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EFFECTS OF LOGGING ON WATER QUALITY: COMPARISON BETWEEN TWO QUEBEC SITES

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ABSTRACT

The impact of logging on water quality is compared between two Quebec sites; one on the Côte-Nord and the other in Haute-Mauricie. Comparative measurements were made at each site in natural conditions, in a stream protected by a green strip and in a watercourse perturbed by logging operations. In Haute-Mauricie, logging with preservation of a green strip increases the color by 65 APHA units while the other parameters are not modified. At the Côte-Nord site, the color and the concentration of calcium and potassium are respectively increased by 88 APHA units, 0,9 and 0,7 ppm. Except for pH at both sites and the dissolved oxygen concentration in the Côte-Nord area, all the parameters studied were affected by logging without protective measures. The dissolved oxygen concentration decreased by 6 ppm in Haute-Mauricie. At the Côte-Nord and Haute-Mauricie sites, the augmentations observed were respectively 10 and 13 ppm for the concentration of suspended sediments, 2 and 3,2 °C for water temperature, 1,2 and 3 ppm for potassium, 4,4 and 2 ppm for iron, 531 and 497 APHA units for color and finally 12 and 18 µmhos/cm for the conductivity. The different responses to the treatments between the two sites are not completely explained by this study.

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RESUME

L'influence de l'exploitation forestière sur la qualité de l'eau est étudiée à deux sites situés au Québec, l'un sur la Côte-Nord et l'autre en Haute-Mauricie. Des mesures comparatives ont été effectuées à chaque site en milieu naturel, dans un ruisseau protégé par une lisière boisée, et dans un autre non protégé lors des exploitations forestières sur le bassin. En Haute-Mauricie, après la coupe avec lisière boisée, la coloration de l'eau augmente de 65 unités APHA, tandis que les autres paramètres ne sont pas modifiés. Sur la Côte-Nord, la coloration ainsi que les concentrations en calcium et en potassium augmentent de 88 unités APHA, 0,9 et 0,7 ppm respectivement. A l'exception du pH aux deux sites et de la concentration en oxygène dissous sur la Côte-Nord, tous les autres paramètres étudiés sont modifiés par la coupe sans mesure de protection. La concentration en oxygène dissous diminue de 6,0 ppm en Haute-Mauricie. Sur la Côte-Nord et en Haute-Mauricie, les augmentations respectives sont de 10 et 13 ppm pour la concentration des sédiments en suspension, 2 et 3,2 °C pour la température de l'eau, 1,2 et 3 ppm pour le potassium, 4,4 et 2 ppm pour le fer, 531 et 497 unités APHA pour la couleur, et finalement 14 et 18 µmhos/cm pour la conductivité. Cette étude ne permet pas d'expliquer totalement la différence des réactions aux traitements entre les deux sites.

INTRODUCTION

Water quality is defined by its physical, chemical and biological characteristics (Lee, 1980) which are related to the climatic, geochemic, physiographic, edaphic and vegetative factors of the site. Thus a change of the terrestrial ecosystem caused by logging might result in changes in the water characteristics. As clearcutting covers 2 500 km^2 each year in Quebec it is important to consider the effects of this activity on the physico-chemical properties of water. Among the characteristics studied more emphasis is placed on the suspended sediments because this is considered the major problem (Dyrness, 1967; EPA, 1975; Lee, 1980; O'Loughlin et al., 1980; Satterlund, 1972; Swanston and Swanson, 1976) and a good index of the impact of logging on water quality (Brown, 1980; Plamondon et al., 1976; Satterlund, 1972). The objective of this paper is to compare the effects of logging with and without a buffer strip on nine water quality parameters at two sites located in different regions.

LITERATURE REVIEW

Suspended sediments

The increase of suspended load in the streams following the logging operations has received much attention in the United States (Packer, 1967). The magnitude of the impact is related to the logging method, the physical nature of the land and to the rate of revegetation of the site (Lee, 1980). The cutting by itself (Bates and Henry, 1928; Brown and Krygier, 1971; Fredriksen, 1970; Hoover, 1944; Lieberman and Hoover, 1948, Likens et al., 1979; Lull and Satterlund, 1963; Meehan et al., 1969; Packer, 1967) and the extraction of the logs by aerial cables (Brown and Krygier, 1971; Fredriksen, 1970; Megahan, 1975) do not contribute substantially to the suspended load in the streams.

From the studies carried out in Western and Eastern States of the U.S., it is generally reported that the access network is the main source of sediments input to the water (Anderson and Wallis, 1963; Brown and Krygier, 1971; Douglass and Swank, 1975; Dyrness, 1967; Fredriksen, 1970, 1972; Fredriksen et al., 1975; Kochenderfer and Aubertin, 1975; Packer, 1967; Rice and Wallis, 1962). The additional input is variously attributed to stream crossing by tractors (Fredriksen, 1972), to improper culverts (Copeland, 1963), or to road surface erosion (Megahan and Kidd, 1972). Logging without concern for streams has been shown to increase the average or maximum concentration of suspended sediments from 3 to 3 500 times the natural level (Anderson and Wallis, 1963; Copeland, 1963; Dils, 1957; Douglass and Swank, 1975; Fredriksen, 1970; Gilmour, 1971; Hoover, 1952; Hornbeck and Reinhart, 1964; Lynch et al., 1975; Megahan, 1975; Reinhart et al., 1963; Rice and Wallis, 1963; Rogerson, 1971).

Adequate planification of the logging operations reduces to a minimum the impact on water quality (Douglass and Swank, 1972; Hornbeck and Reinhart, 1964; Kochenderfer and Aubertin, 1975; Patric and Aubertin, 1977; Powell, 1980; Reinhart et al., 1963). The effect of logging on suspended sediments has been shown to be very brief for selection cutting (Reinhart et al., 1963), and to last up to one (Haupt and Kidd, 1965), two (Kochenderfer and Aubertin, 1975), three (Beschta, 1978; Brown and Krygier, 1971), and four (Megahan and Kidd, 1972) years after clearcutting.

Water temperature

The canopy, by reducing the energy input to the surface, minimizes the daily fluctuations of water temperature (Pierce et al., 1970). Removing the vegetation causes an augmentation of water temperature proportional to the area exposed to solar radiation (Brown, 1970). The increases vary usually between 2 and 10°C according to site conditions (Brown and Krygier, 1970; Greene, 1950; Lee and Samuel, 1976; Levno and Rothacher, 1967; Lynch et al., 1975; Meehan et al., 1969; Nicolson, 1975; Patric, 1970; Pierce et al., 1970; Plamondon, 1980; Swift and Messer, 1971). The preservation of a green strip after clearcutting the rest of the watershed is sufficient to maintain water temperature near the natural level (Brown and Krygier, 1970; Brown et al., 1971; Kochenderfer and Aubertin, 1975; Swift and Baker, 1973; Swift and Messer, 1971).

Dissolved oxygen

Logging reduces the dissolved oxygen concentration by increasing the water temperature (Churchill et al., 1962) and by adding debris which curtail air mixing (Ice, 1978) and favour the growth of oxygen consumers (Berry, 1975; Ponce, 1974; Ponce and Brown, 1974). The diminution of oxygen concentration after logging range from low (Pierce et al., 1970) to high (Hall and Lantz, 1969) depending on the combination of the factors involved.

Other water quality parameters

Taken globally the changes in alkalinity, conductivity, color and concentration of NO_3^-, PO_4^{---}, K^+, Ca^{++}, Mg^{++}, Na^+, Cl^- and Fe^{+++} are small after logging (Aubertin and Patric, 1974; Brown et al., 1973; Douglass and Swank, 1975; Feller, 1974; Fredriksen, 1971; Fredriksen et al., 1975; Fredriksen and Ross, 1974; Hart and Debyle, 1975; Hetherington, 1976; Hewlett, 1969, 1979; Kochenderfer and Aubertin, 1975; Lynch et al., 1975; Nicolson, 1975; Powell, 1980; Singh and Kalra, 1975; Snyder et al., 1975; Tarant, 1970; Tiedemann, 1973; Verry, 1972). A notable exception are the results from New Hampshire where the concentrations of NO_3^-, Ca^{++} and K^+ greatly increased after logging (Hornbeck et al., 1975; Likens et al., 1970; Pierce et al., 1972). The differences between these results and the others are attributed to the suppression of vegetation with herbicides (Fredriksen, 1971) and to the shallow depth and coarse texture of the soil (Brown, 1980). Some studies show a larger effect during the second year after logging on NO_3^- (Fredriksen, 1971; Fredriksen et al., 1973; Hornbeck et al., 1975; Likens et al., 1970; Pierce et al., 1973; Tiedemann, 1973), Na^+ (Likens et al., 1970; Tiedemann, 1973), Ca^{++} (Likens et al., 1970), PO_4^{---} (Hewlett, 1979), pH (Tiedemann, 1973) and conductivity (Hornbeck et al., 1975; Pierce et al., 1972).

EXPERIMENTAL SITES AND METHODS

The Côte-Nord and Haute-Mauricie sites are respectively located at 500 (Fig. 1) and 250 km (Fig. 2) to the northeast and northwest directions of Quebec City. The former site is cooler and wetter than the latter (Table 1). Both sites are situated on the Canadian shield in the boreal forest zone (Rowe, 1972) at the same altitude (Table 1). The topography is more broken on the Côte-Nord and the bedrock is composed of different types of gneiss at each site. The unconsolidated material is morainic, shallow and coarse at the

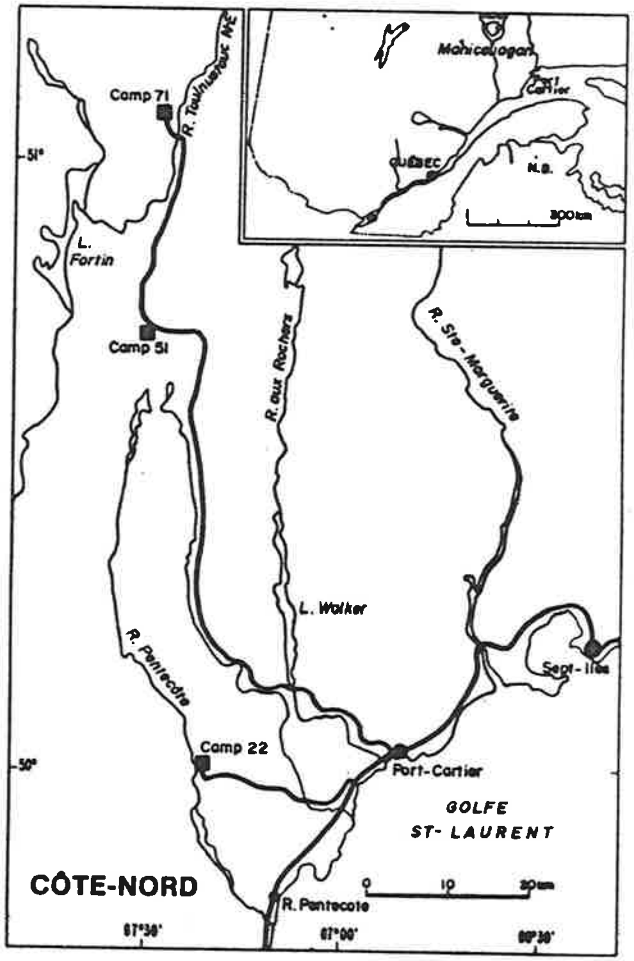

Figure 1 - Location of Côte-Nord study area

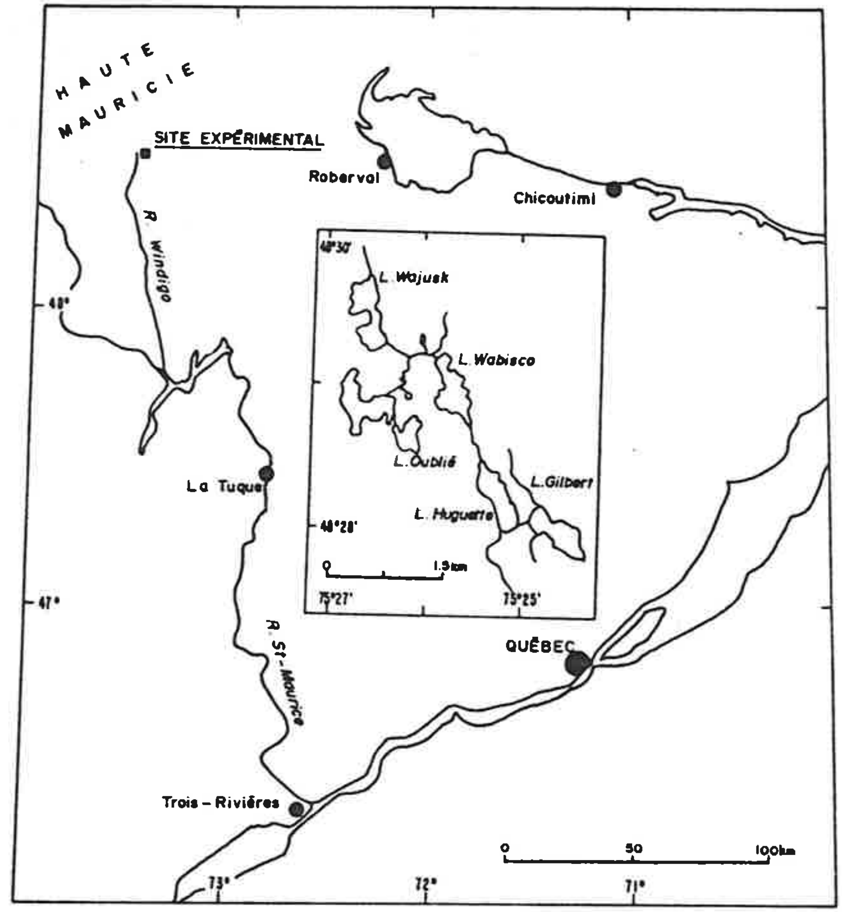

Figure 2 - Location of Haute-Mauricie study area

Table 1 - Main characteristics of Côte-Nord and Haute-Mauricie study areas

	Côte Nord	Haute Mauricie
Latitude	50°43'	48°31'
Longitude	67°30'	73°25'
Degrees days above 5,6 °C (°C)	825	1 100
Mean January temperature (°C)	-21	-19
Mean July temperature (°C)	14	17
Mean annual temperature (°C)	- 3	1
Mean annual precipitation (mm)	1 220	750
Snow fall fraction (%)	38	33
Altitude (m)	590	572
Land slope (%)	13	11
Boreal Forest (Rowe, 1972)	B.1b	B.1a
Bedrock - gneiss	Plagioclase	Granit
	Biotite	Migmatite
Unconsolidated material		
- on rock outcrops	Till shallow	Till shallow
- on lower ground	Moraine	Fluvio-glacial material

Côte-Nord site while deeper fluvio-glacial deposits are most common in Haute-Mauricie.

The effects of the treatments were determined using the paired basin design (Hewlett and Pienaar, 1973). At the Côte-Nord site, the data were collected in 1974, one year prior to logging in watersheds 7A, 7B, 7C, 5A and 5C (Fig. 3 and 4). These served as control whereas watersheds 5G and 5H nested in 5C were partly clearcut in 1975. The cutting was done with chain saws and the boles were skidded in length by rubber tire tractors. A 10 m wide buffer composed of standing trees was kept along the stream 5G after clearcutting 62% of the watershed (Table 2). Only 26% of the area of watershed 5H was clearcut but the stream was crossed at several points by the skidders and the lower section was also used as an access.

Watershed Gilbert at the Haute-Mauricie site was almost completely clearcut during the fall 1976 and the summer 1977 (Fig. 5) Two logging methods were used. The so-called conventional method is the one described for the Côte-Nord site and the Koehring method refers to a machine which combines all the operations: falling, stripping the branches, sectioning, hauling, and piling. The stream was crossed many times by the machinery. A strip of standing trees about 30 m wide was kept along Huguette stream. The Wajusk watershed is used as the control. The calibration period lasted two years prior to logging.

The concentration of inorganic suspended sediments was determined by filtering (Filters Millipore XCW 04700) hand grabed samples of 500 ml. The weight of the inorganic material was obtained after ashing during two hours at 800°C. The concentrations are expressed in ppm. Water temperature was measured with thermographs (Peabody Ryan, model D8), mercury min - max thermometers or punctually read with a thermistor. Dissolved oxygen, pH and conductivity were measured with portable meters (Chemtrix or YSI models). Calcium, potassium,

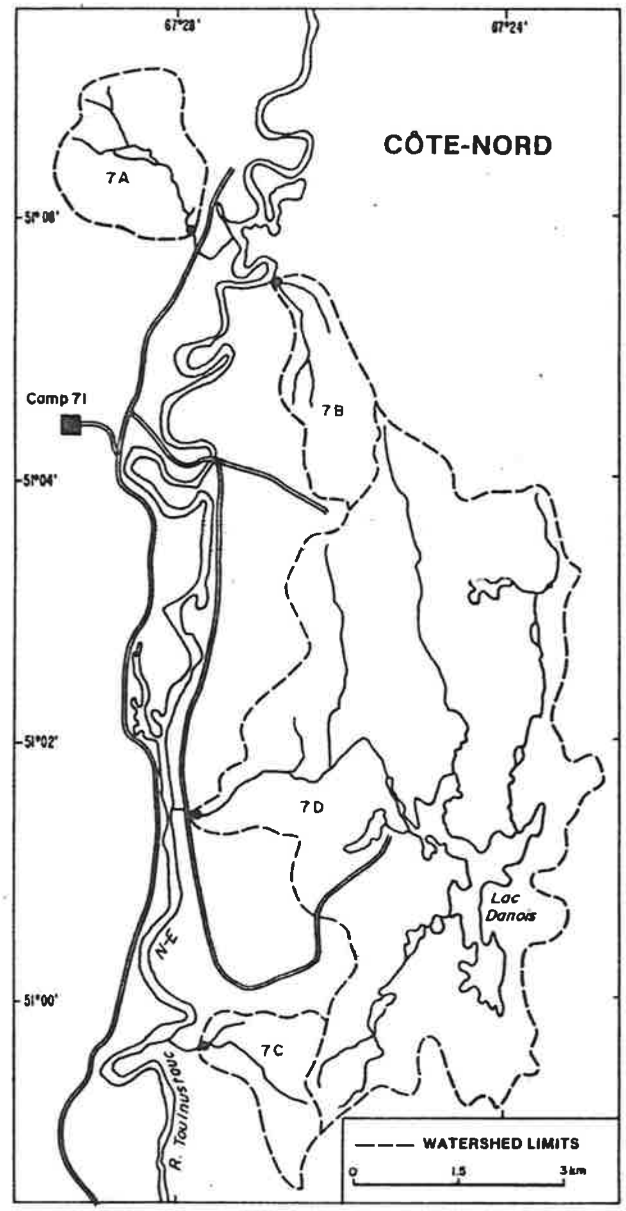

Figure 3 - Location of the watersheds near camp 71

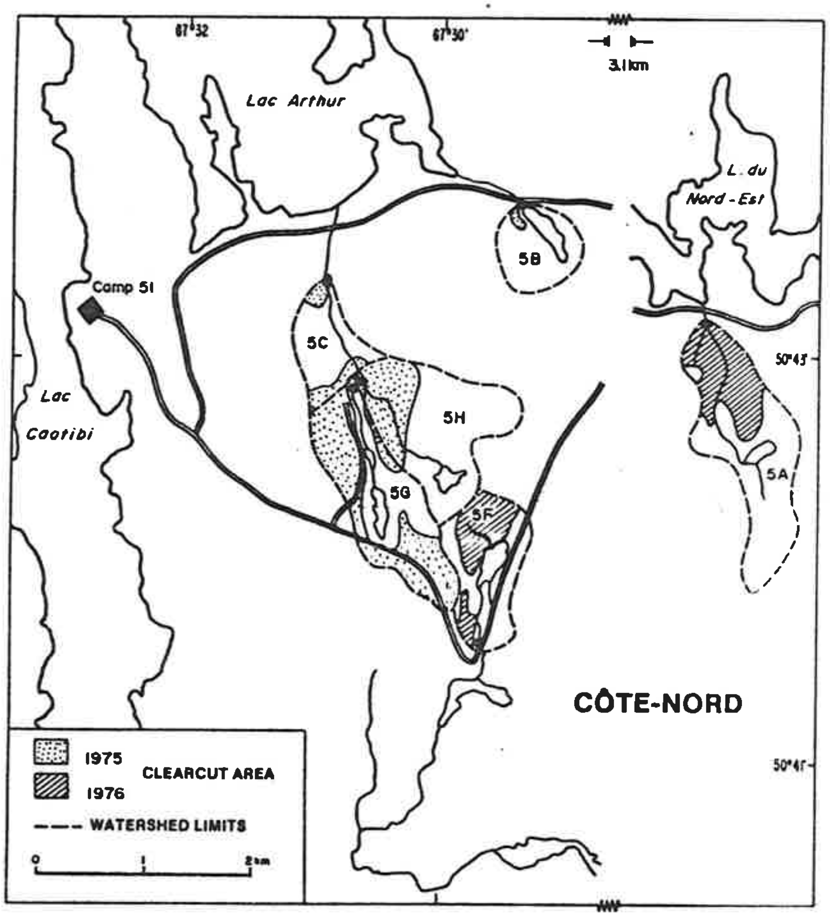

Figure 4 - Location and treatments of the watersheds near camp 51

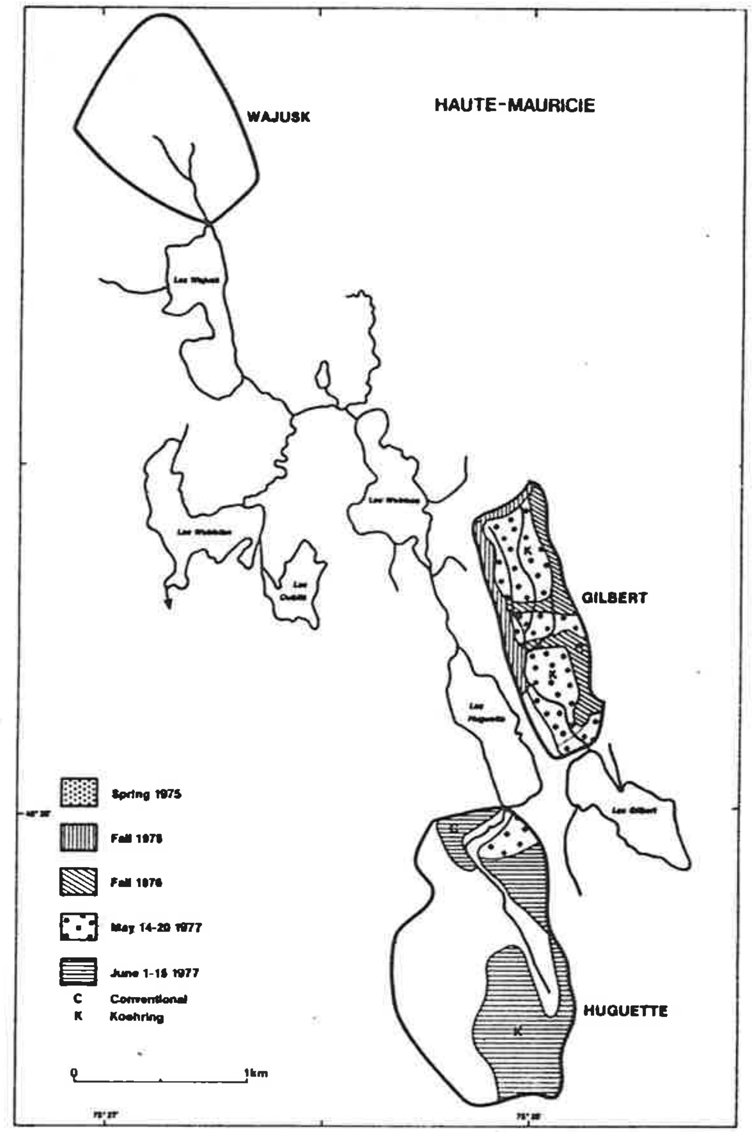

Figure 5 - Location and treatments of the watershed at the Haute-Mauricie site.

Table 2 - Main watershed characteristics

Study area	Watershed	Area (km²)	Mean altitude (m)	Land slope (%)	Stream slope (%)	Years before cutting	Year of cutting (%)	Area clear-cut (%)	Width green strip (m)
Côte-Nord	7A	4,09	545	15	1	-	Control	-	-
	7B	3,10	658	15	9	-	Control	-	-
	7C	2,34	650	13	14	-	Control	-	-
	5A	1,33	631	20	9	-	Control	-	-
	5C	3,17	580	12	2	1[a]	-	-	-
	5G	1,33	578	11	1	1[a]	1975	62	10
	5H	1,28	588	8	3	1[a]	1975	26	0
Haute-Mauricie	Wajusk	0,83	576	8	2	-	Control	-	-
	Huguette	1,36	573	11	2	2	1977	40	30
	Gilbert	0,62	576	3	2	2	1977	100	0

[a] The data before logging were collected in watershed 5C which includes both watersheds 5G and 5H.

iron and color were measured in the laboratory from samples collected with polyethylene bottles. The analysis follow the methods prescribed by "Standard Methods for the Examination of water and wastewater, 1966" (APHA, 1966). The precision of the measurements is usually better than the natural variability encountered in the field. The sampling frequency ranged from daily to bi-monthly according to the parameters, the year and the site (Tables 3 and 4).

The treatment effects are obtained by the difference between observed and predicted values as if no modification occurred in the watershed. The predicted values were estimated simply by assuming a constant difference between the control and the logged watersheds before and after the treatments. The regression analysis was not used because it is not statistically sound (Reinhart, 1967; Ward, 1971; Wicht, 1967) and furthermore the prediction must extend beyond the range of the values encountered in natural conditions from which the relation is calculated.

RESULTS

Suspended inorganic sediments

The concentrations corresponding to different probabilities of being exceeded were calculated by using the orthogonal polynomial method. The natural concentration of suspended inorganic sediments remains, 90% of the time, below 5 ppm (Fig. 6 and 7) and the summer means do not exceed 2 and 3 ppm (Table 5) for the Côte-Nord and Haute-Mauricie sites respectively. Logging with buffer strips did not affect the concentrations. In the 5H and Gilbert streams, which were crossed by skidders, the mean concentrations increase by 10 and 3 ppm respectively (Table 6). The corresponding peaks are 104 and 45 ppm as compared to 4 and 7 ppm for their respective controls, with the exception of a 815 ppm peak caused by road fill slumping not included in the calculations for Haute-Mauricie.

Table 3 - Number of measurements for each water quality parameter at the Côte-Nord site.

Parameter	1974 Control (7A,7B,7C 5A)	1974 Natural (5C)	1975 Control (7A,7B,7C 5A)	1975 Buffer (5G)	1975 No Buffer (5H)
Suspended sediments	222	17	123	49	49
Water temperature	26	16	64	32[a]	
Dissolved oxygen	222	17	123	49	49
Calcium	7	7	7	7	7
Potassium	7	7	7	7	7
Iron	7	7	7	7	7
pH	11	11	10	10	10
Color	7	7	7	7	7
Conductivity	223	17	131	54	54

[a] Measured in stream 5C only

Table 4 - Number of measurements for each water quality parameter at the Haute-Mauricie site.

Parameter	1975-76 Control (Wajusk)	1975-76 Natural (Huguette)	1975-76 Natural (Gilbert)	1977 Control (Wajusk)	1977 Buffer (Huguette)	1977 No buffer (Gilbert)
Suspended sediments	103[a]	5	5	86	86	86
Water temperature	36	36	36	18	18	18
Dissolved oxygen	44	44	44	23	23	23
Calcium	44	44	44	19	19	19
Potassium	6[b]	6[b]	6[b]	31	31	31
Iron	6[b]	6[b]	6[b]	30	30	30
pH	46	46	46	22	22	22
Color	47	47	47	22	22	22
Conductivity	46	46	46	29	29	29

[a] Pooled measurements taken in several undisturbed streams during 1975-76-79.
[b] Measures taken in 1980 three years after logging.

The cumulative frequency curves show a two and ten fold increase of the concentrations following stream perturbations at the Haute-Mauricie and Côte-Nord respectively.

The greater logging effect at the Côte-Nord site is explained by the use of a stream section for access by skidders and the higher slope in this particular stretch.

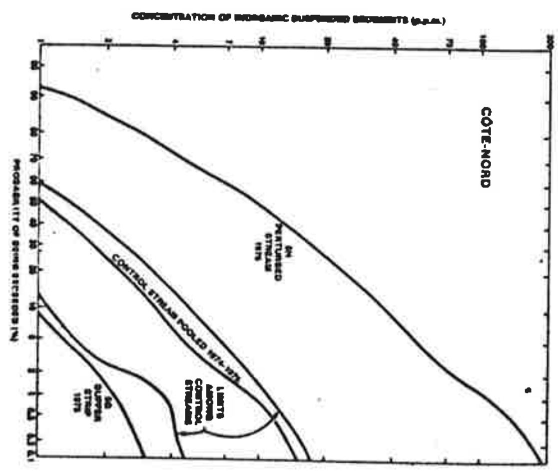

Figure 6 - Concentrations of inorganic suspended sediments and probability of being exceeded at the Côte-Nord site.

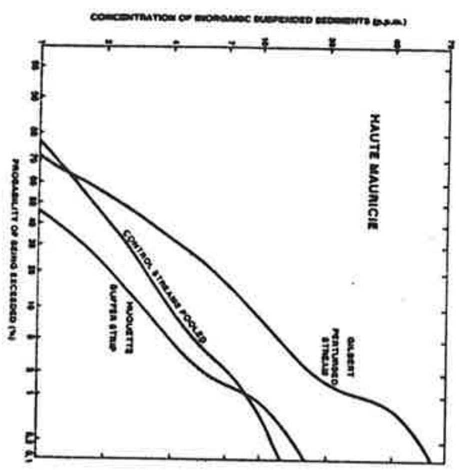

Figure 7 - Concentrations of inorganic suspended sediments and probability of being exceeded at the Haute-Mauricie site.

Table 5 - Mean summer values of the water quality parameters before and after logging at the Côte-Nord and Haute-Mauricie sites.

Site and period to logging	Watershed	Treatment	Suspended sediments (ppm)	Water temperature (°C)	Dissolved oxygen (ppm)	Calcium Ca (ppm)	Potassium K (ppm)	Iron Fe (ppm)	pH	Color (APHA)	Conductivity (µmhos/cm)
Côte-Nord											
Before (1974)	Controls	Control	2	10,1	10,1	1,2	0,2	0,1	5,2	61	22
	5C	Natural	1	8,6	10,2	1,3	0,3	0,2	5,6	54	21
After (1975)	Controls	Control	1	10,3	9,6	2,1	0,2	0,1	5,8	116	22
	5G[a]	Buffer	1	9,8[b]	9,5	3,1	1,0	0,2	6,0	197	25
	5H	No buffer	12		8,9	3,3	1,5	4,6	5,8	640	35
Haute-Mauricie											
Before (1975-76)	Wajusk	Control	1	9,3	7,9	1,6	0,1[d]	0,8[d]	5,2	121	18
	Huguette	Natural	1	10,2	9,0	1,5	0,3[d]	0,7[d]	4,5	141	26
	Gilbert	Natural	2	10,5	7,4	1,6	0,2[d]	0,9[d]	5,0	158	18
After (1977)	Wajusk	Control	3	7,6	7,9	1,4	0,3	0,6	4,7	148	19
	Huguette	Buffer	2	8,8	8,4	1,3	0,6	0,8	4,1	233	33
	Gilbert	No buffer	6	12,0	1,0	-[c]	3,8	3,0	4,5	682	37

a Watersheds 5G and 5H are tributaries of watershed 5C
b Water temperature was measured in stream 5C only
c The titration method could not be used because of water coloration
d Measurements taken three years after logging

Table 6 - Estimated differences of the mean values of water quality parameters after logging at the Côte-Nord and Haute-Mauricie sites

Parameter		Côte-Nord Buffer	Côte-Nord No buffer	Haute-Mauricie Buffer	Haute-Mauricie No buffer
Suspended sediments	(ppm)	0	10*	0	3*
Water temperature	(°C)	-	2[a]*	0,3	3,2*
Dissolved oxygen	(ppm)	-0,2	-0,5	-0,6	-6,0*
Calcium	(ppm)	0,9*	1,1*	0	-
Potassium	(ppm)	0,7*	1,2*	0,3	3*
Iron	(ppm)	0	4,4*	0,1	2*
pH	(pH unit)	-0,2	-0,4	0,1	0
Color	(APHA)	88*	531*	65*	497*
Conductivity	(μ-mhos/cm)	4	14*	6	18*

(Differences of mean values)

* Differences attributed to the treatments

a Assuming that the temperature did not change in stream 5G shaded by trees

Water temperature

At the Côte-Nord site water temperature was measured in the controls and in stream 5C which receives the treated tributaries 5G and 5H. Assuming that the buffer strip prevented any temperature change in stream 5G and equal flow from both tributaries, the measured increase of 1°C at station 5C would translate into a 2°C augmentation in stream 5H (Table 6). No significant water temperature change could be detected in Huguette stream while Gilbert shows an average increase of 3,2°C. The augmentations of the maximum daily temperatures reached 4,5 and 6,5°C respectively at the Côte-Nord and Haute-Mauricie sites. The increase in the Gilbert stream being higher than in 5H is probably due to the greater length exposed to the sun, 3 000 as opposed to 1 000 m.

Dissolved oxygen

The oxygen concentrations in the controls at the Côte-Nord and Haute-Mauricie sites are respectively around 10 and 8 ppm (Table 5). There is no significant change of the mean summer concentration of oxygen in the two streams with buffer strips and in the 5H (Table 6). However in the latter, the concentration decreased by 2 ppm during two weeks in August at the end of the logging period. On average the diminution was 6,4 ppm in the Gilbert stream and the concentration reached 0 ppm during logging in June. The lower section of the Gilbert stream has a slope of less than 1% and was loaded with debris impounding the water. Lower debris accumulation and a 4% slope in the cut section of 5H helped maintain the oxygen concentration near natural level.

Calcium

The average concentrations increased by 0,9 and 1,1 ppm in stream 5G and 5H respectively. However the calcium concentrations in stream 5C in 1974 and

and then 5G and 5H in 1975 fluctuated within the range of the control values. No change could be detected in Huguette stream while the titration could not be made in Gilbert because of high coloration. The natural concentrations are in the same range at both sites and the apparently bigger change in Côte-Nord cannot be attributed to any particular cause. The availability of calcium increases with the organic matter decomposition, the exposure of new soil layers and washing of the soil. Road and piling area construction in watershed 5G exposed more mineral soil than the operations in the Huguette watershed. The relations between causes and effects remain speculative.

Potassium

The mean potassium concentration in streams 5G and 5H increased by 0,7 and 1,2 ppm (Table 6) respectively above the natural concentration of 0,3 ppm (Table 5). No change appears in the Huguette stream while the average augmentation was above 3 ppm in the perturbed Gilbert stream. The higher potassium increase in the Haute-Mauricie for the unprotected stream cannot be explained. The same speculations as for the calcium could be made. On the other hand the potassium availability is more related to living matter than is the case for calcium.

Iron

The buffer strips along the 5G and Huguette streams maintained the iron concentration near natural levels. The mean increases in concentrations are 4,4 and 2 ppm in the 5H and Gilbert creeks respectively. Iron is available everywhere in large quantity and its passage to solution is related to the organic compounds. Both streams show a similar increase in color and the higher augmentation of iron concentration in 5H as compared to Gilbert cannot be explained.

pH

The reduction of 0,2 to 0,4 pH unit after logging at the Côte-Nord site (Table 6) cannot be attributed with certainty to logging when compared to the natural variability.

Color

The coloration increases by 88 and 531 APHA units respectively after logging watersheds 5G and 5H. Similarly the augmentations in the Huguette and Gilbert streams reach 65 and 497 units. Both sites show a similar change due to logging.

Conductivity

The streams with buffer strip do not show a significant change in conductivity after logging. Similar increases of 14 and 18 μmhos/cm were detected in streams 5H and Gilbert respectively (Table 6).

CONCLUSION

The physical and vegetative characteristics of both study areas are similar.

The response to logging is the same for the pH, the color and the conductivity. The different responses to suspended sediments, water temperature and dissolved oxygen are respectively related to the degree of perturbation and slope, the area of stream exposed to the sun and turbulence. The variable responses to the concentration of calcium, potassium and iron can be attributed to so many factors that it is impossible to pinpoint a specific cause in this type of study. The small and short duration changes do not impair water quality.

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