Landscape controls on phosphorus loading to boreal lakes: implications for the potential impacts of forest harvesting

K.J. Devito, I.F. Creed, R.L. Rothwell, and E.E. Prepas

Abstract: For 12 low-order lakes in the Western Boreal Forest of Canada, lake position in the groundwater flow system and surface hydrologic connection to wetlands accounted for 57% of the variation in the change in postharvest (1997) relative to preharvest (1996) open-water median total phosphorous concentration ([TP]). Changes in [TP] decreased with calcium and magnesium concentrations, indicating that the largest increases in [TP] are likely to occur in lakes located in areas of groundwater recharge or shallow local discharge. Changes in [TP] increased with the area of wetland connected to the lake, a measure of near-surface hydrologic flushing of TP to the lake. However, the remaining variation (43%) in the TP response of lakes to harvest was not explained by landscape-based criteria. This study illustrates that in landscapes with complex hydrogeology, factors controlling the chemical responses of lakes to disturbance are complex, remain poorly understood, and require further study.

Résumé : Pour 12 lacs de bas ordre de la forêt boréale occidentale du Canada, la position du lac dans le système d'écoulement de l'eau souterraine et sa connexion par hydrologie de surface aux terres humides expliquait 57 % de la variation du changement dans la concentration médiane de phosphore total ([PT]) dans les eaux libres après exploitation (1997) par rapport à la période avant exploitation (1996). Les changements dans [PT] diminuaient avec les concentrations de calcium et de magnésium, ce qui indique que de fortes augmentations de [PT] sont susceptibles de se produire dans les lacs situés dans les zones de recharge souterraine ou de décharge locale à faible profondeur. Les changements dans [PT] augmentaient avec la superficie de terres humides connectées à un lac, ce qui constitue une mesure de la chasse de PT près de la surface vers le lac. Toutefois, la variation restante (43 %) de la réaction des lacs à l'exploitation sur le plan du PT ne pouvait pas s'expliquer par des critères liés au paysage. Notre étude montre que, dans les paysages à hydrogéologie complexe, les facteurs qui régissent la réaction chimique des lacs à la perturbation sont eux-mêmes complexes, sont encore mal compris et demandent des recherches complémentaires.

[Traduit par la Rédaction]

Introduction

Increasing demand for aspen in pulp and paper production has caused a rapid increase in logging of the mixed-wood boreal forest of western Canada. Riparian forest buffers, strips of forest left between harvested blocks and adjacent surface waters, have been considered important sinks for particulate and dissolved nutrients in hydrologic flows and are thereby used to mitigate changes resulting from increased nutrient loads to lakes following tree harvest (Castella et al. 1994). However, present guidelines for assigning buffer strip widths in Alberta, where a large portion of the Western Boreal Forest (WBF) occurs, are based on "rule of thumb" or research conducted in temperate, humid forest ecosystems in steep terrain (Bern 1998; Weller et al. 1998). Recently, several deforestation experiments on headwater drainage basins have been conducted to examine the impacts of logging on surface water quality in the Canadian boreal forest (reviewed in Buttle et al. 2000). These studies, which are empirical in their approach, focus on the humid climate and comparatively simple hydrogeologic settings of the eastern boreal region. There have been few studies in the WBF. The drier climate, deeper surficial glacial deposits, and larger groundwater flow systems (Tóth 1970) that are characteristic of the WBF make generalizing results from other regions within the boreal forest problematic.

The role of buffer strips in conserving the nutrient status of lakes following logging was assessed in 12 headwater lakes in the WBF in Alberta as part of the multidisciplinary Terrestrial Riparian Organisms, Lakes and Streams (TROLS) research project (E.E. Prepas et al., unpublished data). The area logged and the buffer strip width remaining after logging in the catchment did not explain a significant amount of the variation in changes in the concentration of total phosphorus ([TP]) during the short term (2 years) of this posttreatment study (E.E. Prepas et al., unpublished data). Based on these findings, we asked (*i*) if landscape features influence the variation in surface water quality among lakes and (*ii*) which of these landscape features could control the changes in [TP] in response to logging?

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In regions with deep surficial deposits, a lake's position within the groundwater flow system and its connection to the surface water drainage system (i.e., stream or lake order) have been shown to be important determinants of surface water quality and the potential susceptibility of a lake to disturbance (Winter 1992; Webster et al. 1996; Kratz et al. 1997). In many geomorphic regions, wetlands and ephemeral draws represent major conduits of near-surface and surface transport of water and water-soluble nutrients, and they may greatly affect the susceptibility of streams and lakes to disturbances within the catchment (Dillon et al. 1991; Creed et al. 1996; Hill and Devito 1997). Furthermore, surface and subsurface transport through riparian areas may be as important as the width of the riparian area in determining the effectiveness of the buffer strip in reducing nonpoint nutrient loading to surface waters (Hill 1996; Bern 1998; Devito et al. 2000).

In this paper, we test whether landscape features that consider surface and subsurface hydrologic linkages between terrestrial and aquatic systems provide essential information to understand and predict the variation in changes of [TP] in the TROLS lakes following harvesting. In an introductory paper to the TROLS study, E.E. Prepas et al. (unpublished data) examined how catchment features and internal processes explain some of the variability in pre- and postharvest lake water chemistry and the subsequent influence on plankton communities in the TROLS lakes. Herein, we ask three specific questions. (*i*) Is the hydrogeologic setting of a lake, which defines the degree of subsurface hydrologic connections to the lake that delivers water from within the drainage basin or areas far removed from the drainage basin, related to the changes in TP following a disturbance? (*ii*) Is the efficiency of surface water drainage within a drainage basin, as defined by the size and connectivity of wetlands and ephemeral draws to the lake, related to the changes in TP following a disturbance? (*iii*) Is the pathway of water moving through the riparian forest to the lake, defined by the curvature of the topographic profile of the riparian forest adjacent to the lake, related to the changes in TP following a disturbance? An improved understanding of landscape controls on hydrochemical linkages in the TROLS lakes is used to anticipate how forestry practices may interact and impact these linkages.

Methods

Study area

The Boreal Plains Ecozone covers approximately 40% of Alberta, extending from northeastern British Columbia through to southwestern Manitoba. Within the Boreal Plains Ecozone, the Boreal Mixedwood Ecoregion forms a broad band north of the aspen forest and south of the coniferous forest (Rowe 1972).

The area consists of landforms of glacial, fluvio-glacial, and lacustrine origin (Ozoray and Lytviak 1980), where undefined drainage systems in flat areas can occur in close proximity to recently incised valleys (i.e., Athabasca River). The region is underlain with soft sedimentary bedrock (upper Cretaceous shales, siltstones, and sandstones) that subsequent glaciation formed into the rolling moraines of the uplands and the lacustrine deposits of the lowlands. The glacial drift ranges in thickness from 20 to 200 m and is interbedded with clays, sands, and gravels (Tokarsky and Epp 1987).

Soils that have developed at the surface of the glacial drift are highly variable, ranging from well to poorly drained and from shallow to deep organic layers. The forest is a natural mosaic of stands of different ages and species composition interspersed with wetlands, streams, and lakes. The majority of the wetlands can be characterized as fen or bog peatlands, with minerotrophic swamp and marshes common along lake margins. In dry habitats, jack pine (*Pinus banksiana*) is the dominant tree species, while balsam fir (*Abies balsamea*) is also present. In mesic habitats, trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) are the dominant tree species, occurring as mixed and pure stands. In wet habitats, the dominant tree species are black spruce (*Picea mariana*), balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), and tamarack (*Larix laricina*) (Rowe 1972).

The climate is continental. For three regions within the Boreal Mixedwood Ecoregion, Lac La Biche (LLB), South Calling Lake (SCL), and South Pelican Hills (SPH), the 30-year average annual precipitation is 474 mm, with 70% of the precipitation occurring between May and September. Average potential evapotranspiration is 514 mm, based on long-term monthly temperature. The annual average temperature is 1.1°C, with mean monthly temperatures ranging from –16.7°C (January) to 15.9°C (July).

Experimental design

As part of the experimental design of the TROLS project, four low-order lakes were selected in each of three regions on the Boreal Plains (LLB, SCL, and SPH) and received one of the following treatments: reference (no cutting within 800 m of the lake) or cutting to leave a 20-, 100-, or 200-m riparian forest buffer strip in each of three regions (E.E. Prepas et al., unpublished data). During the sampling period for this study period, the area of harvest ranged from 0 to 8% within the catchments defined as reference lakes and from 4 to 30% within the catchments of each treatment lake. For the TROLS project, the chemistry of the lake water was monitored for two years before harvest (1995 and 1996) and for this paper one year after harvest (1997) in the winter of 1996–1997.

To examine the influence of surface and subsurface hydrologic connections, we have analyzed a slightly different data set then presented in E.E. Prepas et al. (unpublished data). Herein, the entire open-water (May–September) median [TP] (micrograms per litre) and the calcium plus magnesium concentrations ([Ca + Mg]) (milligrams per litre) from composite samples of the euphotic zone have been used. TP was the only nutrient used to illustrate the influence of subsurface and surface hydrologic connections, as it is the most responsive lake nutrient to external features (E.E. Prepas et al., unpublished data) and usually limits algal biomass in Alberta lakes (Prepas and Trew 1983). We selected the median [TP] in the pelagic waters as the response variable in evaluating the potential impacts of logging on the lakes. Open-water season estimates of [TP] were used, as it reflects the dominant period of external loading from the catchment on an annual basis as well as internal recycling in the pelagic P cycle (Webster et al. 2000). During the TROLS experiment, total annual precipitation depths and runoff rates from nearby rivers and lake water levels indicated dry antecedent moisture conditions in 1995 and very wet conditions in 1996 and 1997, following the harvest of the catchments in the winter of 1996–1997. To minimize the potential effects of climatic variability on the comparison between the pre- and post-harvest [TP], the analysis focused on changes in [TP] from 1996 to 1997, as both years represent "wetter" conditions. Water levels in the lakes were similar in both years, with the exception of SPH 200 and SCL 200, where a beaver dam gave way in 1997, resulting in a significant drop in lake water level and lake volume. The 1996 median [Ca + Mg] was used in our analyses, as it represented the year with greatest sampling frequency of base cations to characterize the lakes. A complete set of base cation data was not obtained in 1995 or 1997. Nonetheless, the relative ranges in [Ca + Mg] among the lakes for the hydrologically more dynamic 1996 year were similar to the range for the hydrologically drier 1995 year.

Samples were collected from the euphotic zone at the deepest location of each lake about once a month during the open-water season (May–September). The Ca and Mg samples were acidified to pH 3 with nitric acid, and concentrations were measured by atomic absorption spectrophotometer. TP was analyzed using a modified potassium persulfate method (Prepas and Rigler 1982).

Landscape variables

Landscape features that were hypothesized to be important in regulating the [TP] in the pelagic waters included the hydrogeologic setting of a lake within the landscape, the size and organization of surface hydrologic features (wetlands or ephemeral draws), which reflect the importance of saturation overland flow versus subsurface flow as a runoff generation mechanism, and the curvature of the nearshore area, which reflects the potential for filtering of water through the riparian forest and adjacent riparian vegetation. Indices for each of the landscape features were calculated as follows.

The hydrogeologic setting of a lake within the landscape was determined based on a combination of three factors: (*i*) order (ORDER), which was defined using standard stream ordering methods from a 1 : 50 000 scale map of the area, as described by Strahler (1964), (*ii*) the elevation of the lake relative to the surrounding landscape (ELEV), which was defined as the ratio of the change in elevation from lake surface to the regional low (e.g., Athabasca River) with respect to the total change in elevation from the regional low to the regional high (e.g., Pelican Mountains), and (*iii*) the position of the lake within the local to regional groundwater flow system (GRW).

The position of the lake within the potential groundwater flow system was based on a finite element model (FLONET, Waterloo Hydrologic Inc. 1997) of groundwater flow through the surficial tills. Cross sections of all the lakes in each study region were derived from a combination of topographic and stratigraphic maps and water well records. The model simulated the hydraulic head distribution in the groundwater near each lake. For the simulations, it was assumed that the water table defined the upper no-flow boundary and that the underlying upper cretaceous gray shales (Wapiti Formation, Lea Park and Colorado group) defined the lower no-flow boundary. Topography was used to estimate the position of the water table within the landscape. Based on water levels from several water well records, the estimated position of the water table was subdued by 8–10 m at the morainal crest of topographic highs and was assumed to be near the surface in low-lying wetlands. For most of the lakes, information was available on the depth of drift to bedrock, but information was lacking on the heterogeneity within the drift. For a regional study focusing on large-scale processes, the drift can be assumed to be a homogeneous and anisotropic unit (Shaw et al. 1990; Winter 1999). The modeling of the water table presented in this paper therefore represents the potential influence of depth to bedrock and surface topography on groundwater–lake interactions. The hydraulic conductivity of $0.1\ m \cdot day^{-1}$ and anisotropic ratio of 500 were assumed for the drift based on bail tests of shallow piezometers near the LLB study lakes (Evans et al. 2000; K.J. Devito, unpublished data) and published literature (Shaw et al. 1990; Hayashi et al. 1998). A 1- to 2-m layer of gyttja with a hydraulic conductivity of $0.001\ m \cdot day^{-1}$ was assumed to occur at the bottom of each lake. Once the hydraulic heads and potential groundwater flow lines were simulated and graphed, the potential groundwater–lake interaction was classified using four categories: (*i*) a recharging region, (*ii*) a local discharging region, with hydrologic contributions predominantly from the adjacent hillslopes, (*iii*) a local to intermediate discharging region, and (*iv*) a local to intermediate discharging region with potential flow through the lake.

An independent measure of the position of a lake within the groundwater flow system was provided in [Ca + Mg]. The concentration of solutes in the groundwater increases with the time or distance that water travels along groundwater flow systems. Recent studies have shown that the [Ca + Mg] in lakes has proven useful in defining the recharge and discharge interactions of a lake within the groundwater flow system (Kratz et al. 1997; Winter 1999; Webster et al. 2000).

The size and organization of wetlands were used to derive an index of the potential for hydrologic flushing of TP. For each catchment, wetlands were delineated using aerial photography (1996, 1 : 15 000), digitized, and the total wetland area (WETL) and the proportion of wetland area connected to the lake (WETLCO) estimated using GIS software. The maximum distance that two wetlands could be separated and still considered connected was 25 m. The wetland areas were normalized to the lake area (WETL/LkA and WETLCO/LkA, respectively).

To examine the influence of the water table dynamics underlying the buffer strip on the potential effectiveness of the buffer strip in reducing the TP loads to the lake, an index measuring the concavity or convexity of the topographic profile of the riparian forest (CURV) was developed for each of the TROLS lakes. The curvature was computed using digital terrain analysis of the integrated topography and bathymetry for each drainage basin. The digital terrain model was filtered to a 200-m grid resolution (one of the widths of the buffer strips used in the TROLS project); the digital terrain model was not sufficiently adequate to provide reasonable results for finer resolutions. For each grid surrounding the lake's shoreline, the profile concavity or convexity was determined as described in Zevenbergen and Thorne (1987). For each lake, the statistical moments of the frequency distribution of the grids surrounding the lake's shoreline, based on the 200-m buffer widths, were determined.

Lake areas were delineated from aerial photography (1996 and 1997, 1 : 15 000), checked against 1 : 50 000 topographic maps (as described in E.E. Prepas et al., unpublished data), and then digitized and estimated using GIS software. Initial lake volumes were estimated from bathymetric surveys conducted on each lake in 1993. Lake volumes for the two years of this study were adjusted using the average water level depth in 1996 and 1997 relative to 1993, and an average of the two years was used (E.E. Prepas et al., unpublished data).

The a priori prediction that the three landscape features (hydrogeologic setting, potential for hydrologic flushing, and potential for filtering of TP through the riparian area) would explain some of the variation in the change in [TP] among the lakes was tested using simple correlation and multiple linear regression analyses. To further explore the relative importance of these and other landscape features, simple and partial correlation and forward stepwise multiple regression analyses were used. For the forward stepwise multiple regression analyses, the minimum tolerance for entry of a variable correlated with an independent variable in the model was 0.001 and the F value for entry was 4. All statistical analyses were performed using Systat 9 (SYSTAT, Inc. 1999).

Results

Integration of landscape controls on TP loading to lakes

The indices of hydrogeologic setting ([Ca + Mg]), the potential for hydrologic flushing (WETLCO), and the potential for TP filtering (CURV) were selected a priori based on our hypothesized controls on TP loading to the TROLS lakes. The overall model regressing these three indices with change in [TP] was significant (adjusted $R^2 = 0.53$, $p = 0.03$); however, only the coefficients for [Ca + Mg] ($p = 0.01$) and WETLCO ($p = 0.04$) were significantly different from zero.

Forward stepwise regression was conducted using all of the variables listed in Table 1 as well as ELEV, CURV, and WETL and WETLCO standardized to lake volume. Only the variables [Ca + Mg] and WETLCO were selected for the best-fit model to explain the variability in the change in [TP] in the TROLS lakes during these two wet years:

$$\Delta[\text{TP}] \pm 9.1 = 25.7 \pm 8.3 - 0.71 \pm 0.21[\text{Ca + Mg}] + 0.13 \pm 0.05(\text{WETLCO}) \quad (\text{adjusted } R^2 = 0.57,\ p = 0.009). \tag{1}$$

No significant partial correlation was observed between the change in [TP], [Ca + Mg], and any other landscape feature, with the exception of WETLCO/LkA ($r_{[\text{Ca+Mg}]} = 0.61$, $p = 0.05$).

Influence of landscape position on lake TP response

Although most of the TROLS lakes are low-order drainage basins, topographic cross sections revealed that the lakes occur in a range of positions extending from lakes isolated in regional high areas (e.g., SCL 100) to those in regional lows (e.g., SCL 200) (Fig. 1). Modeling the potential influence of surface topography and depth to bedrock on groundwater flow indicates a wide range of groundwater interactions for the TROLS study lakes (Table 1; Fig. 1). Five of the nine lakes located in groundwater discharge areas appear to be connected to intermediate groundwater flow systems with sources of water originating from outside the topographic divide of the lake catchment. The chemical composition of the TROLS lakes is dominated by Ca, Mg, and HCO_3^- and show a considerable range in the median [Ca + Mg] (15–65 mg·L^{-1}) indicative of an increase in concentration with the distance traveled along hydrologic flowpaths within the surficial tills (Webster et al. 1996). The median [Ca + Mg] of the TROLS lakes was positively correlated with the position of the lake in the groundwater flow system (GRW, $r = 0.058$, $p = 0.049$) but was not correlated with lake order (ORDER) or relative elevation (ELEV) (Table 2).

The influence of hydrogeologic setting on the response of the lakes is suggested by the negative relationship between the change in [TP] and [Ca + Mg] ($p = 0.03$) (Fig. 2). The change in [TP] in 1997 (precut) relative to 1996 (postcut) decreased with an increase in [Ca + Mg] or a shift from a lake in a groundwater recharge area to an intermediate discharge area. It should be noted that the magnitude of the change in [TP] observed in lake LLB 200 (L2) carries a large weight in the regression. However, LLB 200 is located at the base of regional high area known as the Mariana highlands and represents the lake with the greatest potential for interaction with larger groundwater flow systems.

Influence of hydrologic flushing and TP filtering in the riparian forest on lake TP response

The TROLS lakes showed a large range in the area of wetland hydrologically connected to the lake (WETLCO) and mean curvature of the topographic profile in the riparian area (CURV). However, the relationships between the change in [TP] and WETLCO and CURV were not statistically significantly ($p = 0.15$). The relationship between the change in [TP] and WETLCO improved when the variation in response to hydrogeologic setting was accounted for ($r_{[\text{Ca+Mg}]} = 0.66$, $p = 0.03$). The largest change in [TP] was

Table 1. Characteristics of TROLS experimental lakes.

Lake	Label	Lake area (ha) (LkA)	Average lake volume, 1996–1997 (10^4 m^3) (VOL)	Lake elevation (m)	Average lake depth (m)	Catchment area ha (CATCH)	Lake order (Strahler 1964) (ORDER)	Relative elevation (%) (ELEV)	Groundwater interaction	Ground-water category (GRW)	Total wetland area (ha) (WETL)	Total wetlands connected (ha) (WETLCO)	Shore–riparian curvature mean (CURV)	Area cut catchment (ha)	Median [Ca + Mg], 1996 (mg·L^{-1})	Median Δ[TP], 1997–1996 (μg·L^{-1})
LLB 20	L0	63	247	574	2.6	644	1	1	D-L&I	3	34	14	0.036	150	29.1	19.8
LLB 100	L1	22	40	628	2.6	135	0	72	R	1	6	4	−1.138	41	15.2	10.7
LLB 200	L2	35	57	627	1.2	229	0	44	D-L&I-FT	4	47	35	−0.100	23	63.2	−26.9
LLB 800	L8	104	379	619	3.0	602	1	58	D-L	2	71	40	0.191	51	22.0	7.0
SCL 20	C0	55	251	623	4.9	631	1	53	R	1	78	39	−0.334	23	51.1	6.6
SCL 100	C1	20	61	644	3.0	263	0	67	D-L&I	3	78	55	0.800	31	42.4	2.8
SCL 200	C2	122	52	321	1.2	6752	3	52	D-L	2	884	159	0.511	670	36.2	12.0
SCL 800	C8	76	169	644	1.7	797	1	67	R	1	124	81	0.141	0	30.3	15.5
SPH 20	P0	172	763	678	4.4	1211	2	35	D-L	2	146	4	−0.529	302	29.5	3.2
SPH 100	P1	52	76	634	1.3	841	2	24	D-L	2	165	158	−0.319	104	28.6	32.8
SPH 200	P2	48	174	652	4.0	1003	1	28	D-L&I-FT	4	136	106	−0.574	170	47.2	13.7
SPH 800	P8	67	158	635	2.3	726	2	24	D-L&I	3	157	102	−0.285	31	40.1	7.5

Note: Variable labels and lake labels indicated are used in Table 2. For groundwater interactions, *R* is recharge, D-L is discharge with local scale, D-L&I is discharge with local and intermediate scale, and D-L&I-FT is groundwater flow through the lake connected to local- and intermediate-scale flow systems.

Fig. 1. Lithology and modeled potential hydraulic head and groundwater flow lines for the SCL region. Simulated groundwater flow lines are based on topography and depth to bedrock. Numbers in labels above lakes refer to the buffer width left following logging.

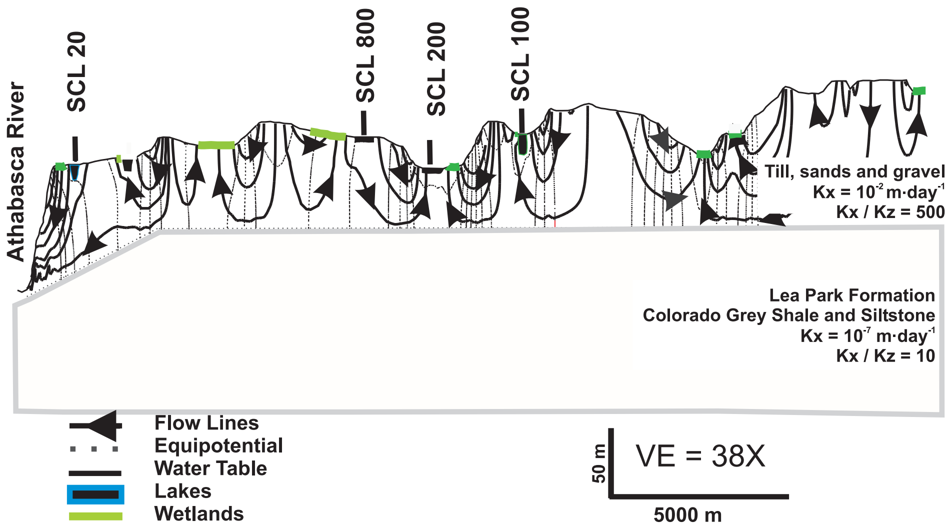
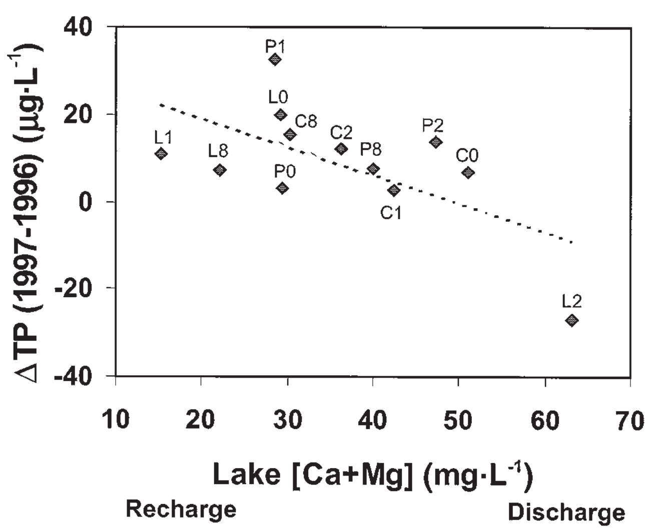


Table 2. Pearson correlation coefficients for landscape characteristics.

	[Ca + Mg]	GRW	ORDER	WETL	WETL/LkA	WETLCO	WETLCO/LkA
Median [Ca + Mg]							
GRW position	0.58*						
Lake ORDER	ns	ns					
WETL area	ns	ns	0.74**				
WETL/LkA	ns	ns	ns	0.86**			
WETLCO area	ns	ns	0.63*	0.65*	0.79**		
WETLCO/LkA	ns	ns	ns	ns	0.58*	0.71**	

Note: See Table1 and text for description of labels. ns, not significant; $*p \leq 0.05$–0.01. $**p < 0.01$.

Fig. 2. Relationship between the median lake [Ca + Mg] in 1996 and the changes in median Δ[TP] for 1997 (postcut) relative to 1996 (precut). For the linear regression (broken line): Δ[TP] = 32.2 – 0.65[Ca + Mg]; adjusted $R^2 = 0.23$, $p = 0.03$. See Table 1 for labels of the lakes.



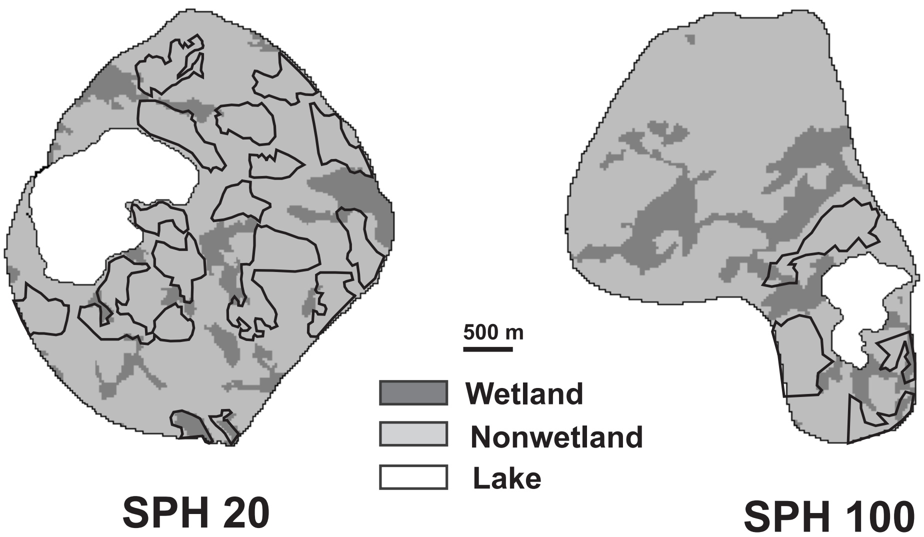
observed in lake SPH 100. This was not expected from the lake's hydrogeologic setting (Table 1); however, SPH 100 has a large area of wetland connected to the lake. For the TROLS lakes, the change in [TP] tended to increase with an increase in WETLCO. In contrast, no significant simple or partial correlation was observed between the change in [TP] and the total wetland area (WETL) or the total wetland area normalized to lake area or volume (WETL/LkA or WETL/VOL) in the TROLS lakes ($p > 0.10$).

The potential importance of the organization of wetlands in influencing the loading of TP to the lake is illustrated by comparing SPH 100, the lake with the greatest increases in median [TP] (65 µg·L^{-1}), with changes observed in SPH 20 (3 µg·L^{-1}) (Fig. 3). Although the percentage of wetland coverage within the drainage basins is similar (12–20%), in SPH 20, the wetlands are situated at a distance from the lake, and the area of wetlands that are connected to the lake represent less than 3% of the lake area. In contrast, the wetlands in SPH 100 are well organized and connected to each other and the lake, with the wetland area connected to the lake (WETLCO) three times greater than the lake area. This results in increased efficiency of water and nutrient transport from the uplands to the lakes.

Discussion

Among the TROLS lakes, the hydrogeologic setting of a lake within the groundwater flow system was found to explain some of the change in median [TP] during 1997 (postharvest) relative to 1996 (preharvest). In regions with deep permeable substrate, differences in the prevailing hydrologic

Fig. 3. Spatial organization of wetland areas (dark shading) and cut blocks (solid black lines) relative to lakes at SPH with 20-m (SPH 20) and 100-m (SPH 100) buffer widths.



linkages within the landscape have been shown to be important in determining the response of lakes to disturbances (LaBaugh et al. 1996; Webster et al. 1996, 2000). In the WBF, as in other forest regions, biologically available soil nutrients are largest in the surface organic and mineral layers, and surface or near-surface hydrologic flows can potentially be a large source of TP to the lakes (Huang and Schoenau 1996; Evans et al. 2000; K.J. Devito, unpublished data). A lake located in a regional recharge or a local discharge would receive proportionally greater inputs from surface or near-surface hydrologic flows, and thus should be more sensitive to a disturbance on the hillslopes adjacent to the lake. As expected, changes in [TP] tended to be largest in TROLS lakes that were located in recharge areas and smallest in lakes where TP exports from adjacent hillslopes were moderated by longer local and intermediate flow systems.

The large range in groundwater interactions observed in the TROLS lakes (recharge, discharge, and flow-through systems) is common in this region (Tóth 1970; Winter 1999). The groundwater modeling results and the relationship between the change in [TP] and [Ca + Mg] observed among the low-order drainage systems of the TROLS lakes further emphasize the influence of hydrogeologic setting on the response of [TP] in lakes of the WBF. The influence of hydrogeologic setting is expected to increase if lakes representing the full range in hydrogeologic settings that exist in this landscape were examined. These findings suggest that future experiments may need to consider the confounding influence of the subsurface hydrology and conduct treatments on lakes representing a full range of landscape settings to properly evaluate the potential impacts of forest harvesting on surface waters of the WBF.

The area of wetland with surface hydrologic connections to a lake was another important variable related to the change in [TP] in the TROLS lakes during the two wet years. Hydrologic flushing from surface soils is an important process regulating the export of nutrients from the land to receiving waters (Hornberger et al. 1994; Creed et al. 1996; D'Arcy and Carignan 1997). Studies in regions characterized by humid climates and (or) rugged terrain have observed relationships between the extent of wetland coverage and the amount of surface and near-surface transport of water and water-soluble nutrients (Dillon et al. 1991; Waddington et al. 1993; Devito et al. 1999). In contrast with these findings, no detectable relationship was observed between the change in [TP] and the total wetland area or total wetland area normalized to lake area in the TROLS lakes. Similar to other recent studies in humid boreal catchments, this study shows that the export of nutrients from land to lakes via hydrologic flushing may be a function of not only the size of near-surface or surface saturated areas (i.e., runoff generating areas) but also their organization and connection to surface waters (Creed and Band 1997). This is to be expected in the more arid climate and flat terrain of the WBF where many wetlands are located within topographic depressions that may not have a surface or near-surface connectivity to the lake (LaBaugh et al. 1998).

The potential importance of the relative catchment area (E.E. Prepas et al., unpublished data) and the organized hydrologic connections within the catchment area are aspects of forest management that have grown from the TROLS program. The large increases in [TP] observed in SPH 100 suggest that lakes with large wetland areas (larger than the lake area) that are connected to the lake have a greater potential for nutrient loading and therefore greater potential susceptibility to the short-term impacts of logging or other disturbances within the catchment. Furthermore, variations in the spatial interactions between cut blocks and surface saturated networks within the TROLS lake catchments may have masked the direct effects of the forest harvesting and, together with variations in hydrogeologic setting, may have contributed to the lack of a relationship between logging intensity (expressed as a percentage or area) and the change in [TP] observed by E.E. Prepas et al. (unpublished data).

The potential for TP filtering by the riparian forest (CURV) was expected to be important in controlling TP export to the lake; however, the relationship was not statistically significant. Convex profiles typically have deep water tables where subsurface flow paths dominate, allowing for P originating from the forest floor in cut blocks to be adsorbed to the soils or taken up by the roots (Frossand et al. 1989; Burt and Haycock 1996). In contrast, concave profiles typically have shallow water tables where saturation overland flow paths and anoxia of waterlogged soils may result in small P removal or may create source areas of P to the lake (Devito and Dillon 1993; D'Arcy and Carignan 1997; Evans et al. 2000). Our use of mean curvatures rather than the distribution of curvatures for a given lake may have contributed to the lack of a significant relationship. Curvatures may vary tremendously within a lake, with disproportionately larger water and TP transport in small sections of convex shoreline around the lake (Weller et al. 1998).

In this paper, we have focused on indices of landscape features, largely at the expense of indices of the lake's basin morphometry or P recycling dynamics. With the P-rich substrates in this glaciated region, P loading from lake sediments may represent a substantial input to surface waters and does explain some of the large variation in the change in [TP] observed among the TROLS lakes (E.E. Prepas et al., unpublished data). However, the influence of internal P recycling dynamics on [TP] appears to be consistent enough among the lakes and between the years of this study to observe variations in the external input of TP resulting from the considerable range in landscape position and wetland connection of the TROLS lakes.

It is important to note that the significant relationships observed between the change in [TP] and the hydrogeologic setting and hydrologic flushing indices include both the reference and the treatment lakes. E.E. Prepas et al. (unpublished data) observed a similar relationship with relative catchment size using 11 of the 12 TROLS lakes. However, E.E. Prepas et al. (unpublished data) did not detect a significant relationship between the percent area logged or buffer strip width and the change in [TP]. The observed significant relationships between hydrogeologic setting and hydrologic flushing indices and the change in [TP] in this study may reflect the differential potential for surface hydrologic connections among the lakes during high-runoff years rather than the influence of logging or buffer strips. As this analysis is confined to only 2 years of sampling, longer term studies of changes in [TP] will be needed to determine the importance of logging and other landscape features in addition to climate (E.E. Prepas et al., unpublished data). Nevertheless, annual precipitation in 1996 (576 mm) was the largest recorded in almost 30 years. Runoff in nearby rivers increased from about 50–90 mm for a 10-year period preceding harvesting in the TROLS lakes to about 200 mm in 1996. Although the precipitation in 1997 (487 mm) was near the long-term average (468 mm), runoff estimates remained at around 200 mm. During harvesting of the TROLS lakes, the large antecedent moisture conditions greatly increased the potential for efficient transport of TP to the lake via surface hydrologic pathways. The variation in the response due to climate is a focus of present research (I.F. Creed and K.J. Devito, unpublished data).

The amount cut (0–30% of the catchment) and shortness of the study may have contributed to the lack of a direct relationship between harvest or the buffer strip width and changes in [TP] in the TROLS lakes (E.E. Prepas et al., unpublished data). A significant proportion (43%) of the variation in the change in [TP] was not explained by landscape-based criteria, illustrating that the factors controlling lake chemistry and the potential for changes in lake chemistry in response to disturbances are complex and remain poorly understood. Nonetheless, the findings of this study improve our understanding of the transport of TP along upland–riparian–lake hydrologic linkages, provide a physical basis for assessing the potential susceptibility of lakes to harvesting in regions with complex hydrogeology, and provide direction for the experimental design of future studies.

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