on water yield and nutrient export in the potentially phosphorus-rich streams on the Boreal Plain. Prior to the 1998 Virginia Hills fire, few opportunities existed on the Boreal Plain to support this hypothesis.
2. This research initiative has trained and educated highly qualified personnel including graduate students, research associates and technical staff in the area of watershed disturbance.

MANAGEMENT IMPLICATIONS

1. The Virginia Hills study represents the first aquatic study involving wildfire in watersheds with merchantable trees situated on the Boreal Plain.
2. The study of wildfire in the two Virginia Hills streams brings to completion the original thrust of the western aquatic portion of the Sustainable Forest Management Network of Centres of Excellence.
3. On the Boreal Plain, increases in surface water nutrient content are to be expected in disturbed watersheds in merchantable tree habitat.
4. Forest Mangers will soon face the challenge of modelling the biological implications of landscape and forest management practices to freshwater communities.
5. Sustainable forest management on the Boreal Plain must be linked with watershed processes, with a focus on nutrient dynamics and bioindicators.

FOLLOWUP

A new initiative is underway in co-operation with industrial and academic partners, to link critical watersheds and the detailed forest management planning processes. Please refer to http://forward.lakeheadu.ca/. This will be the first initiative to use water quality as an indicator in sustainable forest management practices.

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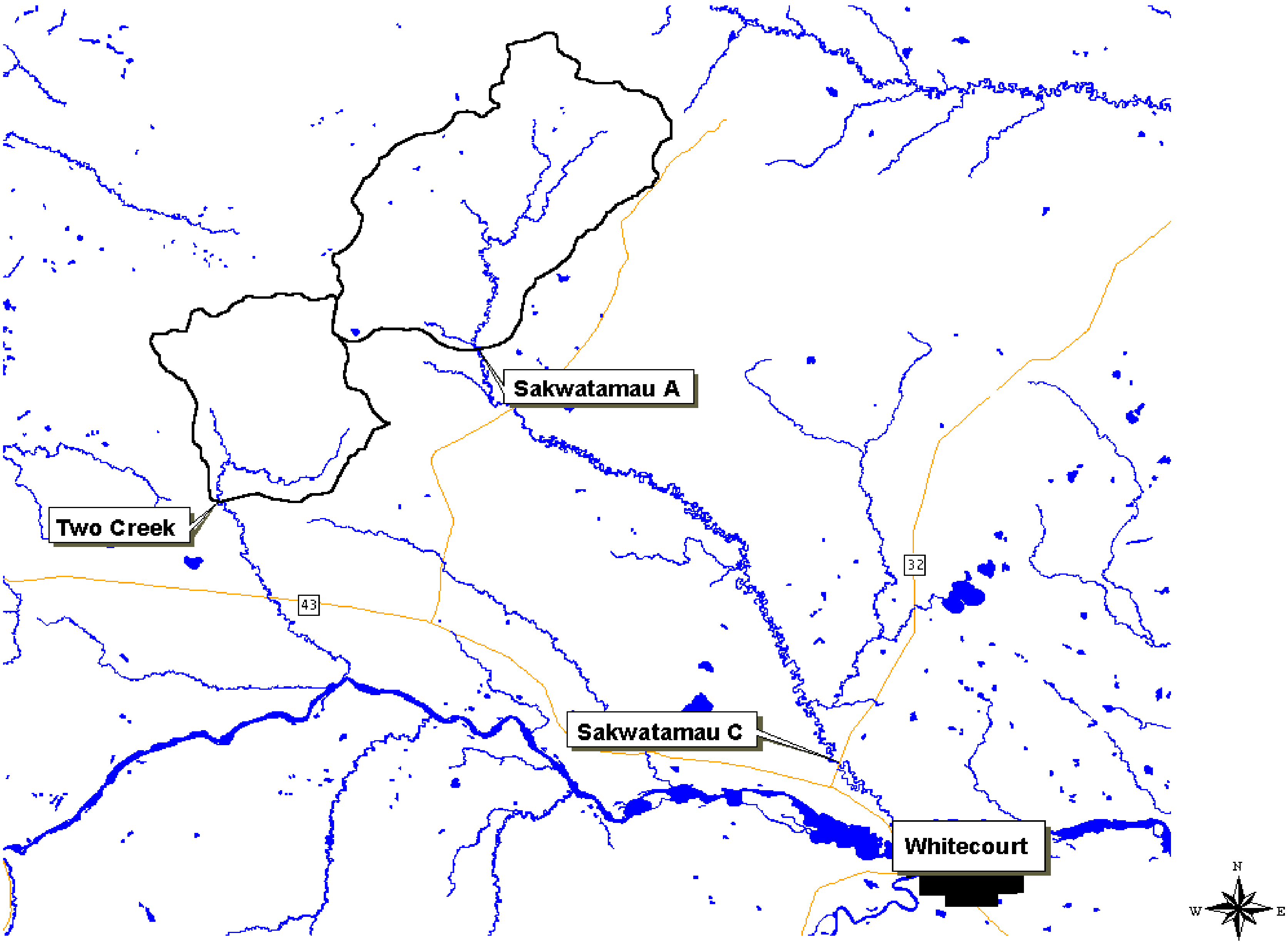
FIGURE CAPTIONS

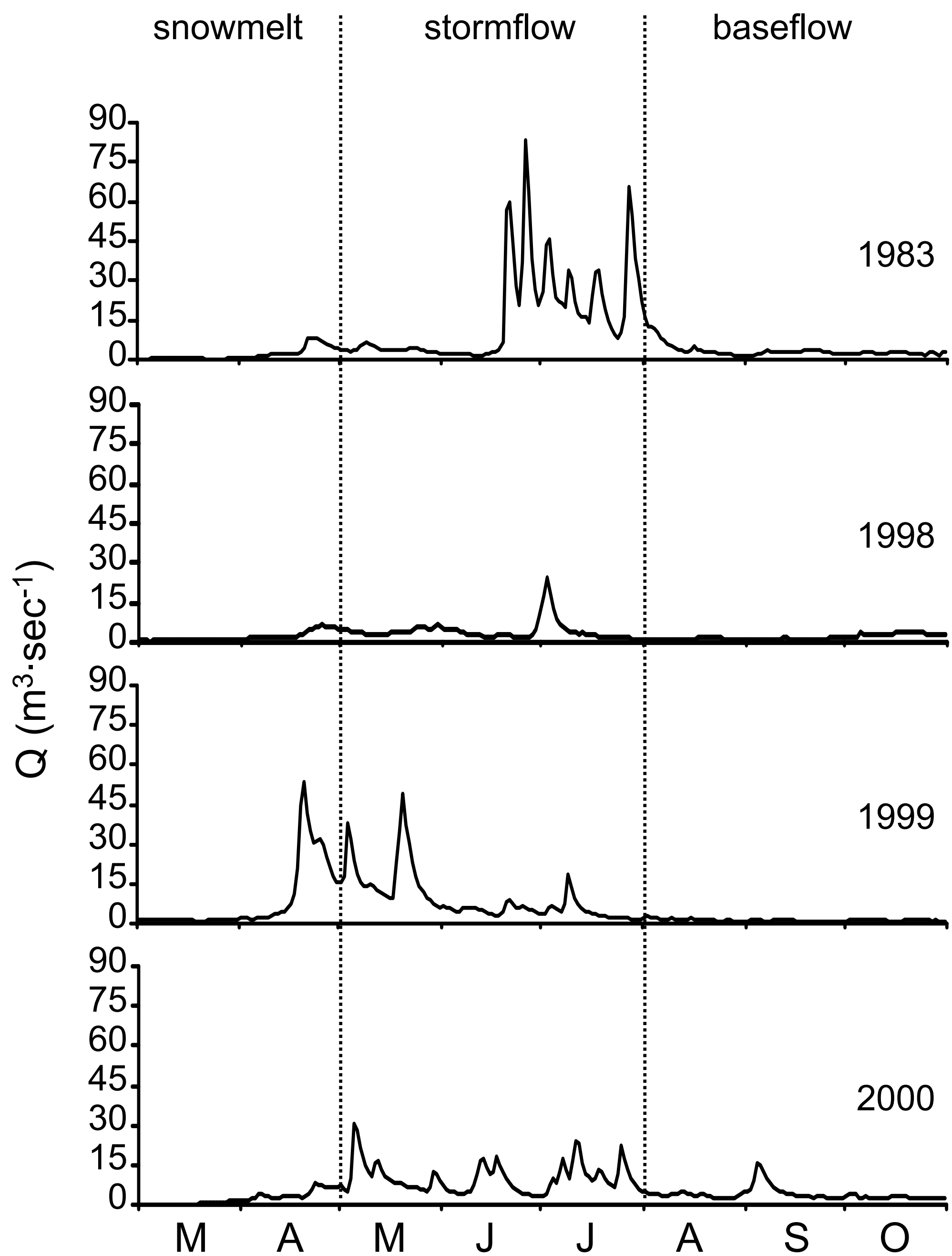
Figure 1: Study area within the Swan Hills, AB.

Figure 2: Discharge (Q) for the permanently gauged site for seasons dominated by snowmelt (Mar. through Apr.), stormflow (May through July) and baseflow (August through October).

Figure 3: Total precipitation during the winter (November through April), early-summer storm season (May through July), and baseflow season (August to October) for the Whitecourt, AB weather station.



Sakwatamau A
Two Creek
43
32
Sakwatamau C
Whitecourt
N
W
E
S


snowmelt
stormflow
baseflow
Q (m³·sec⁻¹)
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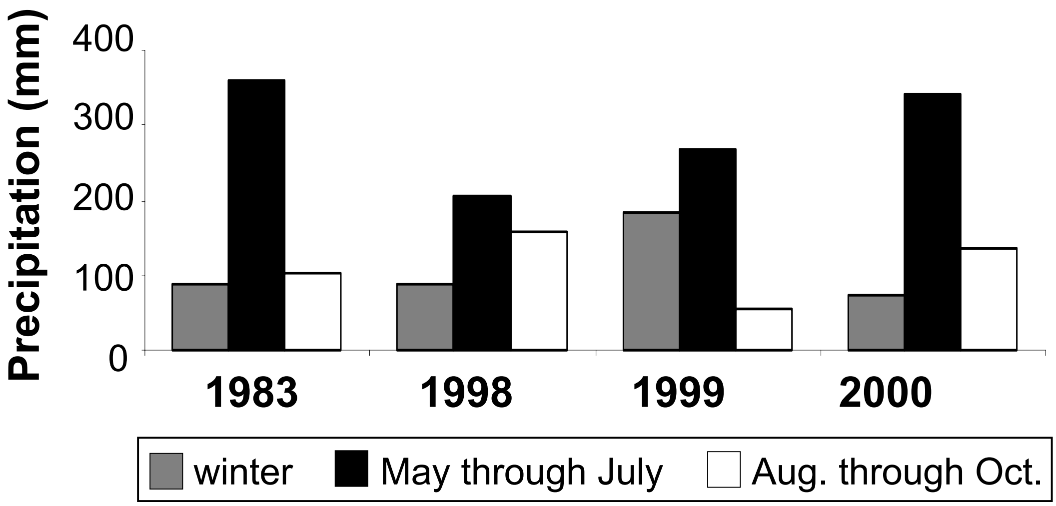
75
60
45
30
15
0
1983
1998
1999
2000
M
A
M
J
J
A
S
O


Precipitation (mm)
400
300
200
100
0
1983
1998
1999
2000
winter
May through July
Aug. through Oct.