A PHOSPHORUS BUDGET FOR WAHLEACH RESERVOIR

FINAL REPORT

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Prepared by

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SUMMARY

A phosphorus budget was developed for Wahleach Reservoir to determine the importance of fertilizer relative to that supplied by natural sources in contributing to the reservoir food web and to determine the fate of phosphorus applied in fertilizer. The period of calculation was June 1 2000 through May 31 2001. Phosphorus inputs were from stream inflow, fertilizer, atmospheric deposition, and fish stocked to the reservoir in 2000. Exports included phosphorus in water released from the reservoir through the penstock and spillway, and in fish harvested in the sport fishery. Phosphorus retention was partitioned among three components: sediments, the water column, and fish. All components were measured or derived from the literature except for phosphorus retention in sediments that was determined by difference. Sediment trap techniques were used to examine rates of phosphorus sedimentation. Comparison of trap data to mass balance calculations showed that the traps underestimated phosphorus sedimentation rates by approximately 12 times. Trap effectiveness could be improved by reducing duration of deployment to minimize loss due to decomposition in the traps.

Wahleach Reservoir was a highly effective phosphorus trap in 2000 - 2001. There was a net P retention of 803 kg (201 $\mathrm{mgP \cdot m^{-2} \cdot yr^{-1}}$) or 47% of TP loading. This net phosphorus retention was due to high retention rates of the soluble P fractions (89% of SRP and 58% of TDP retained) while there was a 33% net loss of the particulate phosphorus load. High retention of soluble fractions was attributed to uptake by phytoplankton to form larger particle sizes. Very high retention of soluble P that occurred in the spring and summer exceeded losses of soluble and particulate P in fall and winter. Fluvial inputs of phosphorus and P in fertilizer represented 97% of TP loading. The minor phosphorus sources included atmospheric deposition and P loading in fish stocked in 2000. P loading in fertilizer represented half of the TP load but it represented 57% of the load of soluble P. If we only consider the loading of simple inorganic phosphate (SRP), which is most available for biological uptake, P in fertilizer represented 78% of that load from all sources. This value indicated considerable importance of the fertilizer in contributing to the pool of P for biological production in the reservoir in 2000-2001.

A total of 840 kg of phosphorus (210 $\mathrm{mg \cdot m^{-2} \cdot yr^{-1}}$) was retained in sediments. This amount was greater than net retention because it accounted for loss of phosphorus from the water column over the budget year. The amount was calculated by difference between total phosphorus retention and amounts of phosphorus retained in fish populations (2% of total retained P) and in water between the start and finish of the budget year (-6.6% of total retained P). These calculations showed that reservoir sediment was the main sink for retained phosphorus.

Because TP loading in fertilizer could be distinguished from TP loading from natural sources in mass transport calculations, TP retention and loss was explored to examine the effect of the absence of fertilizer addition on P fluxes. In the absence of fertilizer addition imports and exports approximately balanced, indicating no phosphorus retention in the reservoir. With fertilizer addition, the P load in fertilizer explained all TP retained by sediments, indicating that the fate of added P in fertilizer was the sediments. This fertilizer-enriched phosphorus sedimentation was confirmed in a companion paleolimnoloical study of Wahleach Reservoir. The sedimentation caused by fertilization

is hypothesized to have contributed to improved survival and size-at-age of rainbow trout during years of fertilization compared to years before fertilization via increased production of aquatic insects that are the main food for rainbow trout.

An approximate phosphorus budget was also calculated for each year of 1993 through 2000. Several parameters in these budgets were estimated because of lack of direct measurements across all years. Over those years, phosphorus loading to Wahleach Reservoir increased, mainly due to sequentially increased loads of fertilizer. Before fertilization, the TP load was <760 kg per year (<190 $mg{\cdot}m^{-2}{\cdot}yr^{-1}$). The load increased sharply in 1995 due to an estimated 40% increase in loading from upstream drainages and the addition of 375 kg of P (94 $mg{\cdot}m^{-2}{\cdot}yr^{-1}$) in fertilizer. In 1995, P in fertilizer represented 26% of the complete phosphorus load but with rising fertilization rates every year after 1995, the P load in fertilizer increased to approximately 50% of the total load in 2000. The sequential increase in P loading from fertilizer in 1995 through 2000 was done to achieve a phosphorus load necessary to support *Daphnia* sp, the preferred food of kokanee that is the target species of fish that has been restored in Wahleach Reservoir. Comparison of time course change in TP loading with *Daphnia* density showed that a repeated TP load from all sources of 425-475 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ was required to provide a sustained population of *Daphnia* sp. Close to 90% of this total load or 380-430 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ must be in a soluble form. Half of this load was provided by fertilization in 2000-01. Annual TP loads from sources other than fertilizer in 1993 through 2000 were estimated to be 172-288 $mg{\cdot}m^{-2}{\cdot}yr^{-1}$, which was well below the levels found necessary to support *Daphnia* sp. The difference between TP loads that appear necessary to support *Daphnia* sp. and natural loads in the absence of fertilizer addition was large enough to suggest that continued fertilization is required to support a desirable food supply for kokanee. If fertilization is not continued, a decline of kokanee abundance from present levels may be expected in relation to a potential drop in *Daphnia* density. Whether or not this outcome actually occurs can only be determined with measurements of the abundance and composition of zooplankton and fish if fertilization is stopped.

The increased phosphorus loading rates that started with fertilization in 1995 were accompanied by an even larger export of phosphorus from the reservoir, also beginning in 1995. The result was a net loss of TP in 1995 amounting to 537 kg of phosphorus or 37% of the annual TP load. While a small retention of TP was recorded in 1996, net losses were again determined for 1997 through 1999. Annual TP losses of this magnitude are unusual in an oligotrophic system like Wahleach Reservoir. In order for a significant loss of TP to occur, there must be release of phosphorus from sediment, which is the largest sink for retained phosphorus. P release can occur following a history of nutrient loading but it is favoured mainly during oxygen depletion and reducing conditions that do not exist in Wahleach Reservoir. There are no electrochemical conditions in the reservoir that would favour phosphorus release. Without some evidence to the contrary, assumptions used in calculations showing large nutrient loss may not be valid. The main difference between the multi-year budget calculations and those used for 2000 – 2001 was the assumption that inflow phosphorus concentrations measured in 2000 could be applied to earlier years. In fact there may be substantial time course variation in these data that would greatly affect mass balance calculations.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

In recent years, nutrient addition and fish stocking strategies were applied to Wahleach Reservoir in southwestern British Columbia to restore historical populations of kokanee (*Oncorhynchus nerka*) and rainbow trout (*Oncorhynchus mykiss*) (Perrin and Stables 2001). Although the original Wahleach Lake was barren of fish, it was stocked with kokanee and rainbow trout eggs in the 1920's and 1930's. Kokanee were abundant in the reservoir in the 1940's through the late 1970's (before and after construction of the Wahleach Dam) but numbers declined thereafter and all kokanee disappeared by 1995 (Appendix A). Demise of the kokanee population and low condition of rainbow trout in the mid-1990's was consistent with theory of trophic depression caused by nutrient depletion that was described by Ostrofsky and Duthie (1980) and Hall et al. (1999). Trophic depression in reservoirs is thought to result from burial of submerged organic substrata due to advanced erosion of shorezones, a lowering of oxygen demand leading to increased nutrient retention in sediments, loss of nutrients via water withdrawal from the hypolimnion, and attenuation of nutrient release as labile vegetation, that was originally flooded, is mineralized. The time course decline in nutrient loading is thought to contribute to a corresponding decline in abundance of invertebrates (Popp and Hoagland 1995). In some reservoirs, the depression is caused by adsorption of phosphorus and trace electroactive elements (e.g. iron) onto substrates of dissolved organic carbon (DOC) that can be abundant as leachates from previously flooded vegetation and forest floors (Schallenberg 1993, Jackson and Hecky 1980, Guildford et al. 1987). In reservoirs that have high flushing rates, rapid export of soluble and particulate nutrients may occur, resulting in low phytoplankton biomass (Schallenberg 1993). Invertebrates that have relatively long life cycles compared to phytoplankton may be particularly susceptible to a seasonal decline in water retention that is associated with a cycle of water storage and release. If rates of entrainment exceed rates of reproduction and population replacement, long-term sustainability of fish food organisms in pelagic habitat may not be possible. Eventually, lower trophic production may lead to declining availability of food for fish resulting in a decline in fish abundance (Thornton et al. 1990). This depression sequence can proceed in 10 - 20 years from the time of impoundment, a timing that corresponds to the rise and fall of the kokanee fishery in Wahleach Reservoir after impoundment.

Competition for food with threespine stickleback (*Gasterosteus aculeatus)* that was illegally or accidentally introduced to the reservoir (Perrin and Stables 2001) was thought to have exacerbated the decline of the kokanee population. Population surveys showed that 6 million stickleback or 1.5 fish/m^2 were present in 1997, at which time kokanee had disappeared. Number of stickleback declined to 350,000 fish by 2000, largely due to piscivory by over 20,000 triploided cutthroat trout that were introduced in 1997 through 2000 (Perrin and Stables 2001). Annual introductions of 50,000 kokanee in 1997 through 2000 in combination with this predation pressure on stickleback supported a recovery of the kokanee population that was estimated to be over 50,000 fish in 2000. Kokanee spawners were found present in all inflow streams in 2000 and were found near peak historical numbers in 2001 (BC Hydro, unreported data), which is first evidence of population sustainability since treatments began in 1997.

Optimizing food availability with nutrient addition has provided other support for kokanee. In 1995 through 2001, the reservoir was fertilized with an annual load up to 232 $mgP \cdot m^{-2}$ (late May through September) at a molar N:P of 25:1 in 1995-1997, declining to 19:1 in 1999, 13:1 in 2000, and 12:1 in 2001. The nutrient addition created a bottom-up trophic surge, enhancing availability of fish food organisms through the benthic and pelagic food webs (Perrin and Stables 2001). The cutthroat trout grew to sizes up to 2 kg and, with a concordant increase in size and abundance of wild rainbow trout; they supported a revitalized recreational fishery. Results to date show that "bottom-up" and "top-down" control mechanisms can be linked to achieve restoration of fish populations in Wahleach reservoir. The project is expected to continue until stickleback are depleted to trace numbers, four age classes of kokanee are proven present in the reservoir, and kokanee are found spawning in tributary streams in two more years. Fish that survived from stocking in 1998 and 1999 were confirmed to spawn in 2000 and 2001. Two more years of spawners will confirm that all stocked cohorts survived to spawning age to contribute to sustaining the population.

An important part of assessing the reservoir treatments is determination of the importance of phosphorus loads relative to that supplied by natural sources and a determination of the fate of phosphorus loads. The important ingredient in fertilizer is phosphorus (P) because it is the nutrient that limits trophic production in montane lakes of the Fraser Valley (Johnston et al. 1999). For managing this project over many years, it is useful to define the relative importance of the phosphorus load that is required to support food production for fish species of interest. Is it small or large relative to that coming from natural sources? In this project, all sources of phosphorus entering Wahleach Reservoir were compared. The amount of P that is exported annually from the reservoir was compared to imports to determine phosphorus retention and flux rates before and after fertilization started. P retention that contributes to fish yield should increase in years after fertilization compared to that in years before fertilization because a proportion of the added P becomes bound in both pelagic and benthic food webs. The work involved detailed measurement of P imports, sedimentation, and exports for the year June 1 2000 through May 31 2001. It also included estimates of P flux in years before and years after fertilization started using available data from those years (mainly exports) and best estimates of imports. Pre-fertilization years included 1993 and 1994 when Inglis (1995) compiled some pretreatment water chemistry data from the reservoir. Fertilization years included 1995 through 2000 for which reservoir chemical data were also available. Results were interpreted with respect to the importance or lack of importance of fertilization as one of several treatments in contributing to fish population restoration in Wahleach Reservoir.

2.0 RESERVOIR MORPHOMETRY, BATHYMETRY AND DRAWDOWN

Wahleach Lake Reservoir is located in the Skagit Range of the Cascade Mountains, southwest of Hope, British Columbia. The reservoir was formed with construction of the Wahleach dam that was completed in 1952. The dam increased the original lake volume from approximately 17 x 10^6 m^3 to a storage volume of approximately 60 x 10^6 m^3 at full pool in 1953. The surface area increased from approximately 282 ha to approximately 410 ha after impoundment. The original lake water surface elevation of 628.5 m increased to 641.6 m at the spillway crest after impoundment.

The B.C. Ministry of Water Land and Air Protection (MWLAP) provided an original bathymetric map. The reservoir outline for that map was produced from air photos taken on July 21, 1980 (BC80065:105 and 181). Bathymetric data were from a survey completed on September 28 and 29, 1981 by MWLAP staff. These data were not originally georeferenced and thus contour lines were drawn by sight between depth marks on survey transects.

For this project, a reference point was inserted onto the original map to digitize the locations of depth measurements. Depth data were transferred to actual bottom elevations by determining the difference between surveyed depths and water surface elevation on the day of the survey. Digital data were entered into Genamap GIS, from which reservoir surface dimensions, volumes, and other lineal measures were determined. All data were then transferred into Mapinfo, a desktop mapping system, from which Figure 1 was produced. Using data to produce Figure 1, a regression model to predict surface area from elevation was developed ($r^2 = 0.99$, $p<0.001$). The model was linear and had the form:

Surface Area = (15.687 x water surface elevation) – 9,648.012

The following reservoir description is based on the GIS data and from information provided by BC Hydro (1993).

Wahleach Lake Reservoir is 6.1 km long and it has an average width of 0.9 km north of Flat Creek and 0.42 km south of Flat Creek at full pool (Figure 1). It extends southward from the Wahleach Dam and includes the original Wahleach Lake, which was approximately 3.3 km long and 0.75 km wide. The reservoir is thought to be dimictic (mixes twice a year) and ice cover is typical in December through March.

Wahleach is a storage reservoir controlled by a dam, spillway, and penstock to a powerhouse. The dam is an earth fill structure, 18 m high and 418 m long and it is equipped with a concrete spillway having a top elevation of 641.6 m and a capacity of 122 $m^3 \cdot s^{-1}$. A siphon located on the dam can be used to release up to 0.6 $m^3 \cdot s^{-1}$ to the northern section of Jones Creek, but it has operated only sporadically in all years examined in this project (1993 through May 31 2001).

Active control of surface elevation in the reservoir depends on water demand at the powerhouse and stream water supply originating from snowpack and rainfall. Water is supplied to the powerhouse (60 MW), located at Cheam View adjacent to the Fraser River, via a 4.5 km tunnel and surface penstock. The intake is located on the west side of the reservoir equidistant between the north and south ends at an elevation of 618.59 m.

The reservoir surface elevation at full pool is 641.6 m (spillway crest elevation of the dam) above a datum of mean sea level, but this elevation can drop by up to 18.3 m at complete drawdown to reach a minimum elevation of 623.3 m in early spring. Snow melt recharges the reservoir in spring and early summer, mainly from Wahleach Creek, Flat Creek, Boulder Creek, and four small creeks collectively known as Glacier Creeks. On occasions, some water from Boulder Creek is diverted to lower Jones Creek, away from the reservoir to supply fish habitat near the confluence of Jones Creek with the Fraser River. In the year June 1 2000 through May 31 2001 when the detailed phosphorus budget was compiled, the reservoir surface elevation was drawn down to 629.67m producing a maximum drawdown of 11.93 m (Figure 2). Penstock maintenance was completed on June 6 - 19 2000, resulting in no outflow from the reservoir in that 14 day period. Maximum water depth at full pool is 26.6 m located centrally within the reservoir basin. At complete drawdown in the detailed budgeting year, that depth declined to 14.67 m. The reservoir surface area at full pool (elevation of the spillway) is 412 ha but it declined to 230 ha at the maximum drawdown, producing a dewatered zone of approximately 182 ha. Most dewatered areas at drawdown occur at the north and south ends of the reservoir and over an alluvial fan formed by the discharge of Flat Creek (Figure 1).

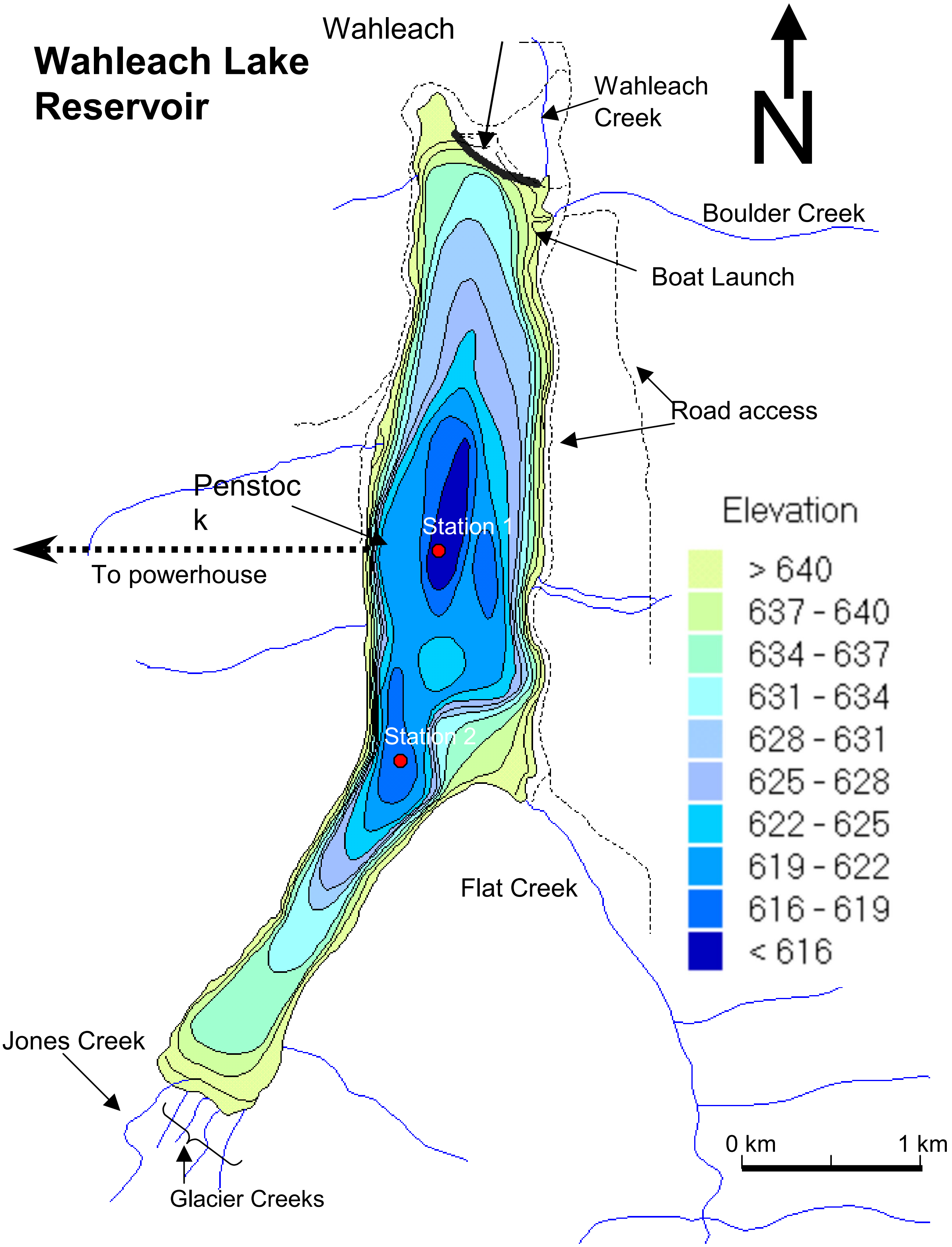

Figure 1. Geographic location of Wahleach Reservoir including sampling site detail and bathymetry.

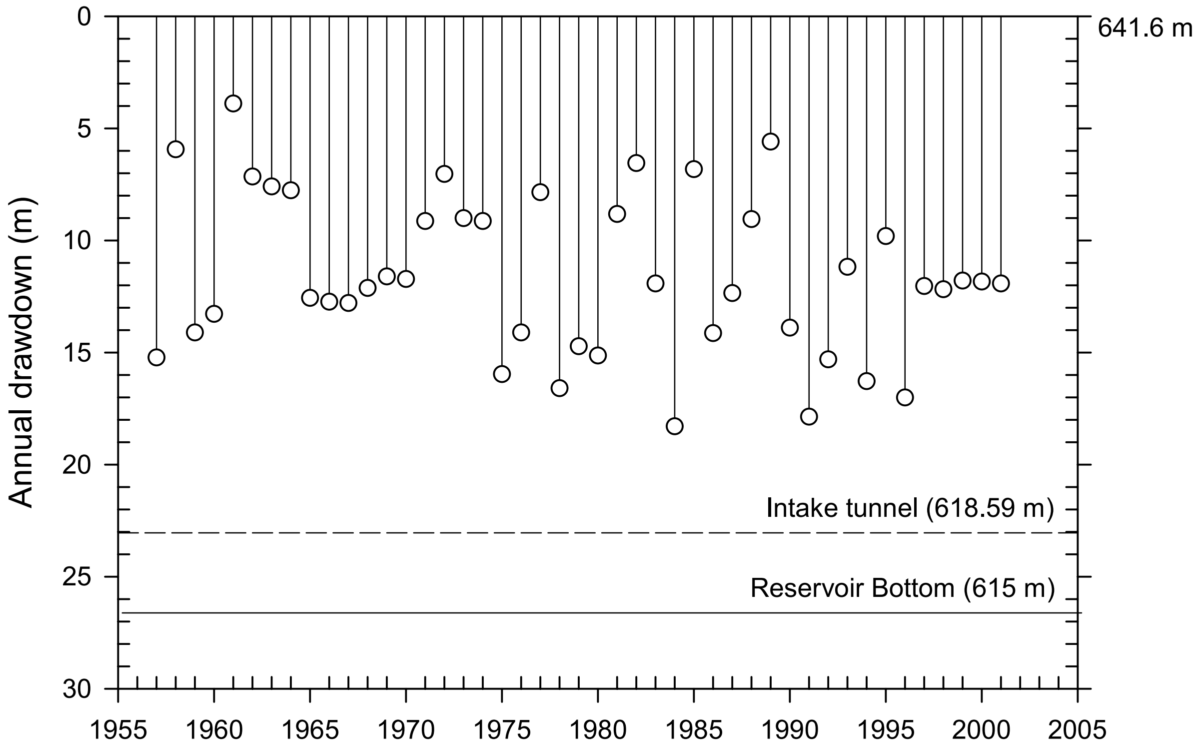

Figure 2. Annual drawdown in Wahleach Reservoir beginning in 1956. The top line of the figure indicates the top water surface elevation of 641.6 m and the dotted lines indicate elevations of the intake tunnel and reservoir bottom.

In the phosphorus budget year of June 1 2000 through May 31 2001, the surface elevation increased from an elevation of 634.5 m in early June to reach a peak elevation of 640.6 m on July 31 (Figure 3). At that top elevation, maximum water depth was 25.6 m, live storage was 56.2 x 10^6 m^3 (Figure 3) and the surface area was 401 ha (based on an elevation of 640.6 m). Surface elevations progressively declined thereafter, reaching 629.7 m on April 25 2001.

To produce these changes in surface elevation, local inflow was about 3 times greater than reservoir outflow in June 2000; it was equal to or less than outflow July 2000 through March 2001; and it was greater than outflow in April and May 2001 (Table 1). Water detention time determined as mean storage volume divided by mean outflow for the period of measurement was close to 3 months in spring through fall months, declining to one to two months in winter and early spring. The annual water detention time was 76 days (Table 1).

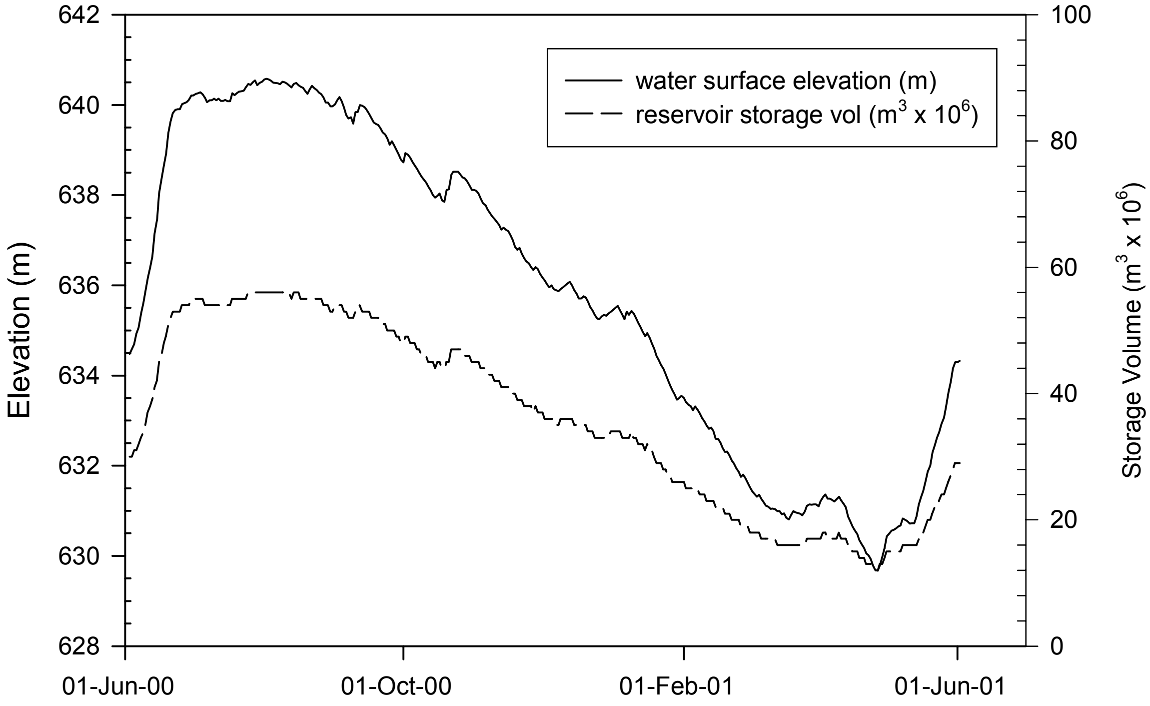

Figure 3. Changes in live storage and water surface elevation in the phosphorus budget year, June 2000 through May 2001.

Table 1. Mean water detention time in Wahleach Reservoir during the budget period of June 2000 through May 2001.

Month	mean flow and water detention time		
	Inflow ($m^3 \cdot s^{-1}$)	Outflow ($m^3 \cdot s^{-1}$)	Water detention time (d)
June 2000	15	5.2	99*
July – September 2000	6	6.8	92
October - December 2000	3.5	5.3	87
January – March 2001	2.8	4.9	54
April – May 2001	6.9	4.7	44
Annual Mean	5.5	5.5	76

*water detention time in June 2000 was relatively high due to a 14 day period of no outflow for maintenance of the penstock and powerhouse.

3.0 METHODS

3.1 Components of the detailed phosphorus budget of 2000 – 2001.

In natural waters, phosphorus can occur in dissolved forms as orthophosphate, polyphosphates and organic phosphates. Particulate phosphorus can be composed of phosphate minerals, adsorbed phosphate, and organic particulate phosphate. The different fractions are commonly referred to as total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). The analysis for total phosphorus (TP) includes all dissolved and particulate size fractions. Total dissolved phosphorus (TDP) is a subset of TP and includes the complete dissolved fraction ($<0.45\ \mu m$) including SRP. Some of the larger molecular weight fractions contained in TDP can be biologically available but only after enzymatic hydrolysis to release phosphate ions. Particulate phosphorus (PP) can be determined as the difference between TP and TDP. The analysis for SRP always includes the orthophosphate ion, which is considered biologically available but it can also include acid-labile P compounds (Harwood et al. 1969) and thus overestimate biologically available P (Rigler 1968). SRP is mainly the free orthophosphate component of TDP. SRP is the most biologically available phosphorus fraction and is frequently present in low concentrations because algae and bacteria can quickly assimilate it. The TDP fraction, which requires degradation by bacterial or algal phosphatases before biological uptake can be used as a P source but only when simpler phosphate supplies are depleted. In rivers, reservoirs, and lakes receiving loads of mineral and particulate phosphorus, some of the TP component is not tied up in biomass but it can occur as part of mineral particulates, and may become bioavailable only through dissolution of the minerals - a process occurring over long time scales. In Wahleach Reservoir, which does not receive inputs of rapidly weathering parent materials containing phosphorus (e.g. there are no silts from apatite-bearing volcanic rocks), inorganic particulate phosphorus is considered a small component of all forms making up TP. All four analytical size fractions of phosphorus including TP, TDP, SRP, and PP were included in the phosphorus budget.

The phosphorus budget was computed for the year, June 1 2000 through May 31 2001. Within this year, some data were stratified by season to distinguish time course trends. Spring was data in April through June, summer was July through September, fall was October through December, and winter was January through March.

The phosphorus budget was a calculation of imports and exports to determine amounts of phosphorus that were retained or lost over the measurement period. The simple mass balance model was:

$$R_p = I_p - O_p \qquad \text{eq. 1}$$

Where: R_p was retention of phosphorus,
I_p was total loading of phosphorus, and
O_p was total export.

I_p can include inputs from inflow streams (Q_i) dry and wet atmospheric deposition (A_i), inputs from fertilizer (F_i), and return of P from sediments (S_i) including mineralization and release of P from sediments settling through the water column and release of P from sediments on the reservoir bottom. I_p also includes phosphorus called B_i that was introduced in 52,000 kokanee and 3,045 cutthroat trout that were stocked in June 2000 (Perrin and Stables 2001).

Fluvial export through the penstock and over the spillway (Q_o) and phosphorus removed in the recreational fishery (B_o) made up the components of O_p.

Release of P from sediments can be important in mesotrophic and eutrophic lakes (Carignan and Lean 1991, Penn et al. 2000) but it is unlikely to be substantial in Wahleach Reservoir. P release can be large following a history of nutrient loading (Carignan and Lean 1991) but it is favoured mainly during oxygen depletion and reducing conditions (low redox potential) that decouples iron – phosphorus complexes and other adsorption sites. P release by oxic sediments that are likely present in Wahleach Reservoir has been experimentally shown to be negligible or negative (Bostrom and Pettersson 1982) although some diffusive return of P from sediments to the water column can occur in the presence or absence of anoxia (Twinch and Peters 1984). Typically, this diffusive return can only occur after a long history of high nutrient loading that has produced advanced mesotrophic or more commonly eutrophic conditions (Eckert et al. 1997). While a decline in oxygen concentrations over the water profile has been detected annually after fertilization, seasonal anoxia does not occur in Wahleach Reservoir (Perrin and Stables 2000). With this evidence we can assume that P return from sediments is likely to be negligible and need not be considered further.

Using the component terms, equation 1 can be rewritten as:

$$R_p = (Q_i + F_i + A_i + B_i) - (Q_o + B_o) \qquad \text{eq 2}$$

Where: R_p is retention of phosphorus
Q_i is phosphorus input from inflow streams
F_i is phosphorus input in fertilizer
A_i is atmospheric deposition of phosphorus,
B_i is phosphorus added in fish that were stocked in the budget year,
Q_o is phosphorus export through the penstock and over the spillway, and
B_o is phosphorus removed in fish harvested in the fishery

R_p actually represents three components; one being the mass of P settling to sediments (S_p), one being change in the mass of P contained in the water column over the budget year (W_p), and one including the change in mass of phosphorus in fish over the budget year (F_p). Hence, we can expand the mass balance into equation 3:

$$S_p + W_p + F_p = (Q_i + F_i + A_i + B_i) - (Q_o + B_o) \qquad \text{eq 3}$$

Q_i was determined as local inflow multiplied by phosphorus concentration. Reservoir inflows, also known as “local inflow”, were determined daily by BC Hydro as the difference between measured outflows ($m^3 \cdot d^{-1}$) and daily change in reservoir volume ($m^3 \cdot d^{-1}$). Inflow streams including Boulder Creek, Flat Creek, Glacier Creeks, and Jones Creek were not metered. The concentration of each phosphorus fraction was measured approximately monthly in each of Boulder Creek, Flat Creek, Jones Creek, and any one of the Glacier Creeks that was flowing into the reservoir at the time of sampling. P concentration for days between dates of water sampling was linearly interpolated between measured values. For any one day, the average concentration of each phosphorus fraction ($\mu g \cdot L^{-1}$) determined from all sampled streams was multiplied by local inflow ($m^3 \cdot d^{-1}$) to yield mass loading of P in units of mass/day. The sum of daily imports provided Q_i for any time period of interest.

Q_o was determined as the volume of water released from the reservoir multiplied by phosphorus concentration. Reservoir outflow in the budget year was entirely water passing the turbines. There was no episodic spill at the dam and no water released via the siphon to lower Jones Creek. Phosphorus concentration was measured on the same day as the inflow streams (approximately monthly) either in hypolimnetic water in the reservoir adjacent to the penstock intake using a Van Dorn water sampler (first three dates including June through August 2000) or in outflow from the turbines (all other dates). Interchangeable use of data from these two sites was considered acceptable because hypolimnetic water is unaltered between the point of withdrawal and the end of the penstock.

Atmospheric deposition of phosphorus (Ai) was estimated to be 0.15 kg/ha/yr, which was the maximum deposition rate measured at comparable elevations in the UBC Research Forest at Haney in the Fraser Valley during long-term small watershed studies (Feller and Kimmins 1979. M.C. Feller, Faculty of Forestry, University of BC, pers. Comm.). The UBC forest is the closest location to Wahleach Reservoir where precipitation monitoring occurs. Precipitation collections have continued for more than 20 years at that site. In the work at Haney, phosphorus concentrations in collected rainfall and snow were commonly less than analytical detection (Feller and Kimmins 1979), resulting in phosphorus deposition estimates that were greater than actual rates. For this reason, the estimate used in this study is considered an overestimate of the actual rate.

F_i included 857 kg of phosphorus in fertilizer that was added to the reservoir in 2000 (Perrin and Masuda 2001).

B_i was the average phosphorus concentration in fish tissue multiplied by the mass of fish stocked in 2000. Phosphorus content in fish was set at 0.36%, which is the value reported by Larkin and Slaney (1997) for non-spawning fish in mixed populations. Perrin and Stables (2001) reported that 3,045 cutthroat trout at an average weight of 105.4g and 52,000 kokanee at an average weight of 4.77g were stocked in 2000, yielding approximately 2 kg of phosphorus added in stocked fish in the budget year.

B_o was the average phosphorus concentration in fish tissue multiplied by the mass of fish harvested in the recreational fishery in 2000. Phosphorus content in fish was again set at 0.36% (Larkin and Slaney 1997). Perrin and Stables (2000) estimated that 947 cutthroat trout and a similar number of rainbow trout were removed in the fishery between May 1 and August 31 1999. No creel data were available for 2000, but if we assume similar effort to that in 1999, approximately 1,900 fish may have been removed in 2000. Given a mean size of approximately

300g reported by Perrin and Stables (2000), the mass of phosphorus removed in the fishery was approximately 2 kg. Using these calculations, imports of phosphorus in stocked fish and exports of phosphorus in harvested fish approximately balanced in the budget year.

W_p was the difference in mass of P in the reservoir above the sediments between the start of the budget year and that at the end of the budget year. P mass was determined as reservoir volume multiplied by average water column concentration of phosphorus. Reservoir volume was determined from surface elevation data as described in section 2.0. The mean water column P concentration was the average of surface and/or bottom samples collected on the two closest days to the start and finish of the budget.

F_p was the difference in mass of P in fish present in the reservoir between the start and finish of the budget year. P mass in fish was the sum of the product of fish population size, mean fish wet weight, and estimated P content in fish biomass among all fish species. Phosphorus content in fish biomass was set at 0.36% of wet weight biomass as recommended by Larkin and Slaney (1997). Since a fish population estimate and measurements of fish size were not available at the start of the budget year, data from the closet time, which was October 1999 (reported by Perrin and Stables 2000), was used. Data closest to the end of the budget year was October 2000. While these dates span a complete year, they are offset from the budget year by 7 months. They provide a reasonable approximation of change of P mass in fish but may contain error associated with the offset time course.

The only parameter in equation 3 that was not measured, directly or indirectly was Sp, the mass of P retained in sediments. Sp was determined by difference between all other parameters to balance equation 3 as shown in equation 4:

$$S_p = ((Q_i + F_i + A_i + B_i) - (Q_o + B_o)) - (W_p + F_p) \qquad \text{eq 4}$$

Sedimentation rates were measured to determine the amount of phosphorus bound in seston that settles to sediments. Some of this phosphorus can be bound in particulates entering the reservoir from allocthonous sources. Other phosphorus is initially taken up into phytoplankton but then settles to sediments when phytoplankton dies. Phosphorus in phytoplankton biomass that is ingested by zooplankton can be used in growth and reproduction and some can be excreted. Some of that excreted phosphorus can be reused by phytoplankton after hydrolysis to simpler phosphate. Phosphorus in phytoplankton that dies and is not used by zooplankton settles to sediments where it may be used by benthos as a nutrient in detrital biomass. Measurements of phosphorus sedimentation allowed us to determine the minimum mass and proportion of imported phosphorus was due to internal sedimentation and potential retention in sediments. Values were compared to calculated values of S_p. Substantial differences were expected because solubilization in sediment traps can greatly modify nutrient content of trapped material and produce error in rates of nutrient sedimentation (Kahler and Bauerfeind 2001). Alternatively, sediment traps can overestimate sedimentation rates due to “sediment focusing” (Dillon et al. 1990), a process in which sediments in shallow regions of a lake or reservoir are resuspended and settle in deeper regions. Comparison of calculated S_p and that determined from sediment traps, provided insight into the extent of trap effects (decomposition of contents or effects of sediment focusing) associated with seston collection in traps. Once in sediments, phosphorus can be used by the benthos to support production of invertebrates, including aquatic insects that are an important food source for fish in Wahleach Reservoir (Perrin and Stables 2001).

3.2 Components of the multi-year phosphorus budgets.

With the exception of phosphorus sedimentation that was not measured before 2000, components of the multi-year budget were the same as those used in the detailed budget of 2000 – 2001. Imports included:

- Q_i, the surface fluvial sources being Boulder Creek, Flat Creek, Glacier Creeks, and Jones Creek),
- F_i, which was loading of P in fertilizer (data from Perrin and Masuda 2001),
- A_i, which was an estimate of atmospheric deposition of phosphorus (assumed to be the same as in 2000 - 2001, and
- B_i, which was phosphorus introduced in fish that were stocked each year (data from Perrin and Stables 2001).

Exports included:

- Q_o, which was fluvial outflow through the penstock, through the siphon when it was operating, and over the spillway, and
- B_o, an estimate of phosphorus removed in the fishery each year.

Phosphorus removed in the fishery was roughly estimated for each year. I assumed that the mass of P removed in the 1998 and 1999 fisheries was the same as that in 2000, as described in section 3.1. Given a minimal or non-existent fishery in 1993 through 1996 before stocking of cutthroat trout, I estimated that P removed in fish was 0.1 kg in 1993 and 1994, 0.2 kg in 1995 and 1996, and 0.5 kg in 1997. The assumed rise is P removal rates over years is based on the view that interest in fishing was increasing as anglers increasingly became aware of activities related to restoring fish populations.

The annual P deposition rate from atmospheric sources was the sum of daily deposition (0.15 kg/ha/yr (Feller and Kimmins 1979) divided by 365 to yield 0.004 kg/ha/d) rated to daily reservoir surface area measured in 2000. The year 2000 surface areas were considered representative for all years given that surface area fluxes are similar among years.

Q_i and Q_o was determined as flow multiplied by phosphorus concentration for all forms of phosphorus for each year. Daily local inflows and outflows at the turbine, spill, and siphon were available from BC Hydro for all years of interest (1993 through 1999). Phosphorus concentrations in inflow streams were not available for years before 2000. Because headwater phosphorus concentrations may change little over time in montane environments of the Fraser Valley (Feller and Kimmins 1979. M.C. Feller, Faculty of Forestry. UBC. Pers. Comm.), inflow phosphorus concentrations measured in 2000 - 2001 were used for all years. Phosphorus concentrations in turbine flow were those measured in the hypolimnion near the penstock intake as part of the fish population restoration work. Those data were available for 1993 and 1994 on a monthly frequency in spring through fall months as part of pre-treatment data collections and they were available on the same frequency and timing in 1995 through 1999 as part of work to monitor fertilization. Phosphorus concentrations in the episodic spill and siphon flow were approximated with measurements of nutrient concentrations in epilimnetic water at Station 1 shown in Figure 1. Those data were also available on a monthly frequency in spring through fall months in 1993 through 1999. All daily values of phosphorus concentrations between dates of measurement were determined by linear interpolation between measured values.

3.3 Field and Laboratory Methods

For each episode of sampling inflow and outflow sites, field activities were completed in one day from a base in Hope, located 25 km by highway and rough gravel road from Wahleach Reservoir. In ice-free months, the inflow streams were accessed by vehicle (Boulder Creek and Flat Creek) or work skiff (Jones Creek and Glacier Creeks) that was anchored adjacent to a ramp near Boulder Creek (Figure 1). In winter 2001, ice on the reservoir was never sufficiently stable to support a snowmobile, thus requiring access on snowshoes. The snowmobile was used for access to Flat Creek, for which travel on the reservoir was not required. Water samples from the reservoir (June – August 2000) were collected at station 1 located close to the penstock intake (Figure 1). Samples from a depth of 20m in the hypolimnion were collected using a Kahlsico Van Dorn water bottle deployed from the work skiff.

From whole water samples, aliquots were withdrawn for analysis of pH, conductivity, total dissolved solids (TDS), SRP, TDP, and TP. Particulate phosphorus (PP) was determined by difference between TP and TDP. Aliquots for all soluble forms of phosphorus were filtered in the field or at the lab on the day of sampling through pre-ashed glass fibre filters.

Samples for TP and TDP analysis were digested and analyzed by Menzel and Corwin's (1965) potassium persulfate method. SRP was analysed using the molybdenum blue method (Murphy and Riley, 1962). Conductivity and total dissolved solids (TDS) were measured in the field using a Hach CO150 meter. The pH was also measured in the field using a Hanna HI 9025 meter equipped with a Hach One combination electrode and electrolyte dispenser system. All other analyses followed procedures outlined in APHA (1985).

Water column sediment was collected in custom designed and fabricated in-situ sediment traps. Each trap consisted of a PVC tube tower with a detachable bottom collection cup (51 cm total length, 9.7 cm ID mouth, 5:1 aspect ratio) with plastic egg-crate baffles at the mouth of each tube to minimize resuspension within the trap. Traps were deployed on moorings in replicate pairs at two depths in the water column at Stations 1 and 2 shown in Figure 1. Trap moorings were suspended from the surface floats anchored with cinder blocks with one trap pair suspended near the bottom of the surface mixed layer (5 – 10 m depending on water surface elevation) and one pair in the hypolimnion (10 – 25 m). The sediment traps were recovered monthly in July through November 2000 after deployment in June 2000. Due to ice cover in winter, the traps were left installed under ice in December and were recovered on April 28 2001. The deep samplers were lost during this winter period as ice movement caused moorings to fail and caused the traps to become lodged in bottom muds. The traps were replaced and all equipment was redeployed in April 2001 for final recovery in June 2001. At the time of recovery, each trap was drained and contents of the collection cup (1-1.5 L) were transferred to a 2-L plastic bottle and stored on ice.

In the laboratory, the total volume of contents in each trap was determined, the samples were thoroughly mixed, and 50 mL subsamples were filtered onto pre-weighed and ashed glass fibre filters. The filter was dried to a constant weight in a 104°C oven to determine total sediment dry weight. Additional 50-mL subsamples were filtered onto ashed glass fibre filters to determine the particulate phosphorus content of the collected sediment using the colorimetric method of Stephens and Brandstaetter (1983). Total dry weight and phosphorus sedimentation rates were converted to units of mass/day for the complete reservoir by extrapolation to water surface area of the reservoir. In this approach we assume that sedimentation in the samplers was representative of sedimentation over the entire reservoir.

3.4 Statistical analysis

As part of a description of phosphorus concentrations among sampling sites, analyses of variance (ANOVA) were applied to examine reservoir effects on concentration of each form of phosphorus for the one-year budget period. A reservoir effect on phosphorus concentration was considered present if the phosphorus concentration in inflow water was significantly different from that in the outflow water. The presence of a significant effect implied that some process in the reservoir had modified the concentration. An ANOVA was run for each form of phosphorus using data from the complete year where the test was to determine if a significant difference in phosphorus concentration was present between inflow and outflow water. All procedures were run in Systat v8 (SPSS 1998) and a significant probability level was set at p=0.05.

Statistical summaries of particle and phosphorus sedimentation rates were prepared for graphical presentation. A single sedimentation rate was determined for each pair of sediment traps that were deployed together at each depth at each of the two reservoir stations. This approach provided two replicate measurements of sedimentation rate in shallow traps and two replicate measurements in deep traps for each date of measurement, less data from traps that were lost in winter. Data were grouped by season for calculation of mean and standard errors where spring was any period in April through June (2000 and 2001), summer was any period in July through September, fall was any period in October through December, and winter was January through March.

4.0 RESULTS AND DISCUSSION

4.1 Inflow and Outflow Phosphorus Concentrations 2000-01

Mean total phosphorus concentrations in inflow and outflow water were $<7\ \mu g \cdot L^{-1}$ over the complete budget year (Figure 4). In all seasons, TP concentrations in outflow water were greater than in inflow water but differences were small and not significant ($p>0.2$), indicating no effect of processes in the reservoir and fertilizer addition (e.g. Perrin and Stables 2001) on modifying TP concentration between inflow and outflow water. PP and TDP concentrations were greater in outflow than inflow water in three seasons of the year but again the differences were small (Figure 4) and not significant ($p>0.2$). SRP concentrations were significantly lower ($p=0.04$) in outflow water (mean annual concentration of $0.7\ \mu g \cdot L^{-1}$) than in inflows (mean annual concentration of $1.2\ \mu g \cdot L^{-1}$). The net effect of these differences in concentrations in outflow and inflow water was a mean annual inflow TP concentration of $4.3\ \mu g \cdot L^{-1}$ and a mean annual outflow TP concentration of $5.3\ \mu g \cdot L^{-1}$.

Over the year, more than 70% of TP was comprised of soluble phosphorus (Table 3, Figure 4). The proportion of soluble P in TP was highly consistent in inflow water, ranging from 70-80% of TP in all seasons. In outflow water, soluble P was 70-76% of TP in summer through winter but it dropped to 55% of TP in spring. There was a corresponding increase in PP at the same time.

PP in inflow streams was only 20-30% of TP, occurring in concentrations $<2\ \mu g \cdot L^{-1}$ at all times (Table 2, Figure 4). These PP concentrations are low and indicate little transport of phosphorus in particulate organic matter and slow weathering of what are mainly granitic parent materials in the headwaters. Gneiss, which is slow-weathering metamorphic rock, is found with the granite and these complexes. They are flanked to the east and west by belts of folded and faulted, but not highly metamorphosed, sedimentary and volcanic rocks of the late Paleozoic to mid-Cretaceous age (http://collection.nlc-bnc.ca/100/201/300/cdn_rockhound/latest/2000/01/cr0004110_fraservalley.html). Faster-weathering volcanic rocks that can contribute substantially more phosphorus to surface waters than granites are not dominant in the Wahleach Reservoir drainage. PP concentrations in outflow water were 24-45% of outflow TP concentrations, only marginally greater than the proportions in inflow water.

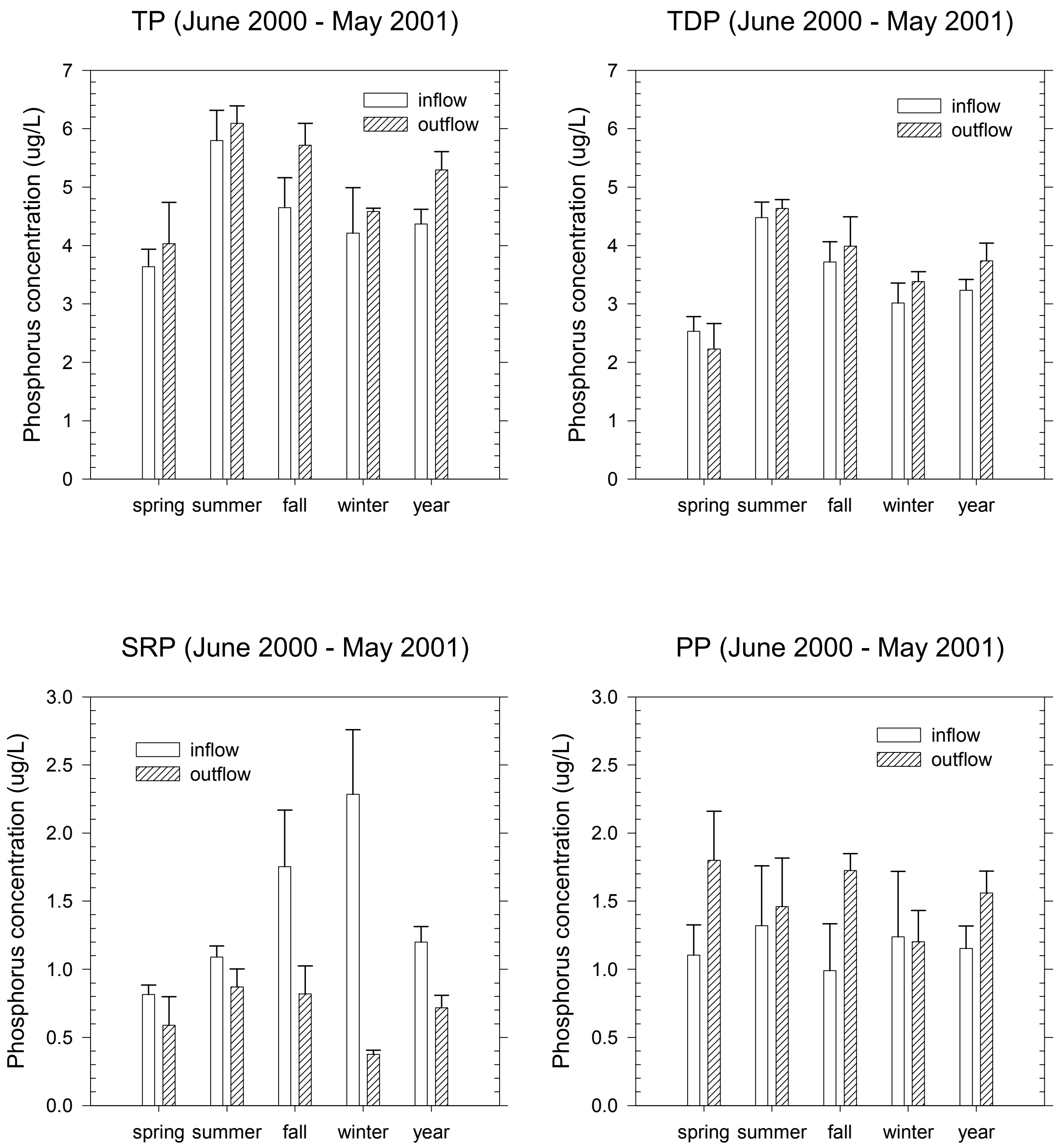

Figure 4. Concentration of each form of phosphorus in Wahleach Reservoir inflow and outflow by season for the year, June 2000 through May 2001.

Table 2. Relative proportion of TP comprised of soluble and particle fractions in inflow and outflow water at Wahleach Reservoir.

Season	Proportion of TP			
	Soluble P (TDP)		PP	
	inflow	Outflow	inflow	Outflow
Spring	0.70	0.55	0.30	0.45
Summer	0.77	0.76	0.23	0.24
Fall	0.80	0.70	0.21	0.30
Winter	0.72	0.74	0.29	0.26
Year	0.74	0.71	0.26	0.29

In spring and summer in inflow streams, soluble phosphorus was mainly comprised of large molecular weight species (Table 3), likely produced as biological exudates from nutrient spiraling processes in streams. In winter, with relatively low biological activity in streams, SRP concentration was greater than that of the larger molecular weight fractions (Table 3), reflecting erosion processes yielding mainly orthophosphate to the reservoir. In outflow water, concentrations of the larger molecular weight fractions were always greater than the SRP fraction (Table 3), indicating substantial biological activity at all times of the year releasing larger molecular weight fractions, leaving an extremely small pool of orthophosphate in solution.

Table 3. Mean concentrations of soluble phosphorus fractions (particles <0.45 μm) in inflow and outflow water at Wahleach Reservoir in the budget year, 2000 – 2001.

season	Inflow TDP ($\mu g \cdot L^{-1}$)	Inflow SRP ($\mu g \cdot L^{-1}$)	Large molecular weight soluble P in inflow ($\mu g \cdot L^{-1}$)*	Outflow TDP ($\mu g \cdot L^{-1}$)	Outflow SRP ($\mu g \cdot L^{-1}$)	Large molecular weight soluble P in outflow ($\mu g \cdot L^{-1}$)*
spring	2.5	0.8	1.7	2.2	0.6	1.6
summer	4.5	1.1	3.4	4.6	0.9	3.7
fall	3.7	1.8	1.9	4.0	0.8	3.2
winter	3.0	2.3	0.7	3.4	0.4	3.0
year	3.2	1.2	2.0	3.7	0.7	3.0

*TDP and SRP were determined by direct analysis. The large molecular weight fraction was determined by difference between TDP and SRP.

4.2 Sedimentation Rates

Mean particle sedimentation rates ranged from 40 mg dry wt$\cdot$m$^{-2}\cdot$d^{-1} (shallow array in winter) to 207 mg dry wt$\cdot$m$^{-2}\cdot$d^{-1} (deep array in summer). Sedimentation rates were lowest in winter, rising in spring to reach a maximum in summer and then declined in the fall (Figure 5).

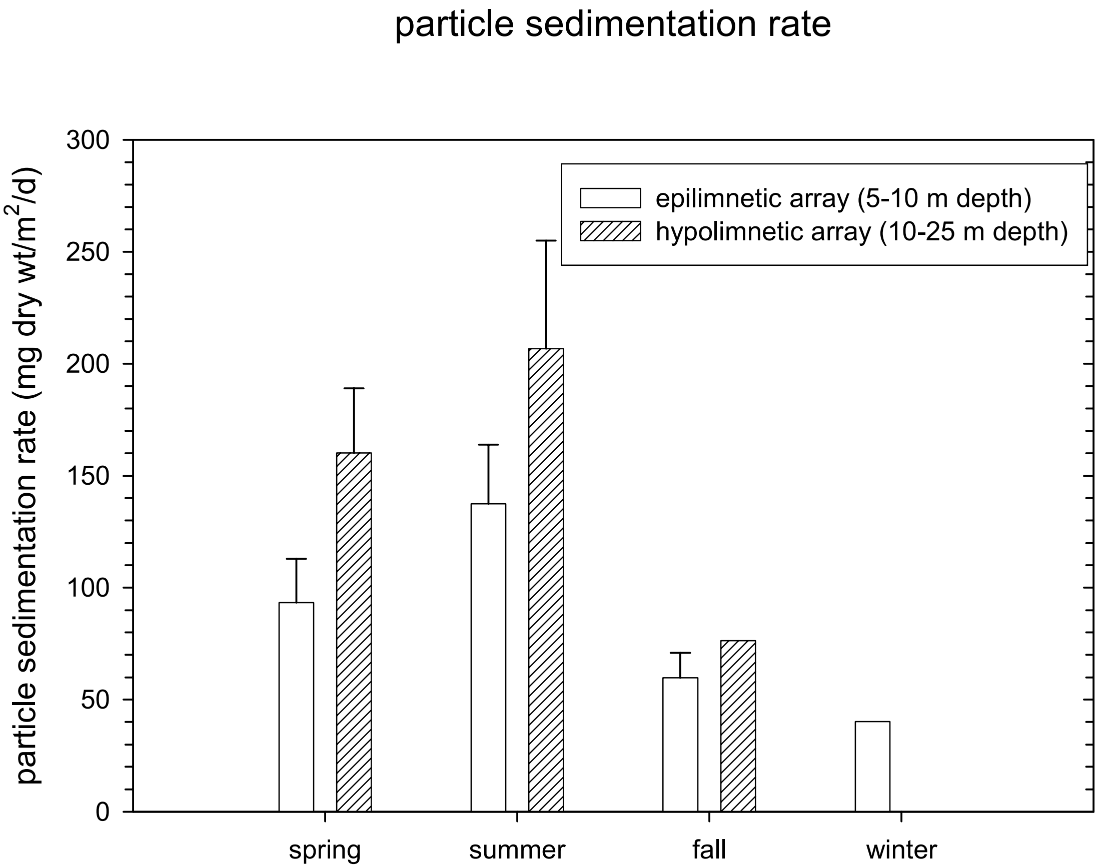

Figure 5. Mean particle sedimentation rates (±SE) by season in shallow (5-10 m) and deep (10-25 m) sediment traps. Deep trap data in winter are missing due to loss of the traps under ice. Spring data are from June 2000 and from April-May 2001. All other data are from 2000.

Mean phosphorus sedimentation rates ranged from 13 $\mu gP \cdot m^{-2} \cdot d^{-1}$ (shallow array in winter) to 84 $\mu gP \cdot m^{-2} \cdot d^{-1}$ (shallow array in summer) (Figure 6). The time course trend of phosphorus sedimentation was the same as that found for particle sedimentation. Rates were lowest in winter, they increased in spring to reach a maximum in summer and they declined in the fall. P sedimentation was marginally greater in shallow water traps than in the deeper traps in spring and summer, while the reverse was found in the fall. Differences between depths, however, were not significant ($p>0.5$), indicating no concentration effect of reservoir morphometry (Wetzel 1983) or sediment focusing effect by sediment resuspension (Dillon et al. 1990) on sedimentation of P.

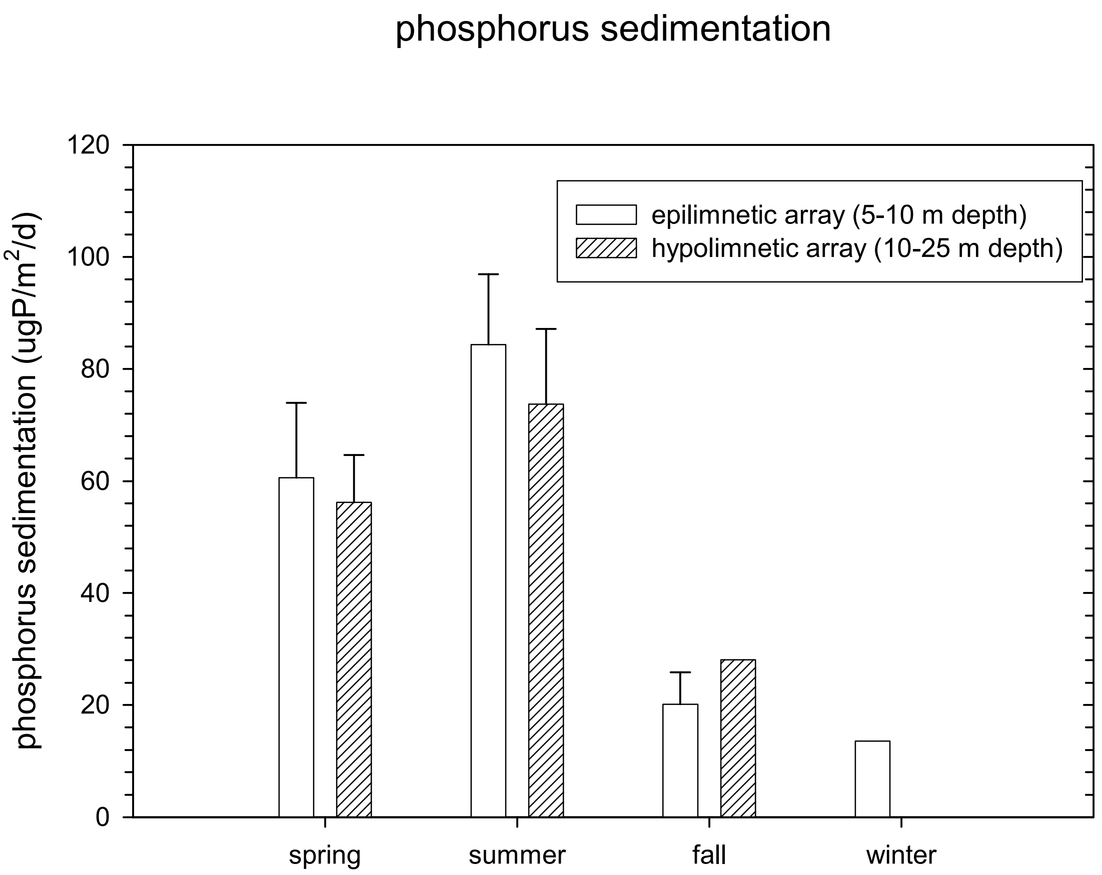

Figure 6. Mean phosphorus sedimentation rates (±SE) by season in shallow (5-10 m) and deep (10-25 m) sediment traps. Deep trap data in winter are missing due to loss of the traps under ice. Spring data are from June 2000 and from April-May 2001. All other data are from 2000.

These sedimentation rates are considered substantial underestimates of actual rates. It is well known that sediment trap techniques can result in non-proportional sampling of particle flux (Buesseler 1991). Animals entering traps may feed on contained particles and enhance particle solubilization (Lee et al. 1988) that can occur at rapid rates even in the absence of animals (Kahler and Bauerfeind 2001). Investigation of trap effects on sedimentation has shown that the bulk of solubilization can occur within a few days after particles are deposited in traps. Noji et al. (1999, in Kahler and Bauerfeind 2001) showed that it can be complete within 10 days and similar rates were reported by Kahler and Bauerfeind (2001). Accounting for loss due to solubility, Kahler and Bauerfeind (2001) found that actual organic carbon or organic matter flux is 2.7 times greater than estimates based on particles recovered from traps. They found that actual organic nitrogen flux was 6 times greater than that determined from particles recovered from traps. The same or greater corrections may apply to phosphorus fluxes, particularly in reservoirs where phosphorus strongly limits primary production and is tightly cycled through microbial components. This problem of decomposition in traps is one reason why Effler et al (2001) suggest that sediment traps should be deployed in short time intervals of one to two weeks in lakes and reservoirs. Unfortunately, logistical constraints did not allow a sampling frequency of less than a month in the present study. The typical sampling frequency was every

29 – 38 days and over winter it was 160 days. Over these durations there may have been substantial solubilization of labile organic matter in the traps, leading to considerable error with the particle and phosphorus flux measurements. Data in Figure 6 suggests that the annual PP flux over the complete reservoir was approximately 66 kg/yr. In section 4.3, I compared this value to that determined using a mass balance approach to report an estimate of error associated with use of sediment traps in determining phosphorus settlement to sediments.

4.3 Phosphorus Budget: 2000 - 2001

Table 4 shows that in the year June 2000 through May 2001, 1713 kg of TP entered the reservoir from streams, fallout from atmospheric sources, fertilizer, and in fish that were stocked in the spring. Total P export, mainly through the penstock amounted to 910 kg, resulting in a net P retention of 803 kg or 47% of TP loading. This net phosphorus retention was due to high retention rates of the soluble P fractions (89% of SRP and 58% of TDP retained) while there was a 33% net loss of the particulate phosphorus load (Table 4). The net loss of PP actually indicates loss of phosphorus bound in seston that was produced within the reservoir. Sedimentation near the intake to the penstock can result in entrainment of particulates in water that was sampled to determine PP concentrations.

This reservoir-produced seston has little relationship with PP entering the reservoir from streams. Retention of soluble P actually represents biological uptake and adsorption to positively charged surfaces, resulting in incorporation of P into more complex structures. These processes cause concentrations of SRP to be substantially lower than TDP and PP in the water column of oligotrophic lakes and reservoirs, including Wahleach Reservoir (Perrin and Stables 2000). Most of those structures would be expected to be organic, associated with bacteria and algae that take up soluble P and form the basis of the food web. These complex structures contribute to seston (living and non-living suspended matter) that settles from the water column and was sampled in the sediment traps. Hence, soluble P loaded to the reservoir contributed to formation of particulate P in the reservoir. More of this particulate P was lost from the reservoir than was loaded to the reservoir as detrital particulate P mainly derived from tributary streams.

Fluvial inputs of phosphorus and P in fertilizer represented 97% of TP loading (Table 4). Over the year, P loading in fertilizer represented half of the TP load but it represented 57% of the load of soluble P. If we only consider the loading of inorganic phosphate (mainly represented by SRP), which is most available for biological uptake, P in fertilizer represented 78% of that load from all sources. This value indicates considerable importance of the fertilizer in contributing to the pool of P for biological production in the reservoir in 2000-2001. Atmospheric inputs and addition of P in fish that were stocked in the spring were only 3% of the total load of TP.

Table 4. Import, export, and net retention of all size fractions of phosphorus in Wahleach Reservoir, June 2000 through May 2001.

P source	P flux (kg/year unless otherwise indicated)			
	SRP	TDP	PP	TP
fluvial inputs (Q_i)	191	599	206	805
atmospheric inputs (A_i)	49	49	0	49
Fertilizer (F_i)	857	857	0	857
fish stocked (B_i)	0	0	2	2
total inputs	1097	1505	208	1713
percent of total inputs due to fertilizer	78.1%	57.0%	0.0%	50.0%
fluvial exports (Q_o)	118	634	274	908
removal in fishery (B_o)	0	0	2	2
total exports	118	634	276	910
P retention (R_p)	979	871	-68	803
percent of P input retained	89%	58%	-33%	47%

A total of 840 kg of phosphorus (210 $mg \cdot m^{-2} \cdot yr^{-1}$) was retained in sediments (Table 5). This amount was calculated by difference between measured R_p and amounts of phosphorus retained in fish populations (2% of R_p) and in water between the start and finish of the budget year (-6.6% of R_p). The loss of TP in the water column was due to lower water volume in the reservoir at the end of the budget year (29.0 x 10^6 m^3) compared to that at the beginning (29.6 x 10^6 m^3) and due to lower average TP concentration in the water column at the end of the year (3.7 $\mu g \cdot L^{-1}$) compared to that at the beginning (5.4 $\mu g \cdot L^{-1}$). Fish represented only 2% of R_p, mainly due to the increase in biomass of cutthroat trout (Table 6). For all components to balance, the loss of TP from the water column meant that TP retention in sediments (S_p) was greater than R_p. Clearly, reservoir sediment was the main sink for retained phosphorus (S_p). This finding is consistent with other phosphorus budget studies that unequivocally show that sediments represent a burial sink for retained phosphorus in systems where redox potential is positive (Klump et al. 1997, Houser et al 2000). Even in eutrophic lakes where anaerobic conditions can be prevalent, sediments can be a sink for phosphorus during seasonal oxidation at the sediment – water interface (Penn et al 2000).

Table 5. Partioning of retained TP (R_p) among water, fish and sediment sinks in Wahleach Reservoir in 2000-2001.

TP retention sink	TP retained (kg)	Areal TP retained ($mg \cdot m^{-2} \cdot yr^{-1}$)	Percent of TP retention
Water above sediments (W_p)	-53	-13.2	-7%
Fish (F_p)	16	4	2.0%
Sediments (S_p)	840	210	105%
All sinks (R_p)	803	201	100%

Table 6. Partioning of retained P among populations of fish species present in Wahleach Reservoir. Gain and loss values are the difference in values between the start and end of the year.

Fish species	Start of year (fall 1999)		End of year (fall 2000)		Gain or loss	
	Wet weight Biomass (kg)	P content (kg)	Wet weight Biomass (kg)	P content (kg)	Wet weight Biomass (kg)	P content (kg)
Three-spine stickleback	790	2.8	727	2.6	-63	-0.2
kokanee	488	1.8	1119	4.0	631	2.2
Cutthroat trout	4924	17.7	8210	29.6	3286	11.9
Rainbow trout	1200	4.3	1867	6.7	667	2.4
All species	7402	26.6	11923	42.9	4521	16.3

The 47% TP retention rate was at the low end of the range measured among other reservoirs. Among BC Hydro projects, R_p was 47% in Carpenter Lake Reservoir (Perrin and MacDonald 1999), 90% in Duncan Lake Reservoir (Perrin and Korman 1997), and 35% in Daisy Lake Reservoir (Perrin 1998). Episodic turbidity was found in these reservoirs and it resulted in PP being the particle size of phosphorus that determined most of TP transport and retention. Most was likely in the inorganic fraction as was found to characterize phosphorus deposition in several reservoirs in New York by Effler et al. (2001). This dominance by inorganic PP was quite different than the importance of soluble P in Wahleach Reservoir. The difference was due to differences in the composition of parent materials in upstream drainages. Slow-weathering granites were common in the Wahleach drainage while the other sites had some presence of volcanic materials that are fast weathering and contain phosphorus in greater amounts than in other rock types. The low TP retention rate in Daisy Lake reservoir was at least in part related to very low water detention time that can be less than one week for more than half the year. Houser et al (2000) reported TP retention rates of 75 – 86% in the water column of three small lakes (up to 3.4 ha) in Wisconsin, increasing to 91 – 98% during nutrient addition. These lakes had very high water detention times of over 800 days that would have enhanced nutrient retention. Schindler et al. (1987) found that sediment retained 89 – 91% of phosphorus input in Lake 227 in the Experimental Lakes Area of Ontario. A large embayment of Lake Michigan, known as Green Bay is an effective nutrient trap, retaining 70 – 90% of TP loading, mainly by burial in sediments (Klump et al. 1997). Based on published models, Lekstrum et al (1994) estimated that Lake Kookanusa (reservoir behind the Libby Dam) retains 60% of inflowing phosphorus.

Sediment traps indicated that phosphorus sedimentation in the entire reservoir amounted to 65.6 kg over the budget year. Comparison of this value to the amount for S_p that was determined in the phosphorus budget (766 kg) indicates that sediment trap techniques underestimated phosphorus settlement to sediments by approximately 12 times or the budgeting techniques contained errors. Potential error associated with sediment traps is greater than that reported for nitrogen and carbon by Kahler and Bauerfeind (2001) but not surprising given the long deployment times of 29 – 38 days over much of the year and up to 160 days in winter. Over these durations, solubilization of contents by decomposition could be enhanced by animal activity (Lee et al 1988) and contribute to phosphorus release from trapped seston, thus greatly underestimating sedimentation rates. In contrast there are no clear explanations for large error in flux rate calculations. Flow data are subject to critical quality control evaluation at BC Hydro and all chemical analyses were completed in an ultra-clean lab dedicated to low level nutrient analysis in which all testing is compared against standards to ensure high accuracy and precision. This comparison suggests that the sediment traps were not reliable in providing an accurate estimate of P settlement to sediments in this study. Trap techniques should only be used where there is opportunity to sample contents within a few days after deployment.

There was substantial seasonal variation in rates of retention of all size fractions of phosphorus (Table 7). In spring, 78% of soluble P and 28% of particulate P loading was retained, while in all other seasons either smaller retention rates or large loss rates were found. These changes corresponded with time course change in water storage volume that is shown in Figure 3. In spring, storage was increasing and reached a peak due to inflows exceeding outflows (Table 1). At this time, there was net retention of all size fractions of P. In summer, water storage was relatively constant because inflows were similar to outflows (Table 1). Highest P loading rates of the year occurred at this time, mainly due to P inputs from fertilizer that represented almost 70% of the TP load at that time. Of 930 kg of TP loaded into the reservoir in summer, 65% was retained, mainly due to 71% retention of soluble P. There was a small loss amounting to 20 kg of PP in summer. In fall and winter when reservoir outflows exceeded inflows and water detention time declined (Table 1), losses of both the soluble and particulate fractions occurred. Table 7 shows that in the fall, more than double the PP load was lost and in the winter more than 3 times the PP load was lost. Imports and exports of soluble P approximately balanced in the fall but exports were almost double imports in winter. Despite the proportionately large losses of TDP and PP in winter and PP in the fall, the absolute mass of imports and exports of soluble and particulate P were lower in fall and winter than in spring and summer. For example, TP loading in winter was only 9% of that in summer and TP export in winter was 52% of that in summer. This comparison shows that net retention of TP over the complete year shown in Table 4 was due to very high retention of soluble P in the spring and summer that exceeded losses of soluble and particulate P in fall and winter.

Table 7. Import, export, and net retention of all size fractions of phosphorus in Wahleach Reservoir, by season, in the year June 2000 through May 2001. Spring data are from June 2000 and from April-May 2001. All other data are from 2000.

P source	P flux (kg/season unless otherwise indicated)											
	Spring			Summer			Fall			Winter		
	TDP	PP	TP	TDP	PP	TP	TDP	PP	TP	TDP	PP	TP
fluvial inputs (Q_i)	219	99.6	319	215	61	275	108	30	138	57	16	73
Atmospheric inputs (Ai)	11	0.0	11	15	0	15	13	0	13	10	0	10
Fertilizer (F_i)	160	0.0	160	640	0	640	57	0	57	0	0	0
fish stocked (Bi)	0	1.9	2	0	0	0	0	0	0	0	0	0
total inputs	**390**	**102**	**492**	**869**	**61**	**930**	**178**	**30**	**208**	**67**	**16**	**83**
percent of total inputs due to fertilizer	41%	0%	33%	74%	0%	69%	32%	0%	28%	0%	0%	0%
fluvial exports (Qo)	86	72	159	249	80	329	177	73	249	122	49	171
removal in fishery (Bo)	0	0.9	1	0	1	1	0	1	1	0	1	1
total exports	**86**	**73**	**160**	**249**	**81**	**330**	**177**	**74**	**250**	**122**	**50**	**172**
P retention (Rp)	304	28.1	332	621	-20	600	2	-43	-41	-55	-33	-88
Percent of P input retained	78%	28%	68%	71%	-33%	65%	1%	-143%	-20%	-82%	-208%	-106%

Because TP loading in fertilizer could be distinguished from TP loading from natural sources, TP retention and loss was explored in a scenario where no fertilizer was applied to the reservoir in the budget year. In considering this analysis, we must determine if TP concentration in outflow was affected by loading of fertilizer because TP concentration in outflow was used to determine TP export. Figure 7 shows that outflow TP concentration increased from the start of fertilization through 1997. After fish stocking began and fertilization continued, outflow TP concentration declined. Given the increasing loads of P over this time, there must have been an increase in mass of P bound in larger complexes including invertebrates and fish or more accumulating in sediments compared to the earlier years of fertilization. The result was no clear relationship between fertilizer loading and TP concentration in reservoir outflow. This outcome does not prove, however, that the addition of fertilizer did not affect TP concentrations in any given year. It only indicates that if any effect was present, it was not consistent among years. Hence, a prediction of TP retention (R_p) in the absence of fertilizer addition was considered an overestimate because of the possibility that TP concentrations in outflow would actually be lower than measured values that were used to simulate effects of removing TP loading in fertilizer.

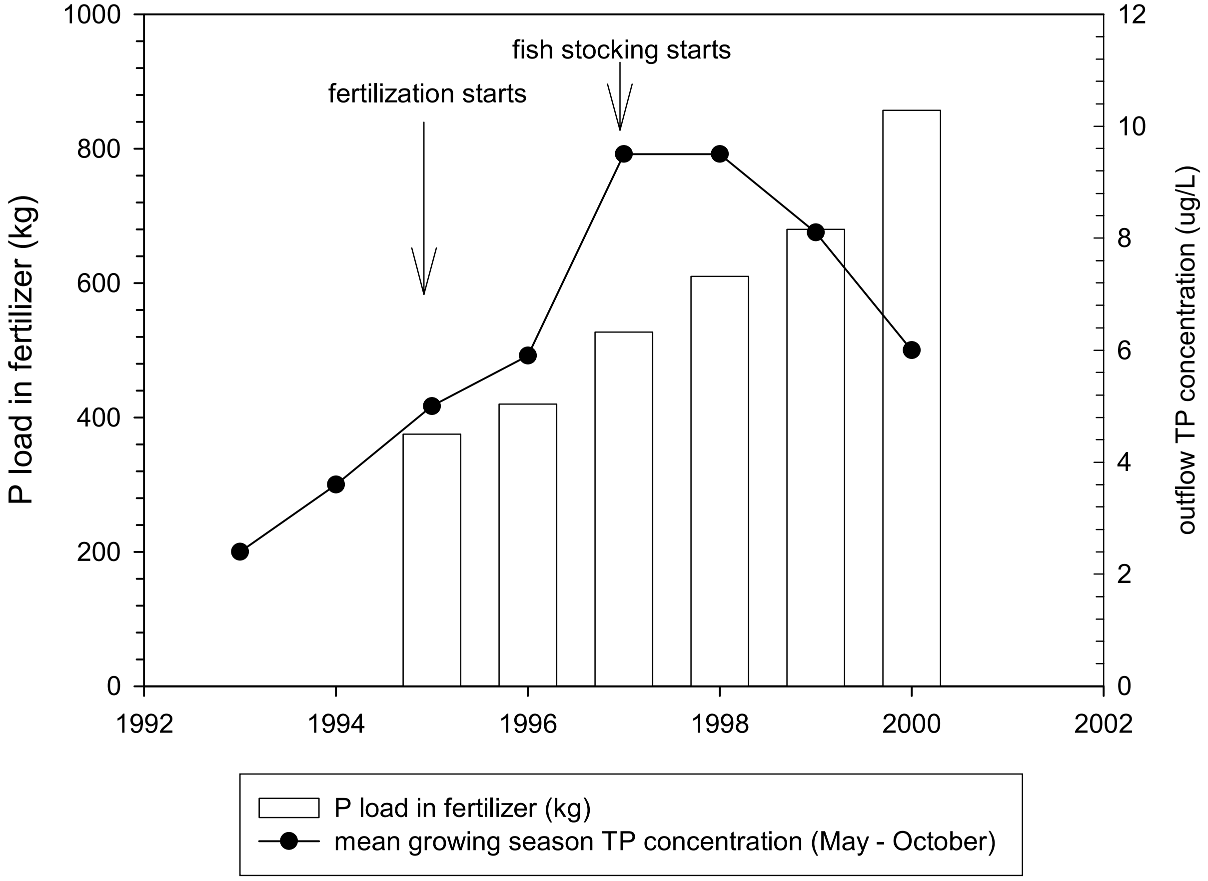

Figure 7. Time course change of P load in fertilizer and TP concentration in outflow or hypolimnetic water

The main effect of not adding fertilizer was an 857 kg decline in soluble P loading to the reservoir in 2000-01 (the amount of phosphorus in fertilizer shown in Table 4). This amount included 160 kg of P in spring, 640 kg in summer, and 57 kg in fall (Table 7). This decline in P loading resulted in lower retention of phosphorus. Table 8 shows that TP retention in spring without fertilization was approximately half that measured with fertilizer added. Because fertilizer represented almost 70% of TP imports in summer, the effect of no fertilizer addition on TP retention was large. With fertilization, 600 kg of TP was retained but in the absence of fertilization, a loss of 40 kg was predicted. Changes in fall (Table 7) were small because of the relatively small load of fertilizer at that time. No change in winter was found because no fertilizer was added in those months. All of these differences were due to the change in loading of soluble P, which was the form of P in the added fertilizer.

Over the complete study year, the effect of not adding fertilizer was to shift from 803 kg of retained phosphorus to an estimated loss of 54 kg, all due to a drop in loading of soluble P from fertilizer (Figure 8). Given that this value of R_p may be an overestimate as described above, the loss of 54 kg may actually be smaller or even a positive value. The important point is that in the absence of fertilizer addition, imports and exports approximately balanced, indicating no phosphorus retention in the reservoir. With fertilizer addition, the P load in fertilizer (857 kg) explained all TP retained by sediments (840 kg as shown in Table 5), indicating that the fate of added P in fertilizer was the sediments. This result did not mean the reservoir was less effective at retaining P at low P loading rates compared to what it was at higher loading rates. It did mean that the reservoir had the capacity to absorb a large load of P over and above natural loads, mainly in sediments, and not release it downstream.

If the fate of phosphorus added in fertilizer is settlement in seston to sediments, there should be a natural record of the effect show up in sediment profiles. Indeed this was revealed in sediment cores examined for a companion report. J. Stockner (Ecometric Ltd. Pers. Comm.) showed that the influx of diatom frustules and associated phosphorus content increased by an order of magnitude between years before fertilization compared to years after fertilization, thus confirming a large effect of fertilization on sedimentation of seston containing phosphorus.

Table 8. Seasonal phosphorus import and export as measured in 2000-01 compared with predicted values if fertilizer was not added.

P source	P flux (kg/season unless otherwise indicated)											
	Spring			Summer			Fall			Winter		
	TDP	PP	TP	TDP	PP	TP	TDP	PP	TP	TDP	PP	TP
total inputs without fertilizer	230	102	331	229	61	290	121	30	151	67	16	83
total inputs with fertilizer	390	102	492	869	61	930	178	30	208	67	16	83
Total Exports	86	73	160	249	81	330	177	74	250	122	50	172
P retention without fertilizer	144	28.1	172	-19	-20	-40	-55	-43	-98	-55	-33	-88
P retention with fertilizer	304	28.1	332	621	-20	600	2	-43	-41	-55	-33	-88
Percent of P input retained without fertilizer	63%	28%	52%	-8.5%	-33%	-14%	-46%	-143%	-65%	-82%	-208%	-106%
Percent of P input retained with fertilizer	78%	28%	68%	71%	-33%	65%	1%	-143%	-20%	-82%	-208%	-106%

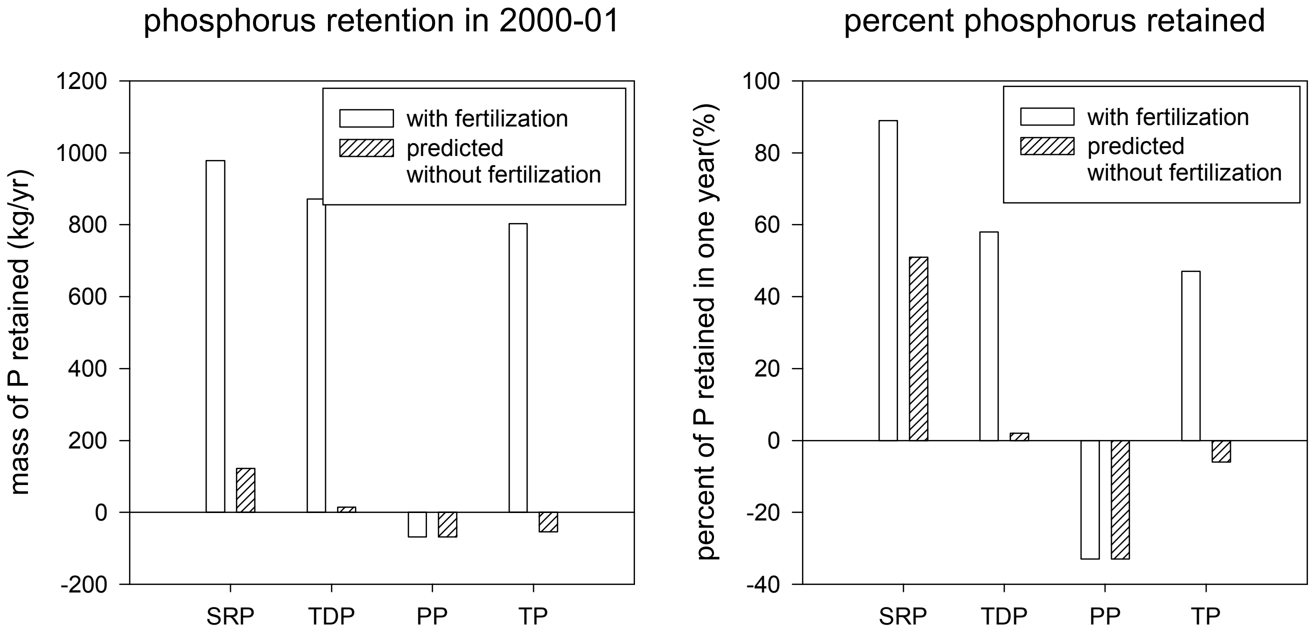

Figure 8. Phosphorus retained in 2000-01 compared with predicted retention if fertilizer was not added in 2000-01.

This result provides some insight into why survival and size-at-age of rainbow trout substantially increased during years of fertilization compared to years before fertilization as reported by Perrin and Stables (2000 and 2001). The survival of older and larger fish in years during fertilization was apparent by the presence of 4+ and older fish that were not present in the spring before fertilization and by the presence of 5+ and older fish that were not present in the fall before fertilization. Before fertilization, mean weight of 1+ fish did not increase over the growing season between spring and fall. Mean weight of the 2+ fish increased by 12% during the growing season before fertilization. In contrast, the 1+ and 2+ fish during fertilization gained 65% and 16% respectively over the spring through fall growing period. The result was that the mean weight of 2+ fish at the end of October during fertilization was 81 g compared to a mean weight of 69.6 g before fertilization. Perrin and Stables (2000) also reported that 89% of organisms ingested by rainbow trout in Wahleach Reservoir were aquatic insects while the remainder were of terrestrial origin. All of the aquatic insects have larval and pupal life stages that use the reservoir sediments, particularly in the littoral zone as food and habitat. Rainbow trout feed on these insects during episodic emergence of adults that rise through the water column. While fertilizer added to the reservoir can be rapidly taken up into phytoplankton and passed through the pelagic food web, the mass balance data suggest that most eventually settles to sediments. It does this via uptake and sedimentation in algal and zooplankton biomass that forms a large component of reservoir seston. Increased primary production must have increased rates of sedimentation of this seston, resulting in increased mass of sediments richer in nutrients that was present before fertilization. The result would be increased production of benthic fauna that supplies food to fish that rely on those invertebrates, particularly rainbow trout. This view is supported with evidence from Twin Lakes in the Fraser Valley where nutrient addition was linked to increased reproductive output, growth and yield of rainbow trout and to increased rates of emergence of insects used as food by rainbow trout (Johnston et al. 1999). Positive benthos response to nutrient addition has also been found in an oligotrophic lake in Newfoundland (Clarke et al. 1997), and from fertilization of oligotrophic lakes in the Canadian arctic (Jorgenson et al. 1992, Welch et al. 1988).

Nutrient flux calculations in reservoirs may be affected by the elevation of water withdrawal into the penstock. If a vertical gradient in nutrient concentration is present with higher concentrations at depth compared to those near the surface, hypolimnetic withdrawal may exacerbate nutrient export. In Wahleach Reservoir, the intake is located approximately 3 m off the reservoir bottom.

To examine a depth effect on P concentration in the water column, a single factor (depth) ANOVA was applied to P concentrations collected in May through October of 1997 through 1999 (n=128). No winter data were available for any years. Depth was stratified into two levels; one being the epilimnion (surface) and the other was the hypolimnion (bottom layers). Results in Table 9 showed no depth effect on TP or TDP concentration ($p>0.1$), which implied that depth of water withdrawal had no effect on export of the dissolved P fraction and on total P in spring and summer months. There was a depth effect on PP with greater concentrations at the surface than at the bottom ($p=0.03$). A decline of PP with depth indicated decomposition of a portion of P bound in sedimenting particles. Slightly higher TDP concentration at depth compared to surface values was evidence of increasing dissolved P concentration produced from decomposition of particulate P. It also indicated that water export calculations may reveal less PP and slightly more dissolved P than typical of surface water in spring and summer. Vertical differences, however, are likely to be small given the small differences in phosphorus concentrations shown in Table 9. Fluxes between particle sizes tended to balance, resulting in no depth effect on TP concentration in spring and summer months. We have no evidence to determine if the same was true in winter months.

Table 9. Mean concentration of phosphorus size fractions ± SE in Wahleach Reservoir in May through October of 1997 to 1999 and probability of a depth effect on P concentration.

P size fraction	Mean P concentration (±SE) in May – Oct 1997 through 1999.		depth effect (*p*)
	surface	Water depth of 20m	
Total dissolve P (TDP)	4.4 ± 0.2	4.9 ± 0.2	0.14
Particulate P (PP)	5.3 ± 0.4	4.2 ± 0.3	0.03
Total P (TP)	9.7 ± 0.4	9.1 ± 0.4	0.32

4.4 Phosphorus Budget: 1993 - 2000

Over the years 1993 through 2000, phosphorus loading to Wahleach Reservoir increased, mainly due to sequentially increased loads of fertilizer (Figure 9). Before fertilization, the TP load was <760 kg per year. The load increased sharply in 1995 due to more than a 40% increase in loading from upstream drainages and the addition of 375 kg of P in fertilizer. In 1995, P in fertilizer represented 26% of the complete phosphorus load but with rising fertilization rates every year after 1995, the P load in fertilizer increased to approximately 50% of the total load in 2000. The P load from fertilizer in 2000 was 857 kg compared to 856 kg estimated to have come from natural sources.

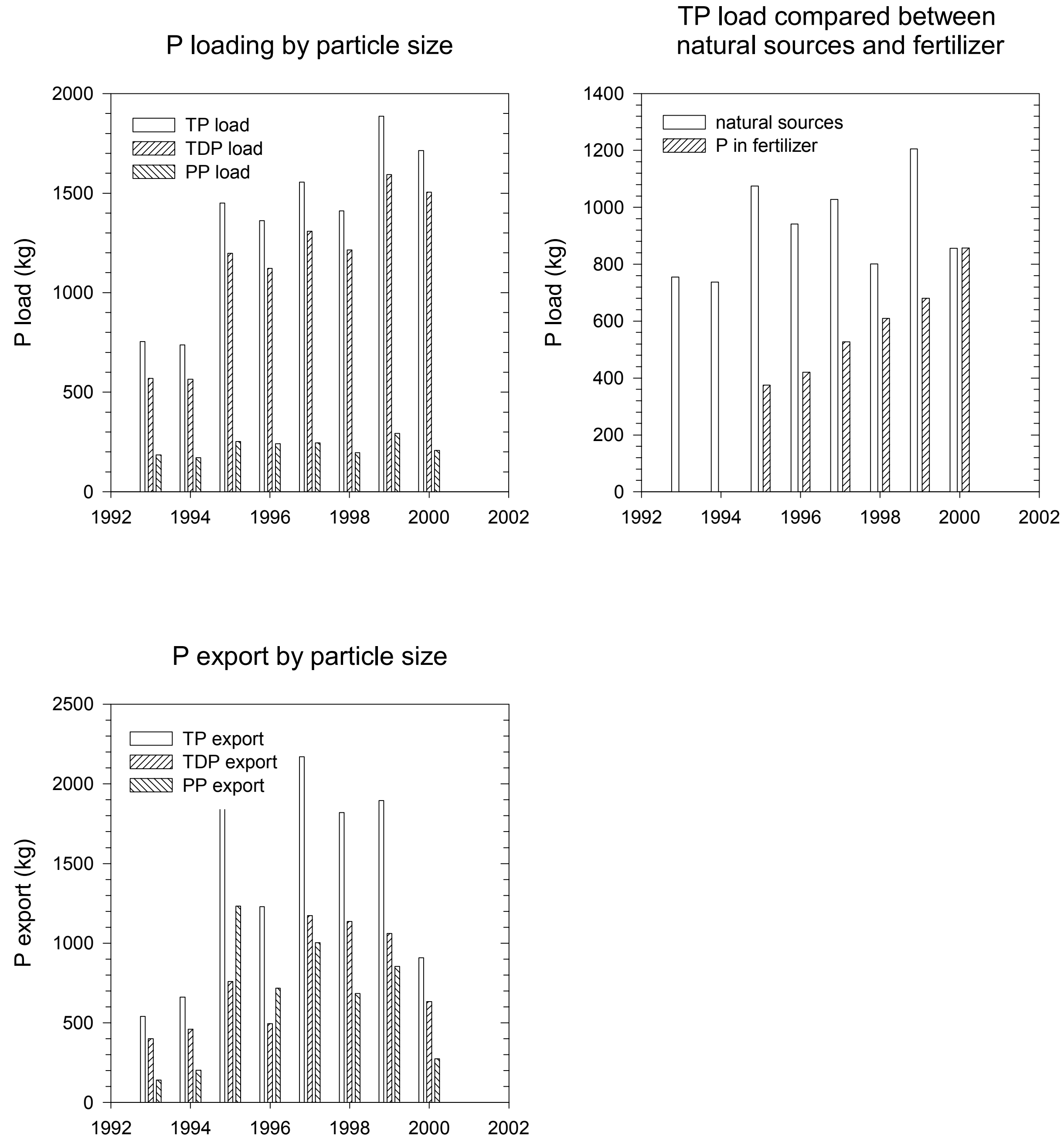

Figure 9. Phosphorus loading and export among all budget years examined in Wahleach Reservoir. P load is shown by particle size (top left) and it is partitioned between natural and fertilizer sources (top right). P export is shown by particle size (bottom).

The sequential increase in P loading from fertilizer in 1995 through 2000 was done to achieve a phosphorus load necessary to support *Daphnia* sp. (Perrin and Stables 2001). Because there were no guidelines or defined loading rates that could be used in early years of the project, P loads started at moderate levels and were adjusted higher each year. *Daphnia* sp. is an important food supply for kokanee, the target fish species for restoration activities in the reservoir. *Daphnia sp.* have a low body N:P ratio and they typically dominate zooplankton communities regardless of planktivore density when ambient seston that makes up food supplies also has a low N:P and a low C:P ratio (Hassett et al. 1997). DeMott and Gulati (1999) showed that high seston C:P that is typical of nutrient-deficient lakes can constrain *Daphnia sp*. abundance. In contrast, they also showed that zooplanktors with low P requirements, including *Bosmina spp*. show little relationship to seston C:P because of a much lower functional demand for P. Phosphorus demand by *Daphnia* sp. is high, even to the point where direct addition of soluble phosphorus to water supporting *Daphnia* sp. can increase its growth rate when ambient phytoplankton have a high N:P, a high C:P, and are P-deficient (Urabe et al. 1997). This change does not occur when phytoplankton is P-replete. This demand for P both in its soluble form in the water column and as P bound in phytoplankton is one reason why mesotrophic or eutrophic lakes will favour *Daphnia* sp. (Stockner and Shortreed 1983) but oligotrophic lakes and reservoirs do not favour *Daphnia sp*. (Stockner and MacIsaac 1996).

In Wahleach Reservoir, *Daphnia* sp. was not found above trace numbers before 1998 when TP loading from all sources was <1500 kg (<375 $mg \cdot m^{-2} \cdot yr^{-1}$) and the soluble fraction was not less than 87% of TP. In contrast, *Daphnia* sp. was abundant at higher TP loading rates in later years. In 1997 and 1998, kokanee were present from annual stocking but relied on a less favoured food supply of aquatic insects, small zooplankton, beetles, and invertebrates of terrestrial origin (Perrin and Stables 2001). Mean growing season (May through October) densities of *Daphnia* sp. increased from trace numbers to 0.1 animals/L in 1998 and 1999 when TP loading from all sources was 1400 – 1900 kg (350 $mg \cdot m^{-2} \cdot yr^{-1}$ to 475 $mg \cdot m^{-2} \cdot yr^{-1}$). *Daphnia* sp. was found in stomachs of kokanee even at these low prey densities. With a subsequent TP load of 428 $mg \cdot m^{-2} \cdot yr^{-1}$ in 2000, mean growing season density of *Daphnia* sp. jumped to 3.3 animals/L and the peak density in August was 10 animals/L (Perrin and Stables 2001). Kokanee preyed on *Daphnia* sp almost exclusively when *Daphnia* density was ≥2.5 animals/L. These time course trends in *Daphnia* density suggest that a repeated TP load from all sources of 425-475 $mgP \cdot m^{-2} \cdot yr^{-1}$ (1,700 – 1,900 kg) was required to provide a sustained population of *Daphnia* sp. as food for kokanee in Wahleach Reservoir. Close to 90% of this total load or 380-430 $mgP \cdot m^{-2} \cdot yr^{-1}$ (1,520 – 1,720 kg) must be in a soluble form based on the relative contribution of TDP to TP shown in Figure 9.

In this study, annual TP loads from sources other than fertilizer were estimated to be 172-288 $mg \cdot m^{-2} \cdot yr^{-1}$ (688 – 1,152 kg), which were well below these levels apparently necessary to support *Daphnia* sp. The difference between necessary TP loads to support *Daphnia* and natural loads in the absence of fertilizer addition was large enough to suggest that continued fertilization is required to support *Daphnia* sp. in densities that can be exploited by kokanee. If fertilization is not continued, we may hypothesize that a decline of kokanee abundance from present levels will occur in relation to an expected drop in *Daphnia* density. Whether or not this outcome actually occurs can only be determined with ongoing measurements of zooplankton abundance and composition and fish abundance, composition, and spawning success.

It is possible that an increase in natural loading of phosphorus may occur if nutrient return from sediments becomes a significant phosphorus source. If this occurs, fertilizer addition may be reduced or applied every other year rather than every year to meet an objective of supporting a sustained population of kokanee. The likelihood of substantial phosphorus return from sediments is remote, however, because it would require oxygen depletion at the sediment – water interface to occur at some time during the year. While this process has never been found in Wahleach Reservoir, it may occur as sedimenting organic matter accumulates over more years of fertilization. If fertilization does not continue, the chance of episodic oxygen depletion leading to seasonal phosphorus release from sediments is remote. Only continued monitoring of water column nutrient concentrations and electrochemical parameters would provide the data necessary to determine if this will occur or not in future years.

The phosphorus loading rate combined from all sources and presented here is difficult to compare to other studies because it includes P from natural inputs as well as fertilizer. Other related studies have typically reported only P load from fertilizer. During fertilization of coastal lakes, Stockner and MacIsaac (1996) used P loading rates of 66 – 100 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ that was found to double or triple primary production. Nutrient loading to Kootenay Lake, British Columbia, is being used to restore the historical abundance of kokanee (Ashley et al. 1999). P loading from fertilizer in this case replicated pre-impoundment phosphorus loads (271 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$). Fertilization of other oligotrophic lakes has included P loading rates of 102 – 164 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ (Langeland and Reinertsen 1982), 27 – 100 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ (Clarke et al. 1997), and 100 – 600 $mgP{\cdot}m^{-2}{\cdot}yr^{-1}$ (Johnston et al. 1999).

The increased phosphorus loading rates that started with fertilization in 1995 were accompanied by a large export of phosphorus from the reservoir, also beginning in 1995. Estimates in Figure 9 show that TP loading increased from 737 kg in 1994 to 1450 kg in 1995, an increase of 713 kg between the two years. Exports increased from 662 kg to 1987 kg over the same time, an increase of 1325 kg between the two years. The result was an estimated net loss of TP in 1995 amounting to 537 kg of phosphorus or 37% of the annual TP load (Figure 10). Figure 10 shows that while a small retention of TP was recorded in 1996, net losses were again found in 1997 through 1999.

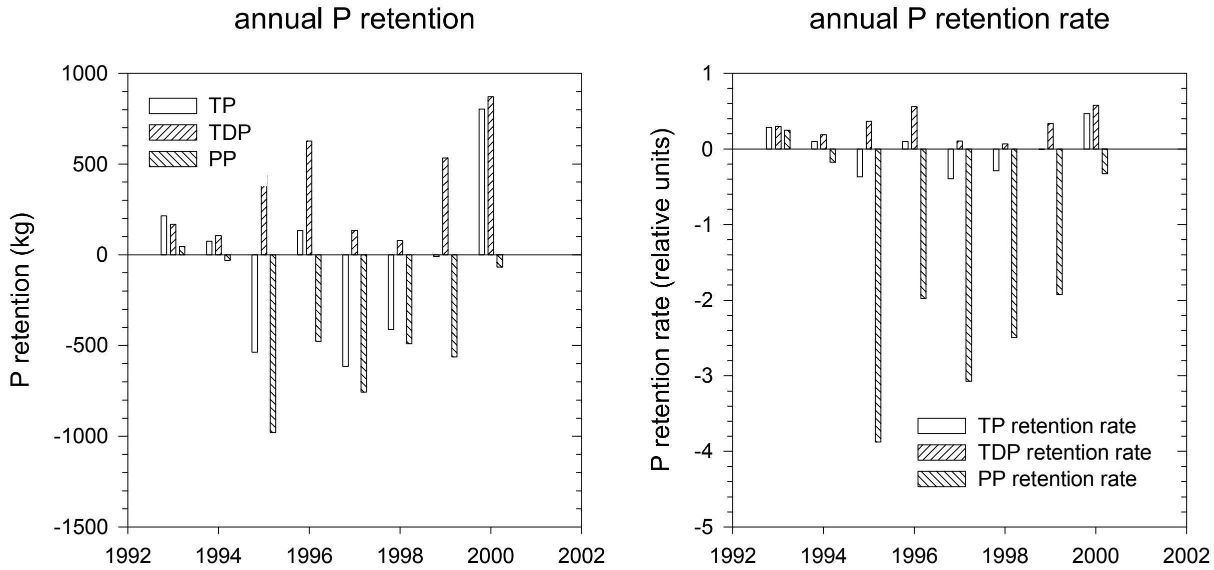

Figure 10. Annual mass of P retained and annual P retention rate determined among all budget years in Wahleach Reservoir. Negative values indicate losses of phosphorus.

Annual TP losses of this magnitude are unusual in an oligotrophic system like Wahleach Reservoir. In order for a significant loss of TP to occur, there must be release of phosphorus from sediment, which is the largest sink for retained phosphorus. P release can occur following a history of nutrient loading (Carignan and Lean 1991) but it is favoured mainly during oxygen depletion and reducing conditions (low redox potential) that decouples iron – phosphorus complexes. P release by oxic sediments that are likely present in Wahleach Reservoir has been experimentally shown to be negligible (Bostrom and Pettersson 1982). While diffusive P return can occur (Twinch and Peters 1984), it is commonly found in eutrophic conditions (Eckert et al. 1997). A decline in oxygen concentrations over the water profile has been detected annually after fertilization in Wahleach Reservoir but seasonal anoxia does not occur (Perrin and Stables 2000). Hence, there are no electrochemical conditions in the reservoir that would favour phosphorus release. Without some evidence to the contrary, assumptions used in calculations showing large nutrient loss may not be valid. The main difference between the multi-year budget calculations and those used for 2000 – 2001 was the assumption that inflow phosphorus concentrations measured in 2000 could be applied to earlier years. In fact there may be substantial time course variation in these data that would greatly affect mass balance calculations.

5.0 CONCLUSIONS

This project has contributed insight into fluxes and fate of phosphorus introduced to Wahleach Reservoir from both natural and fertilizer sources. Important conclusions are listed as follows:

- Mean total phosphorus (TP) concentrations in inflow and outflow water were $<6\ \mu g \cdot L^{-1}$ in 2000-01. Phosphorus concentrations in this range are low and are typical of nutrient deficient waters of southwestern British Columbia. In all seasons of 2000-01, TP concentrations in reservoir outflow water were not significantly different from those in inflow water ($P>0.2$), indicating no effect of processes in the reservoir and fertilizer addition on modifying TP concentration between inflow and outflow water. Soluble reactive phosphorus (SRP) concentrations were significantly lower ($p=0.04$) in outflow water (mean annual concentration of $0.7\ \mu g \cdot L^{-1}$) than in inflows (mean annual concentration of $1.2\ \mu g \cdot L^{-1}$) due to uptake by phytoplankton.
- Over the 2000-01 year, more than 70% of TP was comprised of soluble phosphorus. Particulate phosphorus (PP) in inflow streams was only 20-30% of TP, occurring in concentrations $<2\ \mu g \cdot L^{-1}$ at all times. These low PP concentrations indicate slow weathering of what are mainly granitic parent materials in the headwaters.
- Mean phosphorus sedimentation rates in the reservoir, measured using sediment traps ranged from $13\ \mu gP \cdot m^{-2} \cdot d^{-1}$ (shallow array in winter) to $84\ \mu gP \cdot m^{-2} \cdot d^{-1}$ (shallow array in summer). Rates were lowest in winter, they increased in spring to reach a maximum in summer and they declined in the fall. Particle sedimentation was consistently greater with increasing depth but this was not found in P sedimentation rates. These differences were small but indicate some loss of P from particles due to decomposition during sedimentation.
- Comparison of measured sedimentation rates from traps to those determined from mass balance calculations indicated that trap techniques underestimated phosphorus sedimentation by approximately 12 times. The error was attributed to decomposition in the sediment traps during deployment.
- There was no depth effect on TP or TDP concentration ($p>0.1$) in the reservoir. This finding implied that depth of water withdrawal had no effect on TP or TDP fluxes in spring and summer months**.** Data were not available to explore depth effects in fall and winter. There was a depth effect on particulate phosphorus (PP) concentration in spring and summer with greater concentrations at the surface than at the bottom ($P=0.03$). A decline of PP concentration with depth indicated decomposition of a portion of P bound in sedimenting particles, thus supporting the sediment trap data. Regardless of depth effects on discrete particle sizes of phosphorus, fluxes between particle sizes tended to balance, resulting in no depth effect on TP concentration in spring and summer months.
- In 2000-01 there was a net P retention of 803 kg ($201\ mgP \cdot m^{-2} \cdot yr^{-1}$) or 47% of TP loading. This net phosphorus retention was due to high retention rates of the soluble P fractions (89% of SRP and 58% of TDP retained) while there was a 33% net loss of the particulate phosphorus load. High retention of soluble fractions was attributed to uptake by phytoplankton to form larger particle sizes. The net retention of TP was due to very high

retention of soluble P in the spring and summer that exceeded losses of soluble and particulate P in fall and winter.

- Fluvial inputs of phosphorus and P in fertilizer represented 97% of TP loading in 2000-01. The minor phosphorus sources included atmospheric deposition and P loading in fish stocked in 2000. P loading in fertilizer represented half of the TP load but it represented 57% of the load of soluble P. If we only consider the loading of simple inorganic phosphate (SRP), which is most available for biological uptake, P in fertilizer represented 78% of that load from all sources. This value indicated considerable importance of the fertilizer in contributing to the pool of P for biological production in the reservoir in 2000-2001.
- A total of 840 kg of phosphorus (210 $mg \cdot m^{-2} \cdot yr^{-1}$) was retained in sediments. This amount was greater than net retention because it accounted for loss of phosphorus from the water column over the budget year. The amount was calculated by difference between total phosphorus retention and amounts of phosphorus retained in fish populations (2% of total retained P) and in water between the start and finish of the budget year (-6.6% of total retained P). Clearly, reservoir sediment was the main sink for retained phosphorus.
- Because TP loading in fertilizer could be distinguished from TP loading from natural sources in mass transport calculations, TP retention and loss was explored to examine the effect of the absence of fertilizer addition on P fluxes. In the absence of fertilizer addition imports and exports approximately balanced, indicating no phosphorus retention in the reservoir. With fertilizer addition, the P load in fertilizer explained all TP retained by sediments, indicating that the fate of added P in fertilizer was the sediments. This finding suggested that the reservoir had a capacity to absorb a large load of P over and above natural loads, mainly in sediments, and not release it downstream.
- Retention of the fertilizer load to sediments provided insight into why survival and size-at-age of rainbow trout substantially increased during years of fertilization compared to years before fertilization. Perrin and Stables (2000) reported that 89% of organisms ingested by rainbow trout in Wahleach Reservoir were aquatic insects while the remainder were of terrestrial origin. All of the aquatic insects have larval and pupal life stages that use the reservoir sediments, particularly in the littoral zone as food and habitat. During episodic emergence rainbow trout feed on these insects. While fertilizer added to the reservoir is rapidly taken up into phytoplankton and passed through the pelagic food web, most eventually settles to sediments. It does this via uptake and sedimentation in algal and zooplankton biomass that forms a large component of reservoir seston. Increased primary production must have increased rates of sedimentation of this seston, resulting in increased mass of sediments richer in nutrients that was present before fertilization. Findings from a companion paleolimnological study support this hypothesis. Nutrient-rich sediments can lead to increased production of benthic fauna that supplies food to fish.
- Over the years 1993 through 2000, phosphorus loading to Wahleach Reservoir increased, mainly due to sequentially increased loads of fertilizer. Before fertilization, the TP load was <760 kg per year. The load increased sharply in 1995 due to more than a 40% increase in loading from upstream drainages and the addition of 375 kg of P in fertilizer. In 1995, P in fertilizer represented 26% of the complete phosphorus load but with rising fertilization rates

every year after 1995, the P load in fertilizer increased to approximately 50% of the total load in 2000.

- The sequential increase in P loading from fertilizer in 1995 through 2000 was done to achieve a phosphorus load necessary to support *Daphnia* sp, the preferred food of kokanee that is the target species of fish that has been restored in Wahleach Reservoir. Comparison of time course change in TP loading with *Daphnia* density showed that a repeated TP load from all sources of 425-475 $mgP \cdot m^{-2} \cdot yr^{-1}$ was required to provide a sustained population of *Daphnia* sp. Close to 90% of this total load or 380-430 $mgP \cdot m^{-2} \cdot yr^{-1}$ must be in a soluble form. Half of this load was provided by fertilization in 2000-01.
- Annual TP loads from sources other than fertilizer in 1993 through 2000 were estimated to be 172-288 $mg \cdot m^{-2} \cdot yr^{-1}$, which was well below the levels found necessary to support *Daphnia* sp. The difference between necessary TP loads to support Daphnia and natural loads in the absence of fertilizer addition was large enough to suggest that continued fertilization is required to support a desirable food supply for kokanee. If fertilization is not continued, a decline of kokanee abundance from present levels may be expected in relation to a potential drop in *Daphnia* density. Whether or not this outcome actually occurs can only be determined with measurements of the abundance and composition of zooplankton and fish after fertilization is stopped.
- The increased phosphorus loading rates that started with fertilization in 1995 were accompanied by an even larger export of phosphorus from the reservoir, also beginning in 1995. The result was a net loss of TP in 1995 amounting to 537 kg of phosphorus or 37% of the annual TP load. While a small retention of TP was recorded in 1996, net losses were again determined for 1997 through 1999. Annual TP losses of this magnitude are suspect in an oligotrophic system like Wahleach Reservoir and were not conclusive. In order for a significant loss of TP to occur, there must be release of phosphorus from sediment, which is the largest sink for retained phosphorus. P release can occur following a history of nutrient loading but it is favoured mainly during oxygen depletion and reducing conditions that do not exist in Wahleach Reservoir. There are no electrochemical conditions in the reservoir that would favour phosphorus release. Without some evidence to the contrary, assumptions used in calculations showing large nutrient loss must be regarded as incorrect. The main difference between the multi-year budget calculations and those used for 2000 – 2001 was the assumption that inflow phosphorus concentrations measured in 2000 could be applied to earlier years. In fact there may be substantial time course variation in these data that would greatly affect mass balance calculations. Because of this uncertainty, the mulit-year phosphorus budget calculations were found to contain considerable error and were not examined further.

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APPENDIX A: History of biological and hydrological manipulations and surveys in Wahleach Reservoir.

Date	Survey information	Development information
Before 1926		Jones Lake barren of fish
1926		20,000 rainbow eggs stocked
1936		25,000 kokanee eyed eggs from Nelson hatchery stocked
1937		25,000 kokanee eyed eggs from Nelson hatchery stocked
1938		25,000 kokanee eyed eggs from Nelson hatchery stocked
1939	First kokanee spawners found.	
Jan, 1950		Swan, Rhoades, Wooster engineering consultants complete plan for development of Wahleach Reservoir for BC Electric.
Aug 30, 1950	gill netting collected 9 rainbow and 10 kokanee. Stomachs contained insect larvae, mysids. Described macrophytes and benthic invertebrates at north end. Lake morphometry and stream inflows described. Good spawning in 4 streams. Single outlet stream filled with debris and mud bottom. Secchi=4.4 m.; lake TDS=52 mg•L^{-1} ; lake was temperature stratified; max depth=18.6 m; mean depth=6 m; vol=17,195,429 m^3.	
1953		Wahleach Dam construction complete and reservoir at full pool. Max depth=26.5 m; max storage vol=60,683,100 m^3. Boulder Creek is diverted into Wahleach Reservoir.
1954		Spawning channel for pink salmon is built in lower Wahleach Creek, 100 m u/s of confluence with the Fraser River. Minimum flow of 0.5-0.85 m^3·s^{-1} is released via a siphon at the dam during spawning season.
Jan, 1958		Boyd Barker and Bert Hall purchase a lease for the Restmore Lodge at Laidlaw and several cabins and boats at Jones L. from the Barber estate. The Barber family owned a successful mattress company in Vancouver and the estate owned land around Laidlaw and the resort area at Jones Lake.

Date	Survey information	Development information
1958-59		Access limited to early morning and evening in designated vehicles. Logging trucks use road during day. A fee was paid to Barker and Hall for use of the road.
1959		BC Electric holds flooding rights up to elevation of 632.7 m.
1959 - 65		discussion ongoing regarding problem of public passing private land to access lake, permission to use BC Hydro road beyond public land, and to provide public land on shore of Jones lake for routine access.
May and June, 1964	Creel survey completed: 2.2 fish/h in June and 3.7 fish/h in May.	
1967		Eric Isaacson buys lease to Jones Lake Resorts from Barker and Hall. B.C. Government purchases rights to the access road. User fees no longer collected for use of the road.
March, 1969		Mysid introduction proposed
April, 1969		50,000 Mysids transferred from Sumas R. to Jones Lake. No follow-up assessment.
Fall, 1969	1300 kokanee spawners in Jones Cr. and 400 in Flat Creek. No fish in Boulder Creek.	
May, 1970	Lake survey completed: mean depth=9.87 m; max depth=18.9 m; Secchi=5.7 m; all drainages visible from lake have been clear cut.	
Fall, 1970	Est. cumulative count of 6000 kokanee in Jones Cr. and 500 - 1000 in Flat Creek. No fish in Boulder Creek.	
Apr - Jul, 1970.	Creel survey; 1331 kokanee and 482 rainbow caught: 0.6 kokanee/h and 0.22 rainbow/h.	
May, 1973		Whonnock Lumber fined for sediment transport into Jones Creek caused by road failure and inadequate culverts.
Aug, 1973	Spawning stream survey; Only Glacier, Jones, and Flat Creeks suitable. Flat Cr. is mainly boulders with sand patches but lots of cover. Other two streams are mainly gravel.	
Fall, 1973	Peak count of 2573 kokanee spawners in Flat and Jones Cr. Cumulative count of 6622. No fish in Boulder Creek.	
Sep, 1977	Decline in kokanee numbers recognized and kokanee stocking is proposed.	

Date	Survey information	Development information
1975 - 78		larger than usual draw-down in spring. Low water years.
May, 1978	Sapperton Fish and Game Club question unusually large draw-down.	
Sep, 1978	Cumulative spawner count of 900 kokanee but completed on only two dates. No fish in Flat Creek or Boulder Creek. Anglers report large declines in kokanee catch but rainbow numbers remain high.	
1979		Eric Isaacson sells resort lease to private interests.
Sep, 1979	Spawning stream survey; good spawning habitat available for kokanee.	
Sep - Oct, 1979	Peak count of 2,450 kokanee spawners. Cumulative count of 4.955 in Flat, Jones and Glacier Cr. No fish in Boulder Creek. Anglers complain of very low catches for kokanee and rainbow.	
Jan 1980	ice fishing for rainbow reported to be good. Sizes are 20-25 cm.	
Aug 1980		Waste water discharge permit application submitted by Wahleach (Jones L.) Resorts Ltd. Application refused by Fisheries Branch because of presence of chlorine in effluent.
Apr 1981	Large accumulation of logs and sand which could prevent fish passage noted in deltas of Flat Cr. and Boulder Cr. at draw-down.	
Sep 1981	Peak count of 2,280 kokanee	
Sep 1981	Lake survey completed. max depth=29 m; mean depth=13.4 m; Secchi=6 m; second growth forests well advanced on drainages visible from lake; TDS 29-38 mg•L^{-1}; 18 kokanee and 45 rainbow captured in 5 gill nets. No fish caught in 3 minnow traps.	
Fall 1982		Rip rap placed in Boulder Creek to protect recreation site
Aug 1987	66 rainbow and 6 kokanee captured in 2 gill nets set overnight.	
Oct 1992	41 rainbow and 10 kokanee captured in 2 gill nets set overnight.	
Jun - Oct 1993	First year of pre-fertilization data collection: water chem, phytoplankton, zooplankton, gill netting, stomach content analysis, hydroacoustics, trawl sampling, spawner survey	Wahleach spillway reconstructed; crest height of spillway raised. Spawning channel diversion weir replaced.
May - Nov	Second year of pre-fertilization data collection:	

Date	Survey information	Development information
1994	water chem, phytoplankton, zooplankton, minnow trapping, gill netting, stomach content analysis, hydroacoustics, trawl sampling, spawner survey	
Jul - Oct 1995	Monitoring of fertilizer addition, water chem, phytoplankton, zooplankton, stickleback, kokanee, and rainbow trout. Fish stomach content analysis and spawner survey also completed.	High level fertilization (July 12 - Sep 18) producing a 7 times increase in phytoplankton chlorophyll-a and an 8 times increase in the density of zooplankton
Nov. 1995		Lower Jones Creek spawning channel destroyed by debris torrent
Jun - Oct 1996	Monitoring of fertilizer addition, water chem, phytoplankton, zooplankton, stickleback, kokanee, and rainbow trout. Fish stomach content analysis and spawner survey also completed.	Graded fertilization (Jun 3 - Sep 16) producing a 4 times increase in phytoplankton chlorophyll-a and a 3.5 times increase in the density of zooplankton
May – Oct 1997	Stickleback abundance reaches a peak of 6 million fish.	Stocking with 5000 kokanee and 3000 sterile cutthroat trout. Fertilization continues.
May and June 1998		Stocking with 2,010 sterile rainbow trout on June 25, 2,997 sterile cutthroat on June 17, and 50,000 kokanee on May 28. Fertilization continues
Sep 1998		Stocking with 2,114 sterile cutthroat trout on Sep 8. Half were from Alouette net pens, half from Sayres L. net pens.
May – Oct 1998	Monitoring of fertilizer addition, water chem, phyoplankton, zooplankton, stickleback, kokanee, cutthroat and rainbow trout. Fish stomach content analysis also completed. Stickleback abundance declines to 4.3 million fish. Cutthroat and rainbow at trophy size. Cutthroat all with stickleback in stomachs	Graded fertilization (May - Sep 20) producing an increase in phytoplankton chlorophyll-a and zooplankton density. Angler success increases to over 2 fish per hour. Media attention to Wahleach increases with newspaper and magazine articles.
May – Oct 1999	Monitoring and fertilization continues. Stickleback abundance drops to 450,000 fish and kokanee abundance recorded at 24,500 fish. Trophy sized cutthroat remain, all with stickleback in their stomachs.	10,764 CT and 51,682 kokanee stocked in the spring. Fertilization continues. Angler success maintained at 2 fish per hour.
May - Dec 2000	Stickleback abundance drops further and kokanee abundance increases over that in	Fertilization continues at a rate of 225.43 mgP·m^{-2} which is an increase

Date	Survey information	Development information
	1999. Surveys limited to fish sampling in June (gill netting and minnow traps) and October (gill netting, minnow traps, trawl, hydroacoustics for population estimates). Sampling for determination of a one-year phosphorus budget starts in spring and will continue throughout the following year. Three age classes of kokanee now appear established in the reservoir. A total of 30 kokanee spawners were counted in Boulder Creek in September, representing a 4th age class. These fish were from the brood that was stocked in 1997.	from the rate of 181 $mgP \cdot m^{-2}$ applied in 1999, 162 $mgP \cdot m^{-2}$ applied in 1998 and 141 $mgP \cdot m^{-2}$ applied in 1997. 52,000 kokanee and 3,045 triploided cutthroat trout stocked on June 8 and June 7 respectively.
May – Dec 2001	Field sampling for a phosphorus budget was completed and reporting is ongoing. A creel survey was completed in July through September and reporting is ongoing. A kokanee spawner survey counted several hundred kokanee using all inflow streams, indicating good survival of the year class that was stocked in 1998. Spawner survey reporting is ongoing.	Fertilization continues at a rate of 232 $mgP \cdot m^{-2}$ which is an increase from the rate of 225 $mgP \cdot m^{-2}$ applied in 2000, 181 $mgP \cdot m^{-2}$ applied in 1999, 162 $mgP \cdot m^{-2}$ applied in 1998 and 141 $mgP \cdot m^{-2}$ applied in 1997. No kokanee stocking occurred in 2001 and 1000 triploided cutthroat trout were stocked in early June.

RAW DATA APPENDICES

Raw data appendices are available on CD accompanying this report.