STREAM WATER QUALITY ASSOCIATED WITH FOREST FERTILIZATION IN THE BIGG CREEK WATERSHED NEAR VERNON, B.C.

Prepared for:

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1 BACKGROUND

In early October, 1986 the Vernon Forest District applied fertilizer to approximately 430 ha of forest land in the Bigg Creek watershed. This 27 km^2 watershed is located roughly 20 km northeast of Lumby and ranges from 425 to 1500 m in elevation. Bigg Creek flows northwestward from Kathy Lake for approximately 9 km into the Shuswap River (Fig. 1). A small group of residences is located at the confluence of these two rivers. Bigg Creek supplies water to 11 licences for domestic and irrigation purposes (Min. of Environment, pers. comm., Dec. 1986).

The area fertilized is covered with predominantly lodgepole pine (Pinus contorta Dougl.), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and Engelmann spruce (Picea engelmannii Parry) ranging from 2 to 16 years in age. It is located in the Interior Cedar Hemlock - moist biogeoclimatic subzone. Soils in the study area are deep, well-drained and silt loam over sandy loam in texture. Slopes vary from 10 to 40%. A period of heavy rains preceeded the application of urea at Bigg Creek, however, conditions remained dry for approximately 5 weeks after fertilization.

On October 7, 1986, sulphur-coated urea (46% nitrogen and 12% sulphur) was applied aerially, at a rate of 435 kg/ha, to the area outlined in Figure 2. This treatment resulted in the addition of 200 kg of nitrogen per hectare over approximately 430 ha.

Prior to the commencement of this forest fertilization project, the first of its kind in the Vernon Forest District, concern was expressed regarding the movement of nitrogen, in

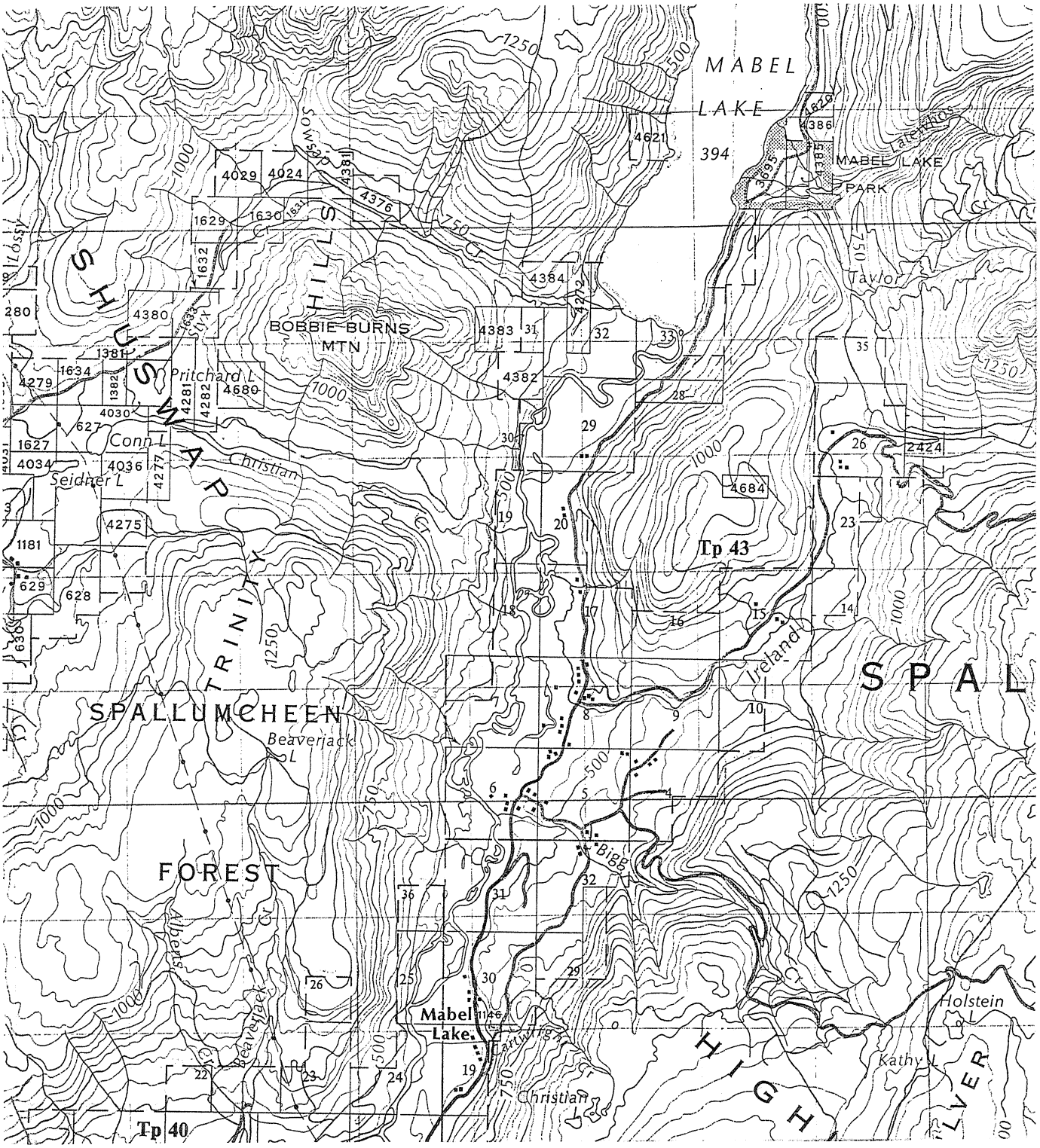


Figure 1. The location of Bigg Creek.

its various forms, from fertilized areas into local streams and subsequently the potential for accelerated eutrophication of receiving lakes and/or a deterioration in drinking water quality. These concerns were directed to the Ministry of Forests and Lands by local residents and the Habitat Management Division of the Department of Fisheries and Oceans (memo dated April, 1986). In response, the Vernon Forest District decided to monitor stream water quality along Bigg Creek prior to, during and after fertilization with urea.

Urea is produced by reacting ammonia with carbon dioxide, under pressure and at high temperatures (Tisdale and Nelson 1975). In moist conditions, urea is quickly hydrolyzed to ammonium carbonate by the soil enzyme urease, in approximately 4 to 7 days (Moore, Currier and Norris 1980). If moisture is limited, the rate at which this process occurs is reduced leading to an increase in soil surface pH and a loss of ammonia by volatilization. Volatilization losses are, however, considered to be small (Moore, Currier and Norris 1980).

The ammonia released through hydrolysis is then either utilized by soil microorganisms and/or vegetation, adsorbed to soil particles, retained in solution in soil water (Moore, Currier and Norris 1980) or is oxidized to nitrite (NO_2^-) and finally nitrate (NO_3^-) (Hem 1970) by nitrifying bacteria. Generally this latter process, referred to as nitrification, depends on soil pH, becoming negligible at a pH of 5 (Moore, Currier and Norris 1980), soil moisture and temperature. Consequently, the rate of nitrification is significantly reduced during the winter months (Moore 1975). Silvicultural activities also influence the processes just described by reducing vegetative cover leading to increased soil moisture and temperature increasing microbial activity and reducing the vegetative uptake of nitrogen.

Nitrite and nitrate are the principal forms in which nitrogen is removed from forested ecosystems. Ammonium ions, which are readily adsorbed onto soil particles, especially in clay soils and soils with high cation exchange capacities, are not readily leached (Moore, Currier and Norris 1980).

Sulphur-coated urea, as applied in the Bigg Creek watershed, was developed to slow the release of nitrogen into the soil to improve its utilization by forest vegetation and to prevent leaching losses. This form of urea is produced by coating granular urea with molten sulphur followed by wax, a microbicide and conditioner (Tisdale and Nelson 1975). The final granule contains 7 to 12% sulphur, approximately 2% wax, 2% conditioner and a fraction of a percent microbicide (Tisdale and Nelson 1975) in addition to nitrogen.

Leaching losses of nitrogen depend on all of the processes outlined above, as well as on the nutrient uptake capacity of the vegetation remaining on-site. Any excesses of nitrogen contained in soil water may then be lost through subsurface and/or surface flow. It is these losses of nitrogen from a fertilized area which may impact on water quality.

2 FERTILIZER NITROGEN AND WATER QUALITY

Fertilizer nitrogen may enter water courses through surface runoff, subsurface drainage and/or direct application. Locally, surface runoff rarely occurs. During major storm events, some surface runoff has been observed from severely compacted skid trails and landings. This nutrient transfer mechanism is, however, not considered to be a major factor at the Bigg Creek site.

The greatest potential for increasing nitrogen

concentrations exists by directly overspraying exposed surface water (Moor 1971; Neary and Leonard 1978; Brown 1980). Overspraying of larger streams can be avoided by marking a buffer zone and providing appropriate instructions to the applicator. It may be impossible to avoid smaller headwater streams. Several of these small feeder streams were oversprayed at the Bigg Creek site, however, all major tributaries were buffered and a swampy area adjacent to Kathy Lake was excluded from fertilization.

Urea which falls directly into open water is subject to processes described in the background section of this report. The ammonia produced through hydrolysis may subsequently be adsorbed on suspended solids or bottom sediments or, may remain in solution (Brown 1980). Nitrogen detected as ammonia in stream water samples is generally a result of direct application into the water course (Meehan, Lotspeich and Mueller 1975).

Nitrogen may also enter streams and lakes through subsurface flow. Nitrogen transferred in this way will generally be detected in stream water samples as nitrate. Nitrite nitrogen is seldom present in well-aerated streams (Hem 1970) in the Pacific Northwest (Brown 1980) and is, therefore, rarely separated from nitrate-N in chemical analyses.

Studies of forest fertilization and water quality, though apparently few (Brown 1980; Moore, Currier and Norris 1980), indicate short-lived increases in urea, ammonia and nitrate-nitrogen concentrations. These monitoring studies range in length from several weeks to 6 months and, in a few cases, an entire year. The results of these studies are most concisely summarized by Moore, Currier and Norris (1980). Table 1 (Moore, Currier and Norris 1980) cites concentrations observed throughout the Pacific Northwest after the application of urea fertilizer.

Table 1: Stream water quality associated with forest fertilization throughout the Pacific Northwest (Moore, Currier and Norris 1980).

Treatment: Aerial application of urea.

Site:	Rate of application lb-N/ac	kg-N/ha	Date of application	Treatment area ac	ha	Peak Concentration Urea-N Pre-treatment	Urea-N Post-treatment	NH_3-N Pre-treatment	NH_3-N Post-treatment	NO_3-N Pre-treatment	NO_3-N Post treatment
						mg/l					
Burns Creek[1]	50	56	Nov 1970	1390	562	0	0	0	0	0	0.068
Canyon Creek	200	224	Nov 1969	3325	1346	0.005	15.20	nd	nd	0.005	0.80
Coyote Creek	200	224	Mar 1970	170	68	0.006	1.39	0.005	0.048	0.002	0.177
Crabtree Creek	200	224	May 1969	570	230	---	24.00	0	0.080	0	0.25
Dollar Creek	200	224	Apr 1971	85	34	0.016	44.40	0.030	0.490	0.060	0.13
Elochoman Creek	200	224	Nov 1969	735	297	0.073	19.10	nd	nd	nd	4.00
Fairchilds Creek	200	224	Apr 1972	475	192	0.008	23.40	0.009	0.280	0.030	0.828
Falls Creek	190	213	May 1970	650	263	nd	nd	0.020	1.28	0.015	1.67
Jackson Creek	150	168	May 1969	235	95	0.007	0.09	0.004	0.044	0.065	0.116
Jimmycomelately Creek	200	224	Apr 1970	120	49	0.002	0.71	0	0.040	0.005	0.042
McCree Creek	50	56	Oct 1970	1265	513	0	0.62	0	0	0	0.210
Mica Creek	200	224	Sep 1972	115	47	0	0.30	0	0	0.15	0.28
Mill Creek	200	224	Dec 1969	565	228	0.02	0.68	0	0.12	0.02	1.32
Nelson Creek	200	224	Apr 1970	95	38	0.016	8.60	0.010	0.32	0.290	2.10
Newaukum Creek	150	168	Sep 1971	6085	2463	0.009	0.26	0	0.008	0.011	0.438
Pat Creek	200	224	Apr 1972	600	243	0.003	3.26	0.007	0.079	0.061	0.388
Quartz Creek	200	224	May 1972	125	51	0.004	1.75	0	trace	0.120	0.70
Roaring Creek	200	224	Mar 1972	660	267	0.007	0.76	0.004	0.040	0.017	0.210
Row Creek	150	168	Oct 1972	6500	2630	0.006	0.13	0.005	0.022	0.004	0.044
Skookumchuck Creek	150	168	Sep 1969	470	191	0	2.63	0.004	0.026	0.005	0.085
Spenser Creek	200	224	Nov 1972	7680	3108	0.019	0.37	0.041	0.123	0.005	0.005
Tahuya Creek	200	224	Oct 1972	4005	1620	0.01	27.20	0	1.40	0.01	1.83
Thrash Creek[2]	200	224	May 1974	300	121	---	---	nd	0.06	nd	1.88
Three Lakes Creek	190	213	May 1970	170	69	nd	nd	0.015	0.13	0.003	2.36
Trapper Creek	200	224	Apr 1970	160	64	0.008	0.70	0	0.010	0.034	0.121
Trout Creek	200	224	Mar 1968	1600	648	0.10	14.00	0.12	0.700	0.03	0.160
Turner Creek	200	224	Mar 1972	870	352	0.004	4.36	0	0.046	0.032	0.243
Waddel Creek	200	224	Dec 1969	1480	600	0.01	2.48	0	0.340	0.02	0.99
Wishbone Creek	200	224	May 1972	115	46	0	0.30	0	0	0.12	0.28

[1] $(NH_4)_2 SO_4$ applied [2] NH_4NO_3 applied nd = no data available or not determined

Increased concentrations of urea are largely caused by direct application (McCall 1970; Moore, Currier and Norris 1980), the magnitude of these increases being directly proportional to the area oversprayed. Concentrations of up to 5 mg/l have been recorded in areas where no buffer strips were established but these levels only persist for a few hours (Moore, Currier and Norris 1980). Moore, Currier and Norris (1980) state that 3 to 5 days after fertilization urea concentrations in stream water will have returned to pre-treatment levels.

Similarly, ammonium (the aqueous form of ammonia (Hem 1970)) concentrations resulting from overspraying are rapidly reduced through adsorption on stream sediments and uptake by aquatic organisms (Moore, Currier and Norris 1980). Peak concentrations recorded are generally 0.10 mg/l or less. These ammonium-N levels are short in duration, generally only a few hours (Moore, Currier and Norris 1980) or days (Meehan, Lotspeich and Mueller 1975). The magnitude of increases in both urea and ammonia will depend on the presence and width of buffer strips and the number of small unprotected feeder streams (Moore, Currier and Norris 1980).

Increases in nitrate-N concentrations have been recorded within a few days (Moore, Currier and Norris 1980) to a week (McCall 1970) after fertilization. As stated previously, the increased levels of nitrate result largely from subsurface drainage. Peak concentrations are generally reported as less than 1.0 mg/l and decrease to pre-treatment levels within 2 (Moore, Currier and Norris 1980) to 4 (McCall 1970) months. Where sampling was continued through the winter, additional peaks in concentration have been recorded coinciding with intense winter storms (Moore, Currier and Norris 1980) through to the following year (Meehan, Lotspeich and Mueller 1975).

These concentrations tend to decrease with each successive storm. Again all peak concentrations were well below the acceptable limits for drinking water (Moore, Currier and Norris 1980).

Hetherington (1984) reports similar trends in two coastal British Columbia streams where urea was applied in mid-September. The fertilizer was applied during dry weather which continued until early November. Nitrogen losses, in the form of nitrate, were greatest during the rainy period which followed. Increased concentrations of nitrate-N persisted slightly above background levels for approximately one year. Urea concentrations returned to pre-treatment levels within 6 days in one stream but persisted for 4 weeks in the second sample stream. Ammonia concentrations decreased to near pre-treatment levels in 13 days with minor increases during several major rainstorms within the two months following fertilization.

Total losses of nitrogen after forest fertilization are estimated to be 2 to 3 percent of the total applied where buffer strips were not established. Where buffer strips were established and overspraying was avoided losses are less than 0.5 percent (Neary and Leonard 1975; Moore, Currie and Norris 1980). Any of this total nitrogen which does enter the aquatic system is rapidly decreased through adsorption on stream sediments, biological utilization and dilution through natural stream mixing and increased water volumes downstream of the area fertilized (Brown 1980; Moore, Currier and Norris 1980).

The actual concentrations of nitrogen, in its various forms, becomes important in assessing the potential for accelerated lake eutrophication and/or toxicity. In the study area, since there are no downstream lakes, eutrophication is not a concern. However, since the Bigg Creek system supplies water for domestic purposes, toxicity is.

Hetherington (1984) cites guidelines for the protection of freshwater life as 0.02 mg/l un-ionized ammonia (NH_3). He further cites toxicity levels of urea and nitrate-N as 7500 mg/l and 90 mg/l respectively.

For drinking water, maximum acceptable nutrient levels have been defined by Health and Welfare Canada in 1968 and subsequently the B.C. Ministry of Health in 1982. The maximum being that limit beyond which greater concentrations of a given substance are capable of producing deleterious health effects or are esthetically objectionable.

For ammonia, the maximum acceptable concentration is 0.5 mg/l. Ammonia reacts readily with chlorine limiting its disinfecting efficiency in community water supplies. It may further promote the growth of organisms and corrosion in distribution lines (Health and Welfare Canada 1968).

For nitrate plus nitrite nitrogen, the maximum acceptable concentration is 10 mg/l. Nitrates "produce an irritation of the mucous membrane of the stomach, and diuresis (increased excretion of urine) accompanied by irritation of the mucous membrane of the urinary bladder" (Health and Welfare Canada 1968). Infants are the most susceptible to this disease which is "an anaemic condition resulting from the reaction of nitrite (NO_2^-) ions with haemoglobin (Neary and Leonard 1978). Generally, reports of this condition are from areas where concentrations of nitrate are in excess of 45 mg/l in water from underground sources (Health and Welfare Canada 1968).

3 METHODS

Water samples were collected at four sites along Bigg Creek as shown in Figure 2. The first two sites (Bigg

1 and 2) were situated above and below Kathy Lake well beyond the area fertilized. Two control sites were selected in order to detect any changes in background nitrogen levels resulting from the lake, should such changes occur. The third site (Bigg 3) was located just beyond the downstream boundary of the fertilized area. The fourth site (Bigg 4), located 4 km downstream of the fertilized area, was initiated on the date of fertilization at the request of local residents and was situated near a domestic water intake.

Samples were obtained every Monday and Thursday for 2 weeks prior to fertilization and for 3 weeks following application. Additional samples were collected during the first major storm following fertilization. All water sampling was carried out between Sept. 23 and Oct. 27, 1986 in accordance with the procedures established by the Water Quality Branch of Environment Canada (1983).

All samples were packaged and sent, via Loomis, to CanTest Ltd. in Vancouver on the day they were collected. CanTest Ltd. analyzed these samples for ammonia and nitrate plus nitrite nitrogen "in accordance with procedures described in "Laboratory Manual for the Chemical Analysis of Water, Wastewater, Sediments and Biological Materials (2nd Edition)" published by the Government of British Columbia, Ministry of Environment, Water Resources Services, 1976 and "Standard Methods for the Examination of Water and Wastewater" 15th Edition, 1980; 16th Edition, 1985, published by the American Public Health Association" (D. Enns, pers. comm., Nov. 1986). Analyses for urea were not carried out both because of the rapid transformation of detectable urea to ammonia and subsequently to nitrate-N, as was described previously, and the capabilities of the lab.

4 RESULTS

The results of water quality analyses for samples collected prior to and after urea fertilization in the Bigg Creek watershed are presented in Table 2. These results are re-summarized in Table 3 to simplify comparison with similar data gathered throughout the Pacific Northwest (Table 1). Monitoring results obtained during an October 1986 fertilization project at Maka Creek, in the Merritt Forest District, are also included.

The tabulated data, which are also presented graphically in Figures 2 and 3, indicate that at no time during the study period did concentrations of either ammonia or nitrate plus nitrite-N approach or exceed the maximum acceptable limit for drinking water.

Pre-treatment concentrations of ammonia and nitrate plus nitrite-N were generally similar at all sites. Concentrations observed on the first day of sampling, during heavy rains, were somewhat higher than the rest at both Bigg 1 and 3. Such peaks are generally the result of increased nutrient flushing by the excess water. Cattle had also been grazing in the area prior to this study. Their previous presence would further enhance nutrient flushing during rainy periods. These data points illustrate the natural variability in background nitrogen levels.

The maximum concentration of ammonia at Bigg 3 occurred after fertilization, however, a similar peak in ammonia had occurred at the control site, Bigg 1, 2 days previously indicating that the peak observed at Bigg 3 falls well within the range of background levels. Post-treatment mean ammonia concentrations are similar to those observed prior to fertilization at all sites. The ranges in concentration also

Table 2: Stream water quality associated with forest fertilization on Oct. 7, 1986 at Bigg Creek in the Vernon Forest District.

Date Sampled	Bigg 1		Bigg 2		Bigg 3		Bigg 4	
	All concentrations = mg/l							
	NH_3	NO_2+NO_3	NH_3	NO_2+NO_3	NH_3	NO_2+NO_3	NH_3	NO_2+NO_3
Sept 23	0.054	(0.720)*			0.019	0.066		
Sept 25	0.014	0.011	0.022	0.011	0.020	L0.010		
Sept 29	L0.010	L0.010	0.016	L0.010	0.011	L0.010		
Oct 2	L0.010	L0.010	0.013	L0.010	0.014	L0.010		
Oct 6	L0.010	0.030	0.011	L0.010	0.019	L0.010		
Fertilizer applied Oct 7								
Oct 9	0.014	L0.010	0.017	L0.010	0.020	0.140	0.014	0.150
Oct 14	0.030	L0.010	0.015	L0.010	L0.010	0.018	L0.010	L0.010
Oct 16	0.019	0.025	0.022	L0.010	0.028	0.032	0.058	0.075
Oct 20	0.010	0.020	0.019	L0.010	0.010	0.027	0.010	0.099
Oct 23	0.014	L0.010	0.021	L0.010	0.014	L0.010	0.018	0.061
Oct 27	0.019	0.027	L0.010	L0.010	0.011	0.017	0.014	L0.010

L = less than = not detected

* = outlier = uniquely high concentration at control site

NH_3 = ammonia-N NO_2+NO_3 = nitrite plus nitrate-N

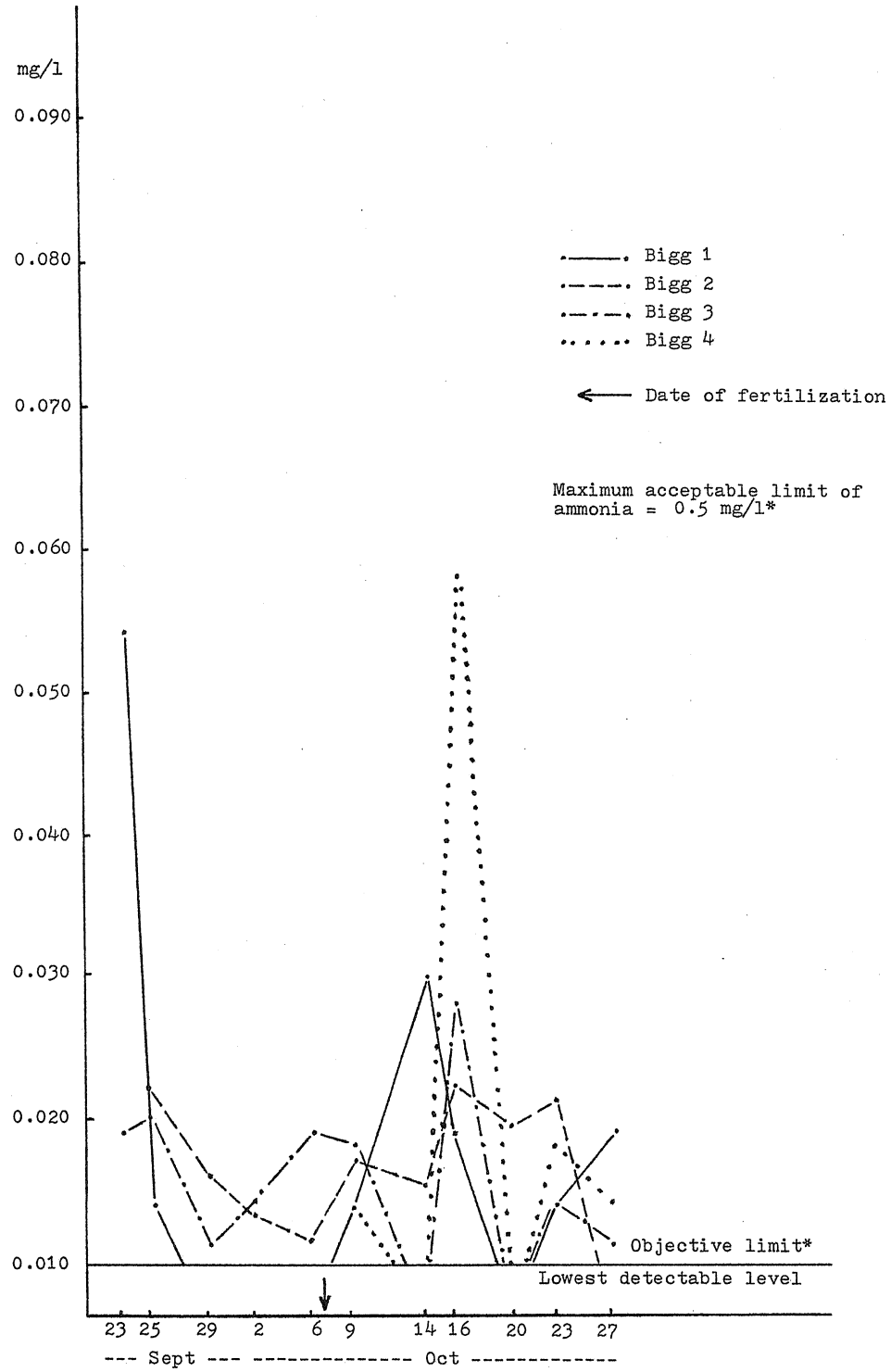
Table 3: A summary of stream water quality results associated with forest fertilization in Oct. 1986 at Bigg Creek, Vernon Forest District and at Maka Creek, Merritt Forest District.

Location	Stand Type and Age	Area Treated (ha)	Approx. Mean Annual Rainfall (cm)	Mean (Range) Pre-treatment Concentration (mg/l) NH_3	Mean (Range) Pre-treatment Concentration (mg/l) NO_2+NO_3	Mean (Range) Post-treatment Concentration (mg/l) NH_3	Mean (Range) Post-treatment Concentration (mg/l) NO_2+NO_3	Peak Post-treatment Concentration (mg/l) NH_3	Peak Post-treatment Concentration (mg/l) NO_2+NO_3
Bigg 1 - C				0.014 (L0.010-0.054)	0.010 (L0.010-0.030)	0.018 (0.010-0.030)	0.012 (L0.010-0.027)	0.030	0.027
Bigg 2 - C	FP1S 16 years	405	90*	0.016 (0.011-0.022)	L0.010 (L0.010-0.011)	0.016 (L0.010-0.022)	L0.010 (L0.010)	0.022	L0.010
Bigg 3				0.017 (0.011-0.020)	L0.010 (L0.010-0.066)	0.014 (L0.010-0.028)	0.039 (L0.010-0.140)	0.028	0.140
Bigg 4						0.019 (L0.010-0.058)	0.064 (L0.010-0.150)	0.058	0.015
Maka 1 - C	FP1Py 13 years & P1	50	60*	0.013 (L0.010-0.020)	L0.010 (L0.010-0.021)	0.027 (0.014-0.088)	0.007 (L0.010-0.024)	0.088	0.024
Maka 2	28 years			0.013 (L0.010-0.022)	L0.010 (L0.010-0.016)	0.016 (0.011-0.022)	L0.010 (L0.010-0.011)	0.022	0.011

L = less than = not detected

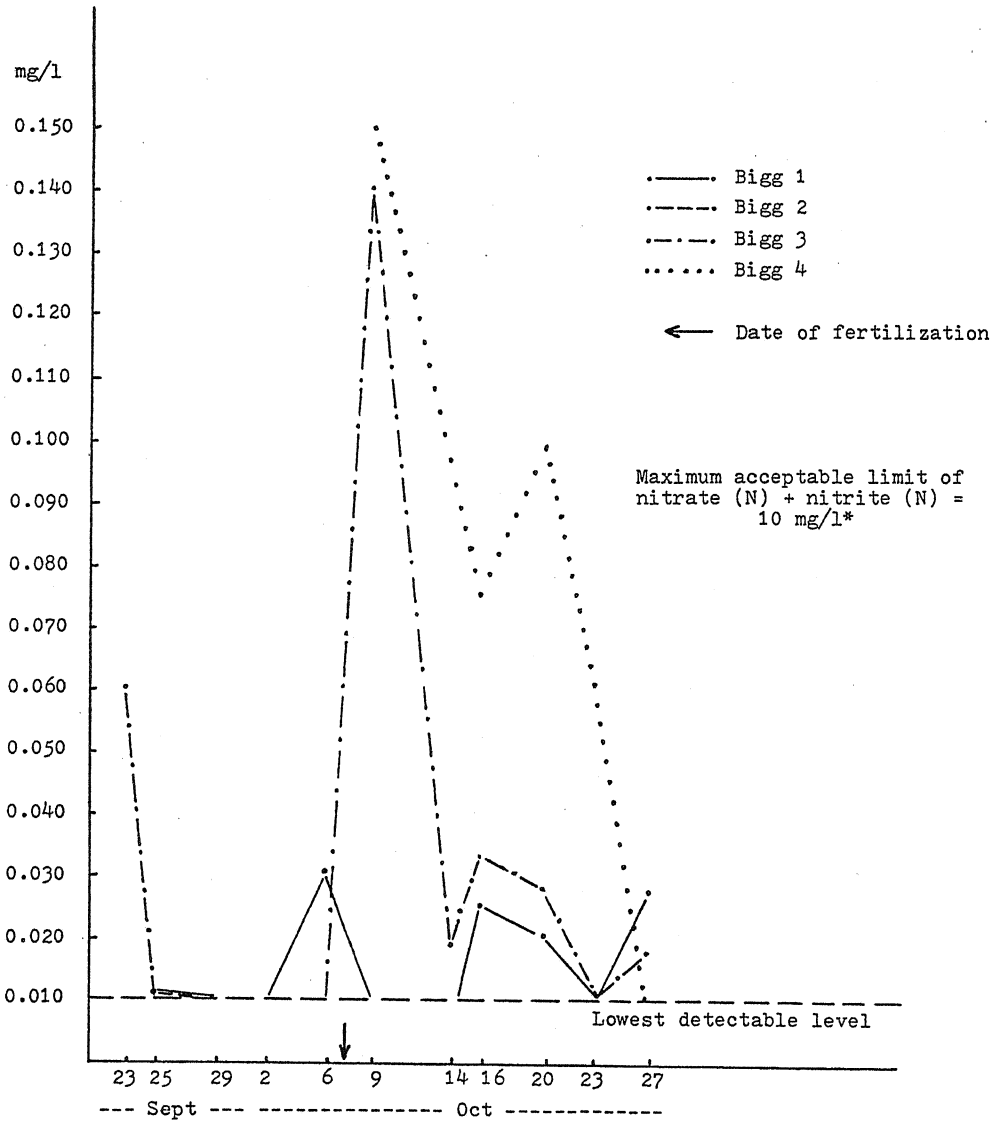
C = unfertilized control

* = data supplied by J. Cheng, Regional Hydrologist, Ministry of Forests and Lands, Kamloops



*Canadian Drinking Water Standards and Objectives - 1968

Figure 3. Ammonia concentrations associated with forest fertilization at Bigg Creek.



* Canadian Drinking Water Standards and Objectives - 1968

Figure 4. Nitrate plus nitrite nitrogen concentrations associated with forest fertilization at Bigg Creek.

indicate no significant differences between pre and post-treatment ammonia levels.

The results of nitrate plus nitrite-N analyses show a slight increase in post-treatment concentrations, including the mean and peak. These concentrations are not, however, large enough to even approach the maximum acceptable limit for drinking water. The increase also does not appear to be persistent, concentrations returning to within the pre-treatment range within 7 days. Any increases in nitrate plus nitrite-N detected at Bigg 3 should be insignificant at Bigg 4 as a result of in-stream processes including dilution through natural stream mixing and increased downstream volumes.

All concentrations, means and peaks were, however, greatest at the downstream site (Bigg 4). This is most likely the result of agricultural increases from fertilized fields and livestock grazing on the bench adjacent to Bigg Creek at this site. Again, these concentrations indicate water well within the ammonia and nitrate plus nitrite-N standards for domestic purposes.

Based on the data obtained during this study, it appears that the application of urea fertilizer, in an area such as the site studied and under similar conditions to those occurring during the study period, has no immediate detrimental effect on water quality. Since the concentrations of nitrogen, in its various forms, vary widely over time, in order to determine the entire range of concentrations which can be expected in a watershed, sampling should be conducted on a regular basis for an entire year both prior and subsequent to fertilization. Such sampling would allow for a more reliable discussion of the significance of any observed peaks or changes in concentration.

Data obtained during a similar study at Maka Creek, in the Merritt Forest District, (Table 3) also show no significant increases in ammonia after fertilization. The Maka Creek data further show no significant difference in nitrate plus nitrite-N concentrations after treatment. These results differ slightly from those at Bigg Creek, most likely as a result of the prolonged dry period, both prior to and after fertilization at the Maka Creek site, consequently minimizing any leaching losses. All concentrations observed at Maka Creek were also well below the maximum acceptable limit.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this brief monitoring project, it appears that forest fertilization with urea, under conditions similar to those occurring at the Bigg Creek site, can be carried out with no immediate detrimental impact on water quality.

As was the case during this study, the application of fertilizer prior to a period of dry weather will minimize the rapid entry of nitrogen into stream channels. The use of buffer strips along major stream channels, thereby eliminating the direct application of fertilizer to the stream, will further reduce the chances of increased nitrogen concentrations.

Toews and Brownlee (1981) recommend that excessive application of fertilizer, ie. greater rates than actually required to achieve increased forest productivity, should also be avoided to minimize any aquatic impacts. Further, that avoiding areas adjacent to lakes and swamps will prevent the flushing of fertilizer during large storms which cause these wet areas to expand and/or overflow resulting in surface runoff. They also suggest that heliports should be located away from streams and lakes to reduce the chances of accidental spills and flushing of extreme concentrations.

Of additional importance is the level of nutrient flushing which accompanies spring runoff. At this time natural nutrient levels will approach a maximum. However, any increases in ammonia and nitrate-N resulting from fertilization should also be greatest at this time of year when compared to upstream levels. Sampling during the spring freshet should, therefore, also be considered as a follow-up to this study or in future water quality monitoring projects.

6 LITERATURE CITED

B.C. Ministry of Health. 1982. British Columbia drinking water standards. Prov. of B.C., Victoria, B.C.

Brown, G.W. 1980. Forestry and water quality. School of Forestry Oregon State Univ., O.S.U. Book Stores Inc., Corvallis, Oreg.

Environment Canada. 1983. Sampling for water quality. Inland Waters Directorate, Water Quality Branch, Ottawa, Ont.

Health and Welfare Canada. 1968. Canadian drinking water standards and objectives. Queen's Printer for Canada, Ottawa, Ont.

Hem, J.D. 1970. Study and interpretation of the chemical characteristics of natural water (2nd edition). Geological Survey Water - Supply Paper 1473. U.S. Gov't Printing Office, Washington, D.C.

Hetherington, E.D. 1984. Streamflow nitrogen loss following forest fertilization in a southern Vancouver Island watershed. Can. J. For. Res. 15:34-41.

Meehan, W.R., F.B. Lotspeich and E.W. Mueller. 1975. Effects of forest fertilization on two southeast Alaska streams. J. Environ. Qual., Vol.4, No.1:50-55.

Moore, D.G. 1971. Fertilization and water quality. USDA Forest Service. Portland, Oreg.

Moore, D.G. 1975. Effects of forest fertilization with urea on stream water quality - Quilcene Ranger District, Wash. USDA Forest Service Res. Note PNW-241. Portland, Oreg.

Moore, D.G., J.B. Currier and L.A. Norris. 1980. Introduced chemicals. In An approach to water resources evaluation of non-point silvicultural sources - a procedural handbook. EPA 600/8-80-012, Environ. Protect. Agency, Athens, GA, Chapt. XI.

Neary, D.G. and J.H. Leonard. 1978. Effects of forest fertilization on nutrient losses in streamflow in New Zealand. N.Z. J. For. Sci. 8(1):189-205 (1978).

Tisdale, S.L. and W.L. Nelson. 1975. Soil fertility and fertilizers (3rd edition). Macmillan Publ. Co. Inc., New York, N.Y.

Toews, D.A. and M.J. Brownlee. 1981. A handbook for fish habitat protection on forest lands in British Columbia. Gov't of Canada, Dept. of Fisheries and Oceans, Habitat Protection Div., Vancouver, B.C.