

Phosphorus Loading
to Kootenay Lake
from the
Kootenay and Duncan rivers
and
Experimental Fertilization Program

by

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1. Introduction

Kootenay Lake, located in southeastern British Columbia, has experienced a series of major perturbations resulting in the 1980s collapse of kokanee salmon (*Oncorhynchus nerka*) stocks. Northcote (1973) describes the cultural eutrophication of the lake that began in the 1950s and peaked in the mid-1960s, with the major source of nutrients being phosphates lost from a fertilizer plant operating on a tributary of the Kootenay¹ River. Daley et al. (1981) describe the reversal of the eutrophication in the 1970s and 1980s. The primary reasons for the reversal were pollution abatement at the fertilizer plant (commencing in the late 1960s), decline and eventual cessation of fertilizer production by the Cominco operation at Kimberley, combined with the construction of hydroelectric dams (Duncan Dam, 1967 and Libby Dam, 1972) whose impoundments retained nutrients in both main inflow tributaries (Duncan and Kootenay rivers, respectively). The combined impact of these events was unforeseen in the late 1960s; nutrient input to the lake declined to below pre-dam conditions and the lake underwent a gradual decline in productivity as predicted by Daley et al. (1981). By the mid-1980s kokanee stocks were virtually non-existent in the South Arm and severely diminished in the North Arm. In 1990, fertilization of the now ultraoligotrophic lake was considered to reverse the decline in lake productivity. Although the Kootenay Lake Fertilization Response Model (Walters et al. 1991) predicted fertilization would not likely be successful, fisheries managers concluded they had no other options.

Kootenay Lake (395 km²; Fig. 1) is long and narrow, with steep sides and a narrow littoral zone. The main lake is 107 km long, approximately 4 km wide with a mean depth of 94 m and a maximum depth of 154 m (Daley et al. 1981). Two major river systems feed the lake: the Lardeau/Duncan system in the North Arm (174 km²) and the Kootenay River in the South Arm (222 km²). Retention time of the main lake is 1.8 years. The outlet of the main lake, at Balfour, BC, forms the upper end of the West Arm. The West Arm (40 km long) is physically and limnologically different from the main lake, comprised of a series of shallow basins (mean depth 13 m) interconnected by narrow river sections.

A 5-year experimental fertilization program began in 1992 with a mixture of liquid nitrogen (N; as 28-0-0 by weight N, P₂O₅ and K₂O) and phosphorus (P; as 10-34-0) added to the North Arm. The seasonal loading and timing of the fertilizer application were designed to approximate P loading to the lake during spring freshet conditions (pre-impoundment by Duncan and Libby dams), then continuing through the summer; fertilizer was added weekly for 20 weeks, beginning in mid to late April and ending in late August or early September (Wright et al. 2002). A barge unit fitted with two 40,000 L liquid fertilizer tanks was steered for 10 km down the centre of the lake in a pre-determined zig-zag course (see Fig. 1 for fertilizer application zone). Each week the fertilizer was distributed equally during the 20 km round trip (10 km each down and up the lake at a rate of 5 km·hr⁻¹). The purpose of the fertilization experiment was to determine the effect of nutrient addition to the lake, with the goal of restoring historical kokanee salmon biomass and productivity (Ashley et al. 1997a,b).

The nutrient additions from 1992–1996 were successful at increasing the biomass of phytoplankton, zooplankton and kokanee in the North Arm of Kootenay Lake where the fertilizer additions took place. Phytoplanktonic algal biomass (hereafter algal

¹ named the Kootenai River in the United States; herein referred to as the Kootenay River throughout its length.

biomass) in the South Arm also increased; in 1996 it measured 2.3 times higher (annual basis) than in 1992 at the start of the experiment. The success of the lake fertilization program has been documented in a series of technical reports and publications (e.g., Ashley et al. 1997b; Wright et al. 2002). Fertilization continued past the original 5-year time horizon as part of a longer-term adaptive management experiment to examine possible carryover of productivity (i.e., the lake retaining nutrients from previous fertilizations; CBFWCP 2004; Duke 1999), and to document trophic level responses to changing loading rates of N and P. Consequently, the P load was decreased from 47.1 t in each of 1992-1996, to 29.5 t in 1997, and 22.9 t in 1998 and 1999. Kokanee escapements (North Arm: Meadow Creek and Lardeau River) increased from an all time low of 270,000 in 1991 to over two million in 1998 and 1999. However, the 2000 Meadow Creek kokanee escapement fell to < 400,000 as did the fry-to-adult survival rate (Wright et al. 2002). Consequently, P loading was increased to 29.5 t in 2000, and restored to the original 47.1 t for 2001-2003.

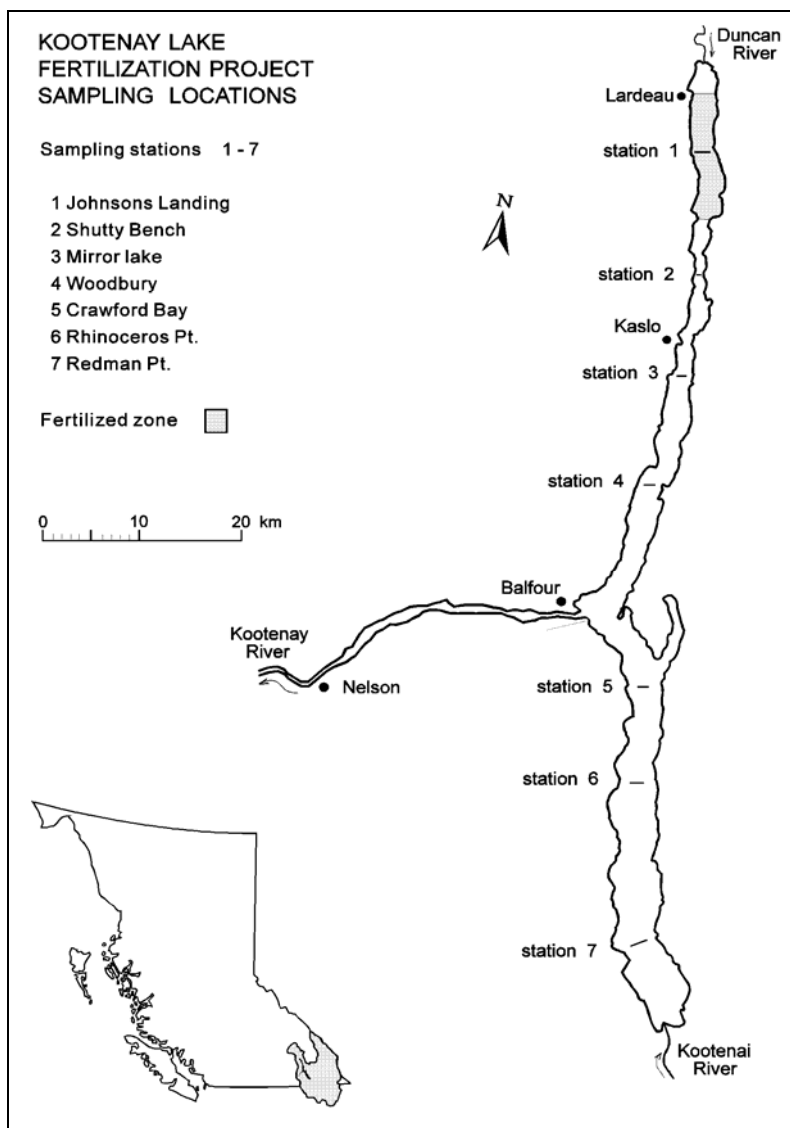


Figure 1. Location map of Kootenay Lake showing fertilization zone and the seven monitoring stations.

An analysis of historical nutrient loading data (1980-) to Kootenay Lake from the Kootenay and Duncan Rivers was conducted after the first 5 years of fertilization (Larkin 1998) to determine if the increased algal biomass seen in the South Arm from 1992-1996 was due to transport of nutrients from the experimental fertilizer treatment in the North Arm, or due to variations in flow and nutrient loading from the Kootenay River and/or fluctuations in Kootenay Lake surface elevations. The available data indicated the annual total phosphorous (TP) influx from the Kootenay River had increased substantially from 1992-1996 chiefly due to increased annual discharge. However, a limited water quality data set, in addition to noteworthy lows and highs in annual discharge and lake elevation, precluded any definitive conclusion as to the cause for the increased algal biomass in the South Arm.

The primary goals of this report are to update the historical nutrient loading to the lake to include the most recent years of the fertilization program (1997-2003), as well as conduct a retrospective analysis of P loading to the lake, to the extent of available discharge and water quality data. Combined with the information from the first 5 years, more definitive conclusions regarding the increased productivity in the South Arm during the experimental fertilization period may be reached. In addition, by examining nutrient loading from both river and fertilizer sources, relationships between P sources and lake productivity (as measured by algal biomass) may emerge. Analogous to Larkin 1998, this report focuses exclusively on P loading since Kootenay Lake is P limited (Lekstrum et al. 1994; Perrin and Korman 1997).

2. Methods

2.1 Kootenay River discharge

Daily discharge data for the Kootenay River near Libby, Montana (~180 km upstream from Kootenay Lake; 1910-2003) were obtained from the United States Geological Service (USGS)². Comparison with data of actual discharge from the dam (obtained from the United States Army Corps of Engineers³) indicates the USGS values are adequate approximations of the outflow from the dam into the Kootenay River.

Daily discharge data for the Kootenay River at Porthill, Idaho (~40km upstream from Kootenay Lake; 1929-2003) were obtained from the USGS⁴. As few small tributary streams join the Kootenay River between the Porthill site and Kootenay Lake, discharge data from Porthill were regarded as adequate approximations of the Kootenay River inflow to the lake. The USGS maintains this station and shares data with the Water Survey of Canada (WSC)⁵; USGS cfs values corresponded with WSC $\text{m}^3 \cdot \text{s}^{-1}$ data. Monthly discharges reported are the mean of daily values; annual discharges are the mean of monthly values.

Daily discharge data for the Kootenay River at Corra Linn, BC (outlet of Kootenay Lake; 1937-2002) were obtained from the WSC⁶.

² 1910-2002 data from <http://waterdata.usgs.gov/nwis/sw/> ; 2003 data from L. Sultz, USGS, *personal communication*. 1910-1971 data from Stn. 12303000; 1972-2003 data from Stn. 12301933; 2003 data provisional at time of acquisition.

³ USACE; 1974-2003; <http://www.nwd-wc.usace.army.mil/cgi-bin/dataquery.pl>

⁴ Stn. 12322000; 1929-2002 data from <http://waterdata.usgs.gov/nwis/sw/>; 2003 data from J. Gralow, USGS, *personal communication*; 2003 data provisional at time of acquisition.

⁵ Stn. 08NH021; http://www.msc-smc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm

⁶ Stn 08NJ158; http://www.msc-smc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm

2.2 Duncan / Lardeau River discharge

Discharge data for the Duncan and Lardeau rivers were retrieved from the WSC for 3 sites: Duncan River below Duncan Dam⁷, Lardeau River at Marblehead⁸, and the Duncan River below Lardeau River⁹. Perrin and Korman (1997) report inconsistencies with the WSC data – specifically, that discharges from the Duncan River below Lardeau River site were occasionally less than the sum of discharges from the Lardeau River site and the Duncan River below the Duncan Dam site. This was also noted in the data obtained for this report. Therefore, for months where data for all three stations were available, and where the mean Duncan River discharge below the Lardeau River was less than the sum from the two upstream stations, the sum of the discharges from the two upstream stations was used (4 instances, all in 1980). For all other months, the Duncan River discharge as measured below the Lardeau River was used. Annual discharges reported are the mean of monthly values after correction.

2.3 Kootenay River P concentration

Water quality data for the Kootenay River were compiled from several sources including the Province of British Columbia EMS database (1965-1997; Kootenay River at Creston, ~20 km upstream of the lake)¹⁰, the Environment Canada Pacific/Yukon Region Water Quality Monitoring Program (1961-2003; Kootenay River inflow to Kootenay Lake)¹¹, the USGS (1983-2001; Kootenay River at Porthill)¹², and the Kootenai Tribe of Idaho (KTOI; 1994-2003; Kootenay River at Porthill)¹³. Data are presented as $\mu\text{g}\cdot\text{L}^{-1}$ as P unless otherwise noted. Analytical results reported as below the detection limit were assumed equal to the detection limit. Monthly concentrations reported for January 1961 – December 2003 are the mean of data from all samples taken within each individual month. Missing monthly concentrations were linearly interpolated from the nearest two monthly values; linear interpolation was justified as no annual trend in TP concentrations was evident. No water quality data were available for dates prior to January 1961, so values for 1960 were estimated using available data from 1961-1968¹⁴. All available data within the month of January for 1961-1968 were compiled and the mean assigned to January 1960. An identical calculation was done for the other 11 calendar months. Values for months with no available data were linearly interpolated from the nearest two calculated monthly values. For all years, annual concentrations reported are the mean of monthly values. Monthly loads, determined from monthly discharges and concentrations, were summed over the year to generate annual loads.

⁷ 1969–2002; Stn. 08NH126

⁸ 1917–1996, 2002; Stn. 08NH007; since 1996, this station has been operated on a 6 year rotation.

⁹ 1963–2003; Stn. 08NH118

¹⁰ 1965-1988 Site 0200013; 1987-1997 Site E206587; L. Thompson (1998) and C. Perrin (2004), *personal communications*.

¹¹ 1961-1968 Site BC08NH0002, Environment Canada; 1979-2003 Site BC08NH0005 data from <http://www.waterquality.ec.gc.ca/WaterQualityWeb/search.aspx>.

¹² Stn. 12322000; <http://waterdata.usgs.gov/nwis/sw/>

¹³ D. Richards (1998) and C. Holderman (2004), *personal communications*.

¹⁴ Pollution abatement measures by Cominco's fertilizer operation at Kimberley reduced TP concentrations in the Kootenay River substantially between 1968 and 1969 (Northcote 1973). Therefore only data prior to 1969 were regarded as adequate approximations of TP concentrations for 1960. 31 values were available for 1961-1968. The TP concentration measured in March 1962 was eliminated from the data set because the phosphate fertilizer plant ceased operation from 7 March to 3 April 1962 due to destruction of the line across Kootenay Lake supplying it with electrical power (Northcote 1973).

2.4 Duncan / Lardeau River P concentration

Water quality data for the Duncan and Lardeau rivers are scarce since no provincial or federal water quality monitoring sites currently operate on either river. Data from two sources were compiled and used in this report. Specifically, Gray and Kirkland (1979) collected P data for 19 consecutive months in 1976–77, which were subsequently reported by Daley et al. (1981). Perrin and Korman's (1997) more recent study of the Duncan system included a complete year of sampling in the Duncan River; the data consist of flow-weighted average concentrations (for each date) measured in the Duncan River below the dam (08NH126) and in the Lardeau River (08NH007). For this report, a set of monthly TP concentrations was constructed by compiling data from the two sources outlined above and determining the mean concentration for each calendar month. This complete 12-month set of monthly values was then utilized for each of 1967-2003. For 1960-1966, the estimate of monthly concentrations was increased to adjust for the assumed degree of retention caused by the impoundment of Duncan Lake by construction of the Duncan Dam in 1967 (90.3%; Lekstrum et al. 1994; Perrin and Korman 1997). Monthly loads, determined from monthly discharges and concentrations, were summed over the year to yield annual loads. Annual concentrations reported are the mean of monthly values.

2.5 Kootenay Lake elevation

Daily surface elevation data for Kootenay Lake, measured at Queens Bay, were obtained from the WSC¹⁵ (1931-2002) and Aquila, Inc. (2003).

3. Results and Discussion

3.1 Kootenay River inflow to Kootenay Lake

The flow regime of the Kootenay River has changed substantially over the past century. The historic discharge of the Kootenay River at Libby (Fig. 2) demonstrates a major change in the flow regime of the river, coincident with the completion of the Libby Dam in 1972. A comparison of annual hydrographs immediately pre- and post-dam (Fig. 3) shows almost a complete elimination of spring freshet flows (May-July), and greatly increased flows from through the winter (Sept–March). The effect of the reduced spring flows on sturgeon spawning was addressed in the early 1990s; since 1992, the Bonneville Power Administration has purchased additional power to allow the storage of water behind Libby Dam in the winter so it can be released in the spring to induce sturgeon spawning without jeopardizing refill (USACE 2004). These experimental flows have changed from year to year according to water availability and increased understanding of sturgeon spawning requirements. Recently, the US Fish and Wildlife Service has called for an outflow capacity increase from the present 25,000-28,000 cfs ($\sim 700\text{-}800\text{ m}^3\cdot\text{s}^{-1}$), to 35,000 cfs ($\sim 1000\text{ m}^3\cdot\text{s}^{-1}$) by 2007 (USACE 2004). The spring releases in May/June are easily discernable in outflow data from the Libby Dam, comparing recent years with years before the program was implemented (Fig. 3).

The historic discharge of the Kootenay River at Porthill (Fig. 4 and 5) also shows the effect of the Libby Dam on the natural hydrograph. Similar to the hydrograph at the upstream Libby location, spring freshet flows (May-July) are substantially reduced, and flows through the winter (Sept–March) are greatly increased. The reduction of the spring freshet flows is mitigated to a small degree by tributaries that join the Kootenay River between the Libby site and the Porthill site (~ 140 km apart). The

¹⁵ Stn. 08NH064; http://www.msc-smc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm).

hydrograph has further changed with the implementation of sturgeon release flows (Fig. 6).

Figure 2

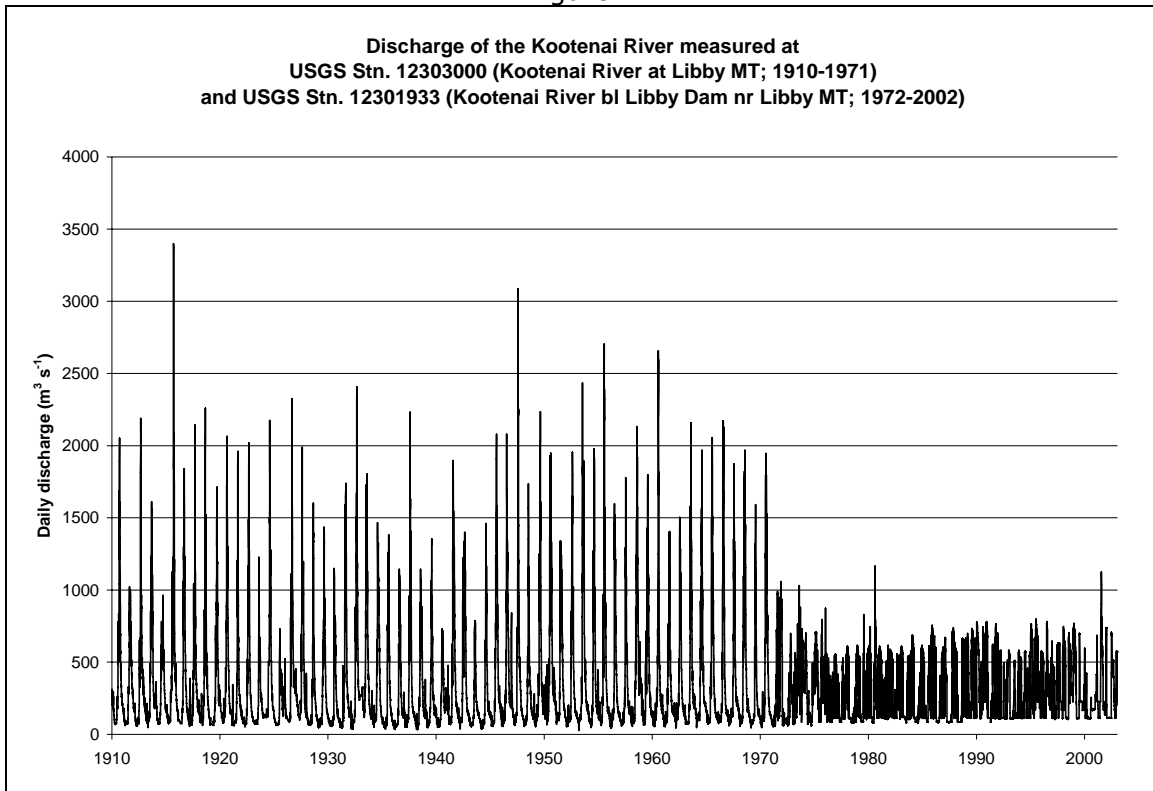


Figure 3

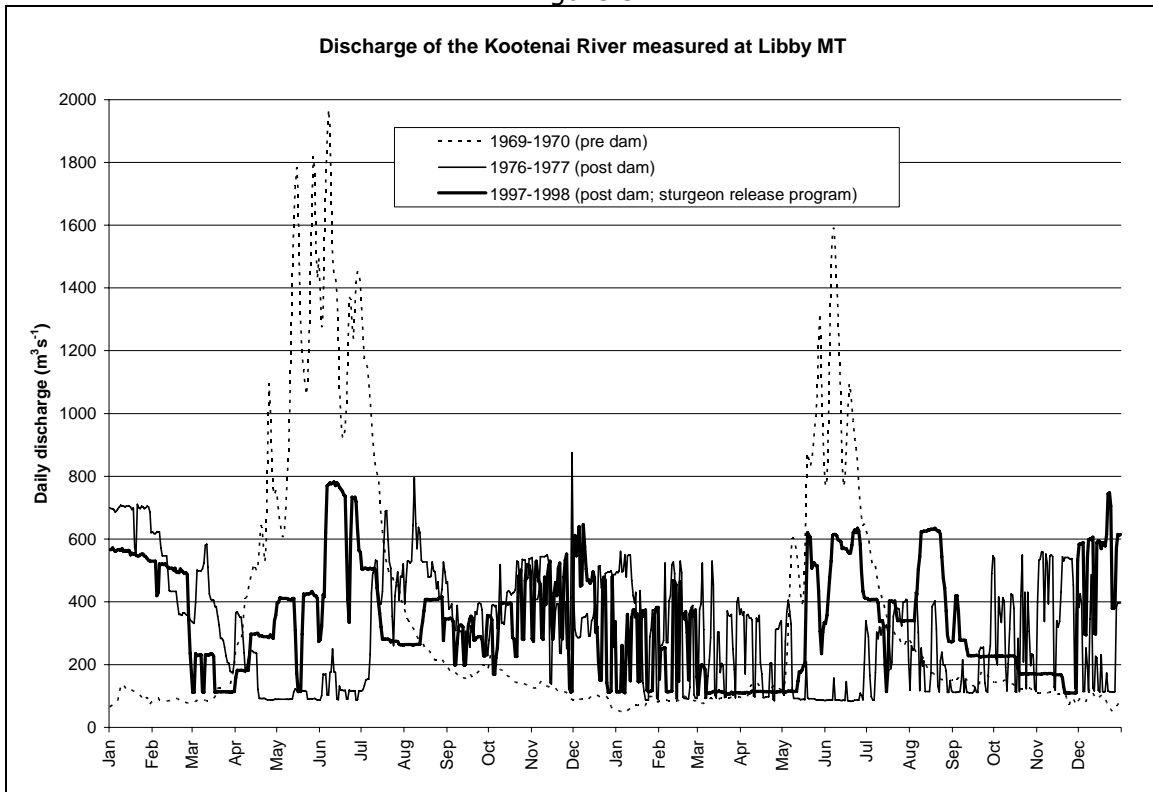


Figure 4

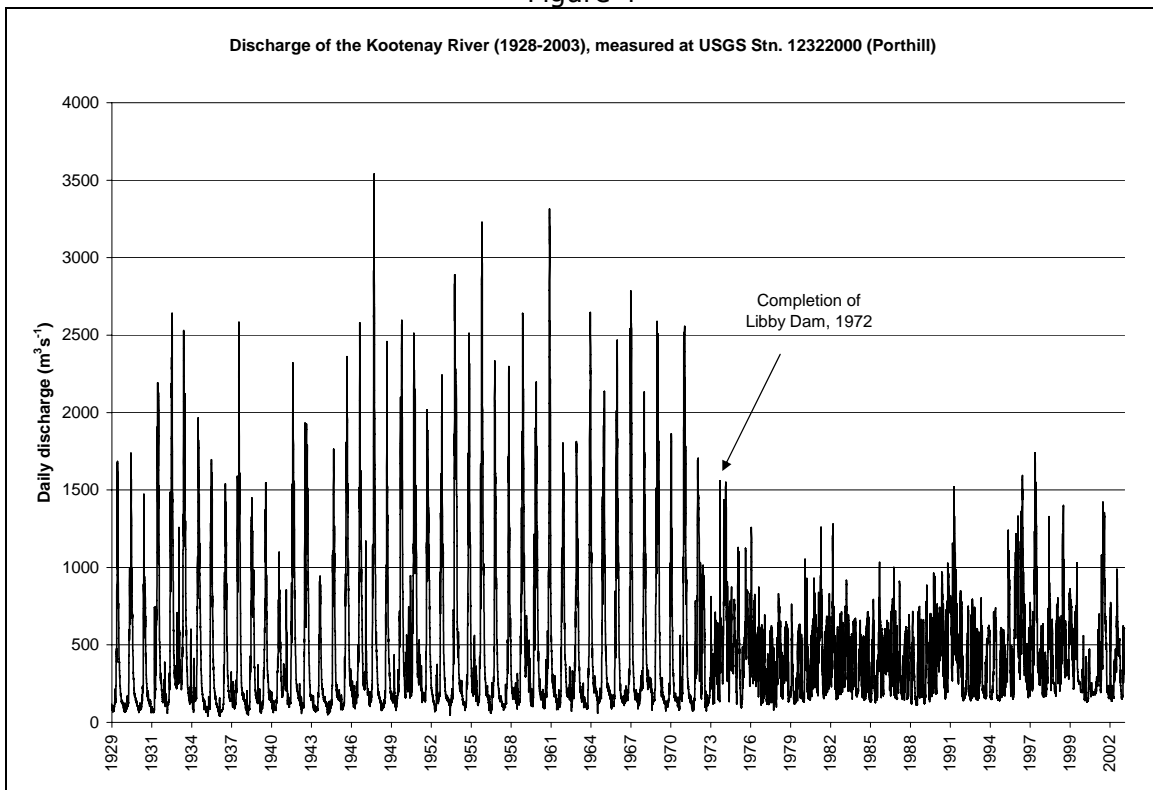


Figure 5

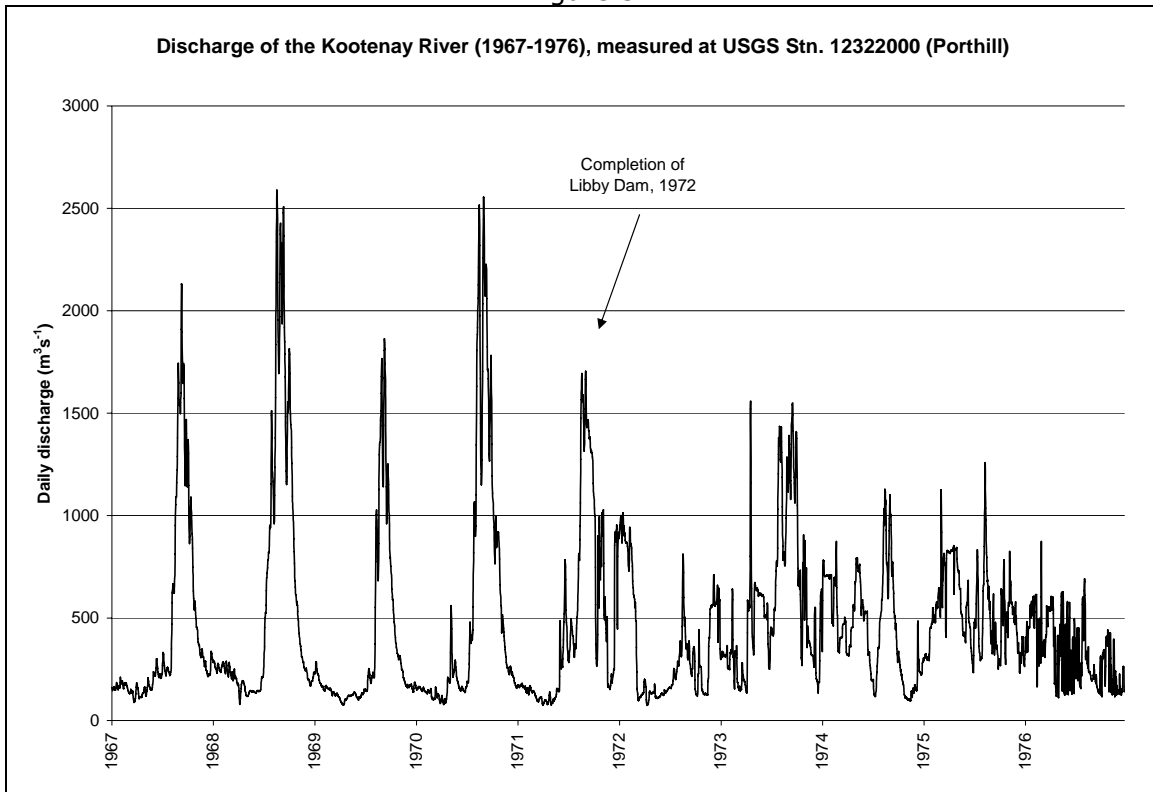
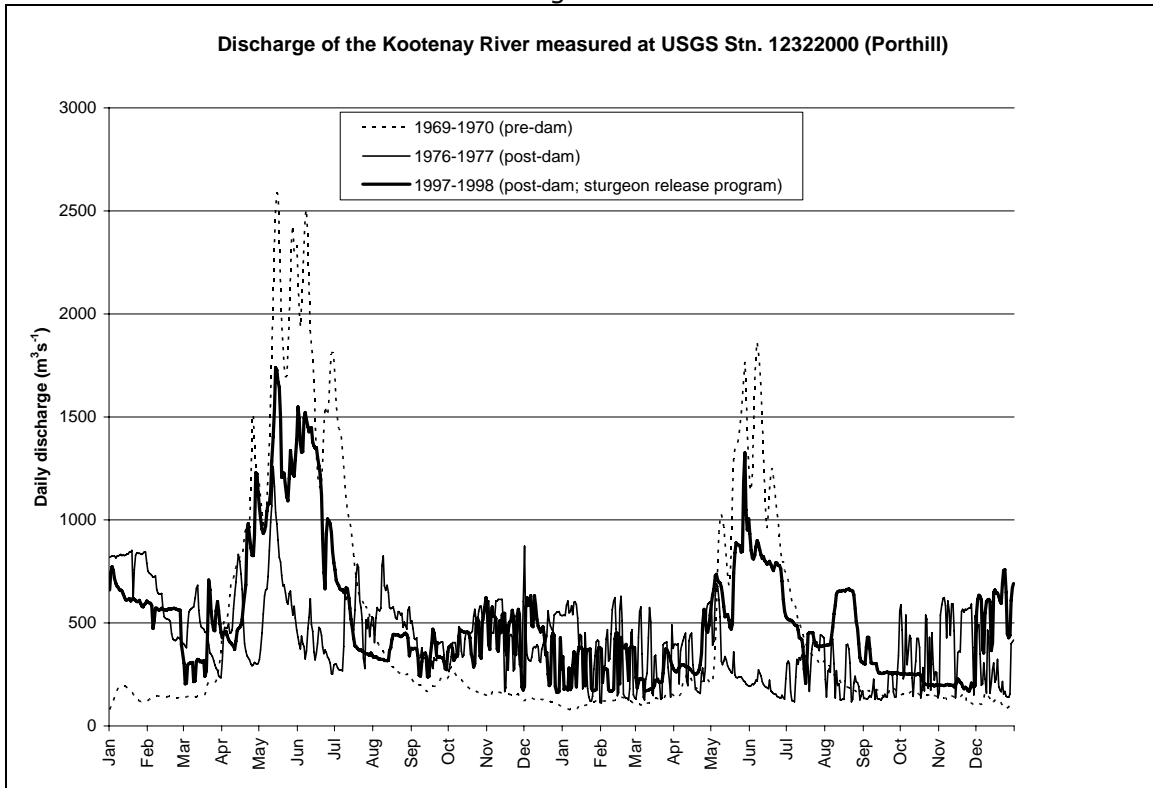


Figure 6



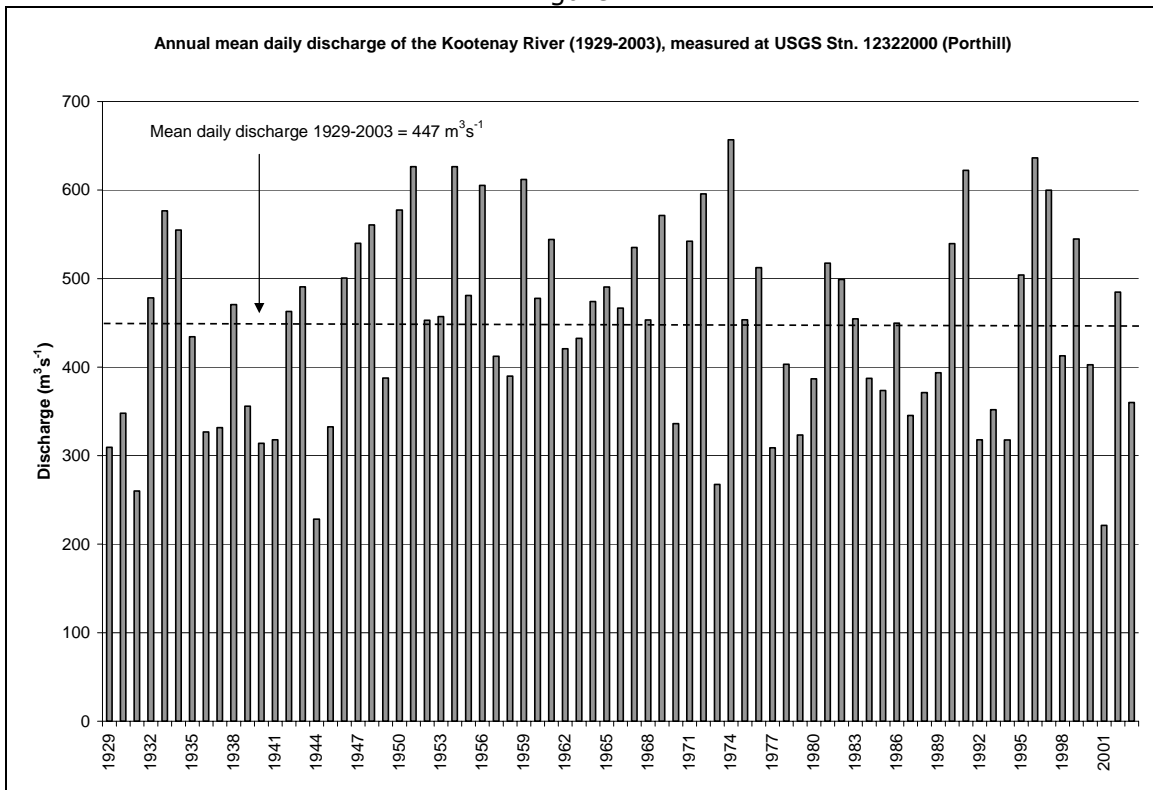
The annual mean inflow from the Kootenay River to Kootenay Lake (as measured at the Porthill station) has varied considerably from 1929-2003 around a long-term average of $447 \text{ m}^3 \cdot \text{s}^{-1}$ (Fig. 7). Of specific relevance to evaluation of the experimental fertilization program, 1992-1994, 1998, 2000-2001, and 2003 were below average flow years (especially 2001, the lowest on record), and 1995-1997, 1999 and 2002 were high flow years (especially 1996, the second highest on record). Discharge data for the Kootenay River do not indicate any significant increase or decrease over the past 74 years that could be attributable to climate change. Mean annual discharge can be weakly predicted by an equation involving Southern Oscillation Index (SOI) values¹⁶ (e.g., Ward and Yassein 2000; Fig. 8).

[1]
$$Q_s = -3.367\text{JanSOI} + 0.058\text{FebSOI} + 2.424\text{MarSOI} - 1.089\text{AprSOI} - 1.75\text{MaySOI} + 3.007\text{JunSOI} + 2.989\text{JulSOI} - 1.075\text{AugSOI} - 0.286\text{SepSOI} - 0.302\text{OctSOI} - 1.592\text{NovSOI} + 2.755\text{DecSOI} + 451.351$$

 $R^2 = 0.267, p < 0.05$

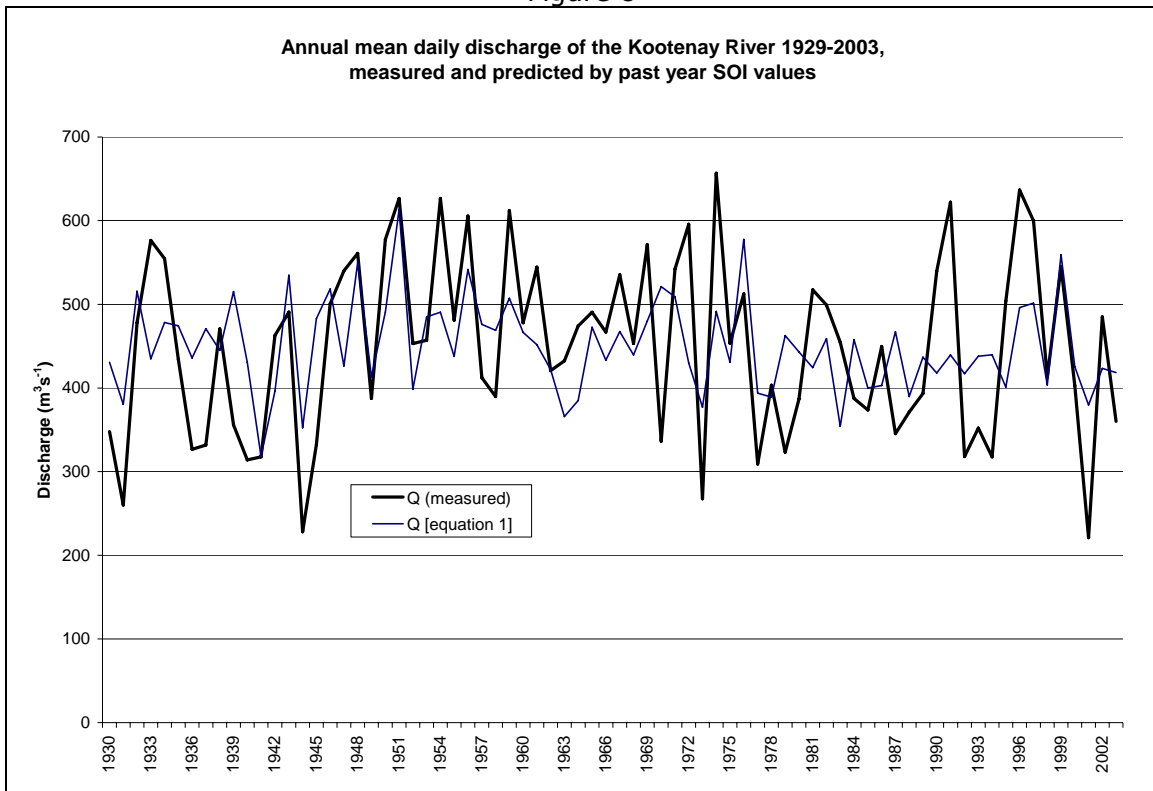
where Q_s = annual mean daily discharge of the Kootenay River in $\text{m}^3 \cdot \text{s}^{-1}$
 JanSOI = mean SOI measured January of previous calendar year
 FebSOI = mean SOI measured February of previous calendar year
 etc. for March-December.

Figure 7



¹⁶ SOI data from <http://www.bom.gov.au/climate/glossary/soi.shtml>.

Figure 8



3.2 Duncan River inflow to Kootenay Lake

The historic discharge of the Duncan River (Fig. 9) illustrates the significant alteration of the natural flow regime by the construction of the Duncan Dam (~12 km upstream of Kootenay Lake) in 1967. The changes to the Duncan hydrograph are similar but less extreme than those discussed for the Kootenay River. Specifically, some reduction and delay of peak spring freshet flows have occurred, along with greatly increased flows through the winter months (Figs. 10 and 11).

Figure 9

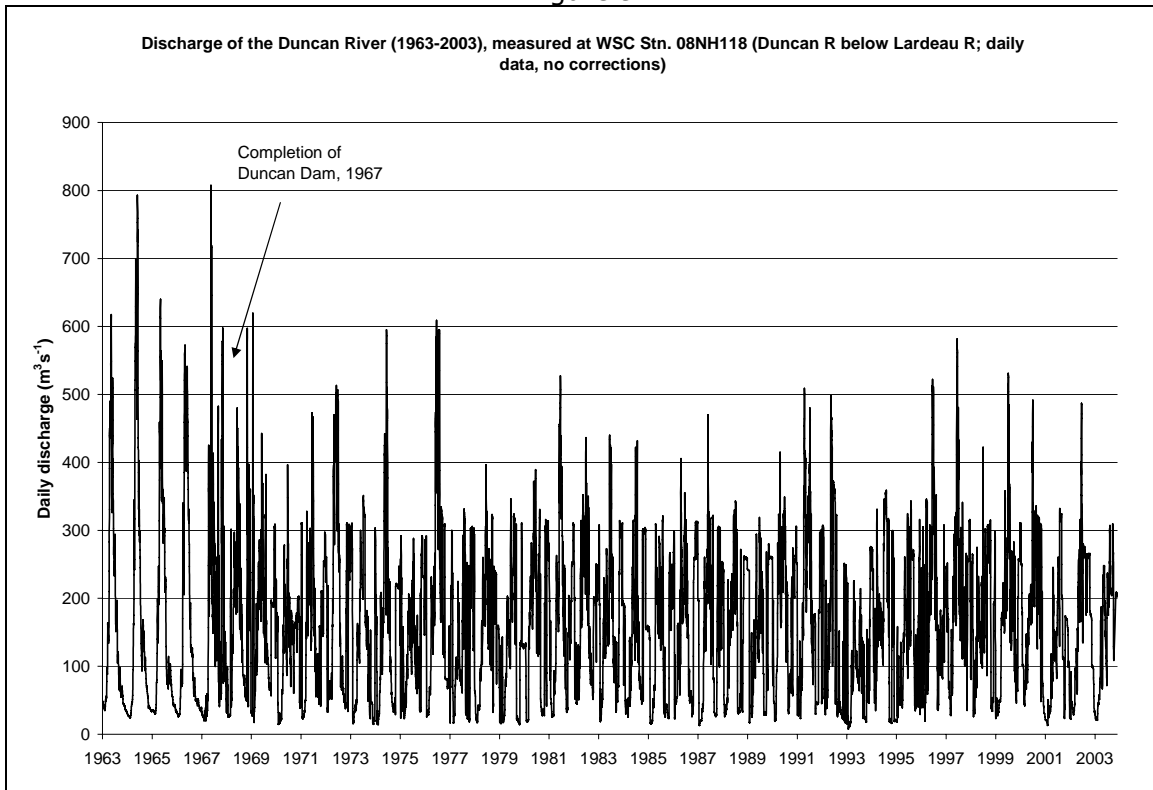


Figure 10

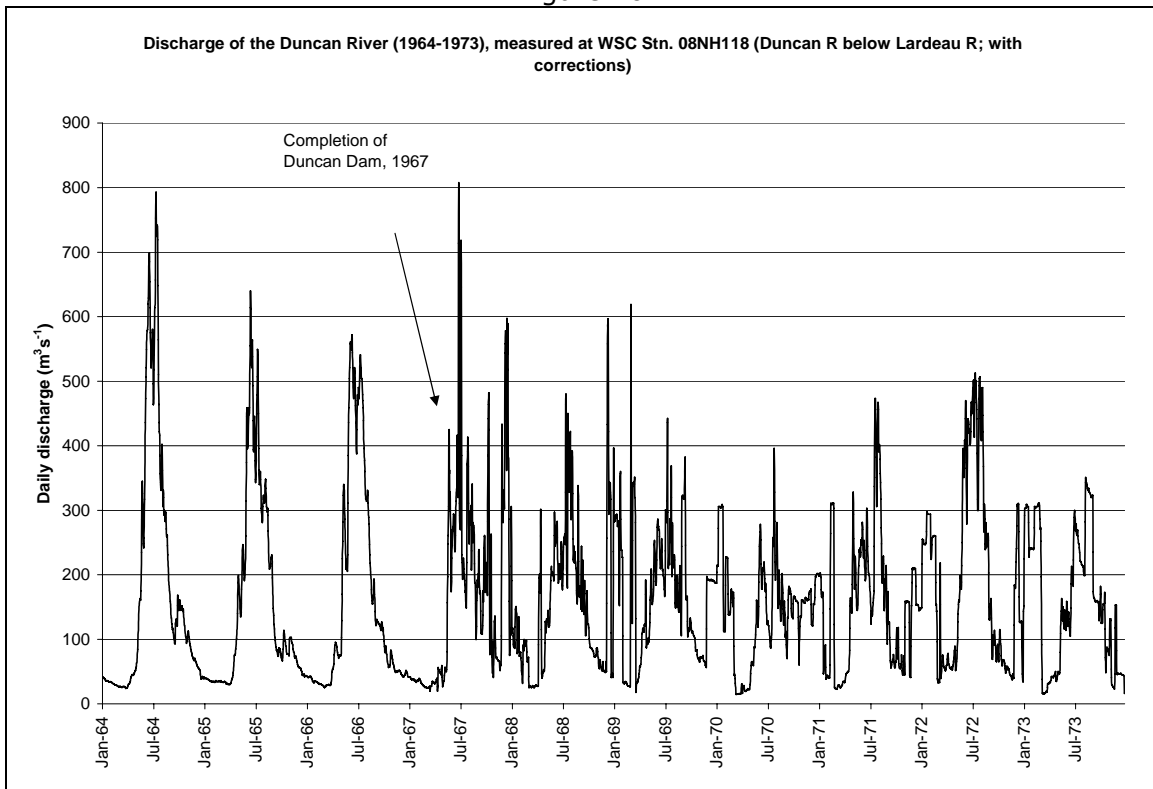
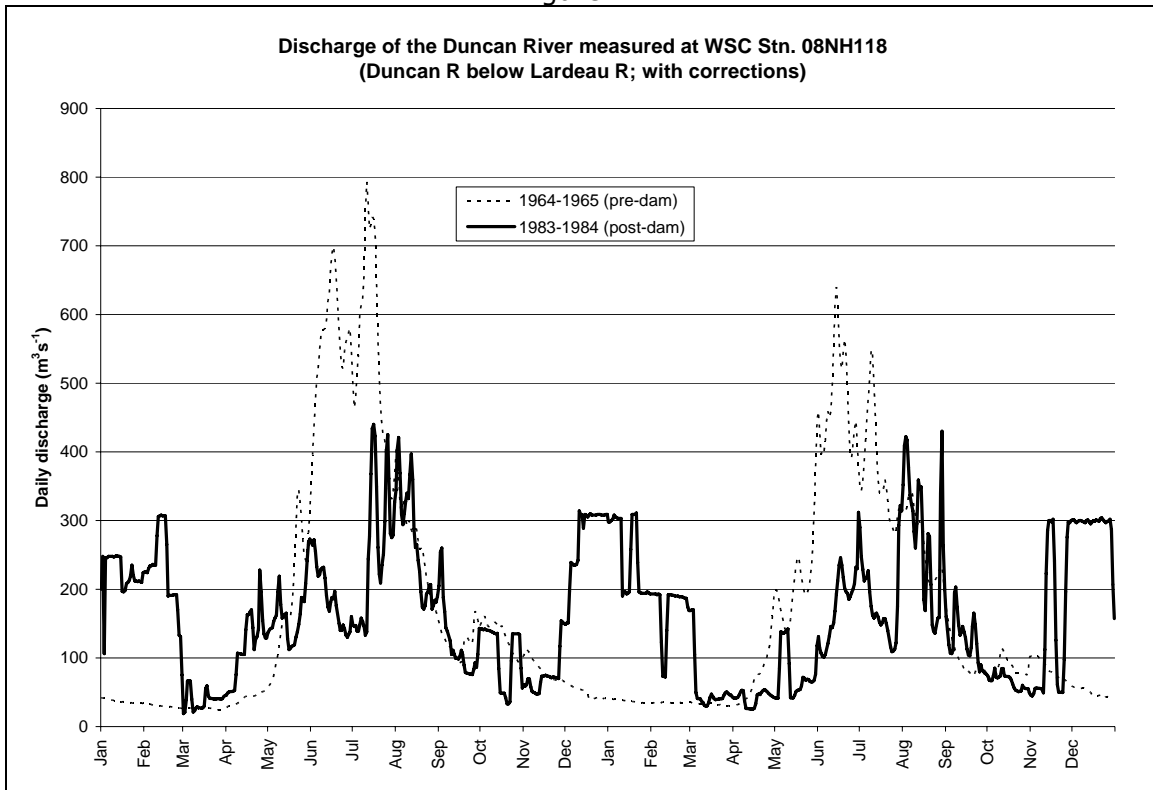


Figure 11



The annual mean daily discharges of the Duncan River from 1963-2003 vary around a long-term average of $161 \text{ m}^3 \cdot \text{s}^{-1}$ (Fig. 12). Of specific relevance to evaluation of the experimental fertilization program, 1993, 1995, 2001 and 2003 were below average flow years, and 1994, 1996-2000, and 2002 were above average flow years (especially 1996, 1997, and 2000). Discharge data for the Duncan River do not indicate any significant increase or decrease over the past 40 years that could be attributable to climate change. Mean annual discharge can be reasonably predicted by an equation involving SOI values (Fig. 13).

[2] $Q_N = 0.522\text{AprSOI} - 1.242\text{MaySOI} + 1.434\text{JulSOI} - 0.579\text{AugSOI} - 0.571\text{SepSOI} + 1.012\text{OctSOI} - 1.539\text{NovSOI} + 1.865\text{DecSOI} + 167.425$
 $R^2 = 0.445, p < 0.05$

where Q_N = annual mean daily discharge of the Duncan River in $\text{m}^3 \cdot \text{s}^{-1}$.

Figure 12

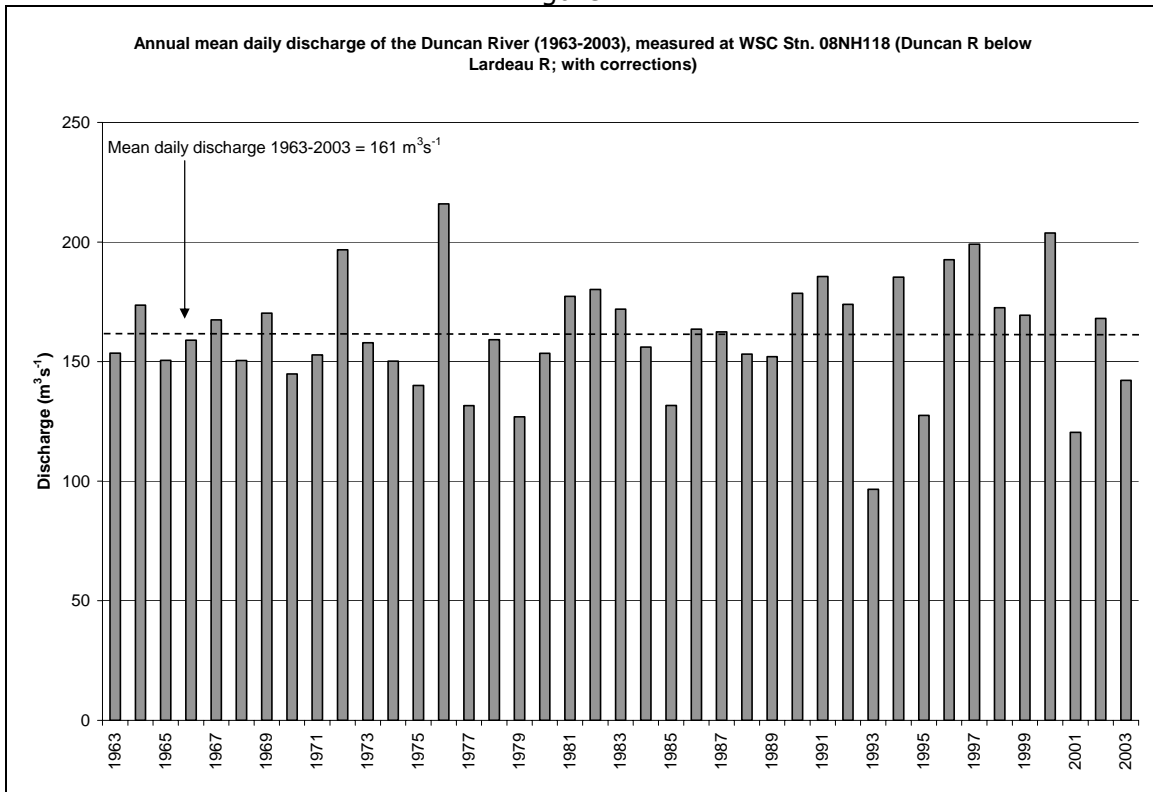
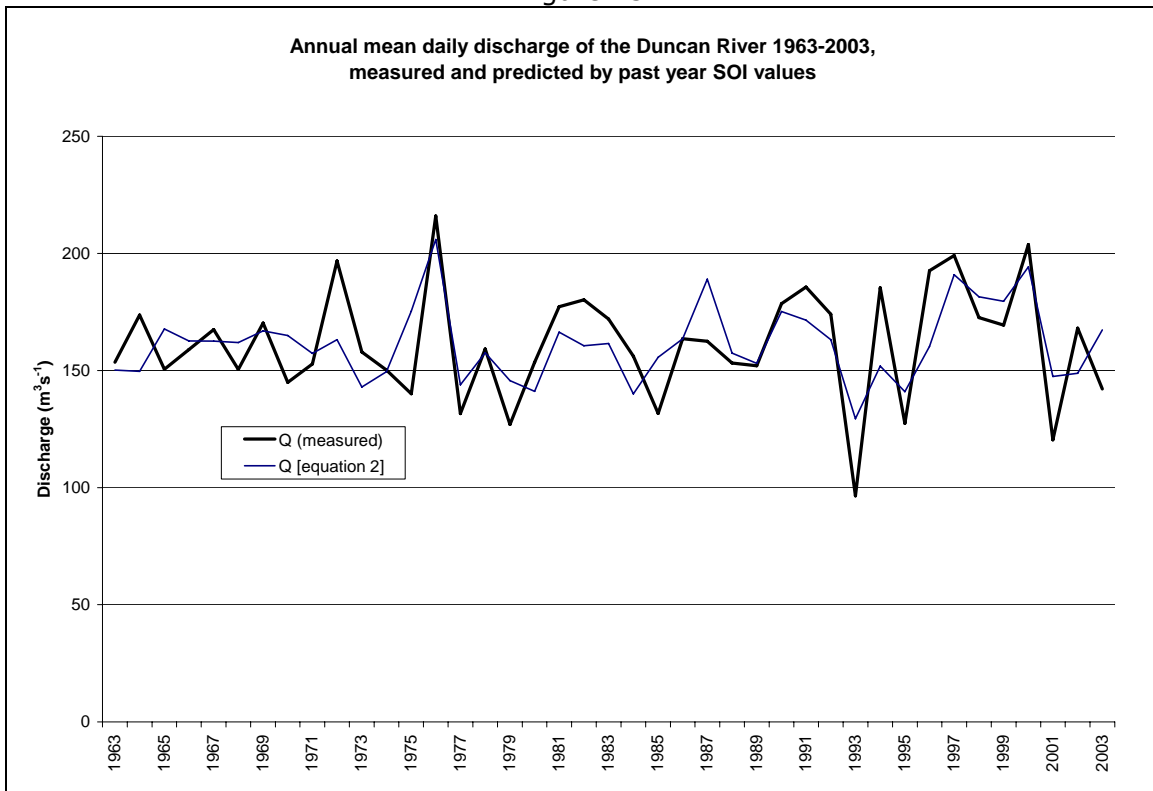


Figure 13



Due to climatic differences and distance between the Kootenay and Duncan subbasins, an above- or below-average discharge year in one basin may not be reflected in the other. Since 1963, mean annual discharges from the Kootenay and Duncan rivers tended in the same direction (higher or lower than long term averages) only 71% of the time. For only 7 of the 12 years of the fertilization period (58%) did the mean annual discharge for both the Duncan and Kootenay rivers tend in the same direction (both above average: 1996, 1997, 1999, and 2002; both below average: 1993, 2001, and 2003; Table 1). For the remaining 5 years (42%), the mean annual discharges tend in opposite direction (Duncan above average, Kootenay below: 1992, 1994, 1998, and 2000; Kootenay above average, Duncan below: 1995).

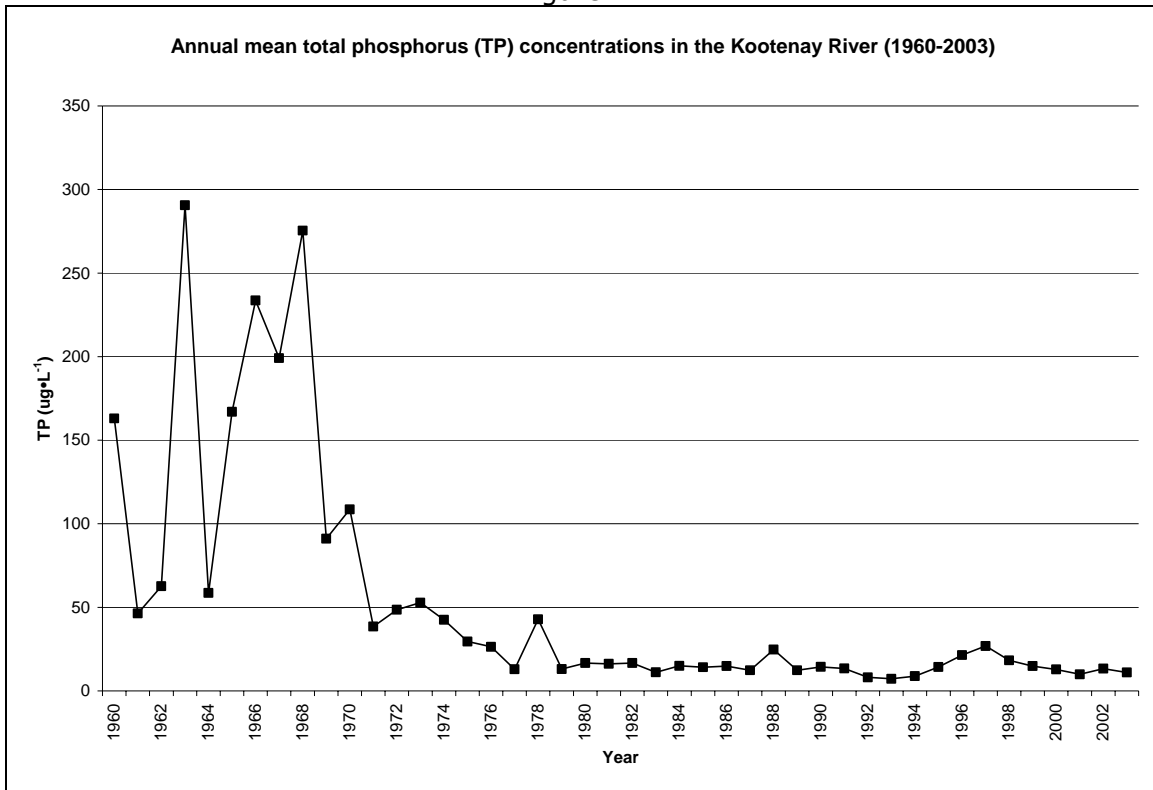
Table 1. Annual mean discharge of the Kootenay and Duncan rivers (1992-2003) and comparison to long term averages.

Year	Kootenay River discharge ($\text{m}^3\cdot\text{s}^{-1}$)	Above or below long-term (1929-2003) average discharge of $447 \text{ m}^3\cdot\text{s}^{-1}$	Duncan River discharge ($\text{m}^3\cdot\text{s}^{-1}$)	Above or below long-term (1963-2003) average discharge of $161 \text{ m}^3\cdot\text{s}^{-1}$
1992	318	below	174	above
1993	352	below	97	below
1994	318	below	185	above
1995	504	above	127	below
1996	637	above	193	above
1997	600	above	199	above
1998	413	below	173	above
1999	545	above	169	above
2000	403	below	204	above
2001	221	below	120	below
2002	485	above	168	above
2003	360	below	142	below

3.3 Kootenay River P Concentrations

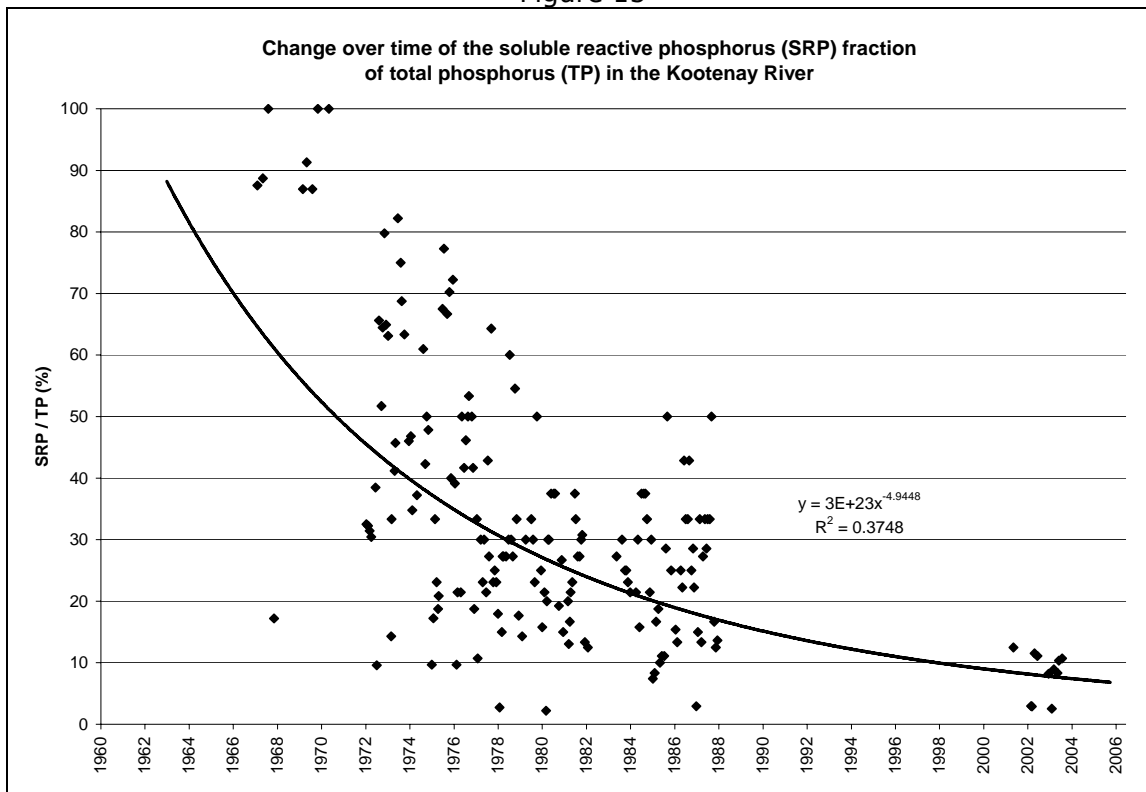
Regular water quality sampling in the Kootenay River upstream of Kootenay Lake began in the 1960s, well after cultural eutrophication of the Kootenay River and Kootenay Lake were underway. TP concentrations in the Kootenay River (just upstream of the lake) from the early- and mid-1960s reflect the large amounts of phosphates entering the Kootenay River from the operation of the Cominco fertilizer plant near Kimberley, BC, nearly 400 km upstream (Northcote 1973; Fig. 14). Annual mean TP concentrations in the river show a dramatic decrease starting in the late 1960s associated with clean up of the Kimberley fertilizer plant beginning in 1969, and completion of the Libby Dam in 1972. For 1961-1968 (pre-dam; pre-fertilizer plant cleanup) annual mean TP concentrations ranged from 46.4 to $290.5 \mu\text{g}\cdot\text{L}^{-1}$ with a mean of $166.7 \mu\text{g}\cdot\text{L}^{-1}$. The effect of the cleanup at the fertilizer plant in 1969 is reflected in an abrupt decrease in TP concentrations from $236 \mu\text{g}\cdot\text{L}^{-1}$ (mean 1966-1968) to $79.4 \mu\text{g}\cdot\text{L}^{-1}$ (mean 1969-1970). Concentrations continued to decline through the 1970s. By 1979, annual mean TP concentrations were rarely above $20 \mu\text{g}\cdot\text{L}^{-1}$; for 1979-2003, annual means ranged from 7.3 to $26.9 \mu\text{g}\cdot\text{L}^{-1}$ with an overall mean of $14.5 \mu\text{g}\cdot\text{L}^{-1}$.

Figure 14



Limited data were available for components of TP such as total dissolved phosphorus (TDP) or soluble reactive phosphorus (SRP; equivalent to dissolved ortho phosphorus). Water quality samples analyzed for both SRP and TP show a substantial decline in the SRP fraction of TP (Fig. 15). From 1967-1970, SRP comprised the vast majority (mean 84%) of TP in the river; this high percentage is not unexpected since the majority of the TP load was derived from phosphate release from the fertilizer plant at Kimberley. (Much of the tailings waste from which it was unprofitable to try to extract any more phosphorus was bulldozed out from an inadequately small-sized tailings pond in spring to coincide with freschet in the St. Mary & Kootenay rivers. Much of the particulate probably settled out, temporarily at least, in the St. Mary and Kootenay rivers, leaving mainly SRP to enter the South Arm of Kootenay Lake (T.G. Northcote, 2004, personal communication)). This percentage steadily declined through the 1970s and 1980s (39.7%, mean 1971-1978; 34.5%, mean 1979-1988; Fig. 15). Recent data indicate this percentage is now less than 10% (8.2%; mean 2001-2003).

Figure 15



3.4 Duncan River P Concentrations

The annual mean TP concentration determined for the Duncan River for 1967-2003 was $11.8 \mu\text{g}\cdot\text{L}^{-1}$. The annual mean TP concentration estimated for 1960-1966 (pre Duncan Dam) was $57.7 \mu\text{g}\cdot\text{L}^{-1}$. SRP concentrations were estimated combining in sequence the mean percent of TDP in TP for the Duncan River (37.6%; data from Gray and Kirkland 1979) and the mean percent of SRP in TDP for the Kootenay River¹⁷ (51.7%). Using this estimate of SRP for the Duncan River (19.4% of TP), the mean annual SRP concentrations for the Duncan River were $11.2 \mu\text{g}\cdot\text{L}^{-1}$ for 1960-1966 (pre-dam) and $2.3 \mu\text{g}\cdot\text{L}^{-1}$ for 1967-2003 (post-dam).

3.5 Kootenay River P Loading to Kootenay Lake

TP loading into Kootenay Lake from the Kootenay River has decreased dramatically since the 1960s, reflecting the reduction in TP concentration in the Kootenay River (Table 2; Fig. 16 and 17; note log scale on left side y-axis Fig. 16). From 1960-1968, the mean TP load delivered to Kootenay Lake was 2,603 t (range 511-7,808 t). The loading decreased through the 1970s; for 1969-1978, the mean load was 882 t (range 127-2216 t). Since 1979, loading has not exceeded 700 t annually; mean annual loading for 1979-2003 is 224 t (range 67-631 t).

SRP loading from the Kootenay River was determined by applying an equation describing the trend over time of SRP percentages of TP (Figs. 16 and 17; $y = 3E+23x^{-4.9448}$; $R^2 = 0.3748$) to the previously calculated mean annual TP load. Table 2 and Figures 16 and 17 (note log scale on left side y-axis Fig. 16) show the estimated SRP loading from 1960-2003 has decreased even more dramatically than

¹⁷ No SRP data were available for the Duncan River. Using the mean percentage SRP in TDP from the Kootenay River is not ideal due to differences in geology of the two drainage basins.

TP. From 1960-1968, the mean SRP load delivered to Kootenay Lake was 1931 t (range 486-6,319 t). The loading decreased through the 1970s; for 1969-1978, the mean load was 380 t (range 38-1,144 t). Since 1979, loading has not exceeded 70 t annually with mean loading of 31 t for 1979-2003 (range 5-65 t); these values are substantially below those estimated for 1951 prior to the installation of the fertilizer plant (232 t; Northcote 1972).

Figure 16

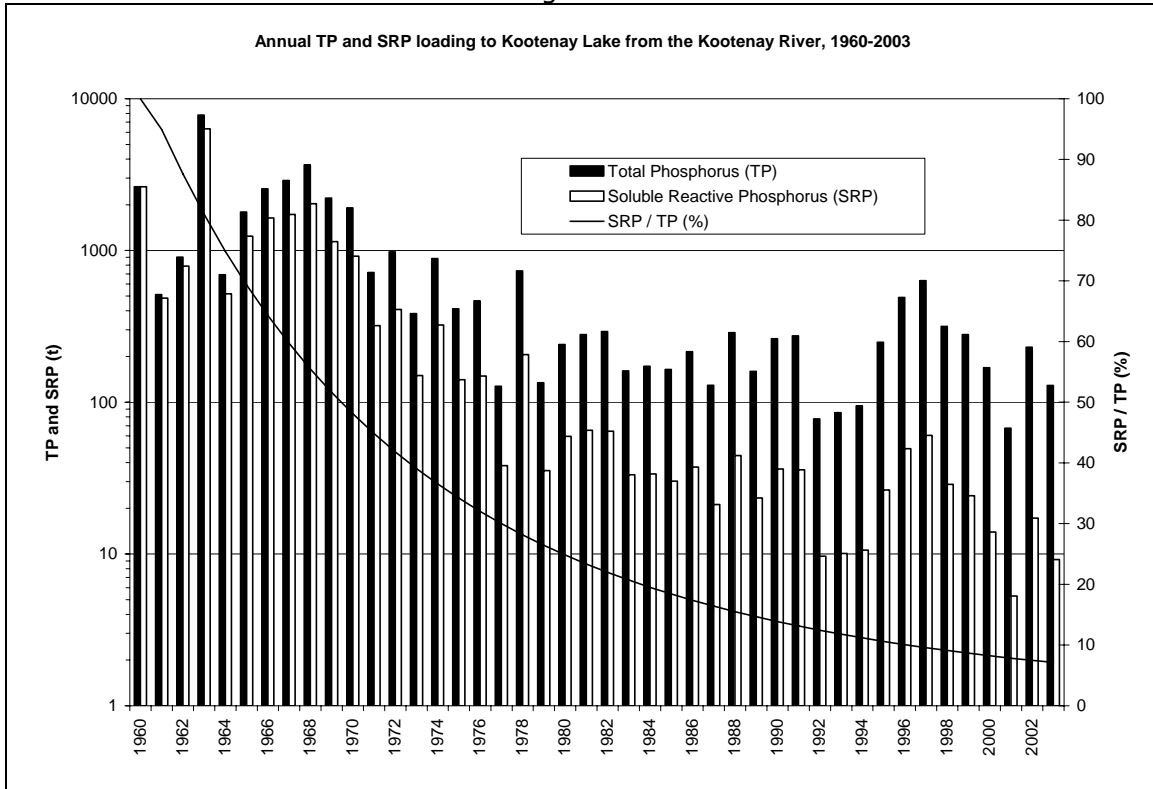
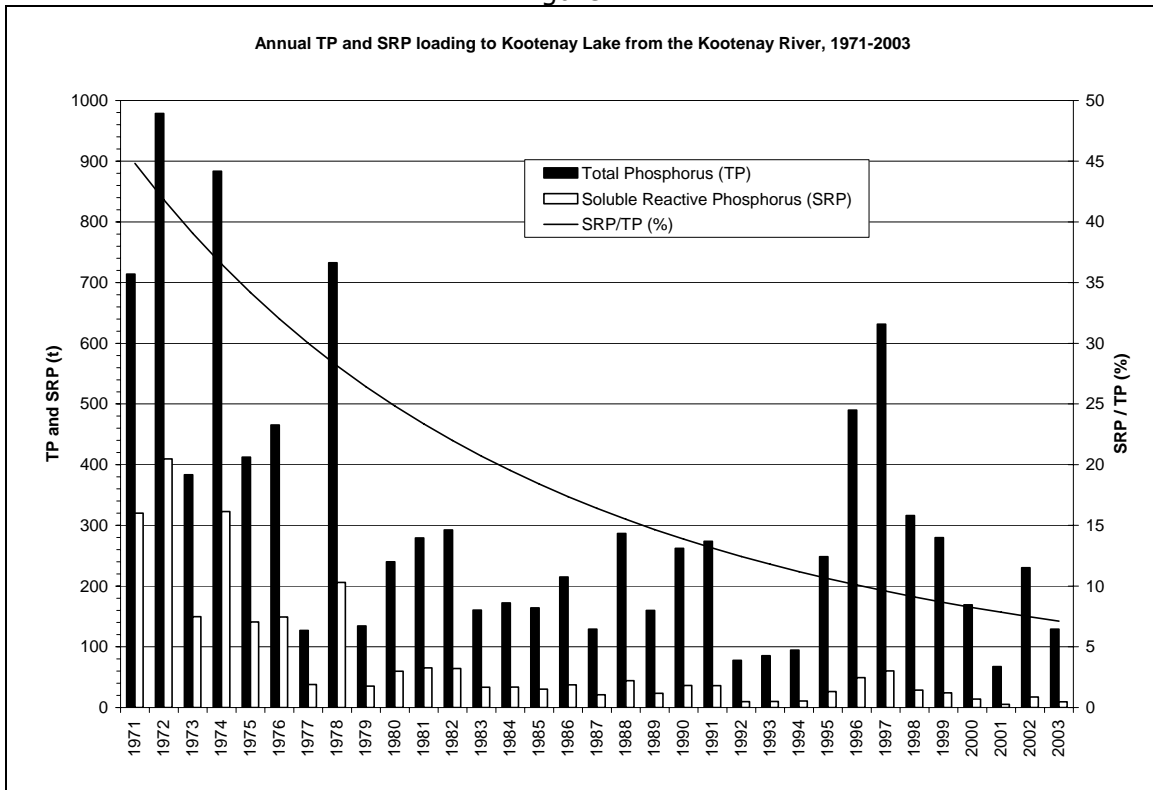


Figure 17



3.6 Duncan River P Loading to Kootenay Lake

TP loading into Kootenay Lake from the Duncan River has decreased dramatically since 1966, reflecting the reduction in TP concentration in the Duncan River due to retention of nutrients behind the Duncan Dam (Fig. 18). From 1960-1966, the mean annual TP load delivered to Kootenay Lake was estimated at 315 t. In contrast, the mean load delivered from 1967-2003 was 65 t (range 42-92 t). SRP loading from the Duncan River was estimated at 19.4% of TP loading (see section 3.4). Mean annual SRP loads have decreased from 61 t (mean 1960-1966, range 58-66 t) to 13 t (mean 1967-2003; range 8-18 t).

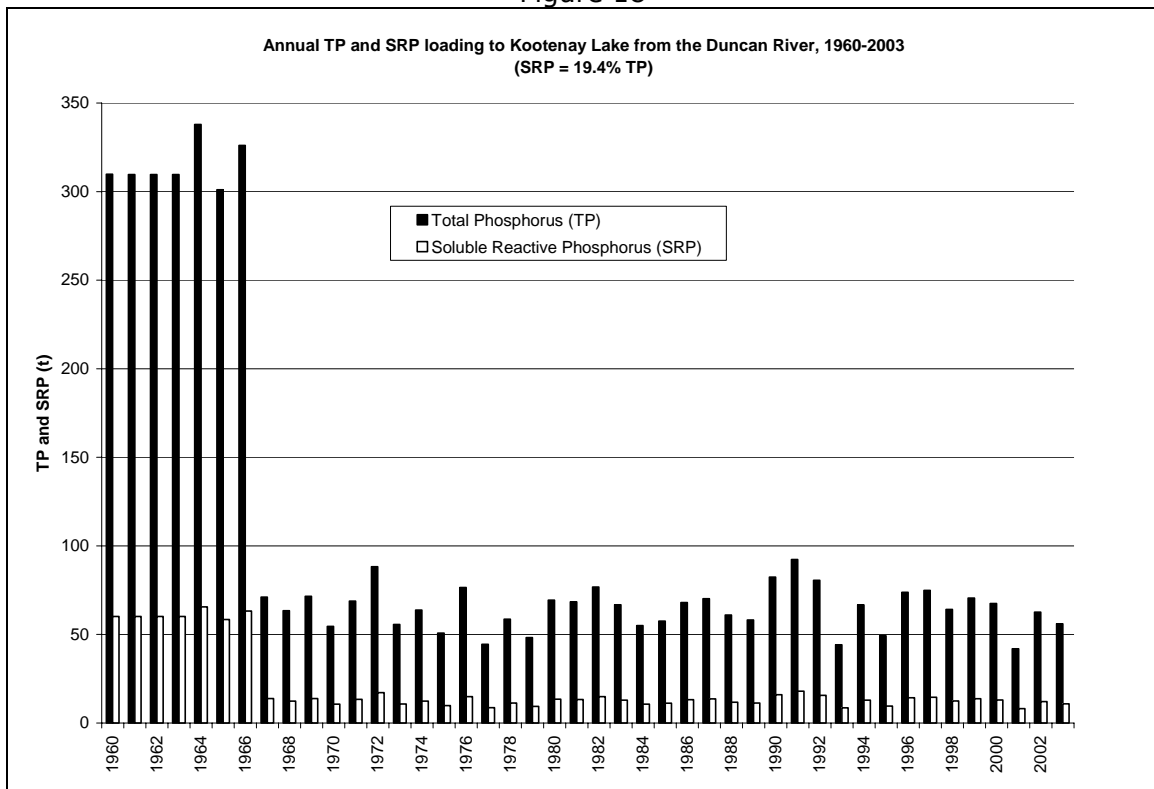
Table 2. TP and SRP loads to Kootenay Lake from the Kootenay and Duncan rivers.

Year	Kootenay River			Duncan River		
	Annual TP load (t)	% SRP in TP	Annual SRP load (t)	Annual TP load (t)	% SRP in TP	Annual SRP load (t)
1960	2628	100.0	2628	310	19.4	60
1961	512	94.9	486	310	19.4	60
1962	902	87.6	790	310	19.4	60
1963	7808	80.9	6319	310	19.4	60
1964	691	74.9	517	338	19.4	66
1965	1791	69.3	1242	301	19.4	58
1966	2547	64.3	1638	326	19.4	63
1967	2890	59.7	1725	71	19.4	14
1968	3660	55.5	2031	63	19.4	12
1969	2216	51.6	1144	72	19.4	14
1970	1908	48.1	917	55	19.4	11
1971	714	44.8	320	69	19.4	13
1972	979	41.8	409	88	19.4	17
1973	384	39.1	150	56	19.4	11
1974	883	36.5	323	64	19.4	12
1975	413	34.2	141	51	19.4	10

Table 2. Continued.

Year	Kootenay River			Duncan River		
	Annual TP load (t)	% SRP in TP	Annual SRP load (t)	Annual TP load (t)	% SRP in TP	Annual SRP load (t)
1976	465	32.0	149	76	19.4	15
1977	127	30.0	38	44	19.4	9
1978	733	28.2	206	59	19.4	11
1979	134	26.4	36	48	19.4	9
1980	240	24.8	60	69	19.4	13
1981	279	23.4	65	68	19.4	13
1982	292	22.0	64	77	19.4	15
1983	160	20.7	33	67	19.4	13
1984	172	19.5	34	55	19.4	11
1985	164	18.4	30	58	19.4	11
1986	215	17.4	37	68	19.4	13
1987	129	16.4	21	70	19.4	14
1988	287	15.5	44	61	19.4	12
1989	160	14.7	23	58	19.4	11
1990	262	13.9	36	82	19.4	16
1991	274	13.1	36	92	19.4	18
1992	78	12.4	10	81	19.4	16
1993	85	11.8	10	44	19.4	9
1994	95	11.2	11	67	19.4	13
1995	248	10.6	26	49	19.4	10
1996	490	10.1	49	74	19.4	14
1997	631	9.6	60	75	19.4	15
1998	316	9.1	29	64	19.4	12
1999	280	8.7	24	71	19.4	14
2000	169	8.2	14	67	19.4	13
2001	67	7.8	5	42	19.4	8
2002	231	7.5	17	63	19.4	12
2003	129	7.1	9	56	19.4	11

Figure 18



3.7 Discharge Balance for Kootenay Lake

Surface inflow to Kootenay Lake originates from the Kootenay River, Duncan River, and Kootenay Lake subbasins, each distinctly different particularly in their size and geological features (see Northcote 1973, Daley et al. 1981 for more detail). Kootenay River discharge at Porthill, ID and Duncan River discharge below the Duncan Dam were summed and compared to Kootenay River discharge at Corra Linn (outlet of Kootenay Lake) to determine the percent of total inflow to the lake for which they accounted. Based on discharge data for 1964-2002, the Kootenay and Duncan rivers comprise 56.6 and 21.0% of the inflow to the lake respectively (total 77.6%). The remaining 22.4% is attributed to the combination of small tributaries entering the Kootenay and Duncan rivers between the discharge gauging stations and the lake, and many small main lake and West Arm tributaries. Daley et al. (1981) completed a previous estimate of this distribution (61.5, 16 and 22.5%, respectively).

3.8 Phosphorus Loading to Kootenay Lake

Phosphorus loading to Kootenay Lake can originate from 3 external sources: atmospheric fallout, ground water seepage and surface inflow. The first 2 external input sources were reviewed by Northcote (1973) and were not thought to be sizable. Estimates of loading to Kootenay Lake discussed here are based solely upon inflow from the Kootenay and Duncan rivers and assume the potential loading from the remaining 22.4% surface inflow is both constant and modest.

Mean annual TP loading (Fig. 19, note log scale; Table 3) from 1960-1972 was 2,451 t (range 782-8,117 t). Since 1973, loading had been relatively constant, and never above 1000 t (mean 1973-2003, 356 t; range 156-947 t). From 1960-1972, the Kootenay River regularly contributed 85% or more of the TP load (mean 87%; range 62-98%). Since 1973, the Kootenay River percentage has gradually decreased (1973-1987, mean 80%; 1988-2003, mean 74%).

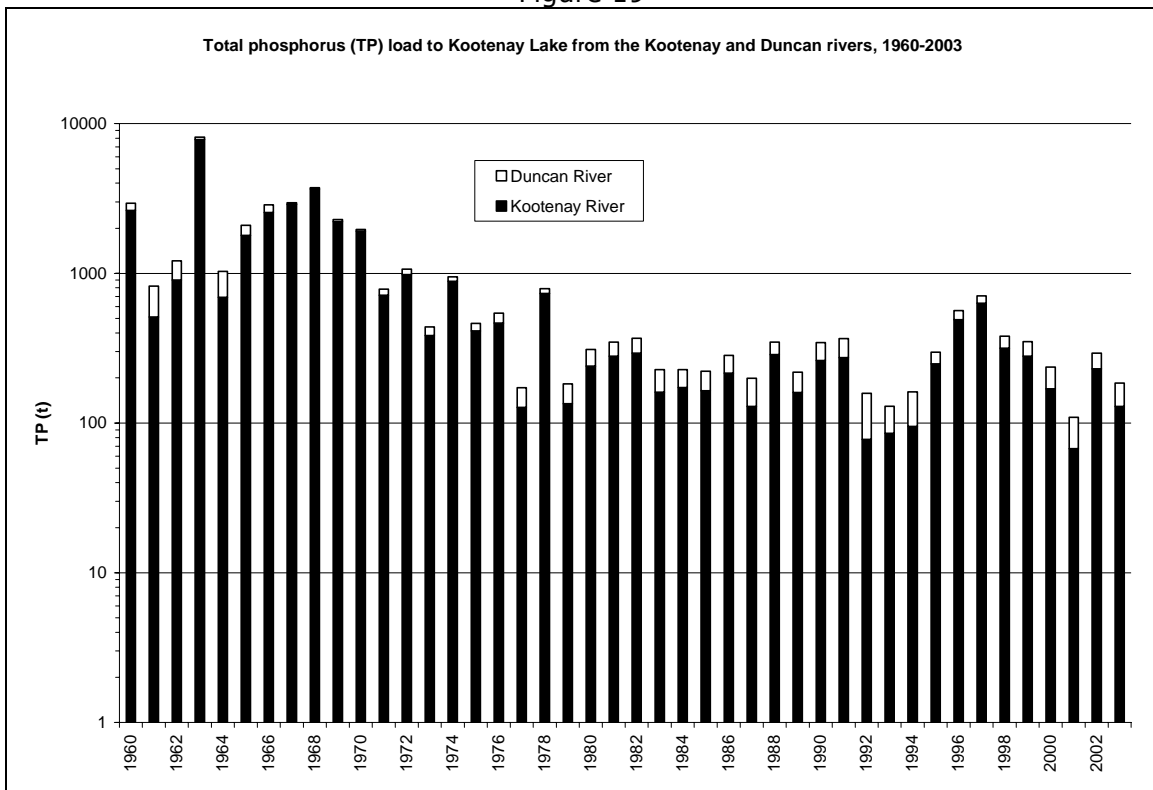
Table 3. Proportion of TP load to Kootenay Lake from the Kootenay and Duncan rivers

Year	Annual TP load			
	Duncan River		Kootenay River	
	T	% of total	t	% of total
1960	310	11	2,628	89
1961	310	38	512	62
1962	310	26	902	74
1963	310	4	7,808	96
1964	338	33	691	67
1965	301	14	1,791	86
1966	326	11	2,547	89
1967	71	2	2,890	98
1968	63	2	3,660	98
1969	72	3	2,216	97
1970	55	3	1,908	97
1971	69	9	714	91
1972	88	8	979	92
1973	56	13	384	87
1974	64	7	883	93
1975	51	11	413	89
1976	76	14	465	86
1977	44	26	127	74
1978	59	7	733	93
1979	48	26	134	74
1980	69	22	240	78
1981	68	20	279	80
1982	77	21	292	79

Table 3. Continued.

Year	Annual TP load			
	Duncan River		Kootenay River	
	t	% of total	t	% of total
1983	67	29	160	71
1984	55	24	172	76
1985	58	26	164	74
1986	68	24	215	76
1987	70	35	129	65
1988	61	18	287	82
1989	58	27	160	73
1990	82	24	262	76
1991	92	25	274	75
1992	81	51	78	49
1993	44	34	85	66
1994	67	41	95	59
1995	49	17	248	83
1996	74	13	490	87
1997	75	11	631	89
1998	64	17	316	83
1999	71	20	280	80
2000	67	29	169	71
2001	42	38	67	62
2002	63	21	231	79
2003	56	30	129	70

Figure 19



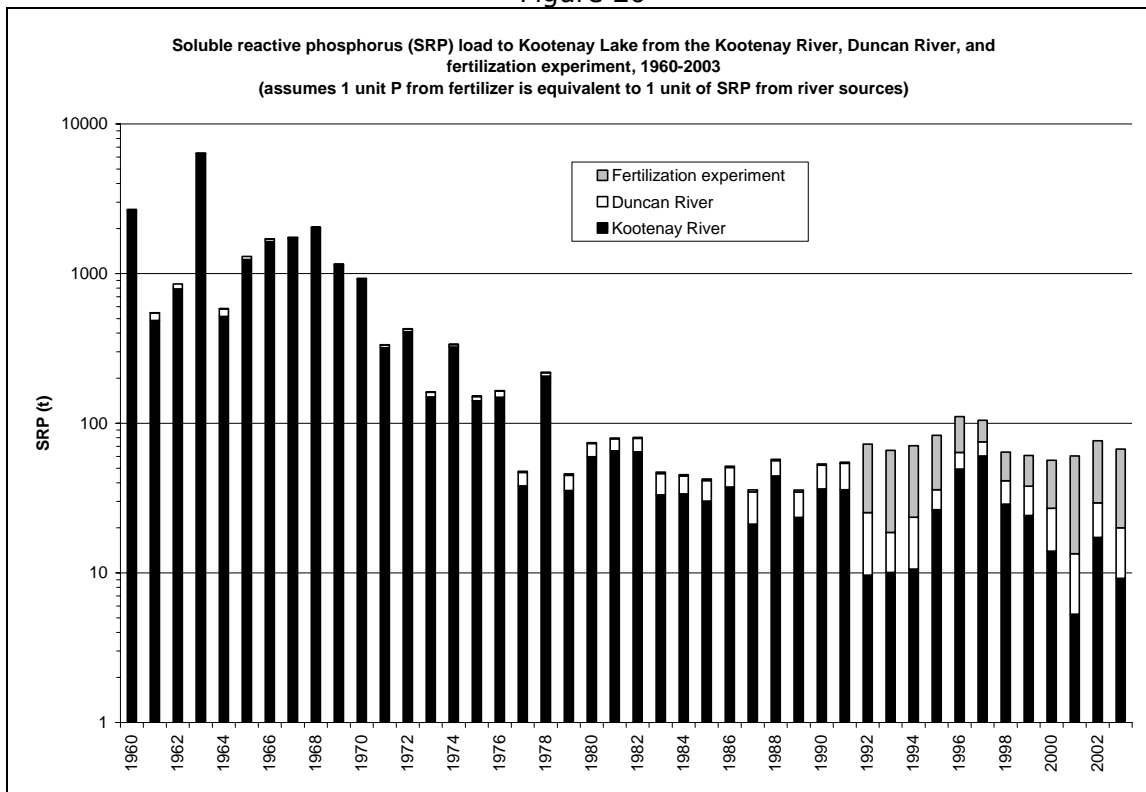
Mean annual SRP load (Fig. 20, note log scale; Table 4) from 1960-1972 was 1,590 t (range 333-6,379 t). Since 1973, loading has gradually decreased (1973-1987, mean 105 t, range 35-335; 1988-2003, mean 68 t, range 35-111 t). Until the late 1970s, the Kootenay River was responsible for more than 90% of the total SRP loading to the lake from the two major tributary rivers (mean 1960-1972, 96%). This percentage has since gradually declined (1973-1987, mean 82%; 1988-2003,

mean 61%). Over the 12 years of the fertilization experiment, fertilizer loading has ranged from 22.9 to 47.1 t and represented 28-78% of the total SRP load (mean 56%; Fig. 20).

Table 4. Proportion of SRP load to Kootenay Lake from the Kootenay River, Duncan River, and fertilization (brackets = % of load neglecting influence of fertilization)

Year	Duncan River		Annual SRP load Kootenay River		Fertilization	
	t	% of total	t	% of total	t	% of total
1960	60	2	2,628	98		
1961	60	11	486	89		
1962	60	7	790	93		
1963	60	1	6,319	99		
1964	66	11	517	89		
1965	58	4	1,242	96		
1966	63	4	1,638	96		
1967	14	1	1,725	99		
1968	12	1	2,031	99		
1969	14	1	1,144	99		
1970	11	1	917	99		
1971	13	4	320	96		
1972	17	4	409	96		
1973	11	7	150	93		
1974	12	4	323	96		
1975	10	7	141	93		
1976	15	9	149	91		
1977	9	18	38	82		
1978	11	5	206	95		
1979	9	21	36	79		
1980	13	18	60	82		
1981	13	17	65	83		
1982	15	19	64	81		
1983	13	28	33	72		
1984	11	24	34	76		
1985	11	27	30	73		
1986	13	26	37	74		
1987	14	39	21	61		
1988	12	21	44	79		
1989	11	32	23	68		
1990	16	31	36	69		
1991	18	33	36	67		
1992	16	22 (62)	10	13 (38)	47.1	65
1993	9	13 (46)	10	15 (54)	47.1	72
1994	13	18 (55)	11	15 (45)	47.1	67
1995	10	12 (27)	26	32 (73)	47.1	57
1996	14	13 (22)	49	45 (78)	47.1	43
1997	15	14 (19)	60	58 (81)	29.5	28
1998	12	19 (30)	29	45 (70)	22.9	36
1999	14	23 (36)	24	40 (64)	22.9	38
2000	13	23 (48)	14	25 (52)	29.5	52
2001	8	13 (61)	5	9 (39)	47.1	78
2002	12	16 (41)	17	23 (59)	47.1	62
2003	11	16 (54)	9	14 (46)	47.1	70

Figure 20



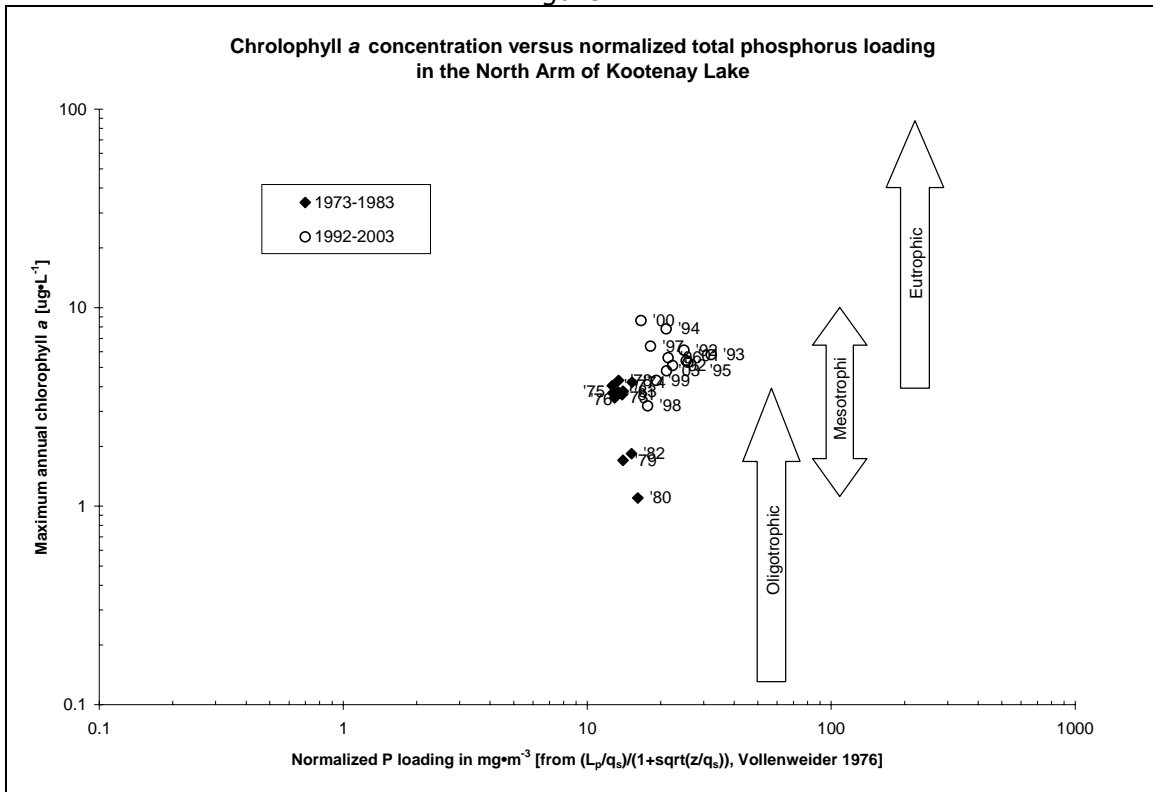
3.9 Impact of phosphorus loading on primary productivity in Kootenay Lake

3.9.1 Chlorophyll *a*

Chlorophyll *a* concentrations have been measured in Kootenay Lake in association with the experimental fertilization program, and to a limited extent prior. Daley and Pick (1990) examined phytoplankton biomass and composition following reversal of Kootenay Lake's cultural eutrophication in the 1970s and 1980s. We compared chlorophyll *a* concentrations in Kootenay Lake from their 1973-1983 data (F. Pick, 2004, *personal communication*) with values measured during the experimental fertilization program (1992-2003; E. Schindler, 2004, *personal communication*) following the method of Vollenweider (1976; Figs. 21 and 22).

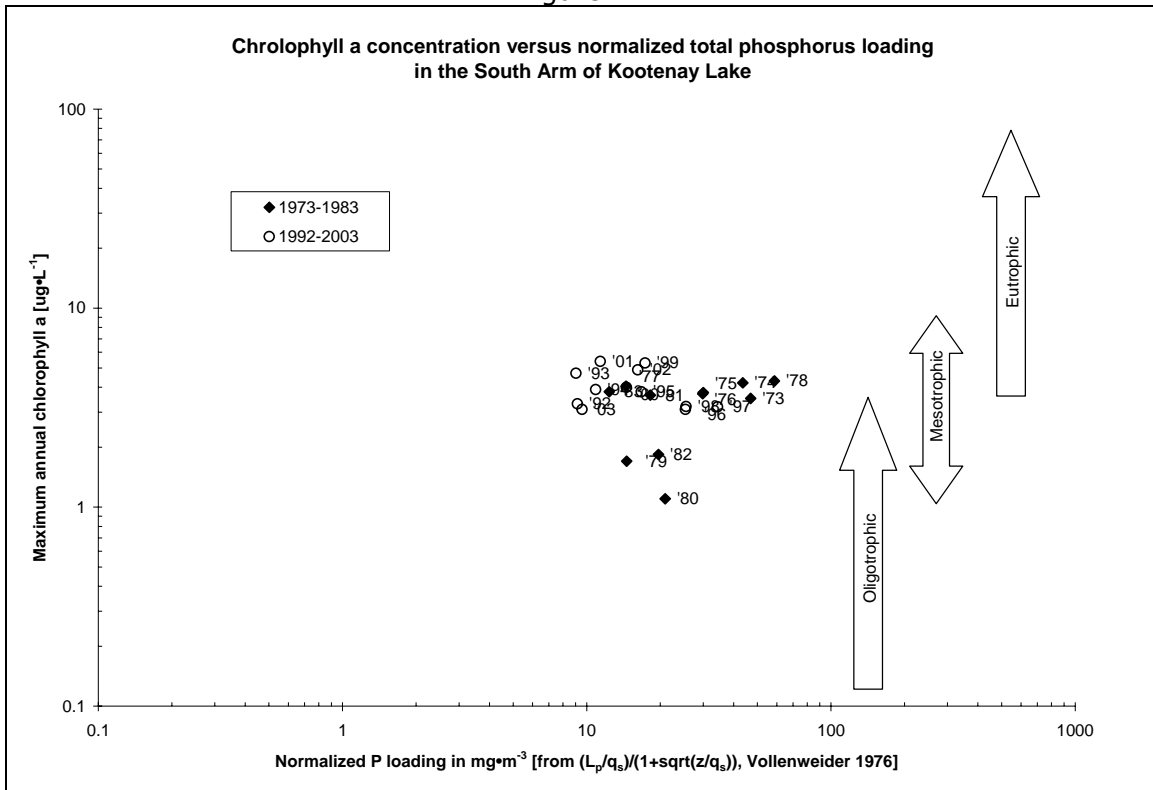
Data from the North Arm of Kootenay Lake (Fig. 21) separate into two distinct groups. The historical data from 1973-1983 show modest chlorophyll *a* and P loading values (mean maximum chlorophyll *a* $3.2 \mu\text{g}\cdot\text{L}^{-1}$; mean normalized P loading $14.0 \text{ mg}\cdot\text{m}^{-3}$). The data from the experimental fertilization period show both higher loading and high annual chlorophyll *a* maxima (mean maximum chlorophyll *a* $5.8 \mu\text{g}\cdot\text{L}^{-1}$; mean normalized P loading $22.3 \text{ mg}\cdot\text{m}^{-3}$). The experimental fertilization is presumed responsible for the majority of both of these increases; a 59% increase in P loading resulted in 76% mean increase in chlorophyll *a* concentration from 1973-1983 to 1992-2003. The normalized P loadings were calculated assuming the P loading to the North Arm comes exclusively from the Duncan River and the experimental fertilization program (although some South Arm transport via internal siche may account for a small amount). No data prior to the construction of the Duncan Dam were available for comparison.

Figure 21



Data from the South Arm of Kootenay Lake (Fig. 22) do not separate into easily defined groups. The historical data from 1973-1983 show slightly higher P loading than for 1992-2003 (mean normalized P loading: $28.1 \text{ mg}\cdot\text{m}^{-3}$ 1973-1983; $17.3 \text{ mg}\cdot\text{m}^{-3}$ 1992-2003) but a lesser chlorophyll *a* response (mean maximum chlorophyll *a*: $3.2 \mu\text{g}\cdot\text{L}^{-1}$ 1973-1983; $4.1 \mu\text{g}\cdot\text{L}^{-1}$ 1992-2003). The normalized P loadings were calculated assuming the P loading to the South Arm comes exclusively from the Kootenay River, with no mixing of fertilizer from the North Arm (unlikely; see discussion to follow in 3.9.2). The 41% decrease in P loading from 1973-1983 to 1992-2003 may reflect lingering effects of cultural eutrophication upstream in the Kootenay River in the 1960s and 70s (i.e., phosphate adsorbed to sediment particles being washed out from sections of the Kootenay River below Libby Dam). No data prior to the construction of the Libby Dam were available for consideration of its impacts. The increase in chlorophyll *a* response (up 23% from 1973-1983 to 1992-2003) may be due to increased bioavailability of P from experimental fertilization in the North Arm mixing to the South Arm; however, the magnitude of this effect is attenuated by the length of Kootenay Lake and does not result in separation of the data groups in Figure 22. Furthermore, natural watershed loading dominates in the South Arm and therefore P loading from the fertilization in the North Arm would constitute a much smaller relative portion of the total P load in the South Arm.

Figure 22



Vollenweider's suggested ranges for the trophic character of lakes are provided in Figures 21 and 22 for perspective; direct comparison of Kootenay Lake data with these ranges is inappropriate since the Vollenweider's ranges are based upon mean annual chlorophyll *a* concentrations, not annual maxima. Kootenay Lake data from recent years suggest mean annual chlorophyll *a* concentrations are approximately half the annual maximum; reducing the y-axis chlorophyll *a* values accordingly brings all of the Kootenay Lake values into Vollenweider's oligotrophic range.

3.9.2 Algal Biomass

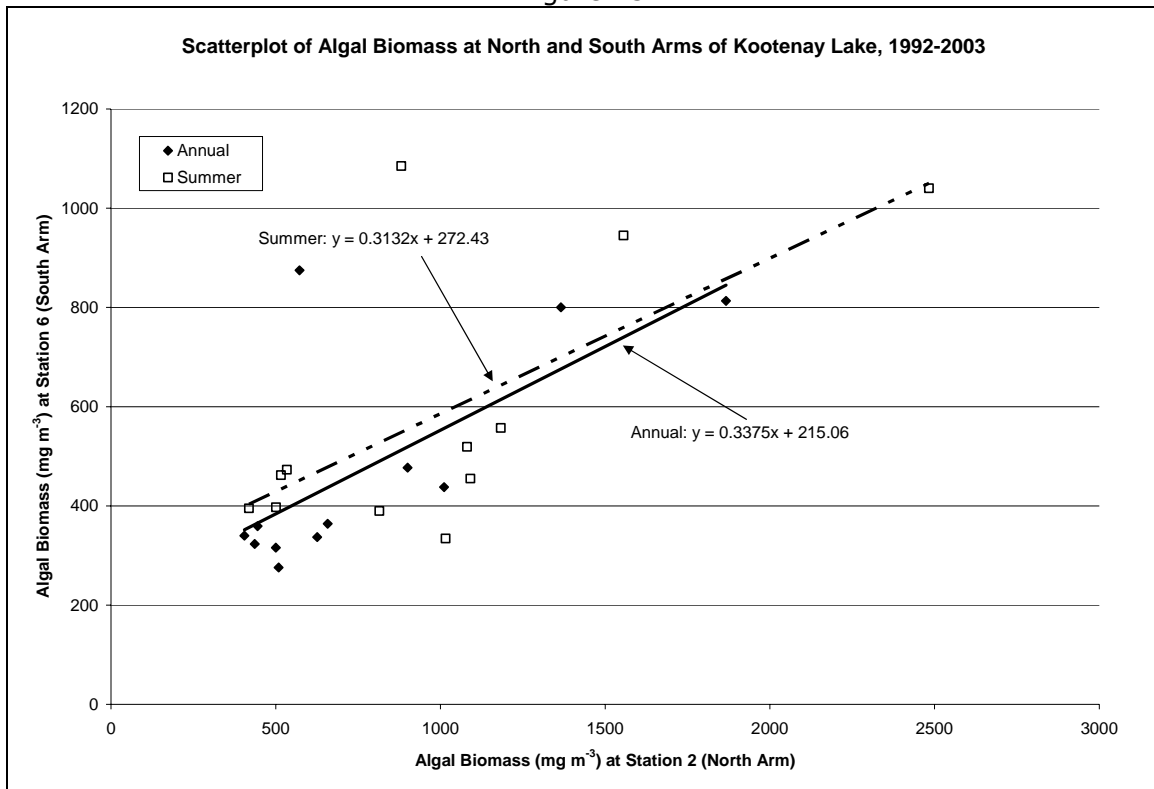
The focus of this section is to determine relationships between algal biomass and the hydrometrics and P loading of Kootenay Lake. Algal biomass in Kootenay Lake has been measured for all the years of the experimental fertilization program and is the exclusive focus of a separate series of reports (e.g., Pick et al. 2003; Table 5). Other measures including zooplankton density, mysid density, and escapements of kokanee trout and rainbow trout are also addressed elsewhere (Wright et al. 2002, etc.).

Table 5. Average algal biomass ($\text{mg}\cdot\text{m}^{-3}$) at the fertilized station (Stn. 2) in the North Arm and the "control" station (Stn. 6) in the South Arm of Kootenay Lake (Pick et al. 2003)

Year	Algal Biomass Annual (April – October) (n = 7–14)		Algal Biomass Summer (June – August) (n = 3–6)	
	Station 2 (North Arm)	Station 6 (South Arm)	Station 2 (North Arm)	Station 6 (South Arm)
1992	445	359	534	473
1993	658	364	1,091	455
1994	900	477	1,183	557
1995	1,366	800	1,556	945
1996	1,867	813	2,483	1,040
1997	626	337	1,081	519
1998	436	323	516	462
1999	405	340	501	397
2000	500	316	419	395
2001	1,011	438	1,016	334
2002	572	875	881	1,085
2003	509	276	815	389

Figure 23 is a scatter plot of the algal biomass at Station 2 in the North Arm vs. Station 6 in the South Arm. Linear regressions of annual ($R^2 = .470$) and summer measures ($R^2 = .442$) are statistically significant ($p < 0.05$) indicating that both ends of the lake are behaving in a similar manner.

Figure 23



Algal biomass in Kootenay Lake can be predicted by equations 3a-6a below, which are based on data from the years of the fertilization experiment (1992-2003).

[3a] $AnnN = -7.49Q_N + 99.245LdN_T - 551.517LdN_S - 28.205LdS_T + 325.966LdS_S - 3514.674Elev_{Min} + 26.26 Elev_{Date} + 1862870$
 $R^2 = 0.955, p < 0.05$

where $AnnN$ = annual mean algal biomass at Station 2 in the North Arm in $mg \cdot m^{-3}$
 Q_N = Mean annual discharge of the Duncan River in $m^3 \cdot s^{-1}$
 LdN_T = Mean annual TP load from the Duncan River in t
 LdN_S = Mean annual SRP load from the Duncan River in t
 LdS_T = Mean annual TP load from the Kootenay River in t
 LdS_S = Mean annual SRP load from the Kootenay River in t
 $Elev_{Min}$ = minimum lake elevation in m
 $Elev_{Date}$ = number of days between minimum and maximum lake elevation

[4a] $SumN = 4.537Q_S + 39.646LdF - 254.327Elev_{Ch} - 1769.198$
 $R^2 = 0.705, p < 0.05$

where $SumN$ = summer mean algal biomass at Station 2 in the North Arm in $mg \cdot m^{-3}$
 Q_S = Mean annual discharge of the Kootenay River in $m^3 \cdot s^{-1}$
 LdF = Fertilizer load in t
 $Elev_{Ch}$ = difference between maximum and minimum lake elevation in m

[5a] $AnnS = 1.563Q_N + 13.799LdF - 5.769LdS_T + 60.219LdS_S - 1010.1Elev_{Min} + 252.31Elev_{Ch} + 534275.5$
 $R^2 = 0.940, p < 0.05$

where $AnnS$ = annual mean algal biomass at Station 6 in the South Arm in $mg \cdot m^{-3}$

[6a] $SumS = 5.977Q_N + 1.078Q_S - 4.38LdN_T + 23.62LdF - 8.506LdS_S + 254.369Elev_{Ch} - 8.141Elev_{Date} - 1533.982$
 $R^2 = 0.934, p < 0.05$

where $SumS$ = summer mean algal biomass at Station 6 in the South Arm in $mg \cdot m^{-3}$

Equations 3b-6b below are simplified versions of equations 3a-6a (still statistically significant; lower R^2):

[3b] $Ann N = 281.028LdS_S - 24.673LdS_T - 3769.358Elev_{Min} + 16.344Elev_{Date} + 1996952$
 $R^2 = 0.713, p < 0.05$

[4b] $SumN = 3.174Q_S + 40.933LdF - 2001.478$
 $R^2 = 0.677, p < 0.05$

[5b] $AnnS = 12.267LdS_S - 1047.955Elev_{Min} + 17.496LdF + 554903.5$
 $R^2 = 0.783, p < 0.05$

[6b] $SumS = 17.668LdF + 272.529Elev_{Ch} - 943.075$
 $R^2 = 0.707, p < 0.05$

Measured and predicted algal biomass are illustrated in Figures 24 through 27.

Figure 24

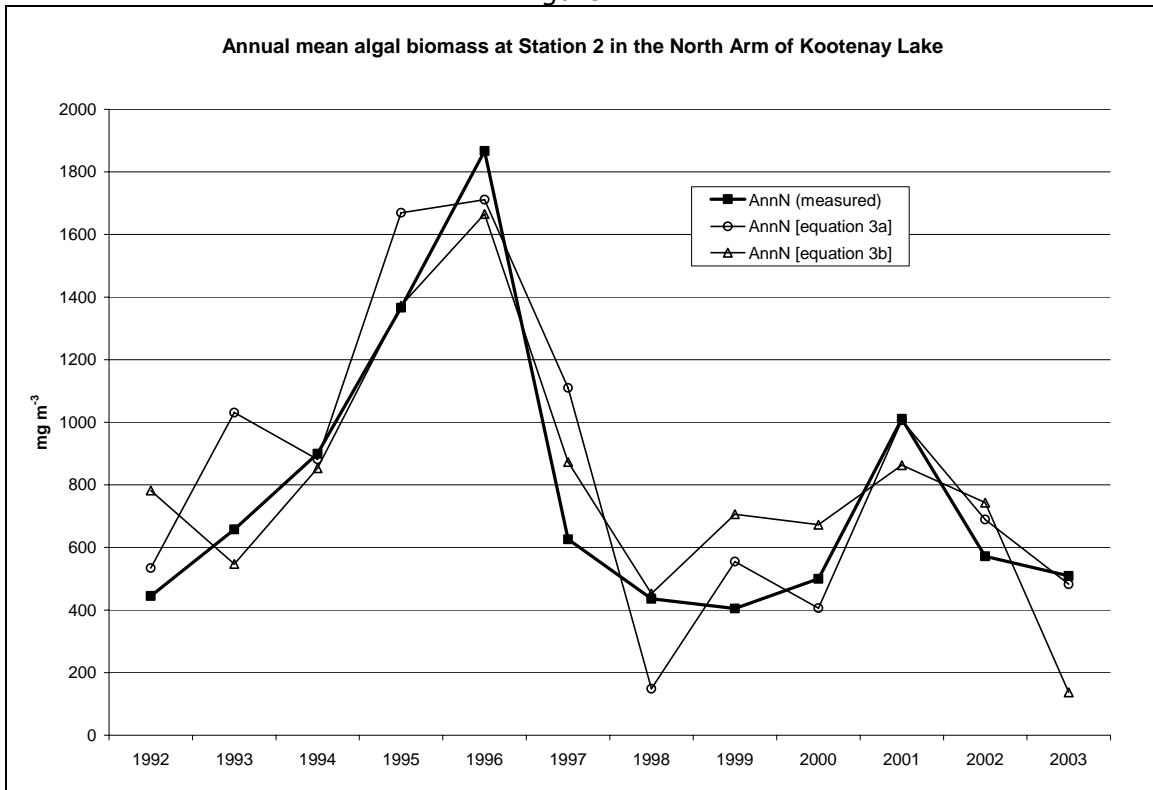


Figure 25

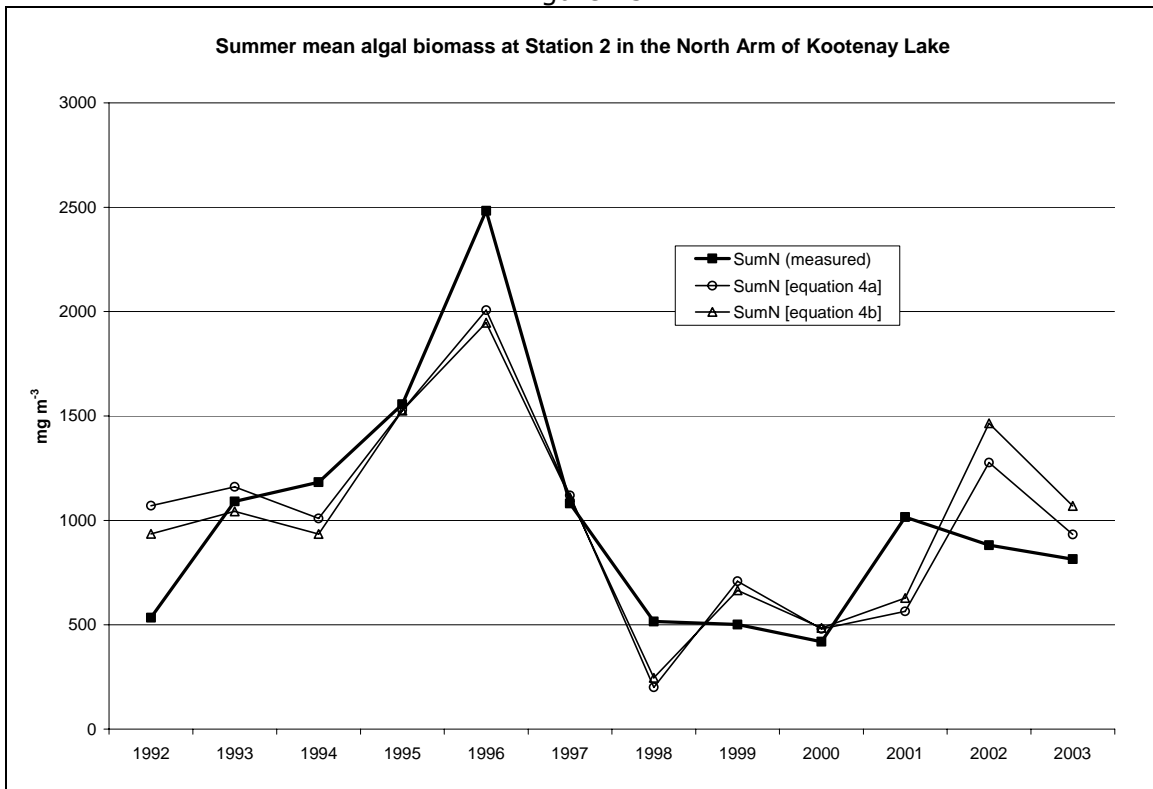


Figure 26

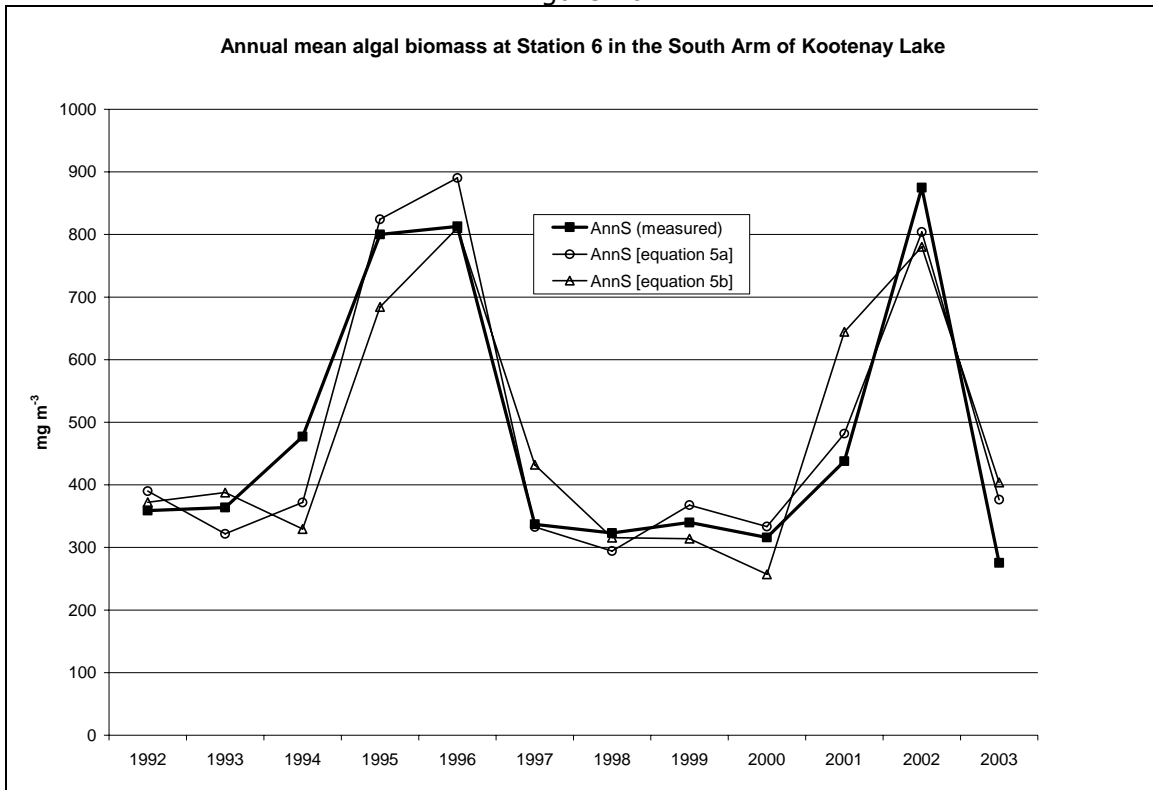
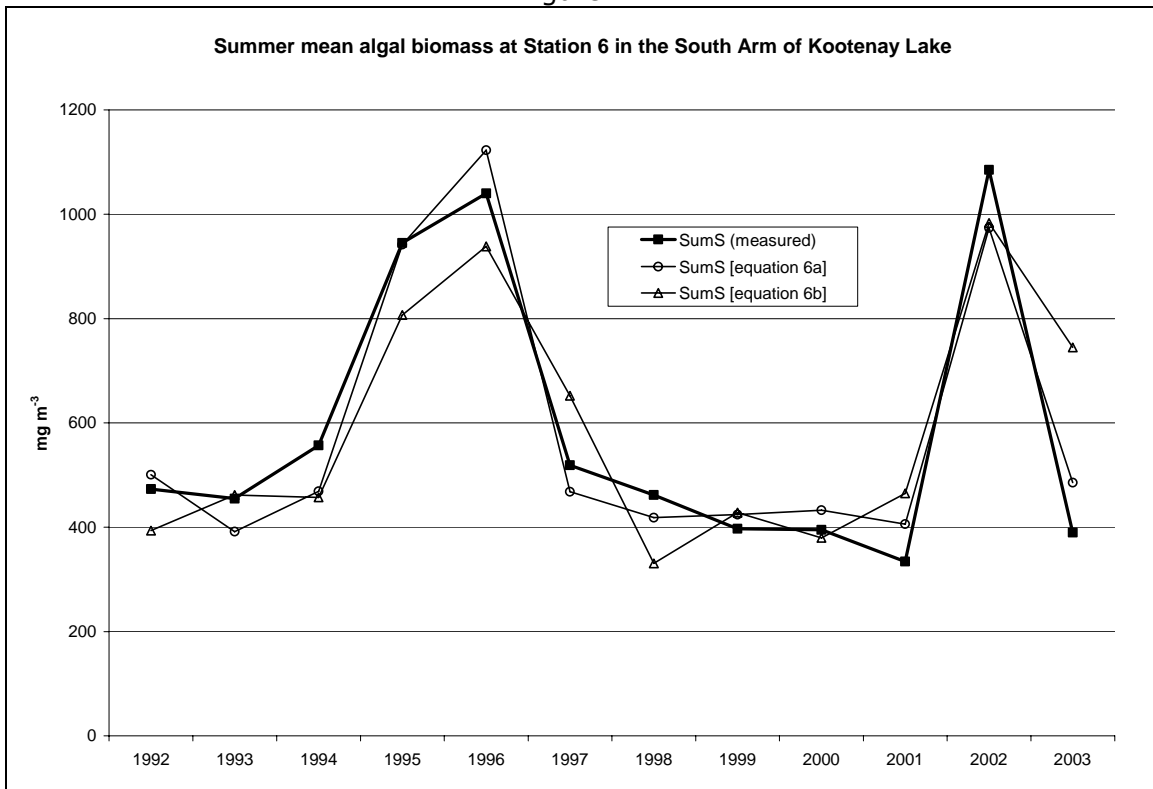


Figure 27



The sizeable number of variables present in equations 3a-6b suggests the dynamics that determine primary production of Kootenay Lake are complex. The years 1992-2003 contain a broad range of hydrometric conditions, including two extreme low flow years (2001 for the Kootenay River; 1993 for the Duncan River), extreme high flow years (1996 for the Kootenay River; 2000 for the Duncan River), and 4 years (1992-1994, 2001) with very low annual maximum lake elevations. In addition, the fertilizer load changed over this 12-year period, ranging from 22.9 to 47.1 t. The presence of these extremes in the source data for equations 3a-6b should enable the equations to accurately predict algal biomass over a wide range of hydrometric conditions.

Lake elevation is evidently an important factor in determining primary production in Kootenay Lake; 7 of the 8 equations contain at least one elevation term. The elevation of Kootenay Lake is controlled by the Corra Linn dam (12 km downstream of Nelson, BC; built in 1939) and is governed by an order from the International Joint Commission. The elevation follows a distinct seasonal cycle with minimum elevation in March, and maximum elevations associated with the inflows of the spring freshet (Figs. 28 and 29). Post-dam peak elevations are generally 2 m or more lower than pre-dam peaks. Annual patterns in lake level were considerably variable during the 12 years of the fertilization experiment to date (Fig. 30). The elevation of Kootenay Lake in 1992, 1993, 1994 and 2001 did not reach a typical annual maximum, but was approximately 1–1.5 m lower. However, 1995, 1996, 1997 and 2002 maxima exceeded typical years. Particularly in the south end of the lake, a low maximum year followed by a high maximum year elicits a boost in primary production (e.g., SumS increased 70% from 1994 to 1995 and 225% from 2001 to 2002). Large changes in elevation could result in nutrient release from exposure of deltaic and shoreline sediments during elevation minima (Vernieu 1997; Perrin et al. 2000) combined with high spring inflows (and elevation maxima) eroding and resuspending sediments. Elevated TP levels found in water samples from the South Arm of the lake in spring months prior to fertilization in the North Arm (Ashley et al. 1997b) provide support for this theory.

Figure 28

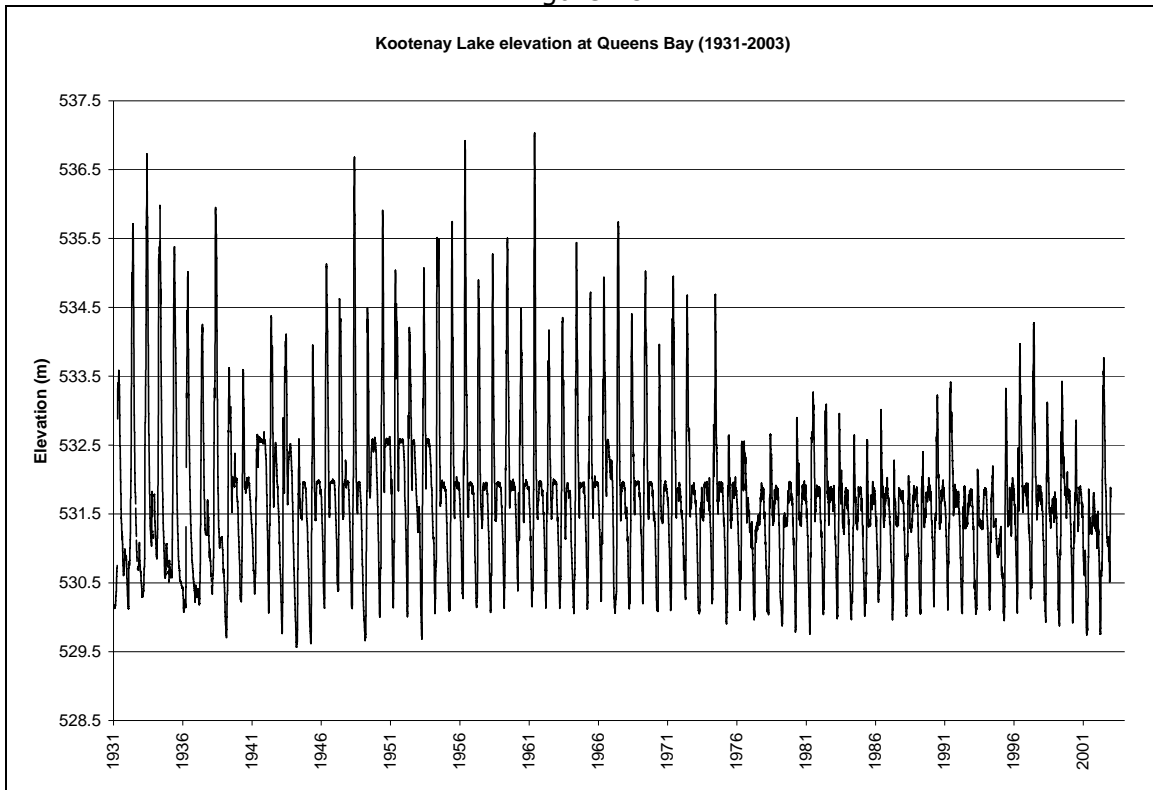


Figure 29

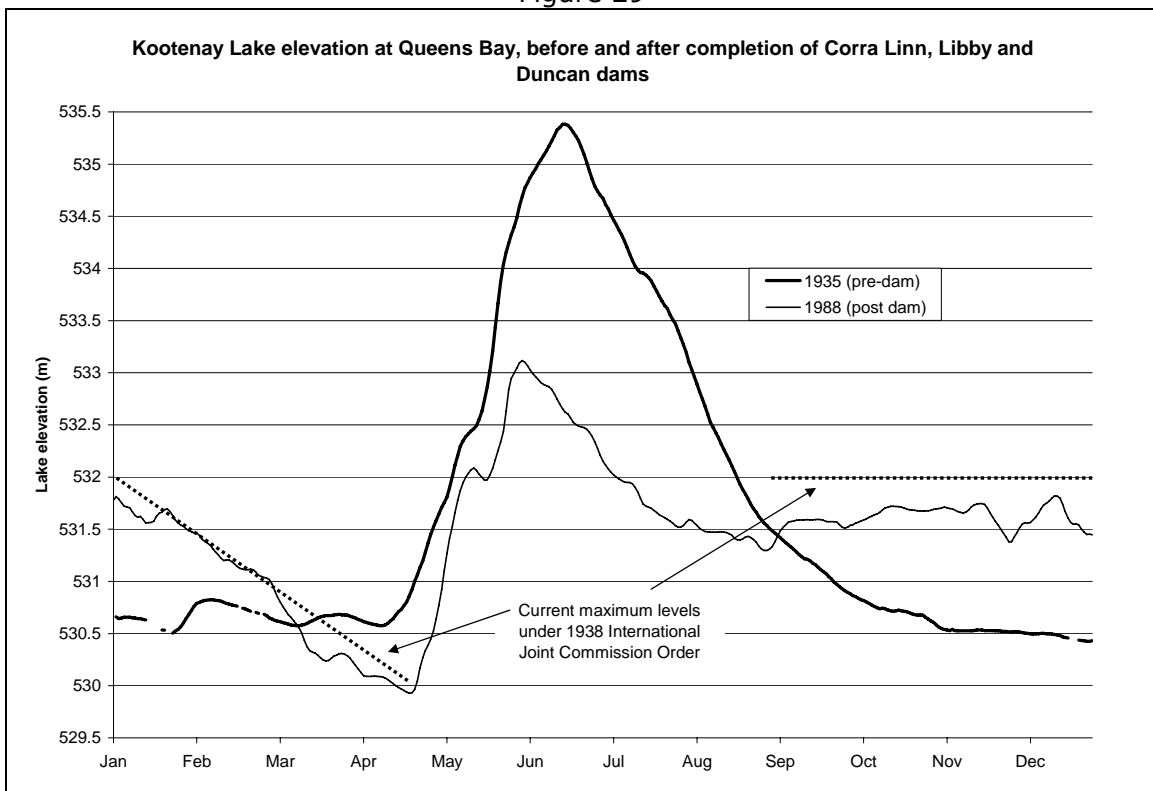
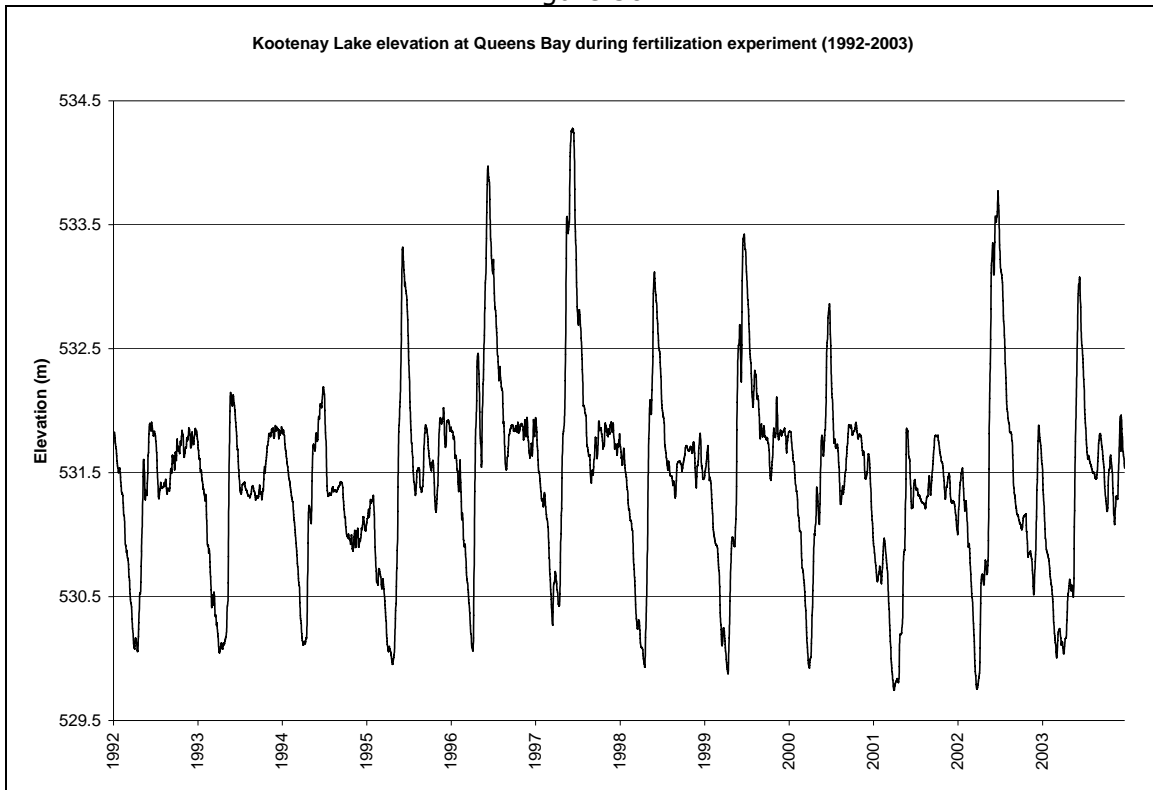


Figure 30



The fertilizer load, LdF , is a positive coefficient in equations for $AnnS$, $SumN$ and $SumS$. The influence of this term in the South Arm equations implies mixing of the fertilizer from the North to South Arm of the lake. The simplified summer algal biomass equations (4b for $SumN$; 6b for $SumS$) include only one variable in addition to LdF : equation 4b reduces summer algal biomass (North Arm) to a function of LdF and Q_S , indicating greater inflow and mixing influence from the South Arm increases primary production in the North Arm; equation 6b reduces summer algal biomass (south) to a function of LdF and $Elev_{Chr}$, reiterating the influence of elevation change on primary production in the South Arm. Notably, a variable for fertilizer load for the preceding year (LdF_{past}) did not appear in any of the equations derived from the regression analysis. This challenges the theory the increase in algal biomass in both arms of the lake from 1992-1996 was due to retention of nutrients in the lake; rather the variables in the equations above suggest the increase was at least partially due to a unique set of hydrometric conditions (i.e., 1992-1994 being low flow, low maximum elevation years followed by 1995-1996 high flow, high maximum elevation years). To investigate this hypothesis further, outputs from equations 4a and 6a were recalculated applying a fertilizer load of 47.1 t to all 12 years. The results (Figs. 31 and 32) indicate algal biomass would still have decreased even if fertilizer loading of 47.1 t·yr⁻¹ had continued past 1996; changes associated with the other terms (inflows, lake elevation change, and nutrient loading from the rivers) would have caused in a decrease in primary production in 1997 and some years beyond. If the fertilizer load is reduced to 0 t·yr⁻¹ for 1997-2003 (as if the fertilization program had ended after its initial 5 years), the resultant values for $SumN$ and $SumS$ drop below 0 for 1997-2003 (data not shown). Although this substitution of 0 t·yr⁻¹ for the fertilizer load is outside of the range of values used to derive equations 4a and 6a, these results suggest that without the nutrients provided by the fertilization program, the reduction in primary production post-1996 may have been much greater than observed.

Figure 31

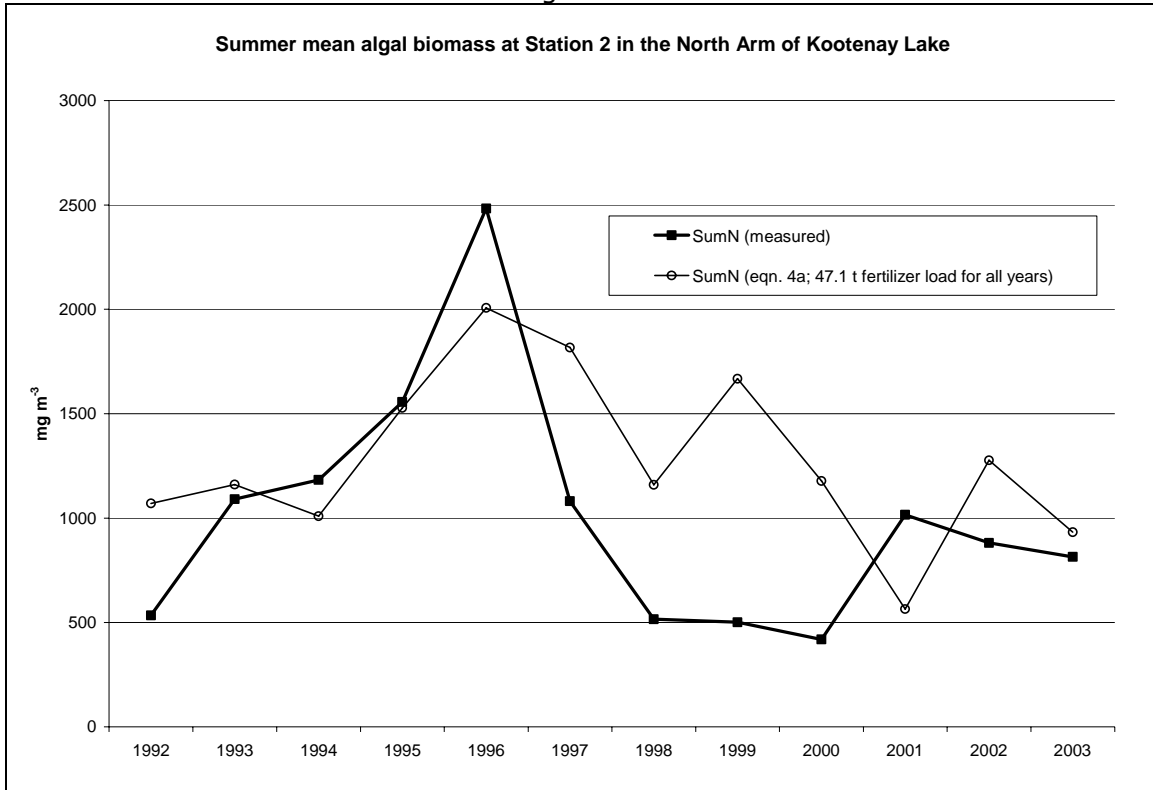
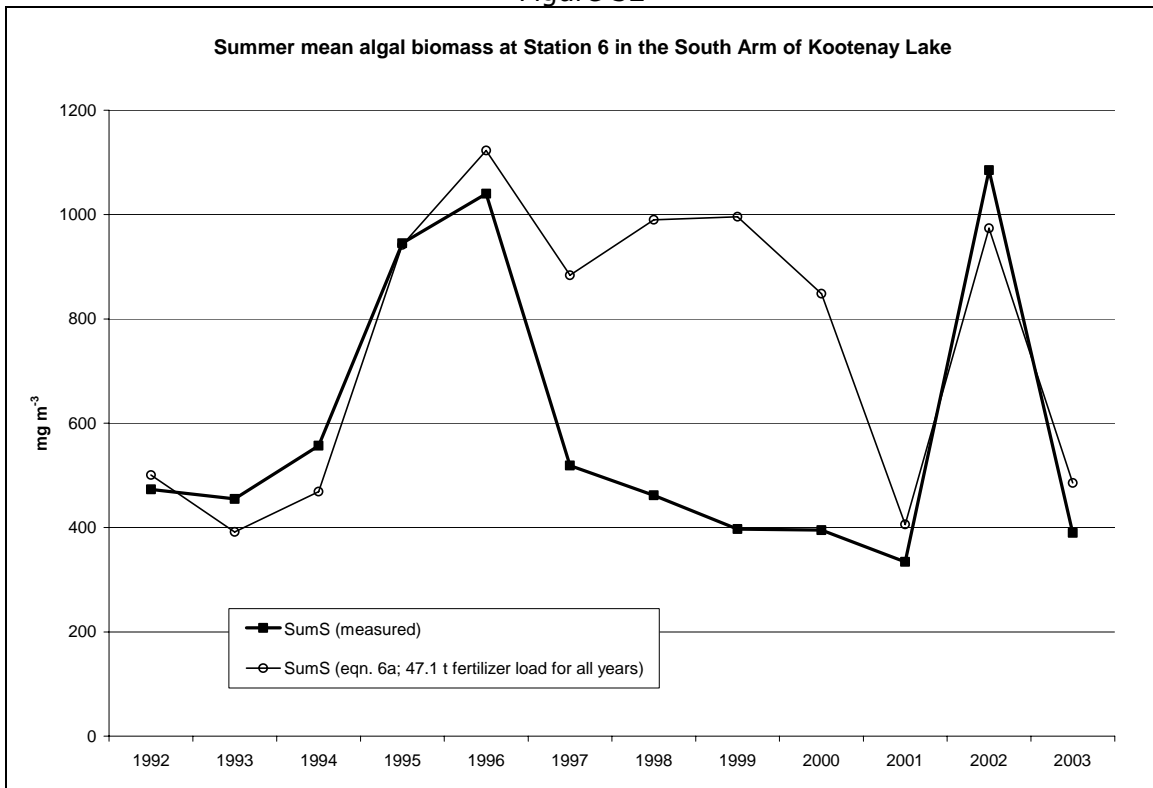


Figure 32



Nutrient loading and inflows from the Kootenay and Duncan rivers also play a role in primary productivity in the lake. LdS/N and $Q_{S/N}$ terms each appear in 5 of the 8 equations. The annual algal biomass equations in particular [3a, 3b, 5a, 5b] have multiple LdS and LdN terms, suggesting outside the summer months of June, July and August, loading from the rivers plays a more significant role. This is not surprising given these months often have higher inflows (April/May due to spring freshet; Sept/Oct due to releases from the dams). Higher inflows from the Kootenay River also boost summer productivity. Three of 4 summer equations have a positive Q_s term (SumN [4a,b]; SumS [6a]); higher summer inflows likely facilitate mixing of the fertilizer within the North Arm as well as to the South Arm. Timing of the loading is apparently important also, at least in the North Arm, where April SRP loading (areal load from the Duncan River and fertilizer combined) is linearly related to AnnN ($R^2 = .480$) and SumN ($R^2 = .488$). Clearer waters may aid early season production in the North Arm (historically clearer water in the North Arm, in addition to delaying of the Duncan River freshet by the Duncan Dam). A study of phytoplankton growth in the lake from the 1960s documented greater early season production in the North Arm vs. the South Arm, attributed to better light penetration and nutrient availability in the North Arm in spring (Northcote et al. 1999; 2005). Fertilizer addition at the end of April is likely also a factor, although LdF does not affect annual algal biomass in the North Arm (LdF term absent from equations 3a and 3b).

4. Summary and Recommendations

1. Libby Dam has substantially altered the hydrograph of the Kootenay River, with a substantial reduction of spring freshet flows, and greatly increased flows during winter months.
2. Duncan Dam has substantially altered the hydrograph of the Duncan River, with some reduction and delay of peak spring freshet flows and greatly increased flows through the winter months.
3. During the 12 years of a large-scale fertilization experiment, record low and high discharges were recorded on both the Kootenay and Duncan rivers.
4. The Kootenay and Duncan rivers comprise 56.6 and 21.0% respectively of the inflow to Kootenay Lake (total 77.6%). The remaining 22.4% is attributed to the combination of small tributaries entering the Kootenay and Duncan rivers between the discharge gauging stations and the lake, and many small main lake and West Arm tributaries.
5. Mean annual daily discharge of the Kootenay and Duncan rivers can be predicted by equations involving Southern Oscillation Index (SOI) values ($R^2 = 0.267$ and 0.445 , respectively).
6. P concentrations in both the Kootenay and Duncan rivers have decreased dramatically over the past 40 years, due primarily to pollution abatement and impoundment of both rivers behind hydroelectric dams.
7. Annual Kootenay River SRP loading to Kootenay Lake has not exceeded 70 t since 1979, with mean annual loading of 31 t for 1979-2003. These values are substantially below the 232 t estimated for the Kootenay River prior to cultural eutrophication or construction of Libby Dam.
8. Duncan River SRP loading to Kootenay Lake has decreased from a mean loading of 61 t annually from 1960-1966 to 13 t annually from 1967-2003.
9. For 1992-2003, fertilizer loading to the North Arm has ranged from 22.9 to 47.1 t and has represented 28-78% of the total SRP load (mean 56%) to Kootenay Lake.
10. Chlorophyll *a* values measured during the experimental fertilization program are higher than historic values from the 1970s and 1980s in both arms of

- Kootenay Lake. The trophic character of the lake remains in the oligotrophic range.
11. The North and South Arms of Kootenay Lake behave similarly with respect to changes in phytoplanktonic algal biomass.
 12. Algal biomass in Kootenay Lake can be effectively predicted by equations derived from Kootenay Lake hydrometrics and P loading.
 13. Lake elevation is an important factor in determining primary production in Kootenay Lake.
 14. In the South Arm of Kootenay Lake, algal biomass surges when a low annual maximum elevation year is followed by a high annual maximum year. The increase may be due to exposure, erosion, then resuspension of sediments by the high spring inflows.
 15. Fertilizer load influences algal biomass in the South Arm of Kootenay Lake, implying mixing occurs between the two arms.
 16. Nutrient retention in Kootenay Lake was not likely responsible for the increase in algal biomass from 1992-1996. If fertilizer loading had remained at 47.1 t after 1996, changes in hydrometrics and nutrient loading from the rivers would have likely caused a decrease in primary production in 1997 and beyond. This implies Kootenay Lake has no year-to-year "memory" of nutrient loading. If the experimental fertilization had not continued after 1996, the decrease in Kootenay Lake primary production observed in 1997 and beyond may have been much greater.
 17. Kootenay River inflows positively affect summer productivity in both ends of Kootenay Lake; higher summer inflows likely facilitate mixing of the fertilizer within the North Arm as well as to the South Arm.
 18. Kootenay River and Duncan River nutrient loading affects annual algal biomass more so than summer algal biomass, indicating loading from the rivers is most important in the spring and fall months.
 19. Early season (April) nutrient loading in the North Arm is predictive of annual and summer algal biomass.

The findings in this report will inform the management of the Kootenay Lake experimental fertilization program. The equations should be useful for the optimization of fertilizer loading as all variables can be forecast and, to varying degrees, manipulated. For example, by forecasting the inflows from winter snowpack/weather patterns, then estimating the nutrient loading and elevation maxima/minima, fertilizer loading could be adjusted to obtain a given target biomass. Annual and even mid-season adjustments may reduce fertilizer costs over the long term. The equations could also be used as predictive tools, to determine the impact on algal biomass of lower or higher fertilizer loading (i.e., for SumN [eqn. 4a], for every extra t of fertilizer added you get 40 mg·m⁻³ increase in algal biomass; for SumS [eqn. 6a], a 24 mg·m⁻³ increase). Experiments regarding the timing of nutrient loading to the North Arm (through earlier fertilizer addition, or earlier spring releases from the Duncan Dam) are also warranted. Taking advantage of the impact of early season production may also reduce fertilizer costs, particularly if the target of the program is largely the North Arm and not the entire lake. Any manipulation of dam operation to affect timing of inflows or lake elevation must be mindful of other considerations (littoral habitat, recreation, etc). And lastly, the equations should be revised regularly (preferably annually) so their predictions can remain as accurate as possible.

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