# Impact of wildfire on discharge and phosphorus export from the Sakwatamau watershed in the Swan Hills, Alberta, during the first two years[1]

**E.E. Prepas, J.M. Burke, D.S. Chanasyk, D.W. Smith, G. Putz, S. Gabos, W. Chen, D. Millions, and M. Serediak**

**Abstract:** Water and phosphorus (P) exports during the peakflow season increased after a fire in early summer 1998 burned 89% of an upland watershed on the Boreal Plain of western Canada. The change in water export between pre- (1983) and post-fire (1998 to 2000) periods was higher in the burned (4th order) than reference stream (3rd order) ($P = 0.01$). Burned to reference stream ratios of particulate P (PP) flow-weighted mean concentrations (FWMC) and export were 1.5 and 2.8, respectively, in year 1 and 2.8 and 6.7, respectively, in year 2 post-fire. Particulate P comprised a similar proportion of total P export in the burned stream before fire and in the reference stream (65%), but a higher proportion after fire during the peakflow season only (77%) ($P < 0.02$). Phosphorus concentration and discharge ($Q$) were positively related in both streams, across all $Q$ intensities measured in the case of dissolved P, but only at $Q > 1.5$ m$^3$ s$^{-1}$ for PP. Changes in P export after fire were evident during peakflow and were largely restricted to the PP fraction. These changes appear to be driven by higher discharge, which enhanced loading of P-rich particulates from the watershed and (or) from the stream channel.

*Key words:* watershed disturbance, watershed management, stream, water quality, fire, phosphorus, discharge.

**Résumé :** Les exportations d'eau et de phosphore (P) durant la saison de débits de pointe ont augmenté après un feu au début de l'été 1998 qui a brûlé 89 % d'un bassin hydrographique des hautes terres des plaines boréales dans l'Ouest canadien. Le changement dans l'exportation d'eau entre les périodes avant (1983) et après le feu (1998 à 2000) était plus élevé dans les zones brûlées (4$^e$ ordre de grandeur) que dans le ruisseau de référence (3$^e$ ordre de grandeur) ($P = 0,01$). Les rapports des concentrations moyennes de P particulaire (PP) pondérées selon le débit dans les zones brûlées par rapport au ruisseau de référence et l'exportation étaient respectivement de 1,5 et de 2,8 dans la première année après le feu et respectivement de 2,8 et 6,7 dans la deuxième année. Le PP comprenait une proportion similaire d'exportation de P total avant le feu dans le ruisseau de la zone brûlée et dans le ruisseau de référence (65 %), mais une proportion plus élevée après le feu durant la saison de débits de pointe uniquement (77 %) ($P < 0,02$). La concentration de P et le débit d'évacuation ($Q$) étaient associés positivement dans les deux ruisseaux, pour toutes les débits $Q$ mesurés dans le cas de P dissous, mais seulement à $Q > 1,5$ m$^3$ s$^{-1}$ pour PP. Les changements dans l'exportation de P après le feu étaient évidents durant les débits de pointe et étaient largement restreints à la fraction PP. Ces changements semblent être causés par un débit supérieur, ce qui augmente la charge en particules riches en P provenant du bassin hydrographique et (ou) du lit du ruisseau.

*Mots clés :* perturbation des bassins hydrographiques, gestion des bassins hydrographiques, ruisseau, qualité de l'eau, feu, phosphore, débit d'évacuation.

[Traduit par la Rédaction]

Received 22 May 2002. Revision accepted 25 February 2003. Published on the NRC Research Press Web site at http://jees.nrc.ca/ on 1 October 2003.

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Written discussion of this article is welcomed and will be received by the Editor until 31 December 2003.

[1]This article is one of a selection of papers published in this Supplement from the inaugural Workshop on the Forest Watershed and Riparian Disturbance Project, Whitecourt, Alberta, May 2001.
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 doi: 10.1139/S03-036 

## Introduction

Canada's western boreal forest is dominated by the Boreal Plain subregion. The Boreal Plain is a relatively dry (mean annual precipitation ~600 mm $a^{-1}$) mixed-wood forest in a low-relief area (mean watershed slope <4%; Prepas et al. 2001*b*), with a thick overburden of phosphorus- (P) rich soils and glacial materials overlying sedimentary bedrock. Wildfires are an important natural disturbance in forests in this subregion (Government of Alberta 2001). Wildfire likely has profound effects on water yield and nutrient export in the potentially P-rich streams on the Boreal Plain, yet these processes are poorly understood. They are complicated by different watershed – surface water relationships in upland- (generally <25% wetland) versus lowland-dominated (generally >25% wetland) watersheds (Prepas et al. 2001*b*). Undisturbed wetlands in upland watersheds tend to be rich fens that sequester inorganic P as calcium and magnesium phosphates (Reddy et al. 1999; Prepas et al. 2001*b*). Conversely, wetlands in lowland watersheds tend to be bogs that release P (Prepas et al. 2001*b*). Thus, mechanisms that mediate the quantity and quality of water exported after wildfire likely differ between upland- and lowland-dominated watersheds on the Boreal Plain.

The effects of wildfire on surface-water nutrient concentrations in upland watersheds on the Boreal Plain have not been determined. Other disturbances such as agriculture and forest harvest have resulted in increased surface-water P concentrations (Cooke and Prepas 1998; Prepas et al. 2001*a*). Following fire, some upland-dominated watersheds on the eastern Boreal Shield had enhanced P export for 3 years or more (Carignan et al. 2000), whereas P export was little changed in others (Bayley et al. 1992). Streams in lowland bog-dominated watersheds on the Boreal Shield, Boreal Subarctic and Boreal Plain exported 2- to 7-fold more P following fire (Bayley et al. 1992; McEachern et al. 2000; P.A. Chambers, NHRI, Saskatoon, Sask, unpublished report.). In wetland-dominated sites such as these, increased P export is probably linked to changes in the water-table level that enhance saturation and removal of organic P (Reddy et al. 1999; Carignan et al. 2000; McEachern et al. 2000). Under these conditions, changes in export of the dissolved P fraction (TDP) should be detectable. However, these mechanisms of saturation and P removal are probably not important in upland-dominated watersheds.

Instead, erosion of watershed soils and stream banks exerts the strongest influence on P export rates in upland-dominated watersheds in forested regions in general (Omernik 1977) and on the Boreal Plain (Munn and Prepas 1986; Cooke and Prepas 1998). Normally landscapes on the Boreal Plain are relatively nonerosive due to low relief. However, infiltration may be impeded in fine-textured Gray Luvisolic soils (Whitson et al. 2003), and rapid increases 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). Therefore, although particulate movement is generally positively related to watershed slope (Prairie and Kalff 1986; Byron and Goldman 1989), particulate flushing can occur in low-relief areas when snowmelt or rain cause an increase in overland flow. Further, in-channel erosion can increase the particulate load in a stream during periods of high flow.

Export of P is intimately linked to precipitation and associated discharge ($Q$) patterns on the Boreal Plain, as in other (e.g., Feller and Kimmins 1984; Byron and Goldman 1989) but not all (e.g., Meyer and Likens 1979) cool forested regions. For example, at the Sakwatamau River, Alberta, 62% of the annual rainfall and 60% of the annual water export occurred during the May through July period (mean 1972–1997) (Environment Canada 2000). During the same period, 91% of the annual total P (TP) export was recorded (Munn and Prepas 1986). On the Boreal Plain, higher $Q$ rates should be associated with tree removal by wildfire (Hibbert 1965). These should be associated with higher sediment loads from burned watersheds (e.g., Schindler et al. 1980; Bayley et al. 1992; Lamontagne et al. 2000) and from enhanced in-channel erosion processes (e.g., Minshall et al. 2001).

The wildfire that occurred in the Virginia Hills regions of the Swan Hills, Alta, in late May through early June 1998 (for details of the fire, see Smith et al. 2003) presented an opportunity to investigate effects of fire on water yield and nutrient export from an upland-dominated watershed. As a component of the Forest Watershed and Riparian Disturbance (FORWARD) (Smith et al. 2003) project, the focus of this study was to evaluate effects of wildfire as a natural disturbance on stream water quality and quantity. Approximately 89% of the forested Sakwatamau River watershed was burned upstream of the sampling site (Sakwatamau A) used during an intensive 1983 study on seasonal patterns of P export (Munn 1984; Munn and Prepas 1986) (Fig. 1). An adjacent forested watershed (Two Creek) was also part of the 1983 study, but was not burned in 1998. In addition, Two Creek lies to the west of the Sakwatamau A watershed and prevailing winds are westerly, thus there was little potential for advection of particulates toward the reference stream during the fire.

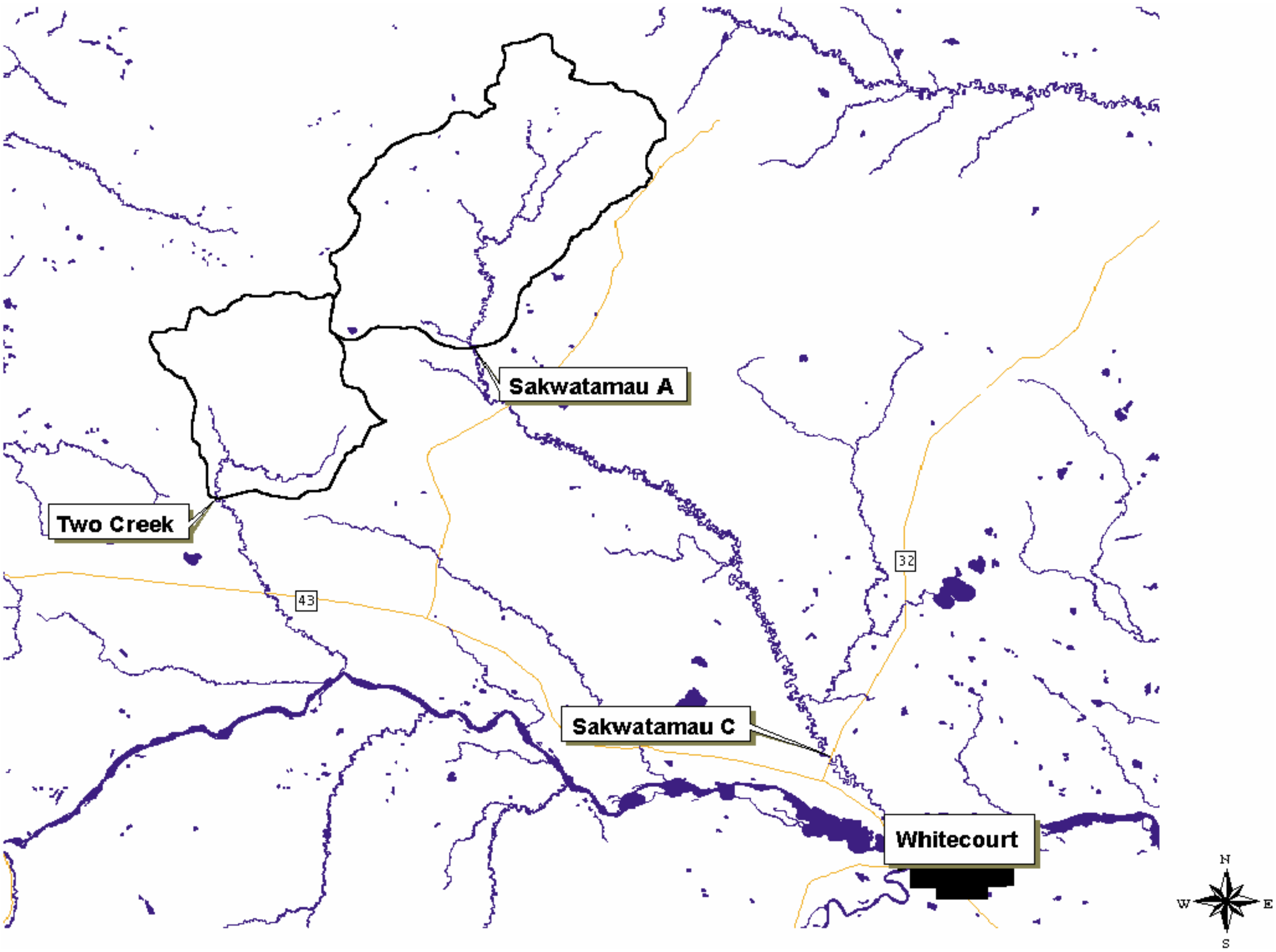
The goal of this project was to compare water and P export from the burned (Sakwatamau A) watershed after the 1998 fire to pre-disturbance exports and to the reference (Two Creek) watershed. We hypothesized that both water and P yields would be higher in the burned watershed after fire. Flow to the stream channel should have increased during storm events, bringing particulates from the watershed and enhancing in-channel erosion; therefore, we expected that particulate P (PP) export would be more affected than TDP export, especially during the summer storm season. Finally, whereas some Boreal Shield watersheds tend to begin recovery toward pre-fire P export levels within at most 3 years (Schindler et al. 1980; Bayley et al. 1992), we expected effects of longer duration on the Boreal Plain due to a drier (Miller et al. 1997) cooler climate. The mean July temperature for the Swan Hills ranges from 10 to 15 °C, versus 15 to 20 °C on the Shield (Hydrological Atlas of Canada 1978). We compare data collected during May through Oct. of 1983 (pre-fire) to results from 1998 (immediately post-fire), 1999, and 2000 (1 and 2 years post-fire). We assume data for 1983 to be representative of the pre-fire period.

## Methods

### Study area

The Sakwatamau and Two Creek watersheds are located in the Virginia Hills region of the Swan Hills in central Alberta (Fig. 1). The channel beds are located in sedimentary shale, sandstone, and mudstone of the Paskapoo formation (Paleocene) (Knapik and Lindsay 1983). Watershed soils are mineral rich Luvisols underlain by 3–5 m of glacial till over bedrock,

**Fig. 1.** Study area within the Swan Hills, Alta.




whereas soils along the streams are Organics and Gleysols (Knapik and Lindsay 1983). The vegetation is similar in the two watersheds and composed of mixed-wood boreal forest dominated by white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*). Shrubs include willows (*Salix* spp.), wild rose (*Rosa acicularis*), river alder (*Alnus tenufolia*), and various berries (Munn and Prepas 1986).

Precipitation, air temperature, evaporation, and $Q$ data for the Sakwatamau C site were obtained from Environment Canada (Canadian Climate Centre, Data Management Division, Downsview, Ont.). The regional climate is dry continental with a prolonged (Nov. through Mar.) winter season. Historical (1972–1997) mean monthly air temperatures ranged from −23.5 to 2.3 °C in winter and from 0.1 to 17.5 °C during the ice-free season (~Apr. through Oct.). Historical mean annual precipitation for the Nov. 1 through Oct. 31 water year was 584 mm, 30% of which fell as snow. Mean annual precipitation for 1983 was 6% below this average (550 mm), whereas for 1998, 1999, and 2000 it was 23%, 13%, and 6% below the average (452, 506, and 548 mm, respectively). The average long-term (1972–1997) evaporation rate for this region was 525 mm $a^{-1}$. An average of 62% of the rainfall occurred from May through July and 35% from Aug. through Oct. In general, stream flow was monitored from Mar. through Oct., and runoff measured at the permanently gauged reach downstream of the study sites (Sakwatamau C, drainage basin area (DBA) = 1127 $km^2$) (Fig. 1) for this time period in 1983, 1998, 1999, and 2000 was 145, 53, 115, and 110 mm $a^{-1}$, respectively. The relationship between total annual precipitation and runoff measured at Sakwatamau C from 1972 to 1997 (precipitation = 1.5× runoff + 366, $r^2 = 0.47$; $P < 0.0001$) suggests that in this region, when precipitation is less than 366 mm $a^{-1}$, annual runoff could theoretically be zero. Variation from the predicted line reflects variation due to time series factors related to the precipitation history of the basin.

The study streams drain into the Athabasca River (Fig. 1). The Sakwatamau River is a 4th order stream at the Sakwatamau A sampling site (relocated 6 km upstream of the 1983 site to abut the edge of the burn) and Two Creek is 3rd order. Both streams have very shallow channel slopes (Table 1). The maximum elevation of burned watershed is slightly higher than the reference watershed, but the sample sites are at similar elevations. The DBA of Sakwatamau A is 1.9 times that of Two Creek. Drainage densities (0.37 and 0.34 $km^{-1}$, respectively) and water chemistry were similar prior to disturbance: both were alkaline (pH 8.1) bicarbonate-buffered systems with moderate colour

**Table 1.** Physical characteristics of the study watersheds.

| Watershed | Drainage basin area* ($km^2$) | Channel slope (%) | Area burned (%) | Area salvage logged (%) | Wetland area (%) | Min/max elevation (m) |
|---|---|---|---|---|---|---|
| Burned | 248 | 0.34 | 89 | 10 | 1.2 | 894/1225 |
| Reference | 131 | 0.45 | 0 | 0 | 3.2 | 890/1100 |

*Recalculated after Munn and Prepas (1986) study using digital mapping techniques.

(58 mg Pt $L^{-1}$) (Munn and Prepas 1986). Total nitrogen to TP ratios of 27 (Sakwatamau A) and 22 (Two Creek) before fire indicated P limitation (Munn and Prepas 1986). There was no beaver activity noted during the study years on the sampled stream reaches.

### Discharge and nutrient chemistry

One reach at each of Sakwatamau A and Two Creek was monitored for stream *Q* and water quality. With the exception of the May through July period of 1998 (during fire), gauge height was measured approximately twice weekly with a staff gauge installed at the beginning of the open-water season. Stream *Q* was determined weekly by measuring current velocity and water depth at 0.5-m intervals across each stream channel with a Price AA (1983) or Gurley pygmy (1998 through 2000) current meter. For dates when only stage height was measured, *Q* was calculated based on the relationship between gauge height and instantaneous stream *Q*. Rating curves were generated annually for each site based on continuous *Q* data from the Environment Canada gauging station at site Sakwatamau C to the study sites (standard error of regressions $< 0.2$).

At each stream site, grab water samples were collected in the middle of the stream at 0.5–0.7 times depth in acid-washed Nalgene bottles. From Apr. through Oct. 1983 (pre-fire year), grab samples were collected at least twice each day during baseflow (Munn and Prepas 1986). From Aug. through Oct. (immediately after fire in 1998) and from Apr. through Oct. (1999, 2000), grab samples were collected once or twice weekly. In addition to these grab samples, automated Isco samplers operated from Apr. through Oct. (1983, 1999, and 2000) and from Aug. through Oct. (1998) to collect samples more intensively during storm events. The Isco samplers were programmed for collection every 4 to 8 h and samples were pooled into 16- to 24-h composites. Water samples were stored on ice in the field and at 4 °C in the laboratory prior to analysis. Samples were analyzed for TP and TDP ($< 0.45 \mu m$) concentration ($\mu g\ L^{-1}$) with the modified (Prepas and Rigler 1982) potassium persulfate method (Menzel and Corwin 1965). Particulate P concentration was calculated as the difference between TP and TDP. Laboratory analyses were conducted with the same methods as described in Munn and Prepas (1986).

### Data analysis

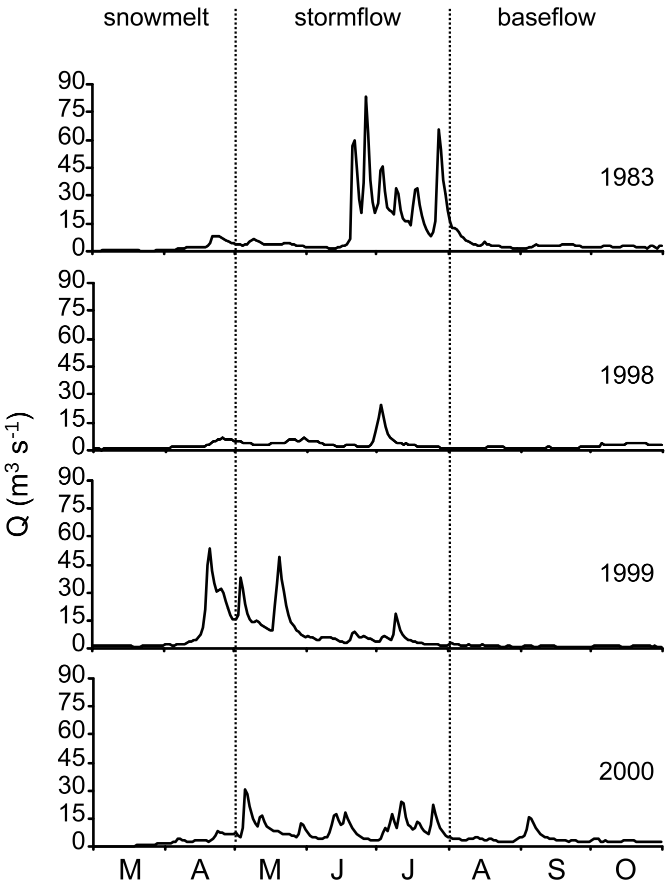
Drainage basin areas were estimated from geographic information system (GIS) databases and compared against 1:50 000 topographic maps (Canada Centre for Mapping, Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa, Ont.). Channel slopes were estimated from 25-m interval contour maps provided by Millar Western Forest Products (Edmonton, Alta). At this resolution, these may be overestimates. Percent disturbance and wetland area were interpolated from GIS maps. Daily P export was calculated as the product of measured or estimated (linear interpolation between sampling dates) P concentration and *Q* for each day (as in Munn and Prepas 1986; Cooke and Prepas 1998). Since there was a relationship between P concentration and *Q*, linear interpolation tended to underestimate P concentrations during storm events. Therefore, in the event that Isco failures or site inaccessibility prevented sample collection during a storm, P concentrations were estimated from the P concentration–*Q* relationship. This peak interpolation was done for approximately 40% of storm events during post-fire years and was not required during the pre-fire year. Water export coefficients for the May through July (storm dominated) and Aug. through Oct. (baseflow dominated) periods were calculated by dividing the total export for each period by the watershed area above the sampling site. Flow-weighted mean concentrations (FWMC; $\mu g\ L^{-1}$) for a given time period were calculated as the sum of the daily P export divided by the sum of the daily *Q* for that time period. Export coefficients and FWMC were not calculated for the storm-dominated season during 1998 because of the fire.

For all statistical tests, alpha was designated as 0.05. Water export coefficients were highly variable, which meant that between-watershed differences in export coefficient were not detectable when all study years were compared. Therefore, within each of the two watersheds, the difference between coefficients for the pre-fire year (1983) and each post-fire year (1998–2000) was calculated, and then compared between watersheds with a Student's *t* test (df = 2 (peakflow) or 4 (baseflow)). The chi-square goodness-of-fit test was used to compare the observed proportion of PP in TP export at the burned site and observed water exports from both sites to expected proportions (df = 1). Discharge and P concentrations were log transformed and regression coefficients for P–*Q* relationships compared with Student's *t* tests (Zar 1996).

## Results

At the permanently gauged site (Sakwatamau C), the May through July period was characterized by peakflow associated with summer storms, whereas from Aug. through Oct., baseflow was dominant (Fig. 2). Stormflow was higher in the pre-fire year (1983) than for the post-fire years; peak *Q* was measured in 1983 ($Q_{max} = 84\ m^3\ s^{-1}$). 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 ($Q_{max} = 25\ m^3\ s^{-1}$). 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

**Fig. 2.** Discharge ($Q$) for the permanently gauged site for seasons dominated by snowmelt (Mar. through Apr.), stormflow (May through July) and baseflow (Aug. through Oct.).




volume exported in 1983, 1999, and 2000, respectively. Peakflow periods were spread out through the open-water season in 2000 ($Q_{max} = 31\ m^3\ s^{-1}$), whereas they occurred earlier in the season in 1999 ($Q_{max} = 54\ m^3\ s^{-1}$). This year was also remarkable in that snowmelt in Mar. and Apr. 1999 was a stronger contributor to annual runoff (34%) than in the other study years (6% to 17%; Fig. 2) due to high snowfall (Fig. 3). However, the early May stormflow peak in 1999 can be attributed to heavy rains (37 mm) on May 1 and 2.

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 (Aug. through Oct.) (Fig. 4). From 77% to 91% of the $Q$ from May through Oct. 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. This is similar to the size of the burned watershed relative to Sakwatamau C (22%). 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 22% (chi square, $P < 0.001$). The reference stream exported 28 378 dam$^3$ of water during May through July 1983, which represents 23% of that exported from Sakwatamau C. In 1999 and 2000, water export from the reference watershed was 18% and 19% of that

**Fig. 3.** Total precipitation during the winter (Nov. through Apr.), early-summer storm season (May through July), and baseflow season (Aug. to Oct.) for the Whitecourt, Alta., weather station.

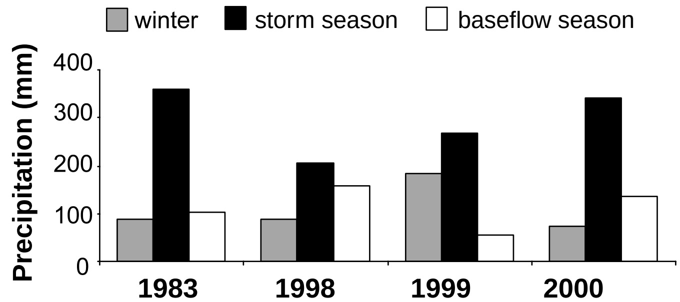
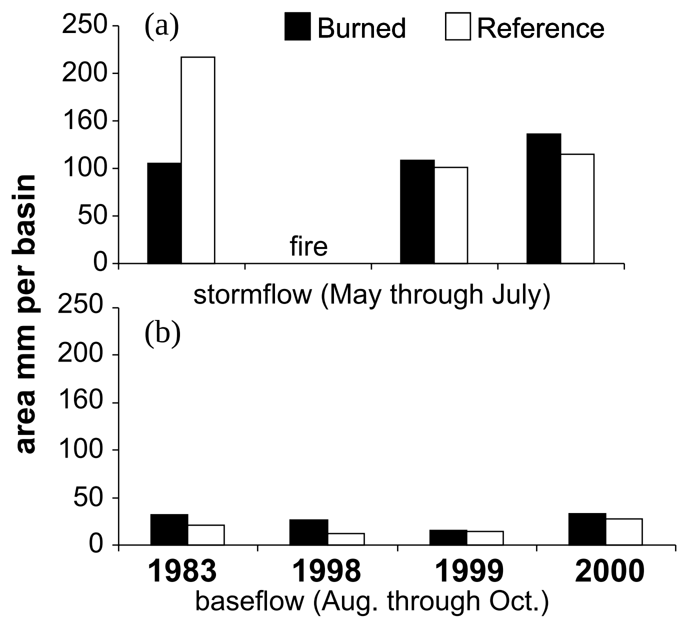



**Fig. 4.** Total water export for the early-summer storm season and baseflow season in the study streams.




from Sakwatamau C, which did not differ from the expected proportion ($P > 0.3$). 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 (Fig. 4). Runoff in the region tended to decline between 1983 and the post-fire years (E.E. Prepas, unpubl. data). However, the trend in the burned stream was opposite; runoff increased after fire relative to 1983. Thus, the response in $Q$ from the burned stream was different than the reference stream under the same regional precipitation regime (Fig. 3). The difference in water export between the pre- and post-fire yrs within each watershed was detectable when the two study streams were compared ($t$-test, df $= 2$, $P = 0.01$) (Fig. 4). In the burned stream, there was a slight increase in water export for the May through July

**Table 2.** Total export and flow weighted mean concentrations (FWMC) of total dissolved (TDP) and particulate phosphorus (PP) in the study streams.

| Year | | Total Export (kg) Burned | Reference | Burned:Reference | FWMC ($\mu$g L$^{-1}$) Burned | Reference | Burned:Reference |
|---|---|---|---|---|---|---|---|
| Baseflow period (Aug. through Oct.) | | | | | | | |
| 1983 | TDP | 83.0 | 29.5 | 2.81 | 10.2 | 9.9 | 1.03 |
| | PP | 53.9 | 24.7 | 2.18 | 6.2 | 7.6 | 0.82 |
| 1998 | TDP | 70.9 | 13.7 | 5.18 | 9.7 | 8.1 | 1.20 |
| | PP | 54.9 | 13.4 | 4.09 | 9.2 | 8.6 | 1.07 |
| 1999 | TDP | 26.9 | 13.4 | 2.01 | 7.1 | 7.2 | 0.99 |
| | PP | 30.5 | 16.2 | 1.88 | 7.9 | 8.8 | 0.90 |
| 2000 | TDP | 175 | 68.6 | 2.55 | 18.5 | 17.8 | 1.04 |
| | PP | 59.2 | 22.3 | 2.65 | 6.1 | 6.2 | 0.98 |
| Summer storm period (May through July) | | | | | | | |
| 1983 | TDP | 417 | 481 | 0.87 | 15.4 | 15.7 | 0.98 |
| | PP | 1492 | 1489 | 1.00 | 46.7 | 42.0 | 1.11 |
| 1998 | TDP | ND | ND | ND | ND | ND | ND |
| | PP | ND | ND | ND | ND | ND | ND |
| 1999 | TDP | 348 | 206 | 1.69 | 11.5 | 13.6 | 0.85 |
| | PP | 1021 | 362 | 2.82 | 29.0 | 19.2 | 1.51 |
| 2000 | TDP | 564 | 430 | 1.31 | 15.9 | 26.8 | 0.59 |
| | PP | 2118 | 316 | 6.70 | 58.5 | 20.9 | 2.80 |

**Note:** ND, no data collected during fire. 1983 data from Munn 1984, Munn and Prepas 1986.

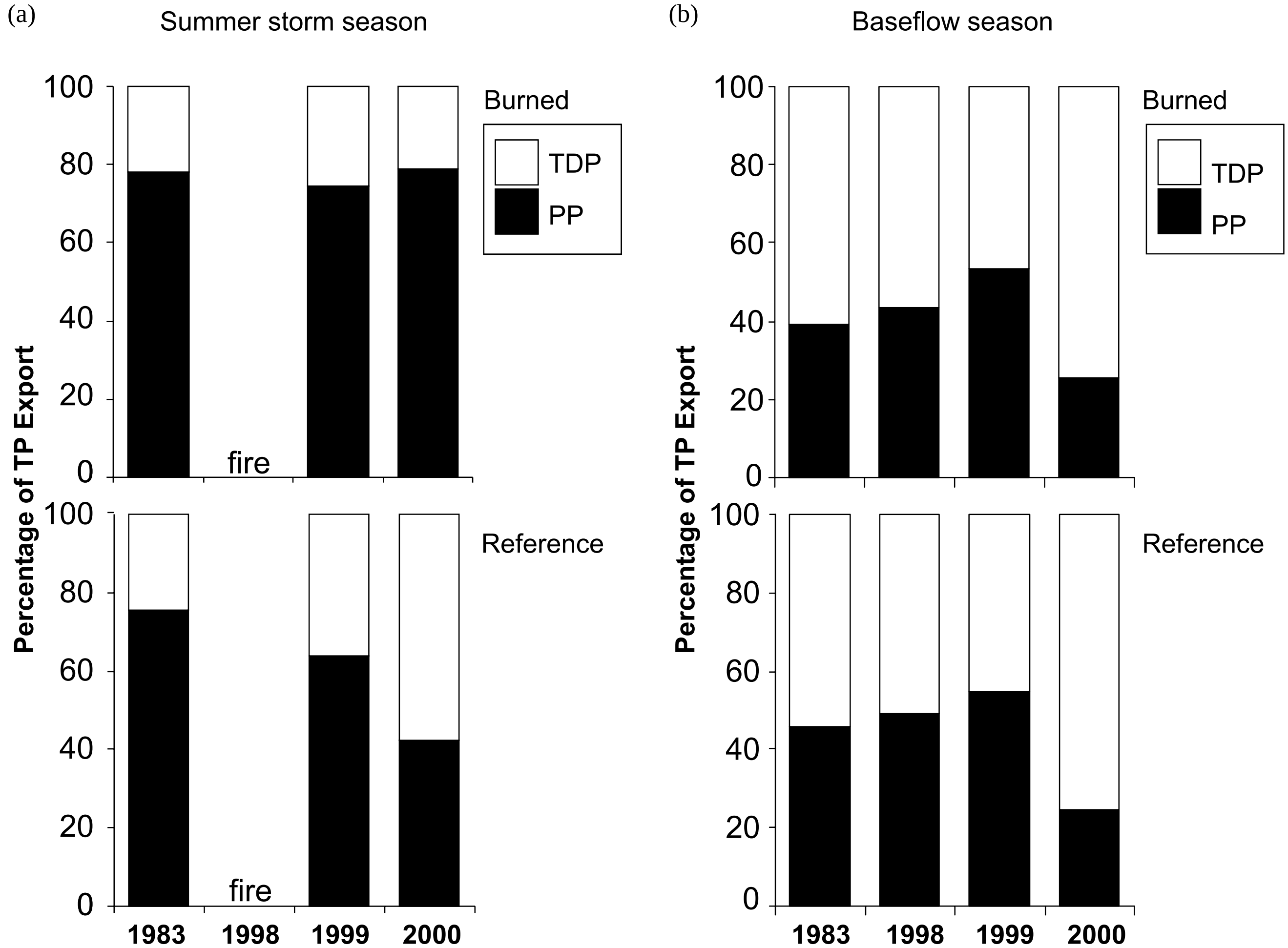
period ($17 \pm 14$ dam$^3$ km$^{-2}$; mean $\pm$ standard error) and in the reference stream there was a strong decrease ($-108 \pm 7$ dam$^3$ km$^{-2}$), despite a trend for rainfall to increase each year after the fire (Fig. 4). No difference was detectable when within-watershed changes in water export were compared in the same manner for the baseflow period ($P > 0.5$). 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 P composition of the water in the two streams was similar during baseflow periods; the burned to reference TDP and PP FWMC ratios were within 20% of unity during all study years (Table 2). Burned to reference ratios of TDP and PP export during baseflow were similar to the DBA ratio of the two basins ($\sim 2$) during all study years, with the exception of the period immediately after fire in 1998 when ratios of both fractions increased. Before fire, the FWMC, 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 PP FWMC ratios were higher after fire ($\leq 2.8$), whereas the TDP ratios were not. The burned to reference PP export ratios increased more dramatically after fire ($\leq 6.7$) and again, the TDP export ratios varied little from unity. Effects of fire on P export appeared to be associated with mechanisms related to export of the PP fraction during storm flows and were more dramatic in year 2 than year 1.

Before the fire, the contribution of PP to TP export did not differ between the two streams during peakflow and baseflow (chi-square; $P > 0.5$ and $P > 0.1$, respectively) (Fig. 5). 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 (PP$= 65 \pm 3$%; $n = 4$) and baseflow seasons (PP$= 42 \pm 5$%; $n = 5$). After the fire, PP comprised $77 \pm 2$% of TP export in the burned stream during peakflow, which was higher than the expected proportion ($P < 0.02$) (Fig. 5*a*). During baseflow after the fire, there was no difference between the expected and observed contribution of PP to TP export in the burned stream (observed $= 39 \pm 14$%, $P > 0.5$) (Fig. 5*b*). By 2000, PP accounted for only 42% of TP exported during the storm season in the reference stream, whereas it accounted for almost twice as much in the burned stream (79%; $P < 0.0001$) (Fig. 5*a*). The contributions of PP to TP export were identical in the two streams during the baseflow period of 2000 (Fig. 5*b*). The same patterns were observed when the PP proportion of the TP FWMC was compared in an identical manner for the peakflow or baseflow periods (data not shown). Thus, as a proportion of TP export and FWMC, PP became more dominant after fire in the burned stream during the summer storm season.

In both streams, there were positive linear relationships between logTDP and log$Q$ ($P < 0.0001$) (Fig. 6), which could explain about 46% of the variation in TDP concentration. In the burned stream, the slopes did not differ between the pre- and post-fire periods (*t*-test comparing slopes of regressions, $P > 0.5$), thus a single regression line represents the pooled data. In the reference stream, the TDP versus $Q$ slope was steeper after than before fire ($P = 0.0002$). 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 ($P = 0.04$ in both cases). Although there was no relationship between PP concentration and $Q$ in either stream at low $Q$ ($< 1.5$ m$^3$ s$^{-1}$), there was a positive relationship at $Q$ rates exceeding 1.5 m$^3$ s$^{-1}$ ($P < 0.0001$), which explained 43% and 56% of the variation in PP concentration in the burned and reference streams, respectively, (Fig. 7). There was no difference between the slopes of the pre- and post-fire PP versus $Q$ line in either the burned or reference stream ($P > 0.1$). The slopes of the PP versus $Q$ lines did not differ between streams

**Fig. 5.** Proportion of total phosphorus export in the dissolved (TDP) and particulate (PP) fractions for the (*a*) early-summer storm season (May through July) and (*b*) baseflow season (Aug. through Oct.) in the study streams.




($P$ > 0.5), but points tended to cluster toward the high end of the graph in the burned stream after fire (hollow symbols). The slope of the PP–$Q$ regression was 5 times steeper than the TDP–$Q$ regression line in the burned stream and 4 to 6 times steeper than the TDP–$Q$ regression lines in the reference stream ($P$ < 0.0001). In both streams, the PP fraction of stream TP concentration increased at high $Q$ rates, whereas TDP concentrations were similarly related across the observed $Q$ range.

## Discussion

Within the burned watershed (Sakwatamau A), the post-fire period was associated with higher water export during the summer storm season relative to the pre-fire period and compared to the reference watershed (Two Creek). On an areal basis, water export from the burned watershed was half that from the reference watershed before fire, but it was similar after fire. Further, water export from the burned watershed relative to the permanently gauged site was proportional to their relative DBA before fire, but it exceeded this value after fire. 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. High $Q$ 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). In the pre-disturbance state, the burned watershed may have had smaller contributing areas (zones that contribute to runoff; Soranno et al. 1996) or more leakage to groundwater than the reference watershed. Whether temporal or spatial alterations to contributing areas and subsurface flow patterns were induced by fire is not known, but the hydrologic component of the FORWARD project will help to elucidate some of these mechanisms in the study watersheds.

The initial increases in water yield observed in this study agree with Schindler et al. (1980), who saw a dramatic (70%) increase in water yield from a burned upland-dominated sub-basin relative to an unburned sub-basin 1 year after a fire on the Boreal Shield. However, whereas water yields were still increasing in year 2 of our study, they declined to pre-fire levels by year 3 after fire in the Boreal Shield study (Schindler et al. 1980). This could be due in part to thinner soils on the Shield. In addition, vegetation regrowth, particularly of jack pine stands, was rapid and prolific after fire on the Shield (Schindler et al. 1980). Similarly, studies from the Pacific Northwest region of North America have noted that alterations in hydrologic pat-

**Fig. 6.** Relationships between total dissolved phosphorus (TDP) concentration and discharge ($Q$) in the study streams.

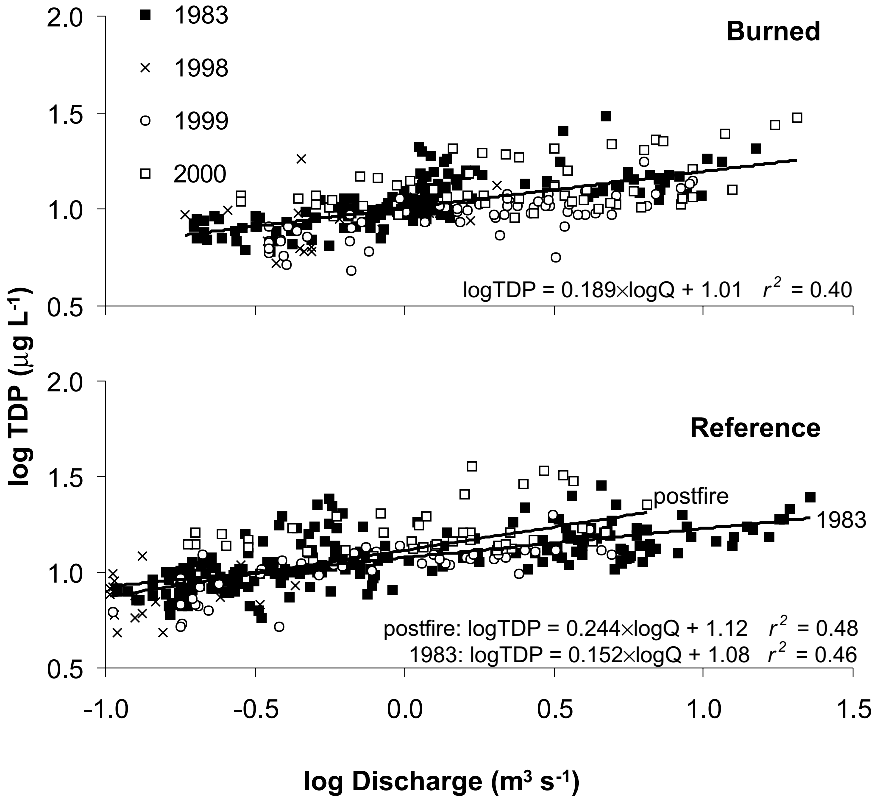
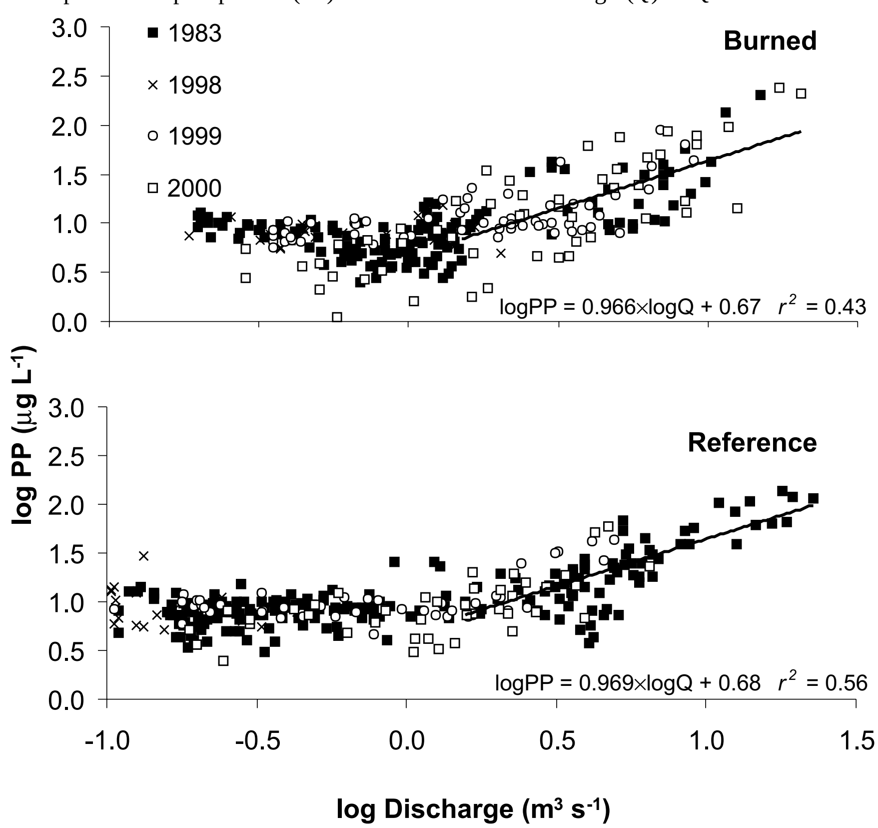



**Fig. 7.** Relationships between particulate phosphorus (PP) concentration and discharge ($Q$) at $Q > 1.5$ $m^3$ $s^{-1}$ in the study streams.



terns tend to diminish 2 years after wildfire (Beschta 1990). This is not surprising, if herbaceous/scrub vegetation is allowed to recolonize the site (Miller et al. 1997) and since these areas receive more precipitation than the Boreal Plain. Although the long-term effects of the Virginia Hills fire on water yield from the Sakwatamau A watershed remain to be seen, there does not appear to be a trend toward pre-fire conditions. Vegetation recovery at the site has been slow, in part because of soil scarification during site preparation and herbicide application to discourage competition by aspen shrubs and grasses with the seedlings. As of spring 2002, there was evidence of herbaceous and shrub growth, but tree recolonization was extremely limited. Tree replanting (lodgepole pine, white spruce) is currently underway at the site.

Particulate P export in the burned watershed was nearly 7 times that in the reference watershed by 2000 and it remained a dominant fraction of TP export after the fire. This was not purely an artifact of more water moving through the burned watershed, since the burned to reference stream PP export ratio was more than 2 times the PP FWMC ratio. In addition, in-stream primary production was probably a minor contributor to high PP exports after fire. During low flow periods when one would expect planktonic producers to take advantage of the higher light conditions after tree removal, PP FWMCs 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 P-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. It is interesting to note that we detected no difference in the slope of the PP–$Q$ relationship in the burned stream compared to reference stream, however, 1983 was a very wet year with heavy rain event concentrated in June and July, thus particulate flushing could have been enhanced in saturated soils. The clustering of points at the high end of the PP–$Q$ regression for the burned stream may indicate that soils in the burned area are more erodable. This is the subject of an ongoing study.

In the reference stream, $Q$ appeared to be lower in post-fire years than in 1983, thus there was likely PP accumulation in the watershed and little opportunity for flushing. Conversely, as a disturbed landscape, the burned watershed had higher PP mobility during periods of high $Q$. Similar to water export, there does not appear to be a trend toward pre-fire conditions in PP export patterns after more than 2 years post-fire. Most of the higher TP export in the burned watershed can be attributed to higher PP export during storm events, due to $Q$-driven erosion of watershed soils and (or) stream sides.

## Acknowledgements

The FORWARD project was funded by Alta. Health and Wellness, Millar Western Forest Products Ltd., Natural Sciences and Engineering Research Council of Canada CRD and Research Grants to E.P., West Fraser Mills, Vanderwell Contractors, and Louisiana-Pacific Canada Ltd. Additional support for this portion of the FORWARD project was provided by the Sustainable Forest Management Network of Centres of Excellence and Alta. Environment. In particular, we wish to thank and acknowledge the support of Jonathan Russell, John Pineau, Rosie Anderson, and Grant Bagnall (Millar Western Forest Products); Murray Summers, Daryl D'Amico, and Stephanie Komarnicki (West Fraser Mills); Greg Lawson (Environment Canada); and Cam McGregor and Dennis Quintilio (Alta. Environment). Meanook Biological Research Station was used as a logistic and analytical support base for the project. J. White and D. Prince (Alta. Health) participated in the initial field and laboratory work. Comments by I. Whitson, T. Charette, and two anonymous reviewers improved earlier versions of the manuscript.

## References

Bayley, S.E., Schindler, D.W., Beaty, K.G., Parker, B.R., and Stainton, M.P. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Can. J. Fish. Aquat. Sci. **49**: 584–596.

Beschta, R.L. 1990. Effects of fire on water quantity and quality. *In* Natural and prescribed fire in pacific northwest forests. *Edited by* J.D.Walstad, S.R. Radosevich, and D.V. Hofstra. Oregon State University Press, Corvallis, Oreg. pp. 219–232.

Byron, E.R., and Goldman, C.R. 1989. Land-use and water quality in tributary streams of Lake Tahoe, California-Nevada. J. Environ. Qual. **18**: 84–88.

Carignan, R., D'Arcy, P., and Lamontagne, S. 2000. Comparative impacts of fire and forest harvesting on water quality in Boreal Shield lakes. Can. J. Fish. Aquat. Sci. **57**: 105–117.

Cooke, S.E., and Prepas, E.E. 1998. Stream phosphorus and nitrogen export from agricultural and forested watersheds on the Boreal Plain. Can. J. Fish. Aquat. Sci. **55**: 2292–2299.

Environment Canada. 2000. Digital Archive of the Canadian Climatological Data (Surface). Atmospheric Environment Service. Canadian Climate Centre, Data Management Division, 4905 Dufferin Street, Downsview, Ont.

Feller, M.C., and Kimmins, J.P. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. **20**: 29–40.

Government of Alberta. 2001. Historical Wildfire Information. Available from http://www. envweb.env.gov.ab.ca/env/forests/fpd/ [accessed on 20 February 2003].

Hibbert, A.R. 1965. Forest treatment effects on water yield. *In* Forest hydrology. *Edited by* W.E. Sopper and H.W. Lull. Pergamon Press, PN. pp 527–543

Hydrological Atlas of Canada. 1978. Department of Fisheries and Environment Canada, Ottawa, Ont.

Knapik, L.J., and Lindsay, J.D. 1983. Reconnaissance soil survey of the Iosegun Lake area, Alberta. Alberta Research Council, Natural Resources Division.

Lamontagne, S., Carignan, R., D'Arcy, P., Prairie, Y.T., and Paré, D. 2000. Element export in runoff from eastern Canadian Boreal Shield drainage basins following forest harvesting and wildfires. Can. J. Fish. Aquat. Sci. **57**: 118–128.

McEachern, P., Prepas, E.E., Gibson, J.J., and Dinsmore, W.P. 2000. Forest fire induced impacts on phosphorus, nitrogen, and chlorophyll *a* concentrations in boreal subarctic lakes of northern Alberta. Can. J. Fish. Aquat. Sci. **57**: 73–81.

Menzel, D.W., and Corwin, N. 1965. The measurement of total phosphorus in seawater based on liberation of organically bound fractions by persulfate oxidation. Limnol. Oceanogr. **10**: 280–282.

Meyer, J.L., and Likens, G.E. 1979. Transport and transformation of phosphorus in a forest stream ecosystem. Ecology, **60**: 1255–1269.

Miller, L.B., McQueen, D.J., and Chapman, L. 1997. Impacts of forest harvesting on lake ecosystems: a preliminary literature review. Wildlife Bulletin No. B-84, BC Environment, Wildlife Branch. Victoria, B.C.

Minshall, G.W., Brock, J.T., Andrews, D.A., and Robinson, C.T. 2001. Water quality, substratum and biotic responses of five central Idaho (U.S.A.) streams during the first year following the Mortar Creek Fire. Int. J. Wildland Fire, **10**: 185–199.

Munn, N.L. 1984. Temporal dynamics of phosphorus in two Alberta streams. M.Sc. Thesis, University of Alberta, Edmonton, Alta.

Munn, N., and Prepas, E.E. 1986. Seasonal dynamics of phosphorus partitioning and export in two streams in Alberta, Canada. Can. J. Fish. Aquat. Sci. **43**: 2464–2471.

Omernik, J.M. 1977. Nonpoint source-stream nutrient level relationships: a nationwide study. United States Environmental Protection Agency Report EPA600/3–77–107.

Prairie, Y.T., and Kalff, J. 1986. Effect of catchment size on phosphorus export. Water Resour. Bull. **22**: 465–470.

Prepas, E.E., and Rigler, F.H. 1982. Improvements in quantifying the phosphorus concentration in lake water. Can. J. Fish. Aquat. Sci. **39**: 822–829.

Prepas, E.E., Pinel-Alloul, B., Planas, D., Méthot, G., Paquet, S., and Reedyk, S. 2001*a*. Forest harvest impacts on water quality and aquatic biota on the Boreal Plain: introduction to the TROLS lake program. Can. J. Fish. Aquat. Sci. **58**: 421–436.

Prepas, E.E., Planas, D., Gibson, J.J., Vitt, D.H., Prowse, T.D., Dinsmore, W.P., Halsey, L.A., McEachern, P.M., Paquet, S., Scrimgeour, G.J., Tonn, W.M., Paszkowski, C.A., and Wolfstein, K. 2001*b*. Landscape variables influencing nutrients and phytoplankton communities in Boreal Plain lakes of northern Alberta: a comparison of wetland- and upland-dominated catchments. Can. J. Fish. Aquat. Sci. **58**: 1286–1299.

Reddy, K.R., Kadlec, R.H., Flaig, E., and Gale, P.M. 1999. Phosphorus retention in streams and wetlands: a review. Crit. Rev. Environ. Sci. Technol. **29**: 83–146.

Schindler, D.W., Newbury, R.W., Beaty, K.G., Prokopowich, J., Ruszczynski, T., and Dalton, J.A. 1980. Effects of a windstorm and forest fire on chemical losses from forested watersheds and on the quality of receiving streams. Can. J. Fish. Aquat. Sci. **37**: 328–334.

Smith, D.W., Prepas, E.E., Burke, J.M., Chanasyk, D.S., and Putz, G. 2003. The Forest Watershed and Riparian Disturbance study: a multi-discipline initiative to evaluate and manage watershed disturbance on the Boreal Plain of Canada. J. Environ. Eng. Sci. **2**(Suppl. 1): this issue.

Soranno, P.A., Hubler, S.L., Carpenter, S.R., and Lathrop, R.C. 1996. Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. Ecol. Appl. **6**: 865–878.

Stark, N.M. 1977. Fire and nutrient cycling in a Douglas-fir/Larch Forest. Ecology, **58**: 16–30.

Verry, E.S. 2000. Land fragmentation and impacts to streams and fish in the central and upper Midwest. *In* Society of American Foresters 2000 National Convention. American Society of Foresters, Washington, D.C. pp. 38–44.

Whitson, I.R., Chanasyk, D.S., and Prepas, E.E. 2003. Hydraulic properties of Orthic Gray Luvisolic soils and impact of winter logging. J. Environ. Eng. Sci. **2**(Suppl. 1): this issue.

Zar, J.H. 1996. Biostatistical Analysis. Prentice Hall, N.J.