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Roberts Creek Study Forest: effects of partial retention harvesting on nitrate concentrations in two S6 creeks three years after harvesting

by

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Cover photo: Overview of Flume Creek harvesting treatments as of spring 2000. Variable retention treatment on F4 is at right, strip shelterwood treatment on F5 is at left.

TABLE OF CONTENTS

Abstract..........2
Keywords..........2
Acknowledgements..........2
1. Introduction..........2
2. Literature Overview..........2
3. Study Area..........4
4. Methodology..........4
4.1 Measurement of Streamflow..........4
4.2 Sampling..........4
4.3 Groundwater..........5
4.4 Chemical Analysis..........6
4.5 Forest Harvesting Treatments..........6
5. Data Analysis..........6
6. Results..........7
6.1 Regression Models that Relate Nitrate Concentrations to Specific Stream Discharge..........7
6.2 Pre- and Post-Treatment Differences in Mean Nitrate Concentrations..........10
6.3 Paired Samples in Streamflow and Groundwater..........13
7. Discussion..........17
8. Conclusions..........19
References..........19

Tables:

1. Summary of forest harvesting at Flume Creek.....6
2. Statistical properties of nitrate concentration data in streamflow 7
3. Mean annual nitrate concentrations and concentration ratios in streamflow and groundwater.....11
4. Significance of comparisons between treatment years..........11
5. Mean nitrate concentrations, nitrate fluxes and ratios of post treatment to pre-treatment levels for the October–December period at Flume Creek..........13
6a & 6b. Results of paired peak nitrate comparisons, F4/F5 vs. F6, based on pre-treatment regressions..........14
6c. Paired peak concentrations of matched nitrate pulses in the pre-treatment period..........16
7. Summary of post- and pre-treatment nitrate ratios..........17
8. Overall average ratios of nitrate concentration and fluxes by treatment year over the pre-treatment period, and proportions logged......18

Figures:

1. Map of Flume Creek..........5
2. Aerial photo of harvested treatment units..........5
3. Relationships used in regression model of nitrate and streamflow, F4..........8
4. Relationships used in regression model of nitrate and streamflow, F5..........8
5. Streamflow, nitrate concentration from samples, and nitrate concentrations from regression model for fall 1996, representing baseline conditions..........9
6. Year 1 streamflow and nitrate concentrations....9
7. Year 3 streamflow and nitrate concentrations....10
8. Mean annual nitrate concentrations in streamflow and groundwater at Flume Creek..........10
9. Seasonal trends in plot average nitrate concentration..........12
10. Nitrate concentrations in groundwater by piezometric head..........12
11. Paired peak nitrate concentrations at F4 and F5 in relation to F6, pre- and post-treatment..........16
12. Off-peak nitrate concentrations at F5 formed relationships with stream discharge used to calculate ratios of post- to pre-treatment nitrate concentrations..........17
13. Example of a modeling approach to interpret the nitrate concentration data in groundwater...18

ABSTRACT

The Flume Creek Paired Watershed Experiment (Roberts Creek Study Forest, Sunshine Coast, BC) was implemented in the early 1990s to provide information on the effects of forest harvesting on drinking water quality. Three study creeks were identified: F4 (39 ha catchment area), F5 (61 ha) and F6 (16 ha). The study creeks have been monitored for streamflow more or less continuously, using high frequency event based automatic sampling to obtain detailed water quality data.

Variable retention (VR) and strip shelterwood treatments were applied to F4 and F5 respectively, in two stages. In the summer of 1998, about half of the target volume on each creek was harvested; the remainder of the cut was taken in summer 1999, leaving F4 and F5 at 39% and 17% harvested. F6 was kept as the control creek. This divided the data into four periods: pre-logging, year 1 (the logging phase following the first entry) and years 2 and 3 (one and two years after logging).

Prior to treatment, nitrate concentration exhibited pulse behavior with the highest concentrations occurring just after fall freshet. Subsequent storms produced nitrate pulses of diminishing concentration as the season progressed. Several parameters were used to assess the changes in nitrate status following logging, including arithmetic and flow-weighted mean concentration, seasonal nitrate flux, and change in peak concentration of paired nitrate pulses relative to the control. Ratios of each parameter for treatment periods relative to control periods were calculated. Overall, nitrate levels at F5 were about 4, 30 and 60 times that of its unlogged state in years 1, 2 and 3 respectively, while at F4 the nitrate levels changed by factors of 12 and 18 times in years 2 and 3, and were unchanged in year 1.

These results are somewhat unexpected. It had been thought that F4 would experience a larger change in nitrate concentration than F5, proportional to harvesting intensity. Instead, the change in nitrate levels at F5 were 3 times the changes at F4. Therefore, the response is likely due in part to differences between the watersheds as opposed to purely a treatment effect. It is speculated that the riparian zone of F5 stores more nitrate than that of F4, and that the large response in water chemistry is due to riparian disturbance.

KEY WORDS

water chemistry, water quality, Flume Creek, Roberts Creek Study Forest, Sunshine Coast.

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1.0 INTRODUCTION

Water quality has long been a concern to residents of the Sunshine Coast. In particular, the Roberts Creek area supports a large rural community, and many residents depend on small creeks for their water supply. There is a perception that forest harvesting and related activities (specifically clear-cut harvesting) might alter water quality in those creeks. There is also a perception that the use of partial harvesting systems might serve to lessen those effects. In an effort to address those concerns, the Flume Creek Paired Watershed Experiment was implemented.

This report builds on two prior reports describing research at Flume Creek (Hudson, 2001; Hudson and Fraser, 2001). These reports describe the baseline water chemistry characteristics of the Flume Creek experimental catchments, and document the observed changes in peak streamflow that occurred as a result of forest harvesting. The observed changes were large and very significant. These changes and the water chemistry characteristics of the creeks suggest a relatively high degree of sensitivity to forest harvesting.

This report forms part of a series of ongoing reports whose purpose is to describe significant findings while the research is in progress. Because of the extremely detailed and complex nature of the data set, it was necessary to limit the scope of the paper. Rather than report on changes in total stream chemistry, we decided to concentrate on observed changes in nitrate concentration in streamflow and groundwater, and export of nitrate from the catchments in surface water. Nitrate is generally considered to be the most sensitive indicator of watershed disturbance, and a preliminary look at the nitrate concentration data at Flume Creek suggested that very substantial changes occurred after the treatments were applied.

2.0 LITERATURE OVERVIEW

A large number of watershed studies on the effects of clear-cut harvesting have been reported in the literature. The classic study by Likens et al. (1970) at Hubbard Brook in New Hampshire found large changes in water chemistry. A sub-basin of Hubbard Brook was entirely clear-cut and vegetation regrowth was suppressed with herbicides for a period of two years following harvesting. This treatment resulted in marked changes in concentrations of dissolved ions leading to concern over stream water quality and site nutrient depletion. Major changes were observed in the first-order stream; however, no changes were reported for Hubbard Brook itself. Likens et al. (1978) presented a mechanism to explain these increases. The temperature and water content of the forest floor were increased following clear-cutting due to reduced shade and evapotranspiration, resulting in increased rate of organic matter decomposition (bacterial conversion of organic nitrogen to NH_4^+) and nitrification (conversion of the mineralized NH_4^+ to NO_3^- and NO_2^- by different bacteria). Nitrification produces hydrogen ion, lowering stream pH and mobilizing base cations.

Since this investigation, similar studies have been completed in various locations with differing results. It has been found that for some forest types, clear-cut harvesting does not increase ion concentrations, but there is an increase in nutrient export due to increased runoff (Patric, 1980; Hopmans et al. 1987). Generally, however, there is an increase in the streamwater concentration of nitrate following clear-cutting. This increase depends on ion mobility and the extent to which forest and stream primary production is limited by specific nutrients.

Martin et al. (1984) studied 15 streams in New England (some unlogged, some with recent logging varying from 16 to 100 % of their area) with different results. The study was based on comparative sampling of creeks logged within two years of the study, using nearby uncut watersheds with similar characteristics as controls. The authors did not find the kind of changes in stream chemistry that were found at Hubbard Brook. Some logged streams experienced slight changes in pH, Ca and Mg, but not others. Nitrogen in streams rose following clear-cutting only in the vicinity of the White Mountains, where Hubbard Brook is located. The failure to detect significant chemical changes was attributed to the following factors: most watersheds were harvested in stages, most were not 100% clear-cut so that nutrient uptake in uncut areas or streamside buffer strips may have moderated the effects in the harvested areas, and soil types in the study creeks may have buffered the impacts. Martin et al. (1985) stress the role of patch or strip cutting or the use of buffers wider than 9 m on each side of the stream in reducing the impacts to stream chemistry.

Nitrate export is one of the most important indicators of watershed disturbance due to logging. Binkley and Brown (1993) reviewed several North American studies that examined the impacts of forest management practices on nitrate concentrations, as well as temperature, dissolved oxygen and suspended sediment. About 70% of the studies reported that mean annual nitrate concentrations were below 0.5 mg/l for both harvested and control watersheds. Exceptions were in the red alder (Alnus rubra) and Douglas-fir (Pseudotsuga menzesii) forests in Oregon (where equally high levels of nitrate existed in the control and treatment watersheds) and in the hardwood forests of Hubbard Brook. Vitousek et al. (1982) determined that the observed changes in nitrate at Hubbard Brook were due to proliferation of both mineralizing and nitrifying bacteria. If mineralizing bacteria were not present or in limited supply, the changes would not occur; if mineralizing bacteria were present but not nitrifying bacteria, there would be a delay in increased nitrate that could be sufficient to allow forest regeneration to prevent any increase in nitrate concentration in streams.

Gibbs (1970) suggested that the world's water chemistry is controlled by precipitation, mineral weathering and evaporation-crystallization, and that other mechanisms are minor in comparison. Vitousek (1977) suggests that in humid climates, evaporation-crystallization is replaced by evapotranspiration, and that those control processes affect specific chemical species differently. In the northeastern United States, sulphate and chloride are controlled by precipitation and evapotranspiration; sodium, silica, magnesium and calcium are controlled by mineral weathering; while nitrate and potassium are controlled by plant uptake. Johnson and Reynolds (1977) showed that bedrock type has a major influence on stream chemistry in its weatherability. Plutonic rocks (e.g. granite) are acidic, with anions dominated by sulphate and chloride, and are least weatherable, producing low concentrations of base cations and silica. Highly weatherable sedimentary rocks, such as shale, produce the highest concentrations of base cations with the dominant anion being bicarbonate. Increases in the streamwater concentrations of ions originating from soil and rock weathering following clear-cut harvesting are well correlated with precipitation. However, ionic forms of N from decomposing vegetation resulting from logging are often rapidly absorbed, either by stream organisms or regenerating vegetation. Hartman and Scrivener (1990) found that nitrate concentrations increased only during large discharges at Carnation Creek, BC.

Different processes act on water to modify its chemistry at different stages. Processes that occur in the forest floor and organic soil horizons include mineralization due to biological action (e.g., Hazlett et al., 1992; Hendershot et al., 1992; McClurkin et al., 1987; Vitousek and Matson, 1985). Nitrate ions are negatively charged, are not held on exchange sites in most soils, and tend to be rapidly leached. Hence, the potential for loss of N after clear-cutting is greatest where the capacity for nitrification is high (Vitousek et al., 1982). Pulse behaviour of nitrate has been noted by several authors (e.g., English *et al.*, 1986, Hazlett *et al.*, 1992; Kendall *et al.*, 1995; Campbell *et al.*, 1995; Hudson & Golding, 1997b). These studies all involved snowmelt runoff. In the earlier studies it was assumed that the nitrate pulses were derived directly from the snowpack. The Campbell *et al.* and Kendall *et al.* studies were designed specifically to test the source of the nitrate in streamwater. They concluded that nitrate eluted from the snowpack goes into storage in groundwater, and that pulses in streamflow originate from flushing of the stored nitrate.

Groundwater chemistry tends to be governed by mineral weathering with concentrations influenced by weatherability as discussed above, and residence time (Denning et al., 1992, Hendershot et al., 1992, Hudson & Golding, 1997b). Relationships between concentrations of base cations and silica, and streamflow, are well defined where mineral weathering is the main control on those chemicals (Hudson & Golding, 1997a). Similar relationships for chemicals that are influenced by other factors are less well defined (Feller and Kimmins, 1984, 1979). In the case of nitrate, because it is apparently stored in groundwater but produced at the forest floor and input through precipitation, its behaviour in streams is complex. At Flume Creek, the pulse behaviour of nitrate has been noted (Hudson & Fraser, 2001). The declining intensity of the nitrate pulses throughout the fall–winter season supports the storage – release mechanism described above.

Hydrologic losses of nutrients have been reported to be greatest following clear-cut harvesting. Generally, increased losses through leaching are short lived, and are minor compared with the quantity of nutrients removed in harvesting. Tiedemann et al., 1988, and Hornbeck et al., 1986, found that nutrients are fairly well balanced during the course of a year by inputs from precipitation and soil weathering.

As noted above, the effects of clear-cut logging on water chemistry have been studied extensively, but the effects of partial harvesting are still largely unknown. In order to gain some understanding of the relative effects of partial harvesting on water chemistry, the Flume Creek Paired Watershed Experiment was implemented in the early 1990's as part of the Roberts Creek Study Forest.

The Roberts Creek Study Forest (RCSF) is located on the southwestern flank of Mount Elphinstone on the Sunshine Coast approximately 40 km north-west of Vancouver, BC (Figure 1). The RCSF is a collection of adaptive management case studies demonstrating a range of cutting patterns in blocks designed to assist the development of future silviculture prescriptions in the lower elevation, naturally regenerated Douglas-fir dominated ecosystem of the southern coast of the BC mainland. The Flume Creek Paired Watershed Experiment is one component of the RCSF, and was implemented to investigate the effects of two partial retention harvesting systems on streamflow and water quality in small S5 and S6 creeks.

3.0 STUDY AREA

The Mount Elphinstone slope is relatively uniform and dissected by first order creeks that drain narrow elongated catchments. The interfluves between these first order creeks are further dissected by zero order creeks. A zero order creek is difficult to identify through the forest cover on air photos, and therefore generally does not appear on maps. It is ephemeral, and does not occupy a clearly defined gully, but nonetheless is capable of carrying very substantial flows. In contrast, first order creeks are perennial and are clearly visible on air photos because they normally occupy gullies.

The Flume Creek Experimental Watershed consists of three small catchments, designated as F4, F5 and F6 (Figure 1) that are typical of the type of drainage pattern described above. All three creeks are classed as S6 under the Forest Practices Code of BC Act and Regulations. F4 and F6 creeks are zero order, whereas F5 is a first order creek at the outlet, with several zero order tributaries. The zero order creeks typically go dry in the summer, in June or July. The first order channel of F5 usually does not go completely dry, but flow reduces to an unmeasurable trickle. The creeks do not start to flow again until soil moisture is recharged again in the fall; this usually requires several rain storms. For example, in 1996 the creeks did not start to rise until mid October.

F6 drains an area of 16 ha and ranges in elevation from 395 to 560 metres above sea level, with a mean channel gradient of 13%. F4 and F5 range from 505 to about 850 metres above sea level, with drainage areas of 39 and 61 ha respectively. F4 has a mean channel gradient of 17%. The first order channel of F5 has a gradient of 6.5%, while the zero order tributaries have an average gradient of 18%. All zero order channel gradients reflect the local land slope.

While S6 creeks are generally not a major concern for forest managers (they do not support fish and water licenses are usually on larger streams), there were several compelling reasons to select S6 creeks for this study:

- One of the main criteria of the study was that the treatments should be operationally viable within the forest management strategy of the Sunshine Coast Forest District. As such the target maximum block size of 10 ha. was used in the harvesting layout.
- Given the above constraint, the study catchments had to be small so that a significant proportion of the creek could be logged in order to maximize the effect of the treatment on the study creeks. The S6 creeks were small enough to allow this, but at the same time they make up only a small proportion of the watershed area of lower Flume Creek at the point where the water licenses are located.
- This constitutes a very realistic scenario in terms of managing for cumulative effects in a domestic or community watershed. Activities that have a large effect on S6 creeks are often un-noticeable on larger creeks due to dilution effects, but are additive if many first order creeks are in an "unrecovered" state at the same time. This is how cumulative effects occur. Understanding the nature of those effects at the level of the first order S6 creek provides the basis for management of sensitive watersheds to avoid significant cumulative effects.

4.0 METHODOLOGY

4.1 MEASUREMENT OF STREAMFLOW

Each creek is equipped with a weir for flow measurement. The weirs are constructed of concrete with a plywood wall at the downstream end to which a sharp crested metal weir plate is attached. The weir plate has a central 90° V-notch section to allow for precise measurement of low flows, but also has a rectangular overflow section to accommodate high flows. The V-notch section has a head of about 0.25 metres, and the rectangular section has a head of about 0.5 metres above the V-notch section. At F4 and F5 the weirs were constructed in straight channel reaches, in late summer when the channels were dry. The channels were deepened, and plywood forms were built into which concrete was poured. The plywood was removed after the concrete had dried. At F6 the creek flows into the ditch as it leaves the forest above the road, and from there flows through a culvert. Therefore, instead of setting the weir into the channel, 2 retaining walls were constructed in the ditch to create a pond. The weir plate is set into one of the walls. Otherwise, the weir was constructed as described above. F5 and F6 were built in September 1994 and F4 in the summer of 1995.

4.2 SAMPLING

Each weir was equipped with an ISCO 3700C automatic pump sampler. The samplers were activated by a signal from the data logger, based on changes in stage. That is, each time a predetermined change in stage occurred, either rising or falling, the data logger would send a pulse to the sampler, which would collect a sample, and then wait for the next signal. The sampler can collect and store up to 24 samples in 500 ml sample bottles. The rise and fall of discharge was used to trigger the samplers in order to obtain samples for a range of flows, and to sample more frequently during storms.

Generally, the samples were retrieved from the sampler every one to two weeks, depending on storm activity. Samples were collected in duplicate by transferring the sample from the sampler bottles into clean 150 ml polypropylene bottles. The samples were transported back to Vancouver the same day and one set of samples was frozen immediately for analysis at the Ministry of Forests Research Branch analytical lab in Victoria. Samples were analyzed for a range of anions and cations as described by Hudson (2001).

The potential for nitrate to volatilize while sitting in the sampler was of some concern. It was originally thought that the cool temperatures in the fall and winter would minimize volatilization. To verify this, during selected site visits a grab sample was collected and the sampler activated manually upon leaving the site, so that the nitrate concentration in the grab sample and the manual ISCO sample should be the same. The manual sample was then left in the sampler. Analysis results indicated no systematic difference between the grab samples and the manual ISCO samples.

4.3 GROUNDWATER

In the summer of 1997, four groundwater study plots were created to study the effects of the treatments on groundwater levels and chemistry (Figure 1). There is one plot in each of F4 and F6 (designated F4-G and F6-G), and two plots in F5 to represent conditions in a leave strip (F5a-G) and a cut strip (F5b-G). The plots were laid out in a 10x10 metre square with

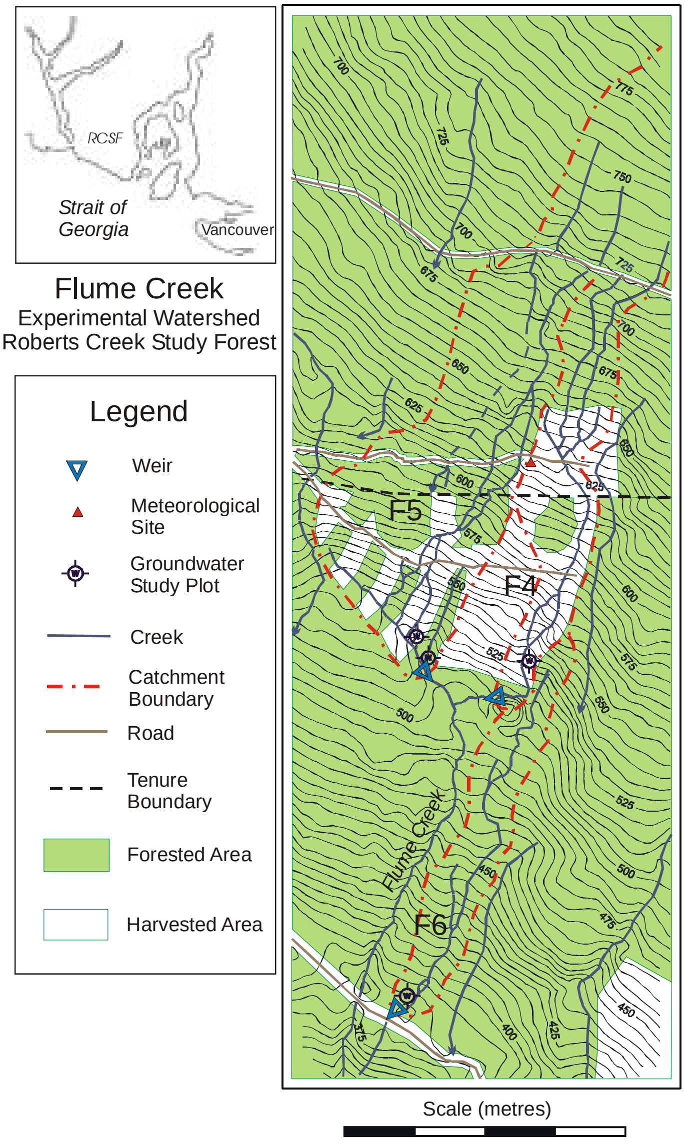

Figure 1 (above): Map of Flume Creek.

Figure 2 (left): An aerial photograph of the harvested treatment units as of June 2000. The strip retention treatment at F5 is in the foreground, and the VR treatment at F4 is on the right-hand side of the photo.

nine piezometers drilled in three rows such that the lowest row was parallel and adjacent to the creek. A water table well was drilled near the plot center and equipped with a pressure transducer connected to a data logger to record fluctuations in water table height. The piezometers were drilled to an impeding layer (i.e., bedrock) and completed with 1-inch (2.54 cm) PVC pipe with a 15 cm completion interval, backfilled with "forestry gravel" to 18 cm, sealed with bentonite, and cemented to the surface.

Groundwater was sampled during regularly scheduled field trips, and more frequently if possible in response to storms in order to capture a representative range of conditions. Samples were collected manually from piezometers using a bailer constructed from a section of copper pipe. The piezometric head was also measured at the time each sample was collected by measuring the depth to the static water level in the standpipes.

4.4 CHEMICAL ANALYSIS

The samples were kept frozen at -80 °C prior to analysis. The samples were thawed and allowed to equilibrate to room temperature. A full suite of analyses was done at the same time, including all major cations and anions. Sub-samples were poured off for ICP and ion chromatography analysis. Nitrate concentrations were analyzed by ion chromatography using a Waters 'Action Analyzer' HPLC system. The anions were separated on a Waters IC-Pak Anion HR column and nitrate was detected by a UV/visible detector for superior detection limits. Calibration was done using NIST traceable ion chromatography standards.

4.5 FOREST HARVESTING TREATMENTS.

The treatments selected for the experiment were a variable retention (VR) harvest, involving a combination of grouped and dispersed retention, and a strip retention cut (Figure 2). The intent of the treatments is that the strip retention treatment should result in half the canopy removal of the VR treatment, expressed as a proportion of the watershed area. The strip retention treatment was originally laid out as five strips with alternating leave strips of equal width. The VR treatment was applied to F4 and involved 18% canopy retention, not including individual reserve trees. The strip retention treatment, applied to F5, retained 49% of the harvested area in the leave strips (Figure 1).

Table 1: Summary of forest harvesting at Flume Creek.

	Total	harvested areas (ha)		% harvested	
Creek	Area (ha)	Year 1	Year 2	Year 1	Year 2
F4	39	9	15	23.1	38.5
F5	61	5.9	10.6	9.7	17.3
F6	16	control watershed		(not harvested)	

Forest harvesting treatments were done in two stages, partly due to a forest tenure boundary that divides the catchments into two parts (Figure 1). The lower part of the watershed falls under the Small Business Forest Enterprise Program (SBFEP) managed by the Ministry of Forests, Sunshine Coast District. The upper part lies within private land owned and managed by Canadian Forest Products Limited (Canfor). Harvesting treatments began in the fall of 1998 in the SBFEP portion. At that time, the three upper (i.e., furthest upstream) strips in F5 and the VR treatment in F4 were harvested. Blowdown that occurred in the reserve patches of F4 and in the leave strips of F5 reduced the residual canopy density somewhat. It is estimated that the reduction is in the order of an additional 3 to 5% of the residual stand. However, as a result of concerns over the stability of the leave strips, the leave strip adjacent to the eastern boundary of F5 was doubled in width, and the lower two cut strips combined into one. This strip was harvested in the summer of 1999. Later that fall, harvesting of the upper part of F4 was completed by Canfor, duplicating the VR treatment that was applied to the SBFEP block.

The harvesting schedule described above resulted in a two-stage canopy removal, such that after year 1, canopy removal was 23.1 and 9.7 % of the total catchment areas of F4 and F5 respectively. After year 2, 38.5 and 17.3 % of F4 and F5 had been harvested (Table 1). Canopy retention was determined by measuring the reserve areas on maps and adjusting those measurements to account for blowdown. Further harvesting on F5 is expected in the year 2002, in the form of a group selection cut in the area above the existing strip retention cut in the Canfor portion that will bring the harvest to about 25% of the forest canopy by watershed area. This will be followed by a second pass in the SBFEP strip retention in the year 2005.

5.0 DATA ANALYSIS

The sequential forest harvesting described above provided the basis for comparison between the pre-treatment period and years 1, 2 and 3. These treatment periods represent:

- Pre-logged state (P): as described by Hudson and Fraser (2001);
- Year 1 (Y1): partial completion of the harvesting of F4 and F5 treatment watersheds;
- Year 2 (Y2): the first year after completion of harvesting in its current configuration;
- Year 3 (Y3): the second year after logging, which the literature shows might be the time when the effect of the harvesting on water chemistry is at a maximum.

There are several ways of looking at nitrate concentrations in streamflow. Previous analyses revealed that water chemistry at Flume Creek responds to an extremely complex interaction between stream discharge and seasonal factors. In addition to this, nitrate exhibits pulse behaviour. An analysis of the effects of forest harvesting on nitrate concentrations must account for all these factors. Using regression analysis, we explored several options for treating the data, as follows:

- Overall annual average nitrate concentration – this was not a very useful quantity in streamflow, but reasonably useful in groundwater data.
- Relationships between nitrate concentrations and stream discharge – these relationships were useful to assess changes in concentration relative to streamflow before and after log-

ging, and also to reconstruct a continuous record of nitrate concentration to calculate nitrate flux over a period of time. However, because of the pulse behaviour a great many regression relationships were used to reconstruct a continuous record.

- In some instances, the nitrate flux proved to be a better relationship to illustrate the changes in nitrate behaviour with season and in response to logging. However, the flux is a derived quantity based on the product of concentration and streamflow, and often the relationship between nitrate flux and stream discharge exists when there is no relationship between discharge and concentration. If there is a relationship between concentration and discharge that is poorly defined, the flux can be used instead to generate a well defined relationship. Otherwise if there is no relationship between concentration and streamflow, it makes no sense to create one artificially using flux as a substitute.
- Paired samples – in the case of nitrate in streamflow, the peak concentrations associated with nitrate pulses were identified. Peak concentrations of the nitrate pulses associated with specific events on F4 and F5 were paired with peak concentrations on F6 for the same event. Regression analysis was used to identify relationships between nitrate peaks for the pre-treatment period, with a prediction interval. For post-treatment matched nitrate peaks, the peak concentration was judged to have been significantly altered by logging if the peak concentration on F4 or F5 relative to that on F6 was outside the prediction interval.
- A similar approach was used to assess changes in nitrate concentration in groundwater, but this proved to be somewhat simpler since there were fewer samples to deal with, and the samples were already matched because the piezometers were sampled manually at approximately the same time.

6.0 RESULTS

The analysis presented here is based on 2,122 samples of streamwater collected between October 1996 and March 2001 (Table 2). Of those samples, 204 were treated as missing because the measured concentrations were below the detection limit of the analytical method. The range in concentration in any year and at any site is high relative to the mean concentration, and the data are highly skewed. This reflects the pulse behaviour of nitrate in streams as noted by Hudson and Fraser (2001).

The most intense pulses occurred around the fall freshet, and the time base of a pulse appeared to depend on the rate at which the stream rose. The intensity of the pulses declined as the season progressed, but started to increase again in the late spring and into summer. In the pre-treatment condition the pulses were often very brief. In a situation such as this, it was easy to miss the peak concentration or even to miss the pulse altogether even with automatic sampling. However, in order to sort out the changes that occurred as a result of logging, the complexity of the processes involved in generating the pulses should be accounted for. Thus, although the relative changes in nitrate in streams that occurred following logging appeared obvious, it was very difficult to devise a meaningful statistical test that would show the significance of the observed changes.

6.1 REGRESSION MODELS THAT RELATE NITRATE CONCENTRATIONS TO SPECIFIC STREAM DISCHARGE

In order to recreate a continuous estimate of nitrate concentration in streams, regression equations of specific stream discharge (Qs, in units of L/s/ha) specific to the period in question were used. Specific discharge was used throughout this analysis because it provided a basis of comparison between creeks. That is, the specific discharge is independent of watershed area and therefore any differences in hydrograph shape

Table 2: Statistical properties of nitrate concentration data in streamflow by creek and by water year.

Variable	N	N missing	Min	Mean	Max	Std. Dev.	S.E. Mean
F6-P1	174	15	0.000	0.117	6.737	0.627	0.048
F6-P2	104	35	0.003	0.057	0.194	0.036	0.004
F6-Y1	152	33	0.011	0.064	1.100	0.124	0.010
F6-Y2	87	15	0.009	0.069	0.383	0.093	0.010
F6-Y3	36	13	0.010	0.041	0.120	0.029	0.005
F4-P1	158	51	0.000	0.106	4.101	0.448	0.036
F4-P2	68	3	0.003	0.107	0.433	0.088	0.011
F4-Y1	180	15	0.001	0.100	0.710	0.136	0.010
F4-Y2	146	2	0.052	0.610	6.389	0.815	0.067
F4-Y3	143	2	0.020	0.917	2.500	0.378	0.032
F5-P1	111	8	0.000	0.051	0.585	0.071	0.007
F5-P2	115	1	0.013	0.086	0.323	0.061	0.006
F5-Y1	200	9	0.013	0.121	0.776	0.165	0.012
F5-Y2	157	0	0.130	1.490	10.772	2.199	0.176
F5-Y3	87	2	0.130	3.514	16.530	3.873	0.415

are due to morphological characteristics of the watersheds. Regressions were of various forms – linear, logarithmic, exponential or power functions were used to fit the estimated nitrate concentrations as closely as possible to observed concentrations. Regressions tended to be different for rising and falling streamflow and/or concentration, and generally the slope of the relationships decreased throughout the fall/winter season.

For example, 22 different regression relationships were used at F4 to model the nitrate concentrations in streamflow in the fall of 2000, and 23 in the fall of 1996. To simplify this situation, only relationships that were used to model nitrate during storms were used. This resulted in six periods of similar regressions for the fall of 2000, and eight for the fall of 1996 (Figure 3). Hysteresis was a very significant factor for the pre-treatment period, resulting in the necessity to use completely different regressions for rising and falling conditions. For readability, only the rising relationships are shown for 1996, whereas hysteresis was generally not as important for the post-treatment period. The situation for F5 was found to be similar to that of F4 (Figure 4).

The change in the regression model within a given year clearly shows the decline in overall concentration throughout the fall season. However, it also shows that the decline in concentration is less during the post-treatment period. At F4, the maximum nitrate concentration that occurs during fall freshet is apparently not affected by harvesting, but nitrate concentrations remain generally elevated compared with the pre-treatment period (Figure 3). At F5, the entire range of nitrate concentrations, including the peak concentration of the fall freshet pulse, is shifted up by about an order of magnitude (Figure 4). At both sites, the pulse behaviour has been fundamentally altered. After about 60 days into the Year 3 season at both sites, the peak concentration of the pulses is about 10x and the off-peak concentrations at least 100x the pre-treatment levels.

These features can also be seen clearly on the streamflow and nitrate hydrographs that were developed from the regression modeling. Using the examples of the fall of 1996 (period P1, Figure 5), the fall of 1998 (Year 1, Figure 6) and 2000 (Year 3, Figure 7) the progression of changes in nitrate concentration are apparent. Note that a common time base is used for all graphs (October 1 to December 31), and an effort was made to keep the Y-axes to a common scale to make all graphs directly comparable. In 1996, the fall freshet was not sampled at F5, and the peak of the nitrate pulses that occurred at F4 (4.1 mg/L) and F6 (6.74 mg/L) were clipped to ensure readability later in the season. In that year, the intensity of the pulses is similar at all three sites, although the timing is different, particularly with the fall freshet pulse, because F4 and F5 generally start to flow before F6. In Year 1 (Figure 6), sampling was

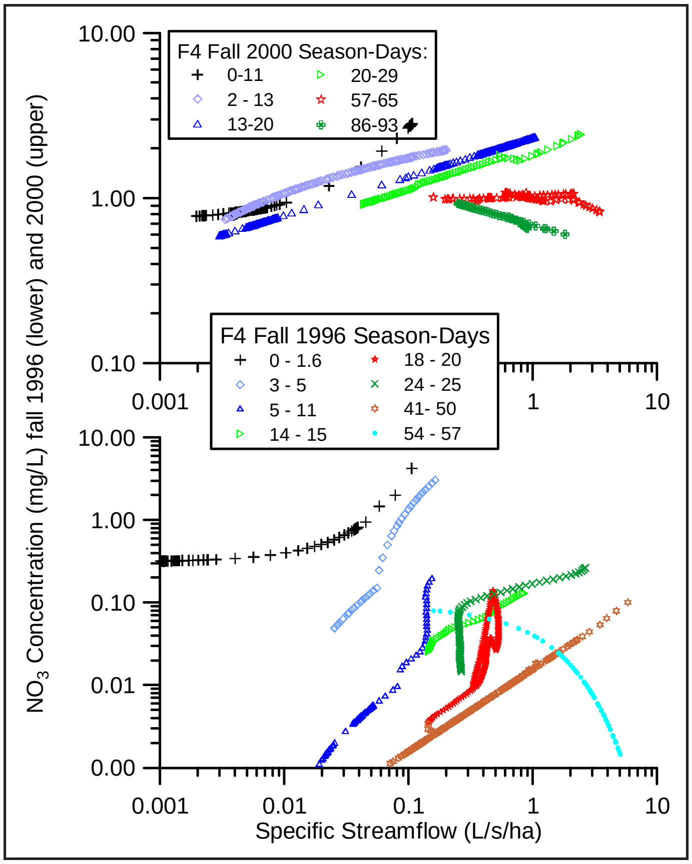

Figure 3. Relationships used in regression model of nitrate and streamflow, F4.

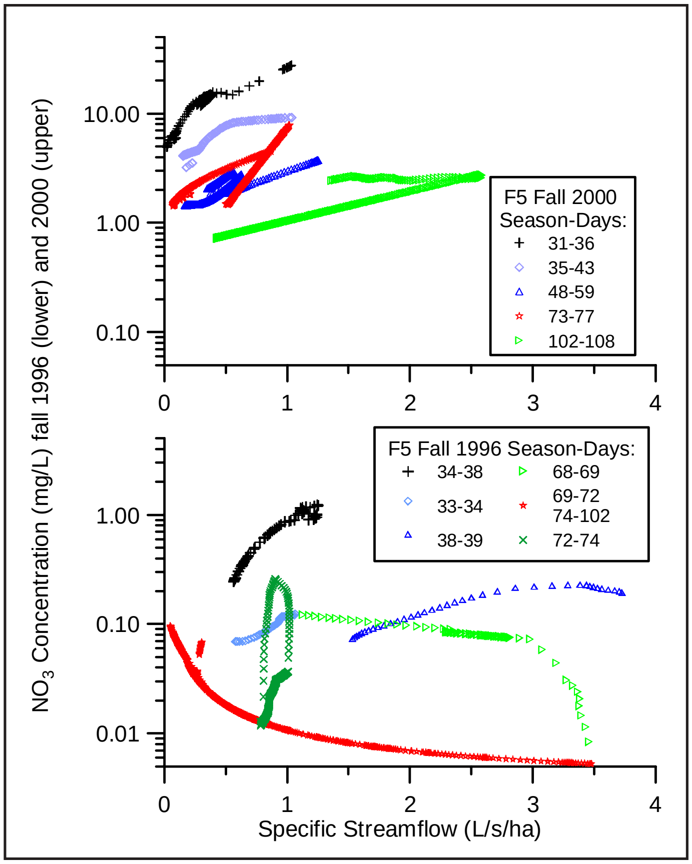

Figure 4. Relationships used in regression model of nitrate and streamflow, F5.

not started until after the freshet; however, at this point elevated nitrate levels at F5 are starting to become apparent. By Year 3 (Figure 7), the effect of forest harvesting on nitrate concentrations at F5 is quite clear. At this point it is no longer possible to maintain a common scale for the nitrate concentrations, which are elevated at both F4 and F5 in relation to F6. Streamflows are also greatly reduced at all sites relative to other years, but at F4 and F5 they are elevated relative to streamflow at F6 due to the documented effects of forest harvesting (Hudson, 2001). The same scale is used for nitrate concentration at F4 and F5, showing clearly the increase in nitrate pulse intensity at F5 relative to both F4 and F6, not only during the freshet, but also in later storms such as the November 23 event.

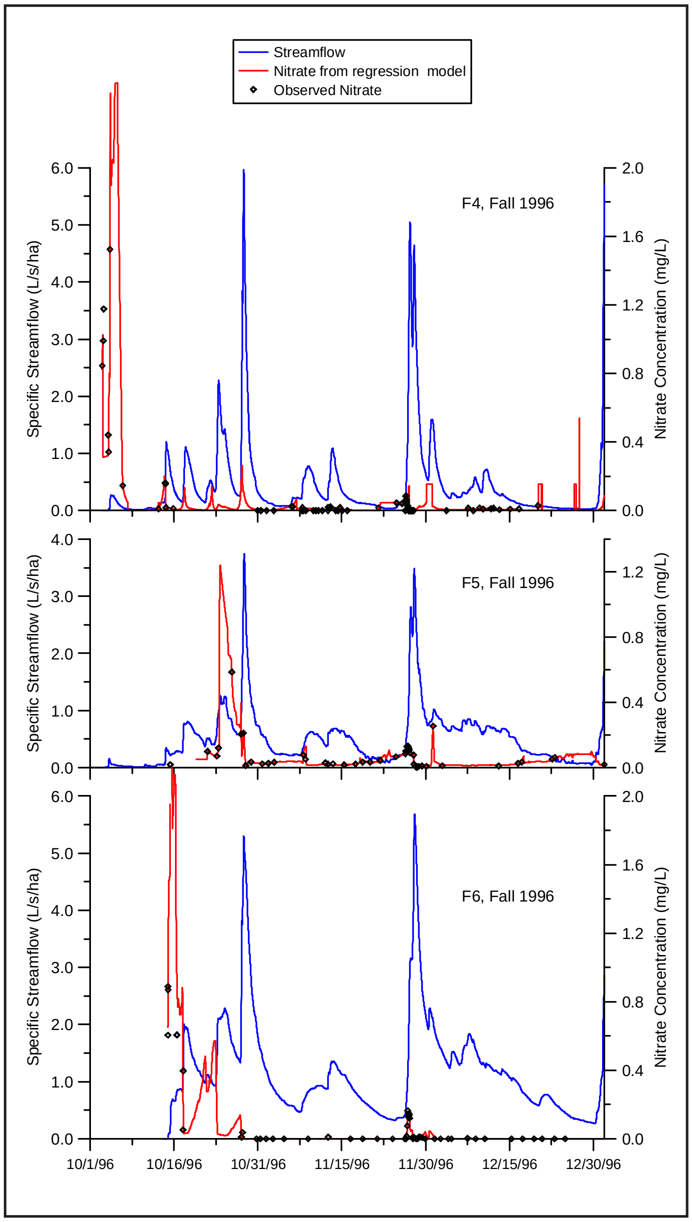

Figure 5. Streamflow (blue lines), nitrate concentration from samples (black diamonds) and nitrate concentrations from regression model (red lines) for the fall of 1996, representing baseline conditions.

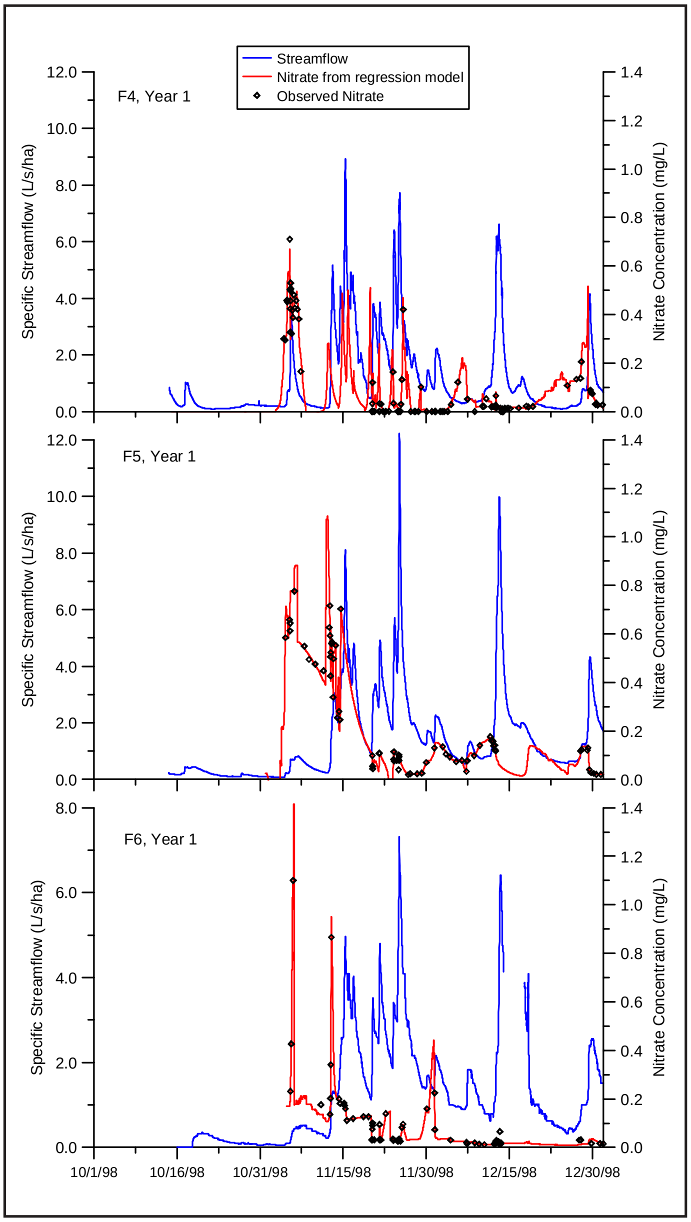

Figure 6. Year 1 streamflow and nitrate concentrations. Note the Y-axes are directly comparable.

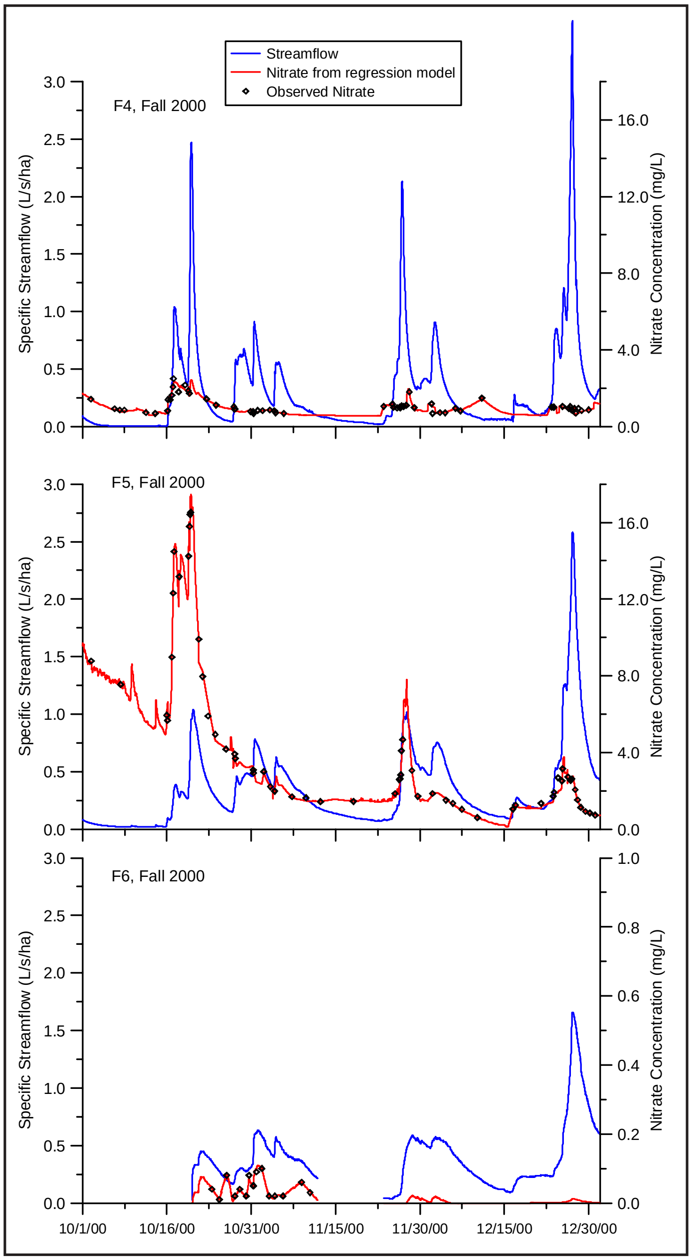

Figure 7. Year 3 streamflow and nitrate concentrations. Note the difference in scales on the second Y-axis. At this point the effects of forest harvesting on nitrate concentrations are clear.

6.2 PRE- AND POST-TREATMENT DIFFERENCES IN MEAN NITRATE CONCENTRATIONS

One way of looking at the effects of logging treatments on nitrate concentrations is by examining annual mean nitrate levels in streamflow and groundwater. Two different measures of mean concentrations were used (Table 3):

- arithmetic means;
- flow-weighted means – nitrate concentration is multiplied by stream discharge that occurred at the time the sample was collected (Q_{sample}). The sum of these products for all samples within a given time period is divided by the total of all Q_{sample} flows.

Because nitrate concentrations are affected by seasonal variables and either streamflow or groundwater levels, the arithmetic mean is not a particularly powerful quantity. Regardless of that, the effects of logging on mean annual nitrate concentration are very clear (Figure 8). Paired t-tests were used to test the significance of the changes in concentration (Table 4). Any t-test comparisons that resulted in no significant difference were then assigned a ratio of 1.0 (Table 3). At F6, there were no samples collected for more than two months between mid November and late January due to an equipment fault. This may be the reason for the low average nitrate concentration in year 3, which is significantly lower than it is in other years, resulting in a Y3/P ratio that is less than 1.0 (Table 3). There are significant differences between mean concentrations in the pre-treatment period and years 2 and 3 at F4. There is no significant change from pre-treatment concentrations in year 1

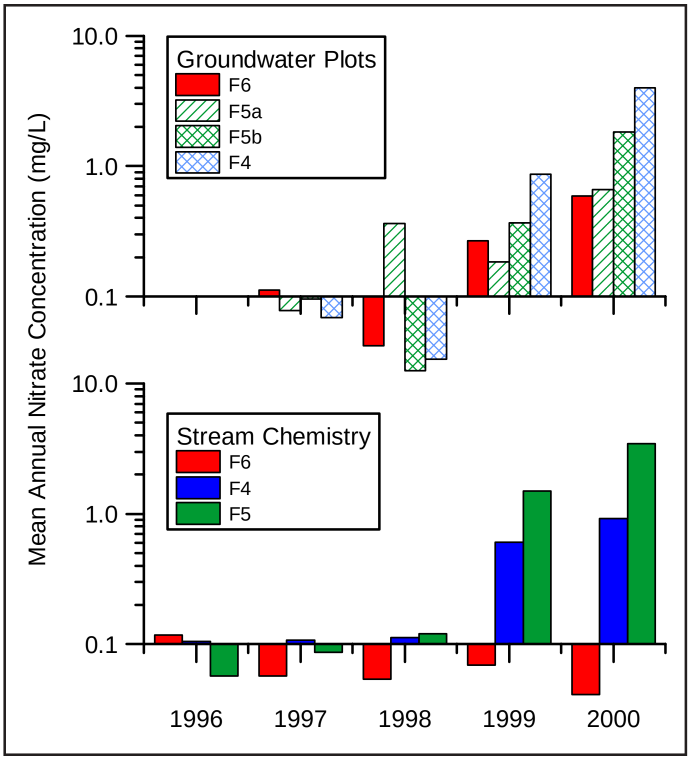

Figure 8. Mean annual nitrate concentrations in streamflow and groundwater at Flume Creek.

Table 3. Mean annual nitrate concentrations (mg/L) and concentration ratios in streamflow and groundwater. The concentration ratios relate the post treatment mean concentrations to the pre-treatment levels. Note that a comparison that has been found insignificant is assigned a ratio of 1.0, flagged by a *.

3a: Streamflow	**F4**	**F4**	**F5**	**F5**	**F6**	**F6**
Water Year/ treatment Year	Arithmetic Mean (mg/L)	Flow Weighted Mean (mg/L)	Arithmetic Mean (mg/L)	Flow Weighted Mean (mg/L)	Arithmetic Mean (mg/L)	Flow Weighted Mean (mg/L)
1996 (P1)	0.105	0.022	0.057	0.028	0.117	0.049
1997 (P2)	0.107	0.127	0.086	0.079	0.057	0.045
1998 (Y1)	0.113	0.048	0.121	0.102	0.054	0.041
1999 (Y2)	0.610	0.415	1.490	1.153	0.069	0.088
2000 (Y3)	0.917	0.814	3.467	3.430	0.041	0.004
Mean concentration ratios in streamflow						
Y1/P	1.0*	1.0*	1.7	1.9	1.0*	1.0*
Y2/P	5.8	5.6	20.8	21.4	1.0*	2.1
Y3/P	8.6	10.9	48.3	63.7	0.5	0.1

3b: Groundwater plots	**F4: VR Harvested 1998 - 1999**	**F5b: Cut Strip (1999)**	**F5a: Leave Strip**	**F6: Control Plot**
Water Year/ treatment Year	**Annual Mean (mg/L)**	**Annual Mean (mg/L)**	**Annual Mean (mg/L)**	**Annual Mean (mg/L)**
1997 (P)	0.069	0.096	0.112	0.078
1998 (Y1)	0.033	0.027	0.042	0.361
1999 (Y2)	0.871	0.365	0.267	0.185
2000 (Y3)	4.000	1.830	0.590	0.660
Mean concentration ratios in groundwater				
Y1/P	0.5	0.3	0.4	4.6
Y2/P	12.6	3.8	2.4	2.4
Y3/P	58.0	19.1	5.3	8.5

due to the harvesting treatment, (implying a Y1/P ratio of 1.0, Table 3), but there are significant changes among all the post-treatments periods. At F5, the changes in nitrate concentrations begin in year 1, after harvesting less than 10% of the watershed area. There is also an apparently significant increase in mean nitrate concentration during the pre-treatment period from P1 to P3 with no harvesting in the watershed, although there is also missing data during the fall of 1997 that may have affected the mean concentration.

The changes that occurred in nitrate in streamflow are also reflected in mean annual nitrate concentrations in groundwater (Table 3, Figure 8). In a manner similar to that of streamflow, nitrate concentrations in groundwater tend to be high in the early season and decline towards the winter (Figure 9). The trends can be shown using the plot-average nitrate concentration on each sampling date. Because the groundwater sampling was done manually, the sampling frequency is not sufficient to show the pulse behaviour, except for year 3 (2000-01). More frequent sampling around specific storms has revealed short-term fluctuations in concentration that may indicate pulse

Table 4. Significance of comparisons between treatment years. N = not significantly different, otherwise the numbers in the cells are the T-ratio and p-statistic (in parentheses).

	F6-P2	F6-Y1	F6-Y2	F6-Y3
F6-P1	N	N	N	N
F6-P2		N	N	2.65 (0.0097)
F6-Y1			N	2.06 (0.041)
F6-Y2				-2.51 (0.013)

	F5-P2	F5-Y1	F5-Y2	F5-Y3
F5-P1	-4.02 (0.0001)	-5.22 (0.0000)	-8.19 (0.0000)	-8.34 (0.0000)
F5-P2		-2.69 (0.0076)	-7.99 (0.0000)	-8.25 (0.0000)
F5-Y1			7.78 (0.0000)	-8.17 (0.0000)
F5-Y2				-4.49 (0.0000)

	F4-P2	F4-Y1	F4-Y2	F4-Y3
F4-P1	N	N	-6.61 (0.0000)	-17.01 (0.0000)
F4-P2		N	-7.37 (0.0000)	-24.26 (0.0000)
F4-Y1			-7.48 (0.0000)	-24.60 (0.0000)
F4-Y2				-4.12 (0.0001)

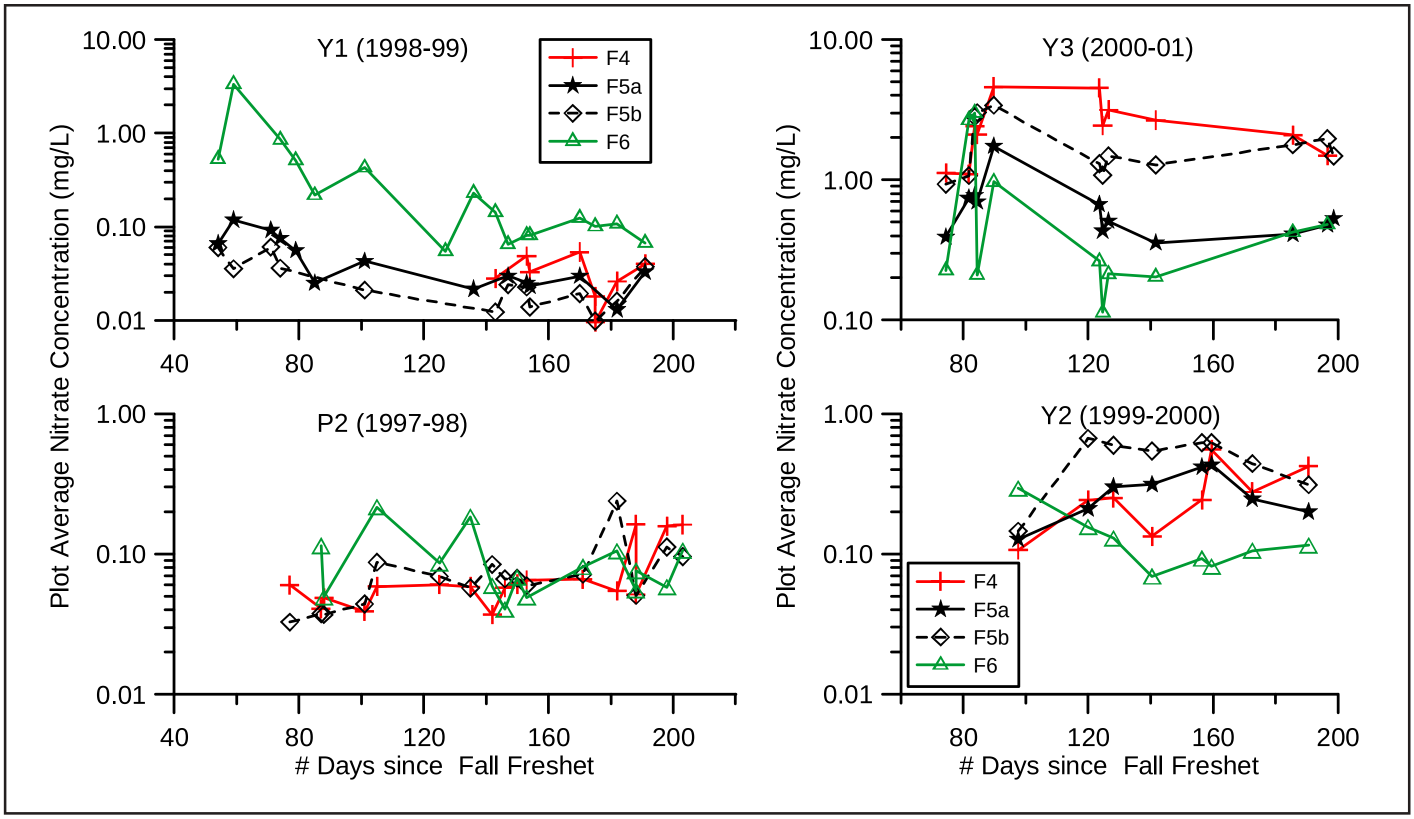

Figure 9: Seasonal trends in plot average nitrate concentration. These graphs show the effect of harvesting in relation to seasonal trends in nitrate concentration.

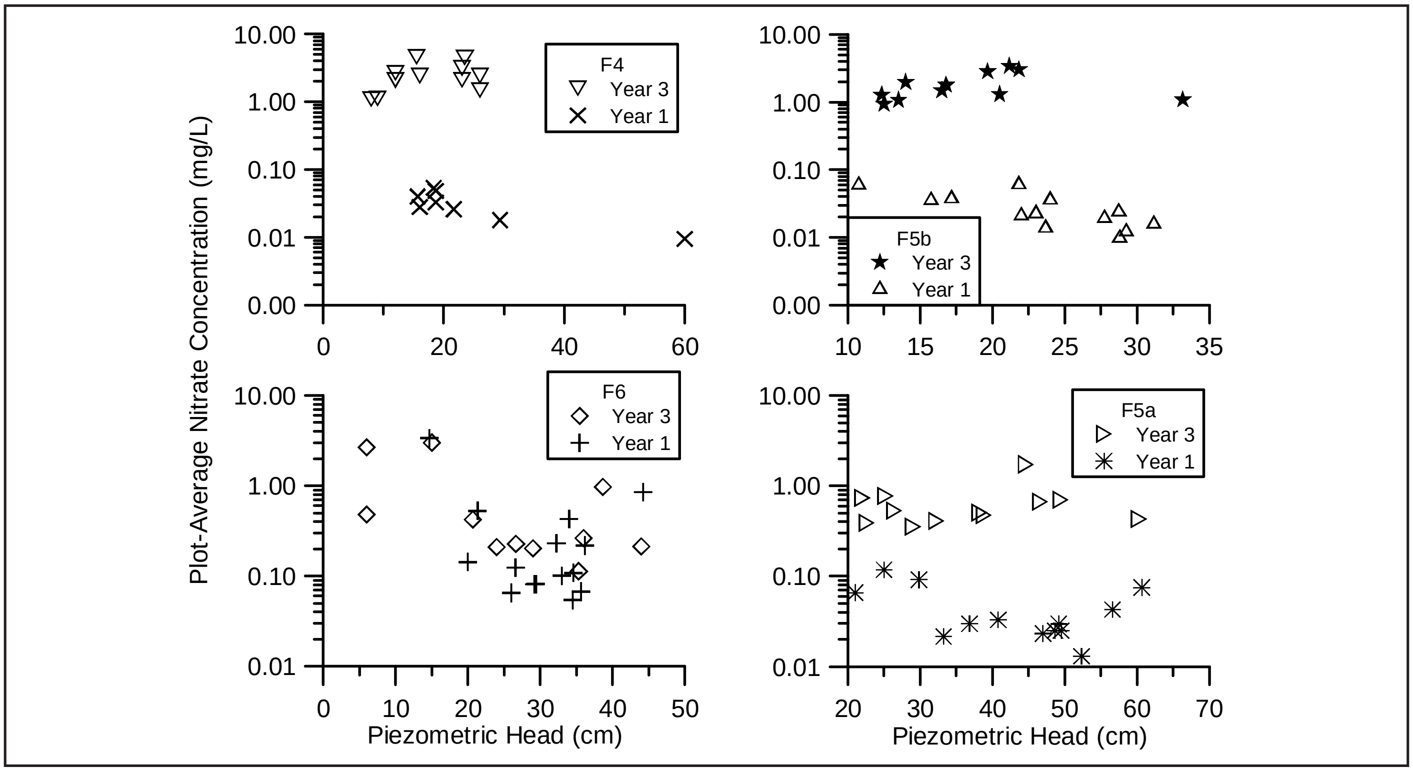

Figure 10: Nitrate concentrations in groundwater by piezometric head; similar to the seasonal trends, these are elevated after logging.

behaviour (Figure 9, top right graph). Also, in most years the sampling did not begin soon enough to capture the high concentrations around fall freshet, except for year 1 (1998-99) when the sampling early in the season helped to define the seasonal trend more clearly than in other years.

Nitrate concentrations in groundwater were also governed by piezometric head (Figure 10). This effect is similar to the relationship between nitrate concentration and stream discharge. Although the relationship between plot averaged mean nitrate concentration and the average piezometric head in all piezometers sampled (Figure 10) is not well defined, the effect of forest harvesting is apparent when comparing Year 1 with Year 3. It should be noted that the groundwater study plots were not affected by harvesting in Year 1. The relationship remains unchanged at F6-G from Year 1 to Year 3, while at all other plots there are elevated nitrate concentrations in Year 3 compared with Year 1 in relation to piezometric head (Figure 10).

The fall period is of particular interest since this is when the largest storms tend to occur. Thus, a comparison for the fall period was warranted, particularly since the nitrate fluxes can be easily calculated for that period based on the continuously modeled nitrate concentrations. While the most important issue in terms of drinking water is the concentration of nitrate, the export of nitrate in streamflow from a watershed, and the changes that occur after harvesting, have important implications for forest ecology. The nitrate flux can be calculated as

$$Flux(g/ha) = \frac{[NO_3^-] \cdot Q_S \cdot L.I.}{1000} \qquad (1)$$

where $[\mathrm{NO}_3^-]$ is the nitrate concentration in mg/L, Q_S is the specific discharge in L/s/ha, and L.I. is the time interval of the streamflow data in seconds. This equation yields the mass of nitrate that leaves the watershed at the stream gauge over the time interval of data collection, which in this case is 15 minutes, or 900 seconds.

The nitrate flux data tells a story similar to that told by the annual mean nitrate concentration (Table 5). The increases in nitrate levels are reasonably consistent regardless of how the data are treated. Comparing the ratios in tables 3 and 5 leads to the conclusion that by year 3 (two years after the harvesting was complete) the overall mean nitrate levels were about 12X pre- treatment levels at F4, and about 51X at F5.

Table 5: Mean nitrate concentrations, nitrate fluxes and ratios of post treatment to pre-treatment levels for the October–December period at Flume Creek.

Water Year/ Treatment Year	Arithmetic Sample Mean (mg/L)	Flow Weighted Sample Mean	Total Flux (g/ha)	Mean Daily Flux (g/ha/day)
	F4	**F4**	**F4**	**F4**
1996	0.196	0.051	170.6	1.9
1997	0.081	0.075	153.3	2.1
1998	0.100	0.095	214.1	3.2
1999	0.562	0.441	2061	31.0
2000	1.079	1.063	2571	28.0
Y1/P	1.0*	1.52	1.32	1.59
Y2/P	4.05	7.01	12.73	15.43
Y3/P	7.78	16.89	15.88	13.93
	F5	**F5**	**F5**	**F5**
1996	0.071	0.058	358	3.9
1997	0.069	0.086	170	3.1
1998	0.227	0.180	1424	23.3
1999	2.057	1.251	6936	116.1
2000	4.488	4.000	9152	99.4
Y1/P	3.26	2.51	5.39	6.66
Y2/P	29.5	17.4	26.27	33.17
Y3/P	64.4	55.6	34.67	28.40
	F6	**F6**	**F6**	**F6**
1996	0.345	0.077	434	5.7
1997	0.057	0.048	294	3.3
1998	0.096	0.045	531	9.9
1999	0.110	0.110	387	7.1
2000	0.046	0.049	40	0.7
Y1/P	0.48	0.72	1.46	2.20
Y2/P	0.55	1.75	1.06	1.58
Y3/P	0.23	0.78	0.11	0.15

6.3 PAIRED SAMPLES IN STREAMFLOW AND GROUNDWATER

Again, due to the complex nature of nitrate behaviour, nitrate samples collected on different creeks at the same time are not necessarily comparable because the timing and magnitude of nitrate pulses are different for each creek. However, Hudson and Fraser (2001) identified relationships between peak nitrate concentrations and seasonal variables for each creek. Thus, the peak concentrations of nitrate pulses at each study creek associated with a given storm are directly comparable. To do this analysis, nitrate peaks associated with storms were identified (Table 6). The analysis was then essentially the same as that used to assess changes in peak streamflow (Hudson, 2001). The only difference is that instead of comparing peak streamflow on F4 and F5 relative to that on F6 before and after logging, the comparison is now being made on peak nitrate concentration.

Because of the skewed nature of the data as noted above, the peak concentration data were log transformed. Regression of the log-transformed data resulted in power functions to describe the peak nitrate concentration at F4 and F5 as functions of that at F6, as follows:

$$C_{F4} = 0.6101 \cdot C_{F6}^{\ 0.5909} \qquad (\text{s.e.} = 0.6469, R^2 = 60.2\%) \quad (2)$$

$$C_{F5} = 0.2981 \cdot C_{F6}^{\ 0.3477} \qquad (\text{s.e.} = 0.6044, R^2 = 33.4\%) (3)$$

Table 6. Results of paired peak nitrate comparisons, F4/F5 vs. F6, based on pre-treatment regressions. If a comparison is not affected by logging, the percent difference is 0.0 and the ratio is 1.0.
6a: Year 1:

	Measured Nitrate Concentration (mg/L)		Calculated Nitrate Concentrations (mg/L)		Percent Differences (%)		Ratios	
Year 1:	at F6	at F4/F5	Expected	Upper 90% Confidence Limit	Measured vs. Expected	Measured vs. Upper 90% Limit	Measured Over Expected	Measured Over Upper 90% Limit
		F4	**F4**	**F4**	**F4**	**F4**	**F4**	**F4**
4-Nov-98	0.43	0.46	0.369	1.228	0.0	0.0	1.0	1.0
7-Nov-98	1.10	0.71	0.645	2.296	0.0	0.0	1.0	1.0
23-Nov-98	0.10	0.12	0.156	0.495	0.0	0.0	1.0	1.0
29-Nov-98	0.14	0.10	0.190	0.605	0.0	0.0	1.0	1.0
9-Dec-98	0.07	0.12	0.130	0.410	0.0	0.0	1.0	1.0
13-Dec-98	0.03	0.07	0.074	0.236	0.0	0.0	1.0	1.0
29-Dec-98	0.03	0.21	0.078	0.250	0.0	0.0	1.0	1.0
15-Jan-99	0.07	0.11	0.126	0.397	0.0	0.0	1.0	1.0
29-Jan-99	0.08	0.11	0.140	0.443	0.0	0.0	1.0	1.0
3-Feb-99	0.04	0.13	0.096	0.305	0.0	0.0	1.0	1.0
11-Feb-99	0.05	0.12	0.106	0.336	0.0	0.0	1.0	1.0
16-Feb-99	0.05	0.31	0.106	0.336	0.0	0.0	1.0	1.0
22-Feb-99	0.04	0.09	0.091	0.289	0.0	0.0	1.0	1.0
27-Feb-99	0.04	0.05	0.096	0.305	0.0	0.0	1.0	1.0
19-Mar-99	0.02	0.07	0.051	0.168	0.0	0.0	1.0	1.0
Average change in nitrate concentration:					0.0	0.0	1.0	1.0
Overall Mean Change					0.0		1.0	
		F5	**F5**	**F5**	**F5**	**F5**	**F5**	**F5**
4-Nov-98	0.43	0.66	0.222	0.667	0.0	0.00	1.0	1.0
7-Nov-98	1.10	0.78	0.308	0.983	0.0	0.00	1.0	1.0
16-Nov-98	0.87	0.72	0.284	0.889	0.0	0.00	1.0	1.0
23-Nov-98	0.10	**0.70**	0.134	0.386	425.3	82.3	5.3	1.8
29-Nov-98	0.14	0.07	0.150	0.434	0.0	0.00	1.0	1.0
4-Dec-98	0.22	0.11	0.177	0.519	0.0	0.00	1.0	1.0
9-Dec-98	0.07	0.18	0.120	0.345	0.0	0.00	1.0	1.0
13-Dec-98	0.03	0.11	0.086	0.251	0.0	0.00	1.0	1.0
29-Dec-98	0.03	0.13	0.089	0.259	0.0	0.00	1.0	1.0
15-Jan-99	0.07	**0.38**	0.118	0.338	223.9	12.6	3.2	1.1
29-Jan-99	0.08	0.11	0.125	0.361	0.0	0.00	1.0	1.0
3-Feb-99	0.04	0.09	0.101	0.290	0.0	0.00	1.0	1.0
11-Feb-99	0.05	0.09	0.107	0.307	0.0	0.00	1.0	1.0
16-Feb-99	0.05	0.12	0.107	0.307	0.0	0.00	1.0	1.0
22-Feb-99	0.04	0.12	0.097	0.281	0.0	0.00	1.0	1.0
27-Feb-99	0.04	0.10	0.101	0.290	0.0	0.00	1.0	1.0
19-Mar-99	0.02	**0.45**	0.069	0.206	554.6	119.69	6.5	2.2
Average change in nitrate concentration:					70.8	12.6	1.7	1.1
Overall Mean Change					41.7		1.4	

Table 6b: Year 2–3.

Table 6b:	Measured Nitrate Concentration (mg/L)		Calculated Nitrate Concentrations (mg/L)		Percent Differences (%)		Ratios	
Year 2 - 3	at F6	at F4/F5	Expected	Upper 90% Confidence Limit	Measured vs. Expected	Measured vs. Upper 90% Limit	Measured Over Expected	Measured Over Upper 90% Limit
		F4	**F4**	**F4**	**F4**	**F4**	**F4**	**F4**
30-Oct-99	0.22	**2.49**	0.251	0.804	893.6	209.8	9.9	3.1
7-Nov-99	0.14	**1.66**	0.188	0.607	780.2	173.1	8.8	2.7
8-Nov-99	0.22	**0.96**	0.251	0.804	280.9	18.8	3.8	1.2
8-Nov-99	0.22	**1.32**	0.251	0.804	424.5	63.5	5.2	1.6
16-Nov-99	0.38	0.67	0.346	1.139	0.0	0.0	1.0	1.0
2-Dec-99	0.35	0.30	0.326	1.080	0.0	0.0	1.0	1.0
7-Dec-99	0.03	**0.30**	0.074	0.246	308.1	22.5	4.1	1.2
17-Dec-99	0.03	0.19	0.069	0.246	0.0	0.0	1.0	1.0
4-Jan-00	0.02	**0.61**	0.066	0.196	822.8	209.0	9.2	3.1
9-Jan-00	0.03	**0.47**	0.081	0.246	479.5	91.7	5.8	1.9
17-Jan-00	0.02	**0.61**	0.067	0.196	808.8	212.1	9.1	3.1
1-Feb-00	0.04	**0.63**	0.095	0.289	565.0	118.6	6.6	2.2
8-Feb-00	0.02	**0.59**	0.067	0.196	782.1	202.9	8.8	3.0
29-Feb-00	0.02	**0.51**	0.055	0.196	826.7	159.5	9.3	2.6
3-Mar-00	0.05	**0.43**	0.104	0.329	310.0	29.6	4.1	1.3
8-Mar-00	0.29	0.33	0.292	0.958	0.0	0.0	1.0	1.0
18-Mar-00	0.04	**0.36**	0.084	0.289	330.1	25.2	4.3	1.3
27-May-00	0.03	**1.02**	0.081	0.246	1154.9	315.2	12.5	4.2
1-Nov-00	0.10	**0.84**	0.156	0.495	436.8	69.7	5.4	1.7
17-Mar-01	0.12	**0.87**	0.174	0.553	399.1	57.4	5.0	1.6
18-Mar-01	0.09	**1.02**	0.147	0.465	593.6	119.5	6.9	2.2
Average change in peak nitrate concentration:					485.6	99.9	5.9	2.0
Overall Mean Change					292.7		3.9	
Year 2 - 3		**F5**	**F5**	**F5**	**F5**	**F5**	**F5**	**F5**
30-Oct-99	0.22	**10.77**	0.177	0.516	5999.3	1988.9	61.0	20.9
7-Nov-99	0.14	**8.57**	0.149	0.436	5641.2	1868.1	57.4	19.7
8-Nov-99	0.22	**3.25**	0.177	0.516	1738.5	529.7	18.4	6.3
8-Nov-99	0.22	**6.08**	0.177	0.516	3341.5	1078.6	34.4	11.8
16-Nov-99	0.38	**2.15**	0.213	0.637	907.6	237.6	10.1	3.4
2-Dec-99	0.35	**0.77**	0.206	0.617	271.2	24.0	3.7	1.2
7-Dec-99	0.03	**0.66**	0.086	0.256	665.3	156.9	7.7	2.6
17-Dec-99	0.03	**0.46**	0.083	0.256	454.1	78.8	5.5	1.8
4-Jan-00	0.02	**0.63**	0.080	0.225	680.9	178.3	7.8	2.8
9-Jan-00	0.03	**0.68**	0.091	0.256	642.6	163.9	7.4	2.6
17-Jan-00	0.02	**0.70**	0.081	0.225	752.9	208.5	8.5	3.1
1-Feb-00	0.04	**0.74**	0.100	0.281	641.5	163.0	7.4	2.6
8-Feb-00	0.02	**0.80**	0.081	0.225	881.8	255.1	9.8	3.6
29-Feb-00	0.02	**0.70**	0.072	0.225	867.1	210.3	9.7	3.1
3-Mar-00	0.05	**0.86**	0.105	0.303	721.5	185.0	8.2	2.9
18-Mar-00	0.04	**0.46**	0.093	0.281	390.8	62.1	4.9	1.6
27-May-00	0.03	**0.45**	0.091	0.256	393.3	75.3	4.9	1.8
1-Nov-00	0.10	**3.01**	0.134	0.386	2148.9	680.6	22.5	7.8
8-Nov-00	0.06	**1.63**	0.112	0.323	1354.6	405.4	14.5	5.1
17-Mar-01	0.12	**1.39**	0.143	0.412	874.8	237.6	9.7	3.4
18-Mar-01	0.09	**2.05**	0.129	0.371	1488.8	451.9	15.9	5.5
Average change in peak nitrate concentration:					1469.4	440.0	15.7	5.4
Overall Mean Change					954.7		10.5	

Table 6c. Paired peak concentrations of matched nitrate pulses in the pre-treatment period: (mg/L)

	F6	F4	F5
11-Oct-96	6.737	4.101	0.945
28-Oct-96	0.037		
23-Nov-96	0.01	0.04	0.044
27-Nov-96	0.16	0.09	0.132
3-Dec-96	0.04	0.13	0.254
24-Dec-96		0.03	0.062
17-Mar-97	0.05		0.043
18-Mar-97		0.02	0.043
16-Apr-97	0.02	0.05	0.083
23-Apr-97	0.03		0.070
19-May-97		0.09	0.088
31-May-97	0.04	0.11	0.12
18-Jun-97	0.05	0.04	0.143
27-Sep-97	0.020	0.079	0.143
31-Oct-97	0.124		0.323
10-Nov-97	0.105		0.056
23-Nov-97	0.194	0.066	0.059
17-Dec-97	0.101	0.153	0.144
25-Dec-97	0.040	0.076	0.063
31-Dec-97	0.069	0.113	0.105
13-Jan-98	0.050	0.146	0.189
15-Jan-98	0.051	0.278	0.25
18-Jan-98	0.071	0.275	0.247
19-Jan-98	0.148	0.278	0.250
21-Jan-98		0.337	0.092
25-Jan-98	0.106	0.069	0.099
3-Feb-98	0.103	0.074	0.078
15-Feb-98	0.145		0.077
17-Mar-98	0.061	0.139	0.077
15-Apr-98	0.045	0.187	0.070

where C_X is the peak nitrate pulse concentration in mg/L at creek X. These regression equations provided the basis for assessing changes in peak nitrate concentration in years 1, 2 and 3 compared with the pre-harvest condition (Figure 11).

Because of the large amount of scatter among the peak nitrate concentrations, the change in concentration due to logging also has a range associated with it. If the peak concentration of a nitrate pulse on F4 or F5 fell outside the 90% prediction interval defined by the pre-treatment regression, then it was deemed to have been affected by logging. Logging is known to result in increased nitrate; there are no cases where the post-treatment nitrate concentration is below the lower 90% (Figure 11). Knowing this, we can use a one-tailed test to assess the change in nitrate concentration following logging. That is, to assess the change in nitrate concentration, we can assume that the nitrate levels were either increased by the logging or not affected. Thus the lower 90% limit was not needed.

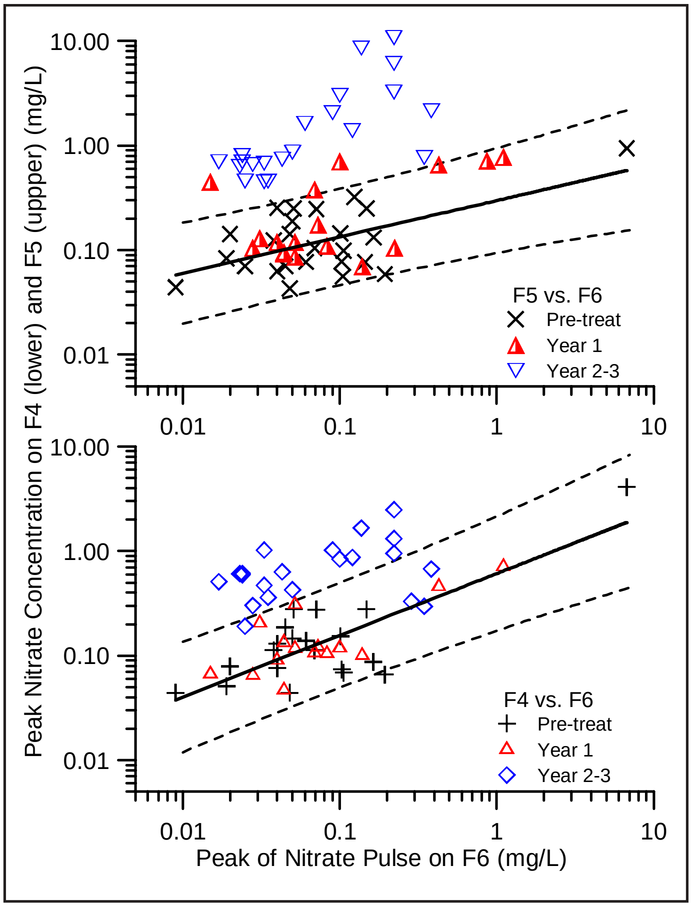

Figure 11. Paired peak nitrate concentrations at F4 and F5 in relation to F6, pre- and post-treatment. The solid lines represent the regression equations (Equations 2 and 3) and the dashed lines represent a 90% confidence interval about each regression line.

For each post-treatment nitrate peak on F4 and F5, the expected value was calculated using equation 2 or 3, and the associated 90% confidence interval was also calculated (Minitab Inc., 1995). If the observed nitrate concentration was greater than the upper 90% limit, then it was increased by logging. In this case, a post- vs. pre-treatment percent increase was calculated, as well as a ratio of the post-treatment concentration over the expected pre-treatment level as defined by equation 2 or 3 (Table 6a, 6b). On the other hand, if the observed nitrate concentration was less than the upper 90% limit, then it was unaffected and a value of 0.0 was assigned for the percent increase and a value of 1.0 for the ratio. In this way, a confidence interval of the logging-induced change in peak nitrate is calculated (Table 6a, 6b).

To complement the calculated changes in peak pulse concentrations, the "off peak" concentrations were also considered. These concentrations represent the background nitrate concentrations that occur during recession periods (Figure 12). The relationships between off-peak concentrations and specific stream discharge allow the changes after logging to be assessed by calculating regression equations for each period (see Figure 12) and applying the equations to other periods. For example the equation from Year 2-3 was used to forecast what the off-peak nitrate concentrations would have been if the watershed was logged at that time. The average ratio of the calculated over observed concentrations was then reported (Table 7).

The various ratios calculated to describe changes in nitrate concentration and flux are summarized in Table 7. This summary presents a fairly complete picture of changes in nitrate concentration that occurred as a result of forest harvesting.

7.0 DISCUSSION

The results reported here were in some ways expected, and in other ways not. The following analysis raises many questions that cannot be answered at this time with the available information.

First, the literature reports that changes in stream chemistry that occur as a result of forest harvesting tend to peak after about two years after logging, and after that the water chemistry begins to return to pre-harvest levels. Our results are consistent with that to the extent that the data set used in this analysis stops two years after the treatment. Thus, we expect that an analysis of data collected in 2001/02 will show the beginnings of a decline in nitrate concentration, but whether this occurs or not will be the subject of future analysis.

The ratios that represent the change in nitrate concentrations and loadings that occurred after logging are consistent regardless of how the data are treated. Therefore, an overall average change in nitrate, averaged over all the different data treatments used in this report, is given in Table 8.

The overall magnitude of the changes in nitrate concentration at F5 was 4.5 times the magnitude of the change at F4. This effect is not consistent with the proportion of the drainage area logged at F5 relative to F4 (Table 8). This leads to the conclusion that the changes at F5 were not entirely due to the forest harvesting. Therefore, it seemed likely that differences between the riparian zones of F4 and F5 resulted in greater storage of nitrate in groundwater at F5. For example, F4 is a headwater stream with a gradient of 17%, while F5 is a second order stream with a channel gradient of 8%. Once disturbed,

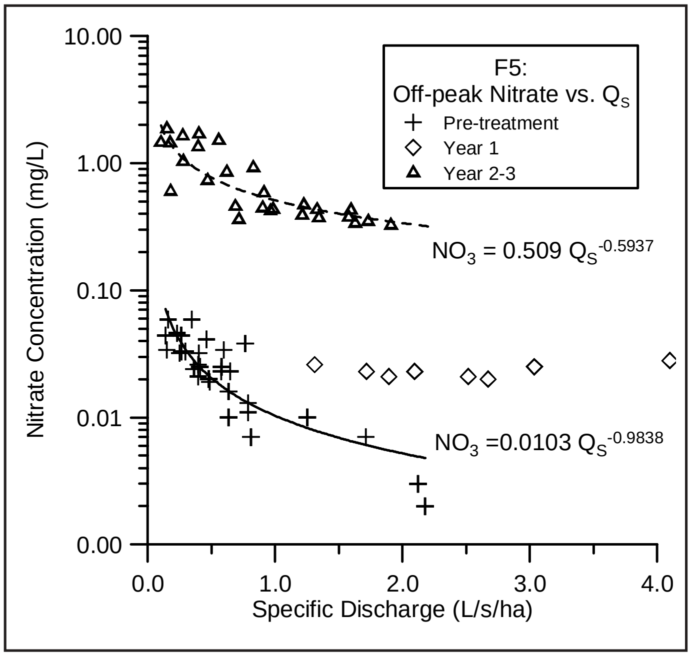

Figure 12. Off-peak nitrate concentrations at F5 formed relationships with stream discharge that were used to calculate ratios of post- to pre-treatment nitrate concentrations.

Table 7. Summary of post-treatment/pre-treatment nitrate ratios (1.0* indicates ratios that are not significant).

	F4	F4	F4	F5	F5	F5	F6	F6	F6
Comparison	annual mean	seasonal mean	seasonal flux	annual mean	seasonal mean	seasonal flux	annual mean	seasonal mean	seasonal flux
Y1/P	1.0*	1.3	1.5	1.8	2.9	6.0	1.0*	1.0*	1.83
Y2/P	5.7	5.5	14.1	21.1	23.5	29.7	1.0*	1.0*	1.32
Y3/P	9.8	12.3	14.9	56.0	60.0	31.5	0.3	0.5	0.21
	Peak Nitrate Pulse		Off-peak Ratio	Peak Nitrate Pulse		Off-peak Ratio	Control watershed (comparison not applicable)		
	Max Ratio	Min Ratio		Max Ratio	Min Ratio				
Y1/P	1.0*	1.0*	1.0*	1.7	1.1	3.6	N/A	N/A	N/A
Y2/P	6.0	1.8	5.9	15.7	5.4	41.3	N/A	N/A	N/A
Y3/P	5.8	1.8	9.9	15.7	5.4	50.8	N/A	N/A	N/A
	Mean annual concentration ratios in groundwater								
		F4		F5a	F5b			F6	
Y1/P		0.5		0.4	0.3			4.6	
Y2/P		12.6		2.4	3.8			2.4	
Y3/P		58.0		5.3	19.1			8.5	

Table 8. Overall average ratios of nitrate concentration and fluxes by treatment year over the pre-treatment period, and proportions logged.

	F4		F5	
Ratio	Nitrate Ratio	P. logged	Nitrate Ratio	P. logged
Year 1 / Pre-treatment	1.2	23.10%	3.2	9.70%
Year 2 / Pre-treatment	7.4	38.50%	26.3	17.30%
Year 3 / Pre-treatment	10.5		42.8	

the nitrate then gets flushed into the stream at a rate proportionate to the concentration in the riparian zone. We looked to the groundwater data to see if any evidence could be found to back up this speculation.

The mean concentrations in groundwater and their response to harvesting are more in line with expectations than the nitrate in streams. Concentrations in groundwater are consistently higher than in streamflow, meaning that the groundwater was a net source of nitrate to streams. Wondzell and Swanson (1996) report similar findings for a stream in Oregon. The ratios of post-to pre-treatment concentrations at the groundwater plots more closely match the proportions of the creeks harvested than the nitrate ratios in streams. However, since the stream integrates the effects of any land use changes in its catchment area, the changes that occurred at a groundwater plot are not necessarily representative of the watershed in which the plot is located.

Observed concentration patterns at F5a-G suggest that it responded to changes from logging in year 3. This was not unexpected – although the site was located in a leave strip, it was thought that harvesting would likely affect all parts of the watershed. Site F5b-G was located at the edge of a cut strip (Figure 1). It was therefore expected to typify the "edge effect". Mean concentrations in F4-G and F5b-G were comparable in pre-treatment and year 1, while after logging in years 2 – 3, mean concentrations at F4-G were at about twice the level of the concentrations at F5b-G. It is likely that another groundwater plot drilled closer to the middle of a cut strip might show higher nitrate concentrations.

One difficulty with interpreting the groundwater data is the sparseness of the data points. Because groundwater was sampled manually, much of the detail in the data set was missing compared with the streamflow data. At this point we concluded that we cannot do anything more with the data without some form of groundwater chemistry modeling to provide the missing detail. Although beyond the scope of this paper, an example of a possible regression approach was attempted (Figure 13).

The data are from plot F5b-G. Nitrate concentrations were modeled using a regression approach as follows:

- Relationships were developed between water table height (measured continuously) and mean piezometric head in selected standpipes – there were different relationships for rising and falling head;
- The piezometers used were standpipes 1, 4 and 7, representing a transect furthest into the cut strip;
- Relationships were also developed between mean head and mean concentration using the same three piezometers – as above, there were different relationships for rising and falling head;
- The above relationships were used to generate the continuous nitrate concentrations in groundwater from the transducer monitoring the water table height.

This simple model was developed for a single example storm. It is based on only 13 samples collected on five different dates, but the model clearly shows that the concentration in groundwater is usually higher than in the stream. A full model based on all groundwater sites will likely provide more information towards explaining the observed changes in nitrate concentrations.

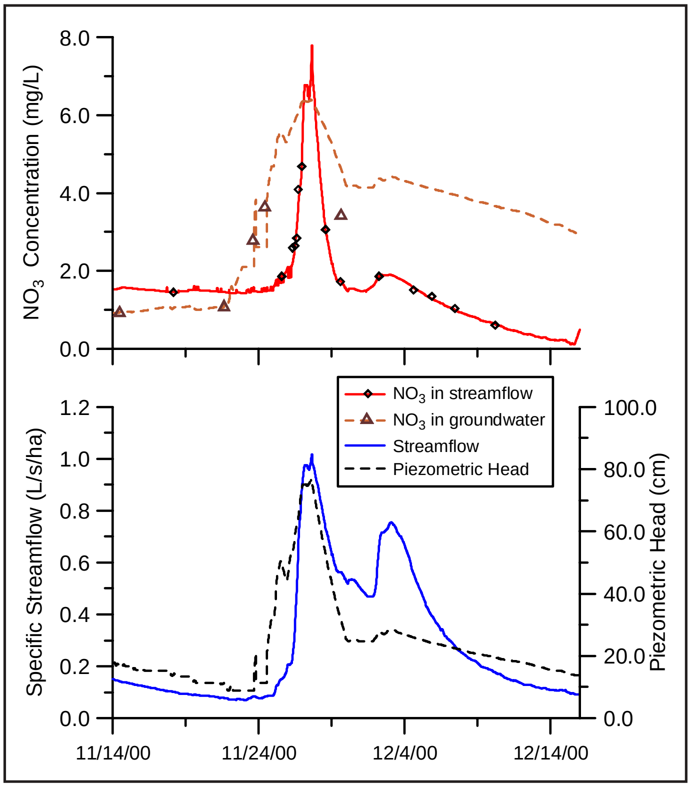

Figure 13. An example of a modeling approach to interpret the nitrate concentration data in groundwater.

8.0 CONCLUSIONS

This report constitutes a step towards reporting the results of streamflow and water quality investigations at Flume Creek, Roberts Creek Study Forest. Reports of this kind are written to provide information as the study is "in progress". They also serve to clarify future directions that should be undertaken in the evolution of the research project.

The changes in streamflow (Hudson, 2001) and water chemistry (specifically nitrate, as per this report) are large in comparison with other studies in progress elsewhere in BC. While this suggests that the creeks are sensitive to changes induced by forest harvesting, future research should also focus on how creeks of this type can be managed to minimize negative effects due to forestry. The results reported here on the changes in nitrate concentration raise several important questions that should be addressed before the results can be incorporated into management guidelines:

1. Are the changes observed at Flume Creek unique, or do similar effects occur elsewhere?
2. Results from similar studies elsewhere in BC have not documented nitrate response of the magnitude reported here. There are several possible reasons why:
    - *Watershed scale:* the creeks studied here are very small; it is possible that first order creeks are inherently sensitive;
    - *Soils / surficial geology:* the sensitivity might be a function of the soil type, or other physiographic features;
    - *Sampling frequency:* it is possible that effects of a similar magnitude do in fact occur elsewhere, but have not been documented due to a lower sampling frequency.
3. Given the above it is essential to address these issues in a systematic way before these results can be used operationally. The next step should be to carry out a study on larger creeks in the Mount Elphinstone area and use ongoing forest harvesting in an opportunistic way to determine if the same effects can be documented in other creeks in the same area. Some possible sites include:
    - Flume Creek mainstem – this stream is already gauged (Figure 1) and contains F4 and F5;
    - Gough, East Wilson and Clack Creeks – drainage areas are about two orders of magnitude larger, and are in the same area as Flume Creek, accessible by the same road, and flow through the RCSF;
    - There are opportunities to monitor the effects of operational harvesting on small creeks by using culverts, thereby providing both the small scale and large scale creeks to determine how these results can be extrapolated across the landscape.

Without carrying out a synoptic study as outlined above, the issue of how to scale up these study results will remain unresolved.

REFERENCES

Binkley, D. & T.C. Brown. 1993. Forest practices as nonpoint sources of pollution in North America. Water Res. Bull. 29(5): 729-740.

Campbell, D.H., D.W. Clow, G.P. Ingersoll, M.A. Mast, N.E. Spahr & J.T. Turk. 1995. Nitrogen deposition and release in alpine watersheds, Loch Vale, Colorado, USA., in: Biogeochemistry of Seasonally Snow-Covered Catchments, eds. Tonnessen, Williams & Tranter, IAHS Publ. 228, 243-253.

Denning, A.S., J. Baron, M.A. Mast & M. Arthur. 1992. Hydrological pathways and chemical composition of runoff during snowmelt in Loch Vale Watershed, Rocky Mountain National Park, Colorado, U.S.A. Water Air Soil Pollut. 59: 107-123.

Feller, M.C. 1977. Nutrient movement through western hemlock - western redcedar ecosystems in southwestern British Columbia. *In* Ecology 58, 1269-1283.

Feller, M.C. & J.P. Kimmins. 1979. Chemical characteristics of small streams near Haney, British Columbia. *In* Water Res. Res. 15(2): 247-258.

Gibbs, R.J. 1970. Mechanisms controlling world water chemistry. *In* Science 170: 1088-1090.

Hartman, G.F. and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Canadian Department of Fisheries and Oceans, Ottawa, Ont. Bull. Fish. Aquat. Sci. 223.

Hazlett, P.W.; English, M.C.; Foster, N.W. 1992. Ion enrichment of snowmelt water by processes within a podzolic soil. *In* J. Environ. Qual. 21(1): 102-109.

Hendershot, W.H., L. Mendes, H. Lalonde, F. Courchesne & S. Savoie. 1992. Soil and stream water chemistry during spring snowmelt. *In* Nordic Hydrol. 23: 13-26.

Hopmans, P., D.W. Flinn, and P.W. Farrell. 1987. Nutrient dynamics of forested catchments in southeastern Australia and changes in water quality and nutrient exports following clearing. *In* For. Ecol. Man. 20: 209-231.

Hornbeck, J.W., C.W. Martin, R.S. Pierce, F.H. Bormann, G.E. Likens, and J.S. Eaton. 1986. Clearcutting northern hardwoods: effects on hydrologic and nutrient ion budgets. *In* For. Sci. 32: 667-686.

Hudson, R.O. and D.L. Golding. 1997a. Controls on groundwater chemistry in subalpine catchments in the southern interior of British Columbia. *In* Journal of Hydrology 201; 1-20.

Hudson, R.O. and D.L. Golding. 1997b. Chemical characteristics of disturbed and undisturbed subalpine catchments in the southern interior of British Columbia. *In* Canadian Water Resources Journal 22(3); 269-297.

Hudson, R.O. and J. Fraser. 2001. Roberts Creek Study Forest: Pre-harvest chemical characteristics of three S6 creeks, Flume Creek Experimental Watershed. Forest Research Technical Report TR-013 (Hydrology). Vancouver Forest Region, Nanaimo B.C., March 2001.

Hudson, R.O. 2001. Roberts Creek Study Forest: Preliminary effects of partial harvesting on peak flows in two S6 creeks. Forest Research Extension Note EN-007 (Hydrology). Vancouver Forest Region, March 2001.

Kendall, C., D.H. Campbell, D.A. Burns, J.B. Shanley, S.R. Silva & C.C.Y. Chang. 1995. Tracing sources of nitrate in snowmelt runoff using the oxygen and nitrogen isotopic compositions of nitrate, in: Biogeochemistry of Seasonally Snow-Covered Catchments, eds. Tonnessen, Williams & Tranter, IAHS Publ. 228, 339-347.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher & R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *In* Ecological Monographs 40: 23-47.

Likens, G. E., F.H. Bormann, R.S. Pierce, J.S. Eaton & N.M. Johnson. 1977. Biogeochemistry of a forested ecosystem. Springer, New York.

Likens, G.E., F.H. Bormann R.S. Pierce & W.A. Reiners. 1978. Recovery of a deforested ecosystem. *In* Science 199: 492-496.

Martin, C.W., D.S. Noel & C.A. Federer. 1984. Effects of forest clearcutting in New England on stream chemistry. *In* J. Environ. Qual. 13: 204-210.

Martin, C.W., D.S. Noel & C.A. Federer. 1985. Clearcutting and the Biogeochemistry of Streamwater in New England. *In* J. For. 83(11): 686-689.

McClurkin, D. C., P. D. Duffy, S. J. Ursic, and N.S. Nelson. 1985. Water quality effects of clearcutting Upper Coastal Plain loblolly pine plantations. *In* J. Environ. Qual. 14: 329-331.

Minitab Incorporated. 1995. Minitab Reference Manual Release 10Xtra. State College, Pa.

Nodvin, S.C., C.T. Driscoll & G.E. Likens. 1988. Soil processes and sulfate loss at the Hubbard Brook Experimental Forest. *In* Biogeochemistry. 5(2): 185-199.

Patric, J.H. 1980. Effects of wood products harvest on forest soils and water relations. *In* J. Environ. Qual. 9: 73-80.

Tiedemann, A. R., T. M. Quigley, and T. D. Anderson. 1988. Effects of timber harvest on stream chemistry and dissolved nutrient losses in Northeast Oregon. *In* Forest Science. 34: 344-358.

Vitousek, P.M. and P.A. Matson. 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. *In* Ecology. 66: 1360-1376.

Vitousek, P.M. 1977. The regulation of element concentrations in mountain streams in the northeastern United States. *In* Ecological Monographs 47: 65-87.

Vitousek, P.M., J.R. Gosz, C.C. Grier, K.M. Melillo & W.A. Reiners. 1982. A comparitive analysis of potential nitrification and nitrate mobility in forest ecosystems. *In* Ecological Monographs 52(2): 155-177.

Wondzell, S.M. and F.J. Swanson. 1996. Seasonal and storm dynamics of the hyporheic zone of a 4th order mountain stream. II: Nitrogen cycling. J. N. Am. Benthol. Soc., 15(1): 20-34.