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**ARROW LAKES RESERVOIR FERTILIZATION EXPERIMENT, YEARS 4 AND 5
(2002 AND 2003)**

by

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The ministry's vision is a clean, healthy and naturally diverse environment that enriches people's lives, now and in the future.

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ARROW LAKES RESERVOIR FERTILIZATION EXPERIMENT, YEARS 4 AND 5 (2002 AND 2003) ABSTRACT

This report presents the fourth and fifth year (2002 and 2003, respectively) of a five-year fertilization experiment on the Arrow Lakes Reservoir. The goal of the experiment was to increase kokanee populations impacted from hydroelectric development on the Arrow Lakes Reservoir. The impacts resulted in declining stocks of kokanee, a native land-locked sockeye salmon (*Oncorhynchus nerka*), a key species of the ecosystem.

Arrow Lakes Reservoir, located in southeastern British Columbia, has undergone experimental fertilization since 1999. It is modelled after the successful Kootenay Lake fertilization experiment. The amount of fertilizer added in 2002 and 2003 was similar to the previous three years. Phosphorus loading from fertilizer was 52.8 metric tons and nitrogen loading from fertilizer was 268 metric tons. As in previous years, fertilizer additions occurred between the end of April and the beginning of September.

Surface temperatures were generally warmer in 2003 than in 2002 in the Arrow Lakes Reservoir from May to September.

Local tributary flows to Arrow Lakes Reservoir in 2002 and 2003 were generally less than average, however not as low as had occurred in 2001.

Water chemistry parameters in select rivers and streams were similar to previous years results, except for dissolved inorganic nitrogen (DIN) concentrations which were significantly less in 2001, 2002 and 2003. The reduced snow pack in 2001 and 2003 would explain the lower concentrations of DIN. The natural load of DIN to the Arrow system ranged from 7200 tonnes in 1997 to 4500 tonnes in 2003; these results coincide with the decrease in DIN measurements from water samples taken in the reservoir during this period.

Water chemistry parameters in the reservoir were similar to previous years of study except for a few exceptions. Seasonal averages of total phosphorus ranged from 2.11 to 7.42 µg/L from 1997 through 2003 in the entire reservoir which were indicative of oligo-mesotrophic conditions. Dissolved inorganic nitrogen concentrations have decreased in 2002 and 2003 compared to previous years. These results indicate that the surface waters in Arrow Lakes Reservoir were approaching nitrogen limitation. Results from the 2003 discrete profile series indicate nitrate concentrations decreased significantly below 25 µg/L (which is the concentration where nitrate is considered limiting to phytoplankton) between June and July at stations in Upper Arrow and Lower Arrow. Nitrogen to phosphorus ratios (weight:weight) were also low during these months indicating that the surface waters were nitrogen deficient. These results indicated that the nitrogen to phosphorus blends of fertilizer added to the reservoir need to be fine tuned and closely monitored on a weekly basis in future years of nutrient addition.

Phytoplankton results shifted during 2002 and 2003 compared to previous years. During 2002, there was a co-dominance of potentially 'inedible' diatoms (*Fragilaria* spp. and

Diatoma) and ‘greens’ (*Ulothrix*). Large diatom populations occurred in 2003 and these results indicate it may be necessary to alter the frequency and amounts of weekly loads of nitrogen and phosphorus in future years to prevent the growth of inedible diatoms.

Zooplankton density in 2002 and 2003, as in previous years, indicated higher densities in Lower Arrow than in Upper Arrow. Copepods and other Cladocera (mainly tiny specimens such as *Bosmina* sp.) had distinct peaks, higher than in previous years, while *Daphnia* was not present in higher numbers particularly in Upper Arrow. This density shift in favour to smaller cladocerans was mirrored in a weak biomass increase. In Upper Arrow, total zooplankton biomass decreased from 1999 to 2002, and in 2003 increased slightly, while in Lower Arrow the biomass decreased from 2000-2002. In Lower Arrow the majority of biomass was comprised of *Daphnia* throughout the study period except in 2002, while in Upper Arrow the total biomass was comprised of copepods from 2000-2003.

The decrease in zooplankton density in 2002 could be explained by the heavy grazing pressure caused by the sharp increase in kokanee numbers. Furthermore, the abundance of *M. relictus*, another predator of zooplankton, has increased since fertilization began in 1999. The increase of *M. relictus* increased predation pressure on larger zooplankton such as *Daphnia* and had an impact on its density and biomass. Since *Daphnia* is the preferred prey of both kokanee and mysids, predation may be suppressing the standing stock biomass of *Daphnia*. The shift in phytoplankton species to a higher biomass of inedible diatoms also could have affected the zooplankton density and biomass.

Since 1999, mysid densities have increased, reaching a number similar to that of more productive lakes. The annual average mysid density and biomass data in 2002 and 2003 (deep stations) suggests that Upper Arrow was more productive than Lower Arrow. In previous years, productivity was higher in Lower Arrow from 1997 to 2001. The trend of higher mysid productivity in Upper Arrow began in 2002 and continued in 2003.

Kokanee densities in 2002 ranged from 300 – 1450 fish·ha⁻¹ in October in Upper Arrow compared with 300–1000 fish·ha⁻¹ in 2001. Densities in Lower Arrow ranged from 500 to 3750 fish·ha⁻¹ in 2002 compared with 500 – 2621 fish·ha⁻¹ in 2001. In Upper Arrow both age 0+ and age 1-3+ fish densities were consistently higher in the lower half of the basin as in 2001. The most notable change since fertilization began was the low number of age 1-3+ fish in the middle of the basin from Halfway River south to Nakusp at only 100 fish·ha⁻¹. These densities were more typical of pre-fertilization densities in the same area. Compared to Upper Arrow, kokanee densities were again higher and more variable in Lower Arrow. Similar to 2001 the small basins between the Narrows and Lower Arrow had very high fry densities at 1300–3100 fish·ha⁻¹. In the main part of Lower Arrow, kokanee fry densities were comparable to Upper Arrow but age 1-3 densities were notably higher. This was supported by trawl sampling which indicated that age 2 fish were more abundant in Lower Arrow. Mean kokanee densities in October 2002 were 651 and 856 fish·ha⁻¹ for Upper and Lower Arrow, respectively.

Kokanee densities in 2003 ranged from 184-629 fish·ha⁻¹ in Upper Arrow, and from 173-938 fish·ha⁻¹ in Lower Arrow. In Upper Arrow both age 0+ and age 1-3+ fish densities

were consistently higher in the lower half of the basin as in 2001. This was in contrast to 2002 when the highest densities of all age groups were found near the fertilization zone. In Lower Arrow age 0+ fish densities, as in previous years, were highest in the narrows and lowest mid-basin. The distribution of age 1-3+ fish in Lower Arrow has changed the last three years from highest numbers at the upper end in 2001, evenly distributed in 2002 and congregated in the lower half of the basin in 2003.

The 2002 Upper Arrow kokanee escapements (263,000) of index tributaries were higher than in 2000 and 2001, (177,000 and 198,000) as well as higher than recorded escapements in the 1990s. The 2002 Lower Arrow escapements (340,500) of index tributaries were higher than 2000 but lower than 2001 (248,500 and 405,000). The 2003 escapement estimates were incomplete due to the serious fire hazard that prevented aerial estimates to be conducted, however the escapement at the Hill Creek spawning channel was higher than 2002 and 2001 but lower than 2002.

Size-at-maturity of Hill Creek spawners decreased slightly in 2001 and more so in 2002, most likely reflecting a density growth response since numbers in the lake have been increased dramatically. The size of 2003 spawners was comparable to the sizes observed in the 1980s and early 1990s. The 2001 data was the first indication of a density dependent growth response and the 2002 data indicated size of fish should decrease as numbers increase. The growth curves for Hill Creek spawners illustrated changes from rapid growth during initial years of fertilization followed by a decline as time advanced.

A major shift in age at maturity of Hill Creek spawners was initially detected in 2000 and length frequency analysis and age data indicated that ages 2+ and 3+ were present in the 2001 spawning population. Prior to 2000, age-at-maturity had been confirmed as predominately age 3+. Age data for 2000 and 2001 Hill Creek kokanee comprised of equal numbers of age 2+ and 3+. No age data was available for 2002, however the size and age frequency analysis of trawl caught fish suggested a mix of ages 2+ and 3+. The 2003 data was determined as age 3+ to be the primary age at spawning based on analysis of size and age of the trawl caught fish.

Kokanee data collected through 2003 indicated a change in the kokanee population has occurred. Higher escapements, increased growth, higher fecundity, higher fry-to-adult survival rates, and spawner-recruit ratios > 1 all support improved growing conditions now exist within the reservoir.

Results of the fourth and fifth year of the Arrow Lakes Reservoir fertilization experiment indicate that kokanee benefited from nutrient addition since 1999. Phytoplankton biomass and nitrogen to phosphorus results need to be closely monitored in order to fine-tune nutrient loading to the reservoir in future years. A continued adaptive management approach needs to be applied to the Arrow Lakes Reservoir to ensure that the preferred food of kokanee is available.

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CHAPTER 1

INTRODUCTION – ARROW LAKES RESERVOIR FERTILIZATION EXPERIMENT, YEARS 4 AND 5 (2002 and 2003)

by

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Introduction

This report describes the fourth and fifth year (2002 and 2003) of a five-year (1999-2003) fertilization experiment on the Arrow Lakes Reservoir, with the results and analysis of monitoring of physical limnology, water chemistry, phytoplankton, zooplankton, Mysid shrimp and kokanee. Concern over the dramatic decline in kokanee, a landlocked sockeye salmon (*Oncorhynchus nerka*) and keystone of the local ecosystem, resulted in a comprehensive study of the Upper and Lower Arrow Lakes Reservoir commencing in 1997. Funding continued to be provided by the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP), with additional funding from the B.C. Ministry of Water Land and Air Protection (MWLAP), presently Ministry of Environment (MoE), and continued funding provided by the Columbia Power Corporation (CPC). During June through October of 2003, the Kootenai Tribe of Idaho (KTOI) provided funding for the discrete chemistry and discrete phytoplankton sampling. A portion of the chapters in this report are written as two separate reports and other chapters combine the 2002 and 2003 results. The two years of pre-fertilization monitoring, 1997 and 1998, are described in Pieters et al. (1998, 1999) and the first three years of fertilization, 1999, 2000 and 2001 are described in Pieters et al. (2000, 2003a, 2003b).

Background

The Arrow Lakes Reservoir originally consisted of two large oligotrophic lakes, the Upper and Lower Arrow Lakes, which lie between the Selkirk and Monashee Mountain ranges in southeastern British Columbia (Fig. 1.1). They were transformed into a reservoir when the Hugh Keenleyside Dam (near Castlegar) was constructed in 1969 as part of the Columbia River Treaty. The Arrow Lakes Reservoir is dominated by the inflowing Columbia River near Revelstoke and the outflowing Columbia River near Castlegar. At full pool the Arrow Reservoir has a surface area (mean elevation of 432.4 m) of approximately 46,450 ha (Upper Arrow 29,557 ha and Lower Arrow 16,893 ha)¹. The Upper Arrow has six major tributaries and 25 minor tributaries; the Lower Arrow has four major tributaries and 26 minor tributaries. The communities of Revelstoke, Nakusp and Castlegar are located on or near the reservoir.

The most common concern in lakes and reservoirs around the world is an excess of nutrients (eutrophication²) which results in high algal productivity leading to 'green and slimy' or 'polluted' water. In contrast the Arrow Lakes Reservoir was naturally low in nutrients and is suffering from a further reduction of these nutrients (oligotrophication, Ney 1996).

¹ The nutritional (trophic) status of aquatic ecosystems is described by the technical Greek-based words eutrophic, mesotrophic and oligotrophic broadly meaning well fed (eu-trophic), moderately fed (meso-trophic) and little fed (oligo-trophic).

Fish Stocks

Over the last one hundred years the Arrow Lakes has supported a variety of sport fish including rainbow trout (*Oncorhynchus mykiss*), bull trout (*Salvelinus confluentus*), kokanee (*O. nerka*), mountain whitefish (*Prosopium williamsoni*), burbot (*Lota lota*), and white sturgeon (*Acipenser transmontanus*). Prior to dam construction activity on the Columbia River in the United States, the Arrow Lakes system also supported anadromous runs of chinook salmon (*O. tshawytscha*), sockeye salmon (*O. nerka*) and steelhead trout. Anadromous fish were known to spawn in the narrow riverine section between the two lakes and in the Upper Columbia River near Invermere using the Arrow Lakes primarily for rearing.

Fish and Habitat Losses

Virtually no pre-dam fish assessment work was conducted on the Arrow Lakes. The only measure of impact was that of Lindsay and Seaton (1978) who estimated 30% of the spawning and rearing habitat in the Arrow Lakes basin was lost due to flooding by the Hugh Keenleyside Dam. The lakes were further influenced by the construction of the Mica Dam on the upper Columbia River in 1973. No estimate of fish losses was made before this dam was built, however, it was later ‘discovered’ that at least some of the trophy rainbow “yellowfin” from the Arrow Lakes spawned upstream of the Mica Dam in specific Canoe River tributaries. The last and likely most significant effect on Arrow Lakes fish stocks resulted from the construction of the Revelstoke Dam in 1984. This dam flooded 150 km of the mainstem Columbia River and 80 km of tributary streams which were used by Arrow Lakes kokanee, bull trout, and to a lesser extent, rainbow trout.

Arrow Lakes kokanee have been severely influenced as a result of dam development, i.e., impoundment, loss of tributary habitat, drawdown, entrainment, etc. The Hugh Keenleyside Dam flooded 30% of their spawning habitat (Lindsay and Seaton 1978) while the Revelstoke Dam blocked upstream passage to 500,000 spawners (Martin 1976). The pre-impoundment annual escapement in the Upper and Lower Arrow Lakes derived from hydroacoustic surveys was estimated at 0.8 to 1.6 million kokanee. Nutrient retention by upstream impoundments (Revelstoke and Mica dams) has substantially reduced reservoir productivity particularly in the Upper Arrow. Nutrients (mainly phosphorus) that formerly entered the Arrow Lakes from the Columbia River are now settling out and/or being utilized in the Revelstoke and Mica reservoirs resulting in decreased productivity in the Arrow Lakes Reservoir. Kokanee, being pelagic planktivores, are typically the first species to respond to decreased reservoir productivity resulting from aging impoundments, a process known as oligotrophication (Ney 1996). The current status of Arrow kokanee is outlined in Chapters 10 and 11.

Sebastian et al. (2000) believe there may be four separate strains of rainbow trout that inhabit Arrow Reservoir watershed including two adfluvial forms, a stream resident form and a fluvial form below the Revelstoke dam. The Arrow Lakes previously supported a trophy rainbow trout fishery for the large, piscivorous yellow finned rainbow trout, which

are an ecological analogue of the Gerrard rainbow trout in Kootenay Lake. An estimated 3,000 adults were lost following dam construction (1,000 spawners and 2,000 fish from the sport fishery). The spawner estimate is based on the return of 500 fish to the base of the Revelstoke Dam (Martin 1976) and an additional 500, which according to area residents, spawned in the narrows between the two lakes. The sport harvest estimate is loosely based on Kootenay Lake data where the annual harvest is twice the escapement. These fish were large (up to 14 kg in size) but quite distinct in appearance from Gerrard rainbow trout by their yellow-orange color on their stomachs as well as on their pectoral, pelvic and anal fins. The flooding of the lakes almost completely eradicated this stock, and from the mid-1970's through the early 1980s, very few of these fish were caught. From 1979 through 1981, attempts were made by the Fisheries Section (Kootenay Region Ministry of Environment) to preserve and enhance this stock by collecting spawning adults blocked at the Revelstoke Dam. Some yearling releases from the Hill Creek hatchery resulted from these collections, however, this program was too labour-intensive and too few adults were collected to justify its continuation. Attempts were made again from 1992 through 1996 to collect spawning adults to preserve this unique stock but too few fish were captured and the program was discontinued. A remnant population remains in the Arrow system, and signs have been placed at major boat launches identifying the differences between Gerrard and yellow-fin trout and requesting that the public voluntarily release any yellow-fin rainbow trout captured while angling.

In order to provide the public with a trophy rainbow trout fishery, Gerrard rainbow trout from Kootenay Lake were stocked into Arrow Lakes Reservoir from 1984-1997 ranging from 15,000-82,000 yearling equivalents each year. These fish comprised from 23-29% of the large rainbow trout harvest in some years. The stocking of Gerrard rainbow trout into Arrow Lakes Reservoir however, was discontinued in 1998 as a result of the decline in kokanee size and abundance. Gerrard rainbow trout are highly piscivorous hence the stocking program will not be initiated until kokanee abundance has been restored to historic levels.

In addition to the trophy rainbow trout, a stock of smaller-sized rainbow that is popular with anglers exists in the Arrow Lakes Reservoir. An estimated 1,250 spawners were lost annually as a result of the 30% habitat loss caused by flooding of the lakes (Lindsay 1978) as well as the 500 spawners which utilized streams tributary to the Columbia River north of the Revelstoke Dam (Martin 1976). Enhancement of this stock of small rainbow trout at the Hill Creek Hatchery commenced in 1983 and continued until 2000. Stocking of Hill Creek rainbow has ranged from 1,500-20,000 yearling equivalents each year.

Sebastian et al. (2000) suggest that current total rainbow trout spawning escapements are probably about 4,000 but probably < 200 of these would be the large piscivorous types.

At least three different strains of bull trout are thought to inhabit the Arrow Lakes Reservoir including an adfluvial, fluvial, and resident form (Sebastian et al. 2000). Adfluvial bull trout are highly dependent upon kokanee as a food source (Sebastian et al. 2000). Bull trout were traditionally one of the main species targeted by anglers in the Arrow Lakes. The impacts from dam construction on this species have been dramatic

primarily because of flooding and blocked access to spawning and rearing habitat. As a result of the Revelstoke Dam, it was estimated that 4,000 adult spawners ($13 \text{ spawners} \cdot \text{km}^{-1}$ of stream habitat) were lost (Martin 1976). The number of kilometers of habitat lost in comparison with remaining habitat in the Arrow system represented a loss of 66% of the total adult spawning population in the lake (Lindsay 1977). The total bull trout spawning population was estimated at approximately 5,000-10,000 adults (Sebastian et al. 2000, p38).

Clearly, dam construction has had a large impact with 2/3 loss of spawning habitat and the significant numbers of fish observed at the base of Mica and Revelstoke Dams for several years after closure of these dams. See Sebastian et al. (2000) for further discussion.

A bull trout stocking program commenced on the Arrow with the construction of the Revelstoke Dam in 1981 with annual releases of juveniles ranging from 5,000 to 130,000. In 1996, a report by Winsby and Stone reviewed bull trout production from the Hill Creek Hatchery and suggested adult brood capture only take place every second year (commencing in 1996) and that the release program incorporate release of both yearling and two year old fish in an attempt to improve survival to adult sized fish.

Sebastian et al. (2000) suggest that current total bull trout spawning escapements in the Arrow Lakes Reservoir are probably in the order of 2,500-4,000.

Compensation

In the late 1970's, a compensation agreement was signed by the Ministry of Environment and BC Hydro to provide funding to replace fish and fish habitat lost due to the construction of the Revelstoke Dam. This program started with an initial assessment of all tributary streams to the proposed Revelstoke Reservoir detailing their potential for natural and/or artificial enhancement (Lindsay 1976). In order to replace what would be lost it appeared at that time that the only viable alternative was artificial propagation.

Construction of the Hill Creek Spawning Channel started in the fall of 1979 and was completed in the late fall of 1980. Water was first directed down the channel in the spring of 1981. The channel is 3.2 km long, 6.1 m wide, has a grade of 0.15%, and has the capacity to hold 150,000 kokanee spawners. The channel has 56 settling basins which provide holding areas for spawning fish, collect displaced gravel for redistribution onto spawning sections, and act as sediment collection points to reduce the impact in spawning areas. The upper 0.2 km of the channel has larger gravel suitable for spawning rainbow trout although kokanee also spawn in this area.

Water for the channel is provided primarily from Hill Creek with the capability, by way of a diversion pipeline, to divert and supplement Hill Creek flows with MacKenzie Creek water up to $0.28 \text{ m}^3 \cdot \text{s}^{-1}$ ($10 \text{ ft}^3 \cdot \text{s}^{-1}$) in order to optimize egg-to-fry survival rates during low flow periods. There are three enumeration fences in the channel to enumerate and control the distribution of spawners in the channel.

The Hill Creek Hatchery was built in 1982-83. The purpose of the hatchery was to produce Arrow Lakes fish lost as a result of the Revelstoke Dam construction. In 1987, with the settlement of impacts caused from construction of the Keenleyside Dam, the hatchery was doubled in size to produce rainbow trout and bull trout for both Upper and Lower Arrow Reservoirs. Water for the hatchery is provided from a number of different sources either separately or in combination from Hill Creek, MacKenzie Creek and two large wells. The hatchery had the capacity to produce 100,000 fingerling bull trout, 20,000 yearling native Hill Creek rainbow trout and 60,000 yearling Gerrard rainbow trout as well as incubate up to 2 M kokanee eggs to the eyed stage. In 2001, the Hill Creek Hatchery was retrofitted to become a pilot hatchery for conservation of Upper Columbia white sturgeon. Due to provincial government cutbacks, the hatchery was closed in April 2003. The Hill Creek Spawning Channel has been maintained by the CBFWCP since April 2003.

At present there are a number of limnological and fisheries studies being conducted on the Arrow Lakes Reservoir to better understand its' fish populations and limnological characteristics. Most of these studies are being funded by the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) which is a joint program between BC Hydro and the Ministry of Environment. This report summarizes the results of the fourth and fifth year of fertilization (2002 and 2003).

Personnel, Affiliation and Responsibilities

Table 1.1. Listing of 2002 Arrow Lakes Reservoir project focus, personnel and affiliation.

Project Focus	Personnel	Affiliation
Fertilization Coordinator	Dr. Beth Wright (Jan. – Jul.) 2002	Fish and Wildlife, MWLAP, Nelson
Fertilizer schedule	Dr. Ken Ashley	Biodiversity Branch, MWLAP, UBC
Fertilizer application	Heather Cooke Bob Millar Grant Thorp	Fish and Wildlife, MWLAP, Hill Creek and Nakusp
Reservoir physical, chemical, phytoplankton and zooplankton sampling	Steve Arndt Harald Manson Don Miller Mark Young (Jan. – June)	CBFWCP, Nelson CBFWCP, Nelson Kootenay Wildlife Services Ltd. Kootenay Wildlife Services Ltd.
Tributary sampling	Karen Bray Diana Koller Harald Manson Dan Gebhart Grant Thorp	CBFWCP, Revelstoke MWLAP, Hill Creek and Nakusp CBFWCP, Nelson Aquatic Resources Ltd. MWLAP, Hill Creek and Nakusp
Phytoplankton analysis and reporting	Dr. John Stockner	Ecologic Ltd.
Stream and reservoir chemistry reporting	Eva Schindler	MWLAP, Nelson
Arrow Lakes Reservoir nutrient budget	Dr. Roger Pieters	Civil Engineering and EOS, UBC
Zooplankton analysis and reporting	Dr. Lidija Vidmanic	Limno-Lab Ltd., Vancouver
Mysid net sampling	Steve Arndt Harald Manson Don Miller Mark Young (Jan. – June 2002)	CBFWCP, Nelson CBFWCP, Nelson Kootenay Wildlife Services Ltd. Kootenay Wildlife Services Ltd.
Mysid analysis and reporting	Dr. Lidija Vidmanic	Limno-Lab Ltd., Vancouver
Kokanee acoustic surveys	Dale Sebastian George Scholten Patricia Woodruff	Biodiversity Branch, MWLAP, Victoria Biodiversity Branch, MWLAP, Victoria B.C. Conservation Foundation
Kokanee trawling	Don Miller and staff	Kootenay Wildlife Services Ltd.
Hill Creek kokanee	Bob Millar	MWLAP, Hill Creek

adult enumeration	Grant Thorp	MWLAP, Nakusp
Hill Creek kokanee fry enumeration	Bob Millar Grant Thorp	MWLAP, Hill Creek MWLAP, Nakusp
Kokanee analysis and Reporting	Harvey Andrusak	Redfish Consulting Ltd.
Regional support and logistics	Jay Hammond Bob Lindsay (Jan – Mar 2002) Colin Spence	Fish and Wildlife, MWLAP, Nakusp Fish and Wildlife, MWLAP, Nelson Fish and Wildlife, MWLAP, Nelson
CBFWCP Technical Committee	Dr. Ken Ashley Gary Birch Jay Hammond Dave Wilson	Biodiversity Branch, MWLAP, UBC BC Hydro, Castlegar Fish and Wildlife, MWLAP, Nelson BC Hydro, Vancouver
Project co-ordination and scientific liaison	Dr. Ken Ashley Harald Manson Colin Spence	Biodiversity Branch, MWLAP, UBC CBFWCP, Nelson Fish and Wildlife, MWLAP, Nelson
Annual report preparation	Eva Schindler	Fish and Wildlife, MWLAP, Nelson
Contract administration	Harald Manson Beth Woodbridge	CBFWCP, Nelson CBFWCP, Nelson

Table 1.2. Listing of 2003 Arrow Lakes Reservoir project focus, personnel and affiliation.

Project Focus	Personnel	Affiliation
Fertilization Limnologist	Eva Schindler (Nov 2003)	Fish and Wildlife, MWLAP, Nelson
Fertilizer schedule	Dr. Ken Ashley	Biodiversity Branch, MWLAP, UBC
Fertilizer application	Brian Barney	Kingfisher Silviculture Ltd.
Reservoir physical, chemical, phytoplankton and zooplankton sampling	Steve Arndt Harald Manson Don Miller Eva Schindler	CBFWCP, Nelson CBFWCP, Nelson Kootenay Wildlife Services Ltd. Fish and Wildlife, MWLAP, Nelson
Tributary sampling	Karen Bray Harald Manson Karla Robison Fred Salekin Grant Thorp	CBFWCP, Revelstoke CBFWCP, Nelson BC Hydro, Revelstoke Golder & Associates Ltd. Hailstorm Ridge Environmental Services
Phytoplankton analysis and reporting	Dr. John Stockner	Ecologic Ltd.
Stream and reservoir chemistry reporting	Eva Schindler	Fish and Wildlife, MWLAP, Nelson

Arrow Lakes Reservoir nutrient budget	Dr. Roger Pieters	Civil Engineering and EOS, UBC
Zooplankton analysis and reporting	Dr. Lidija Vidmanic	Limno-Lab Ltd., Vancouver
Mysid net sampling	Steve Arndt Harald Manson Don Miller	CBFWCP, Nelson CBFWCP, Nelson Kootenay Wildlife Services Ltd.
Mysid analysis and reporting	Dr. Lidija Vidmanic	LimnoLab Ltd., Vancouver
Kokanee acoustic surveys	Dale Sebastian George Scholten Patricia Woodruff	Biodiversity Branch, MWLAP, Victoria Biodiversity Branch, MWLAP, Victoria B.C. Conservation Foundation
Kokanee trawling	Don Miller and staff	Kootenay Wildlife Services Ltd.
Hill Creek kokanee adult enumeration	Grant Thorp	Hailstorm Ridge Environmental Services
Hill Creek kokanee fry enumeration	Grant Thorp	Hailstorm Ridge Environmental Services
Kokanee analysis and Reporting	Harvey Andrusak	Redfish Consulting, Ltd, Nelson
Regional support and logistics	Colin Spence	Fish and Wildlife, MWLAP, Nakusp
CBFWCP Technical Committee	Dr. Ken Ashley Gary Birch Colin Spence Dave Wilson	Biodiversity Branch, MWLAP, UBC BC Hydro, Castlegar Fish and Wildlife, MWLAP, Nelson BC Hydro, Vancouver
Project co-ordination and scientific liaison	Dr. Ken Ashley Harald Manson Colin Spence	Biodiversity Branch, MWLAP, UBC CBFWCP, Nelson Fish and Wildlife, MWLAP, Nelson
Annual report preparation	Eva Schindler	Fish and Wildlife, MWLAP, Nelson
Contract administration	Harald Manson Beth Woodbridge	CBFWCP, Nelson CBFWCP, Nelson

Table 1.3. Arrow Lakes Reservoir physical, chemical and plankton sampling program for 2002

Parameter sampled	Sampling frequency	Sampling technique
Temperature, dissolved oxygen, pH, ORP, specific conductance, turbidity	Jan and Mar-Dec	(a) Hydrolab at 8 AR sampling stations at 1 m intervals from 0 to 50 m, and at 5 m intervals from 50 to 100 m (b) same sampling at Hydrolab sites 1-4
Transparency	Jan and Mar-Dec	Secchi disk (without viewing chamber) at 8 AR sampling stations
Water chemistry: Specific cond., pH, silica, alkalinity and nutrients (TP, TDP, LL SRP, NO_3+NO_2 , NH_3); Total metals (Ca, Mg, Na, K, Cl, SO_4 , CO_3 , HCO_3) were added to June and September analysis for AR 2 and 7 only	Jan and Mar-Dec	(a) Integrated sampling tube at 0 - 30 m at 8 AR sampling stations plus a bottle sample 5 m off the bottom at Stns. 1-3, 6-8 (b) (June and August only) bottle samples every 50 m as depth allows.
Water chemistry: Specific cond., pH, nutrients (TP, TDP, LL SRP, NO_3+NO_2 , NH_3) and temperature sampling	See Chapter 4 for details	Sampling bottle
Chlorophyll <i>a</i> (not corrected for phaeophytin)	Jan and Mar – Dec	Integrated sampling tube at 0 - 30 m at AR 1-8 sampling stations
Phytoplankton	Apr – Oct monthly (twice in June and Aug)	Integrated sampling tube at 0 - 20 m at AR 1-8 sampling stations
Macrozooplankton	Apr – Oct monthly	3 oblique Clarke-Bumpus net hauls (3-minutes each) from 40 to 0 m at AR 1-3, 6-8 sampling stations (150 μm net)
Mysid net sampling	Jan and Mar-Dec	3 replicate hauls with mysid net, two deep and one shallow at AR 1-3, 6-8
Kokanee acoustic sampling	Fall survey	Standard MWLAP Simrad and Biosonics hydroacoustic procedure at 20 transects in Upper and Lower Arrow
Kokanee trawling	Fall trawl series	Standard trawl series using

		oblique hauls at AR 1-3 and 6-8 in Upper and Lower Arrow
Adult kokanee enumeration	Fall spawning period at Hill Creek channel and selected streams	Standard Region 4 MWLAP procedure
Kokanee fry enumeration	Spring monitoring at Hill creek	Standard Region 4 MWLAP procedure

Table 1.4. Arrow Lakes Reservoir physical, chemical and plankton sampling program for 2003

Parameter sampled	Sampling frequency	Sampling technique
Temperature, dissolved oxygen, pH, ORP, specific conductance, turbidity	Jan and Mar-Dec	(a) Hydrolab at 8 AR sampling stations at 1 m intervals from 0 to 50 m, and at 5 m intervals from 50 to 100 m (b) same sampling at Hydrolab sites 1-4
Transparency	Jan and Mar-Dec	Secchi disk (without viewing chamber) at 8 AR sampling stations
Water chemistry: Specific cond., pH, silica, alkalinity and nutrients (TP, TDP, LL SRP, NO ₃ +NO ₂ ⁻ , NH ₃); Total metals (Ca, Mg, Na, K, Cl, SO ₄ , CO ₃ , HCO ₃) were added to June and September analysis for AR 2 and 7 only	Jan and Mar-Dec	(a) Integrated sampling tube at 0 - 30 m at 8 AR sampling stations plus a bottle sample 5 m off the bottom at Stns. 1-3, 6-8 (b) (June and August only) bottle samples every 50 m as depth allows.
Water chemistry: Specific cond., pH, nutrients (TP, TDP, LL SRP, NO ₃ +NO ₂ , NH ₃) and temperature sampling	See Chapter 4 for details	Sampling bottle
Chlorophyll <i>a</i> (not corrected for phaeophytin)	Jan and Mar – Dec	Integrated sampling tube at 0 - 30 m at AR 1-8 sampling stations
Phytoplankton	Apr – Oct monthly (twice in June and Aug)	Integrated sampling tube at 0 - 20 m at AR 1-8 sampling stations
Macrozooplankton	Apr – Oct monthly	3 oblique Clarke-Bumpus net hauls (3-minutes each) from 40

		to 0 m at AR 1-3, 6-8 sampling stations (150 µm net)
Mysid net sampling	Jan and Mar-Dec	3 replicate hauls with mysid net, two deep and one shallow at AR 1-3, 6-8
Kokanee acoustic sampling	Fall survey	Standard MWLAP Simrad and Biosonics hydroacoustic procedure at 20 transects in Upper and Lower Arrow
Kokanee trawling	Fall trawl series	Standard trawl series using oblique hauls at AR 1-3 and 6-8 in Upper and Lower Arrow
Adult kokanee enumeration	Fall spawning period at Hill Creek channel and selected streams	Standard Region 4 MWLAP procedure
Kokanee fry enumeration	Spring monitoring at Hill creek	Standard Region 4 MWLAP procedure

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Figure 1.1. Sampling locations, Arrow Lakes Reservoir, 2002 and 2003.

CHAPTER 2

FERTILIZER LOADING IN ARROW LAKES RESERVOIR YEARS 4 AND 5 (2002 and 2003)

by

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Fertilization Experiment

The 5 year (1999-2003) fertilization experiment of Arrow Lakes Reservoir is modeled on the Kootenay Lake fertilization experiment which commenced in 1992 and has been highly successful in restoring kokanee stocks (Ashley et al. 1997, 1999a,b and Wright et al. 2002). An adaptive management approach has been adopted for the experiment on the Arrow Lakes Reservoir. The fertilization of Arrow is undertaken as a large-scale experiment and as such is subject to the risk of failure. Adaptive management requires that adequate information be collected to assess the progress of the experiment so that necessary changes can be made in a timely fashion.

Fertilizer type

The fertilizer added was a seasonally adjusted blend of agricultural grade liquid ammonium polyphosphate (10-34-0: N-P₂O₅-K₂O; % by weight) and liquid urea-ammonium nitrate (28-0-0: N-P₂O₅-K₂O; % by weight). The fertilizer is purchased from a Canadian supplier, Agrium Ltd.

Seasonal loading and timing

The seasonally adjusted blend of fertilizer (Appendix 2.1) is modeled on the Kootenay Lake fertilization experiment (Ashley et al. 1997, 1999a,b). The application schedule for 2002 and 2003 is given in Appendix 2.2.

The seasonal loading of fertilizer application was intended to approximate pre-impoundment spring freshet conditions for phosphorus (P) loading, (i.e., following a natural hydrograph) and to compensate for biological uptake of dissolved inorganic nitrogen (DIN) as the season progressed. Phosphorus loading peaked in late spring and declined through the summer (see figures in Appendix 2.1). Weekly nitrogen loading began with low rates in the spring and increased through the summer in an attempt to inhibit the growth of cyanobacteria (blue-green algae) which can be associated with low N:P ratios (Smith, 1983; Pick and Lean, 1987).

During 2002, fertilizer treatment started on April 21 and ended on September 5. The fertilizer N:P ratio (weight to weight basis) was modified at 3-4 week intervals and increased from 0.67:1 (i.e., 10-34-0 only) in the initial spring applications to 7.5:1 in the late summer applications. The fertilizer N:P ratio expressed in terms of molar concentrations ranged from 1.5:1 to 16.7:1. Based on an in-lake area of 193 km², this corresponds to a loading of phosphorus that ranged from 7.5-22.5 mg/m²/week.

During 2003, fertilizer treatment started on April 26 and ended on September 07. The fertilizer N:P ratio (weight to weight basis) was modified from the 2002 schedule where the fertilizer N:P ratio was 7.5:1 from July 02 to July 30 and 9:1 from August 06 to September 03. The loading rates of nitrogen were changed to increase the N:P ratio of fertilizer additions because of potential low N:P ratios in the reservoir.

Fertilizer application

The fertilizer was dispensed from the Ministry of Transportation & Highways ferry, the DEV Galena. This ferry runs between Galena Bay and Shelter Bay on the Upper Arrow Reservoir, approximately 30 km south of Revelstoke on Hwy 6 (in the vicinity of Hydroacoustic transect 3 in Figure 1.1). The DEV Galena is 50.3 m long, 18.0 m wide, has a draft of 2.4 m and displaces 518 tonnes. A more detailed description is provided in Pieters et al 2000.

Fertilizer trips

During 2002, a Ford F-550 truck pulling a 3,900 litre fertilizer tank mounted on a 16 foot tandem-axle trailer was used to transport the fertilizer from the Hill Creek site to the ferry terminal. A 5 hp Honda pump was mounted on the back of the trailer and is connected to the trailer tank with a 2 inch (5 cm) diameter hose.

Staff from the Hill Creek Hatchery dispensed the fertilizer into the reservoir from the Galena ferry. This involved filling the trailer tank with the prescribed amount of fertilizer from a tank farm located at the Hill Creek Hatchery (3 tanks, with a combined capacity of approximately 100,000 L). The truck and trailer were pre-loaded onto the ferry and parked in a drive corner. A 2 inch diameter hose connected the pump on the trailer to the diffuser with a quick coupling adapter.

In 2003, the fertilization dispensing application portion was tendered out to a private contractor. The pumping system was modified for a truck-mounted tank and pump. The severe fire season of 2003 also had an impact on fertilizer delivery, as the truckers who hauled the product were reassigned on occasion to haul fire retardant for the fires in Kamloops and Kelowna. Ferry traffic would periodically increase dramatically because of road closures and tourists driving to areas unaffected by the fires and heavy smoke. The 2003 fertilizer application season consisted of 241 application trips over a period of 100 days.

The ferry crossing time was about 25 minutes, the distance traveled was approximately 6 km. The pump was generally activated 5 minutes after leaving each ferry terminal to prevent application of fertilizer in the shallower shore regions, yielding roughly 15 minutes of actual fertilizer distribution per ferry crossing. Initially, half of the fertilizer in the trailer tank was applied on the trip from Galena Bay to Shelter Bay and the remaining fertilizer was dispensed on the return trip.

Acknowledgements

Thanks to Grant Thorp, Bob Millar and Heather Cooke for dispensing fertilizer in 2002, to Brian Barney for dispensing fertilizer in 2003 and especially to the Ministry of Transportation for their assistance with logistics for dispensing fertilizer from the Galena Bay ferry.

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APPENDIX 2.1 FERTILIZER SPECIFICATIONS, 2002

Fertilizer: blend of 10-34-0(ammonium polyphosphate) and 28-0-0 (urea-ammonium nitrate)								
Density of 10-34-0 is 1.415 kg/L and 28-0-0 is 1.28 kg/L @ 15C								
Note: N:P ratios are increased during application period								
Week	Nutrient	N / P Loading	Amount	Amount	Form	N:P ratio	Expected	Expected
Dates	P or N	mg/m2/wk	N or P kg	Fert (mt)	fertilizer	wt:wt	P (ug/L)	Chlor a
Apr-21	P	7.5	1,440	9.7	10-34-0	0.67	1.1	0.8
	N	5.0	970		10-34-0			
	N	0.0	0		28-0-0			
Apr-28	P	7.5	1,440	9.7	10-34-0	0.67	1.3	0.8
	N	5.0	970		10-34-0			
	N	0.0	0		28-0-0			
May 5	P	11.2	2,168	14.6	10-34-0	0.67	1.5	0.9
	N	7.6	1,460		10-34-0			
	N	0.0	0		28-0-0			
May 12	P	15.0	2,895	19.5	10-34-0	0.67	1.8	0.9
	N	10.1	1,950		10-34-0			
	N	0.0	0		28-0-0			
May 19	P	18.8	3,623	24.4	10-34-0	3.00	2.2	1.0
	N	12.7	2,440		10-34-0			
	N	43.7	8,428	30.1	28-0-0			
May 26	P	22.5	4,335	29.2	10-34-0	3.01	2.6	1.1
	N	15.1	2,920		10-34-0			
	N	52.4	10,108	36.1	28-0-0			
June 2	P	22.5	4,335	29.2	10-34-0	3.01	3.1	1.2
	N	15.1	2,920		10-34-0			
	N	52.4	10,108	36.1	28-0-0			
June 9	P	18.8	3,623	24.4	10-34-0	4.50	3.5	1.3
	N	12.7	2,440		10-34-0			
	N	71.9	13,860	49.5	28-0-0			
June 16	P	15.0	2,895	19.5	10-34-0	4.50	3.8	1.4
	N	10.1	1,950		10-34-0			
	N	57.5	11,088	39.6	28-0-0			
June 23	P	15.0	2,895	19.5	10-34-0	4.50	4.1	1.4
	N	10.1	1,950		10-34-0			
	N	57.5	11,088	39.6	28-0-0			
June 30	P	15.0	2,895	19.5	10-34-0	4.50	4.4	1.5
	N	10.1	1,950		10-34-0			
	N	57.5	11,088	39.6	28-0-0			

July 7	P	15.0	2,895	19.5	10-34-0	6.00	4.7	1.6
	N	10.1	1,950		10-34-0			
	N	80.0	15,428	55.1	28-0-0			
July 14	P	15.0	2,895	19.5	10-34-0	6.00	5.0	1.6
	N	10.1	1,950		10-34-0			
	N	80.0	15,428	55.1	28-0-0			
July 21	P	15.0	2,895	19.5	10-34-0	6.00	5.3	1.7
	N	10.1	1,950		10-34-0			
	N	80.0	15,428	55.1	28-0-0			
July 28	P	15.0	2,895	19.5	10-34-0	6.00	5.6	1.8
	N	10.1	1,950		10-34-0			
	N	80.0	15,428	55.1	28-0-0			
Aug 4	P	15.0	2,895	19.5	10-34-0	7.49	5.9	1.8
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			
Aug 11	P	7.5	1,440	9.7	10-34-0	7.54	6.0	1.9
	N	5.0	970		10-34-0			
	N	51.3	9,884	35.3	28-0-0			
Aug 18	P	7.5	1,440	9.7	10-34-0	7.54	6.2	1.9
	N	5.0	970		10-34-0			
	N	51.3	9,884	35.3	28-0-0			
Aug 25	P	7.5	1,440	9.7	10-34-0	7.54	6.3	1.9
	N	5.0	970		10-34-0			
	N	51.3	9,884	35.3	28-0-0			
Sept 1	P	7.5	1,440	9.7	10-34-0	7.54	6.5	2.0
	N	5.0	970		10-34-0			
	N	51.3	9,884	35.3	28-0-0			
			Summary					
		Phosphorus			Nitrogen			
	Load	Amount	10-34-0	Load	Amount	28-0-0	N:P Ratio	No.
	mg/m2	kgs	M. Tons	mg/m2	kgs	M. Tons		
Apr-21	7.5	1,440	9.7	5.0	970	0.00	0.67	1
Apr-28	7.5	1,440	9.7	5.0	970	0.00	0.67	2
May 5	11.2	2,168	14.6	7.6	1,460	0.00	0.67	3
May 12	15.0	2,895	19.5	10.1	1,950	0.00	0.67	4
May 19	18.8	3,623	24.4	56.4	10,868	30.10	3.0	5
May 26	22.5	4,335	29.2	67.6	13,028	36.10	3.0	6
June 2	22.5	4,335	29.2	67.6	13,028	36.10	3.0	7
June 9	18.8	3,623	24.4	84.5	16,300	49.50	4.5	8
June 16	15.0	2,895	19.5	67.6	13,038	39.60	4.5	9
June 23	15.0	2,895	19.5	67.6	13,038	39.60	4.5	10
June 30	15.0	2,895	19.5	67.6	13,038	39.60	4.5	11
July 7	15.0	2,895	19.5	90.1	17,378	55.10	6.0	12
July 14	15.0	2,895	19.5	90.1	17,378	55.10	6.0	13

July 21	15.0	2,895	19.5	90.1	17,378	55.10	6.0	14
July 28	15.0	2,895	19.5	90.1	17,378	55.10	6.0	15
Aug 4	15.0	2,895	19.5	112.5	21,690	70.50	7.5	16
Aug 11	7.5	1,440	9.7	56.3	10,854	35.30	7.5	17
Aug 18	7.5	1,440	9.7	56.3	10,854	35.30	7.5	18
Aug 25	7.5	1,440	9.7	56.3	10,854	35.30	7.5	19
Sept 1	7.5	1,440	9.7	56.3	10,854	35.30	7.5	20
		Phosphorus			Nitrogen			
	Load	Amount	10-34-0	Load	Amount	28-0-0		
	mg/m2	M. Tons	M. Tons	mg/m2	M. Tons	M. Tons		
	273.7	52.8	355.5	1204.8	232.3	702.7		
	mg/m2	P	10-34-0	mg/m2	N	28-0-0		
	in 20 weeks	metric ton	metric ton	in 20 weeks	metric ton	metric ton

APPENDIX 2.2

FERTILIZER SPECIFICATIONS, 2003

Fertilizer: blend of 10-34-0(ammonium polyphosphate) and 28-0-0 (urea-ammonium nitrate)								
Density of 10-34-0 is 1.415 kg/L and 28-0-0 is 1.28 kg/L @ 15C								
Note: N:P ratios are increased during application period								
Week	Nutrient	N / P Loading	Amount	Amount	Form	N:P ratio	Expected	Expected
Dates	P or N	mg/m2/wk	N or P kg	Fert (mt)	fertilizer	wt:wt	P (ug/L)	Chlor a
Apr 23	P	7.5	1,440	9.7	10-34-0	0.67	1.1	0.8
	N	5.0	970		10-34-0			
	N	0.0	0		28-0-0			
Apr 30	P	7.5	1,440	9.7	10-34-0	0.67	1.3	0.8
	N	5.0	970		10-34-0			
	N	0.0	0		28-0-0			
May 07	P	11.2	2,168	14.6	10-34-0	0.67	1.5	0.9
	N	7.6	1,460		10-34-0			
	N	0.0	0		28-0-0			
May 14	P	15.0	2,895	19.5	10-34-0	0.67	1.8	0.9
	N	10.1	1,950		10-34-0			
	N	0.0	0		28-0-0			
May 21	P	18.8	3,623	24.4	10-34-0	3.00	2.2	1.0
	N	12.7	2,440		10-34-0			
	N	43.7	8,428	30.1	28-0-0			
May 28	P	22.5	4,335	29.2	10-34-0	3.01	2.6	1.1
	N	15.1	2,920		10-34-0			
	N	52.4	10,108	36.1	28-0-0			
Jun 04	P	22.5	4,335	29.2	10-34-0	3.01	3.1	1.2
	N	15.1	2,920		10-34-0			
	N	52.4	10,108	36.1	28-0-0			
Jun 11	P	18.8	3,623	24.4	10-34-0	4.50	3.5	1.3
	N	12.7	2,440		10-34-0			
	N	71.9	13,860	49.5	28-0-0			
Jun 18	P	15.0	2,895	19.5	10-34-0	4.50	3.8	1.4
	N	10.1	1,950		10-34-0			
	N	57.5	11,088	39.6	28-0-0			
Jun 25	P	15.0	2,895	19.5	10-34-0	4.50	4.1	1.4
	N	10.1	1,950		10-34-0			
	N	57.5	11,088	39.6	28-0-0			
Jul 02	P	15.0	2,895	19.5	10-34-0	7.49	4.4	1.5
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			
Jul 09	P	15.0	2,895	19.5	10-34-0	7.49	4.7	1.6
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			

Jul 16	P	15.0	2,895	19.5	10-34-0	7.49	5.0	1.6
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			
Jul 23	P	15.0	2,895	19.5	10-34-0	7.49	5.3	1.7
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			
Jul 30	P	15.0	2,895	19.5	10-34-0	7.49	5.6	1.8
	N	10.1	1,950		10-34-0			
	N	102.4	19,740	70.5	28-0-0			
Aug 06	P	15.0	2,895	19.5	10-34-0	9.00	5.9	1.8
	N	10.1	1,950		10-34-0			
	N	125.0	24,108	86.1	28-0-0			
Aug 13	P	7.0	1,351	9.1	10-34-0	9.00	6.0	1.9
	N	4.7	910		10-34-0			
	N	58.4	11,256	40.2	28-0-0			
Aug 20	P	7.0	1,351	9.1	10-34-0	9.00	6.1	1.9
	N	4.7	910		10-34-0			
	N	58.4	11,256	40.2	28-0-0			
Aug 27	P	7.0	1,351	9.1	10-34-0	9.00	6.3	1.9
	N	4.7	910		10-34-0			
	N	58.4	11,256	40.2	28-0-0			
Sep 03	P	7.0	1,351	9.1	10-34-0	9.00	6.4	2.0
	N	4.7	910		10-34-0			
	N	58.4	11,256	40.2	28-0-0			
			Summary					
		Phosphorus			Nitrogen			
	Load	Amount	10-34-0	Load	Amount	28-0-0	N:P Ratio	No.
	mg/m2	kgs	M. Tons	mg/m2	kgs	M. Tons		
Apr 23	7.5	1,440	9.7	5.0	970	0.00	0.67	1
Apr 30	7.5	1,440	9.7	5.0	970	0.00	0.67	2
May 07	11.2	2,168	14.6	7.6	1,460	0.00	0.67	3
May 14	15.0	2,895	19.5	10.1	1,950	0.00	0.67	4
May 21	18.8	3,623	24.4	56.4	10,868	30.10	3.0	5
May 28	22.5	4,335	29.2	67.6	13,028	36.10	3.0	6
Jun 04	22.5	4,335	29.2	67.6	13,028	36.10	3.0	7
Jun 11	18.8	3,623	24.4	84.5	16,300	49.50	4.5	8
Jun 18	15.0	2,895	19.5	67.6	13,038	39.60	4.5	9
Jun 25	15.0	2,895	19.5	67.6	13,038	39.60	4.5	10
Jul 02	15.0	2,895	19.5	112.5	21,690	70.50	7.5	11
Jul 09	15.0	2,895	19.5	112.5	21,690	70.50	7.5	12
Jul 16	15.0	2,895	19.5	112.5	21,690	70.50	7.5	13
Jul 23	15.0	2,895	19.5	112.5	21,690	70.50	7.5	14
Jul 30	15.0	2,895	19.5	112.5	21,690	70.50	7.5	15
Aug 06	15.0	2,895	19.5	135.1	26,058	86.10	9.0	16

CHAPTER 3

HYDROLOGY OF ARROW LAKES RESERVOIR (2002 and 2003)

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Introduction

The Columbia River basin is shown in Figure 3.1.1. The Upper Columbia, in south eastern British Columbia is primarily composed of drainage to three large natural lakes: Okanagan, Arrow and Kootenay. These long, narrow and deep lakes lie in mountain trenches, have glacially carved fjord-like basins and have naturally oligotrophic levels of primary productivity. These lakes are primarily phosphorus (P) limited though nitrogen (N) concentrations can decline in late summer in some lakes to suggest possible co-limitation at certain times.

Okanagan Lake is distinct from the Arrow and Kootenay Lakes with a relatively small and semi-arid drainage basin resulting in long retention times. Because of this and other differences, Okanagan Lake will not be further considered.¹

While definitions vary, the upper Columbia River drainage basin is here defined as that area north of the city of Castlegar where two main rivers join: the Kootenay River draining the Kootenay and Slocan Lakes and the Columbia River draining the Arrow Lakes Reservoir (Figure 3.1.2). The flow through Kinbasket Reservoir, Revelstoke Reservoir and the Arrow Lakes is the main stem of the Columbia River.

Figure 3.1.2 also shows the dams that have been constructed on and above Arrow and Kootenay Lakes. Four of the dams - Keenleyside, Duncan, Libby and Mica - were a result of the 1965 Columbia River Treaty between the U.S. and Canada, and were built for both flood control and/or hydroelectric generation.

The Arrow Lakes Reservoir lies between the Monashee Mountains to the east and the Selkirk Mountains to the west, and is composed of two distinct basins, formerly the Upper and Lower Arrow Lakes which are separated by a narrows. Before impoundment this narrows section was a river, but now is riverine in character only during very low water levels.

Some basic hydrologic and morphometric features of the major lakes, reservoirs and dams in the Upper Columbia River basin are given in Table 3.1. The Whatshan Dam impounds the Whatshan River and drains into the north end of the Lower Arrow at Needles. The Whatshan Reservoir is connected to a powerhouse north of Needles by a 3.4 km tunnel.

This chapter includes discussion of flows used in the nutrient budget in Chapter 6. For ease of comparison, flows for 1997 to 2003 will be discussed.

¹ A large scale limnological program is currently underway in Okanagan Lake; see Ashley et al. (1998, 1999) and Andrusak et al. (2000, 2001) for further detail.

Table 3.1a. Hydrologic and morphometric characteristics of the major lakes and reservoirs of the upper Columbia River basin

Lake or Reservoir	Dam	Date ¹	Area km ²	Outflow m ³ /s km ³ /yr	Vol. km ³	Max Depth m	Mean Depth m
Kinbasket	Mica	1976	310 ⁵	586 ³	18.5		
Revelstoke	Revelstoke	1983	115 ³	749 ¹⁰	23.6		
Whatshan	Whatshan	1951 ³		9.3 ³	0.29		
Up. Arrow	-	-	275 ⁷	1,022 ¹³	32.3	27.8 ⁸	101 ¹¹
Lo. Arrow	-	-	190 ⁷	-	-	10.8 ⁸	57 ¹¹
Arrow	Keenleyside	1967 ¹⁸	465 ⁷	1,080 ⁹	34.1	38.6 ⁸	83 ¹¹
Koocanusa	Libby	1973	186 ⁴	352 ⁴	11.1 ⁴	7.2 ⁴	107 ⁴
Duncan	Duncan	1967	75 ⁴	91 ⁴	2.9 ⁴	3.0 ⁴	147 ⁴
Kootenay L.	Corra Linn	1931 ²	390 ⁴	780 ⁴	24.6 ⁴	36.7 ⁴	154 ⁴

Table 3.1.b. Hydrologic and morphometric characteristics continued

Lake or Reservoir	Length km	Max Width km	Mean Width km	Active Storage Mm ³	Lake Level Variation m	Pre to post impoundment water level increase m	Power Generation MW
Kinbasket	216 ³			14,800 ³	48 ³		1,736 ³
Revelstoke	130 ³				4.5 ³	-	1,843 ³
Whatshan	17 ³		1 ³			-	50 ³
Up. Arrow	124 ¹⁴	4.6	1.9 ¹⁶	4,420 ⁶	-	-	-
Lo. Arrow	116 ¹⁵	2.8	1.6 ¹⁷	2,580 ⁶	-	-	-
Arrow L.	240	4.6	1.8	7,000 ⁶	15.5 ¹²	12.5 ¹²	None
Koocanusa	166 ⁴	1.8 ⁴	1.1 ⁴		52 ⁴	-	
Duncan	45 ³ , 32 ⁴	2.4 ⁴	1.3 ⁴	1,727 ³	30 ³ , 28 ⁴		None
Kootenay L.	107 ⁴	6.1 ⁴	3.8 ⁴		3 ⁴	2.4	

Notes to Table 3.1.a and 3.1.b:

1. Date given is the year filling of the reservoir commences.
2. Lake level regulation began in 1939 (Daley *et. al.*, 1981, p10).
3. B.C. Hydro: http://eww.bchydro.bc.ca/html/lib_comp_psupp_columbia.html.
4. From Daley *et.al.*, 1981.
5. Estimated from (active storage)/(lake level variation).
6. Active storage between mean high and low water levels from elevation-storage curve, Section 3.6.
7. Surface area for mean post-impoundment water level of 432.4 m with narrows included with the Lower Arrow. This area is from the storage-elevation curve, (Table A3.3.2) with 21 km² subtracted from (added to) the Upper (Lower) Arrow area, as the storage-elevation curve includes the narrows in the Upper Arrow (Section A3.3.1).
8. As determined in Section 2.2, footnote 1, for mean water level. Volume of the Upper Arrow does not include the riverine section between Revelstoke and Arrowhead.
9. Corrected Arrow Lakes Reservoir Outflow 1973-1990; see Section 3.2.
10. Water Survey Canada: Columbia R. above Steamboat 73-85, Revelstoke Project Outflow 86-90.
11. Estimated from volume/surface area both at mean post-impoundment water level of 432.4 m.
12. Section 3.5.
13. Revelstoke outflow plus 82% (Sect. 3.8) of the local flow of 333 m³/s which enters Upper Arrow.

14. Length of main stem Upper Arrow (68.4 km) plus Revelstoke Reach (55.3 km); see Figure 1.1 and Section 3.9 for definition. Beaton Arm and Galena Bay are 17 km and 4.7 km long, respectively.
15. Length of Lower Arrow (92.0 km) and narrows (24.0 km). Distances given are length of the curve following the deepest part of the channel.
16. Mean post-impoundment area (275 km^2) divided by the sum of the lengths of the main stem Upper Arrow, Galena Bay, Beaton Arm and Revelstoke Reach.
17. Mean post-impoundment area (190 km^2) divided by the length of the Lower Arrow and narrows.
18. From WSC station "Columbia River at Castlegar" (see Section 3.3), the Keenleyside Dam began controlling flow in July 1968.

3.2 Main Inflow (Q_{in})

The main inflow to Arrow is defined as the flow of the Columbia River, at the location of the Revelstoke Dam, five kilometers north of the city of Revelstoke.

Methods

Daily flow data for 1955-1986 were obtained from Water Survey of Canada (WSC) station 08ND011, entitled "Columbia River above Steamboat Rapids". This station is located approximately 1 km downstream of the Revelstoke Dam and is representative of the main inflow as the drainage area between this station and the site of the Revelstoke Dam is at most 10 km^2 . From the time of the completion of the Keenleyside Dam in 1967, the record of the flow at this station is considered an overestimate as measurement as this station was affected by the high water levels in the Arrow Lakes Reservoir (Don Druce, B.C. Hydro, personal communication). While an attempt was made to correct for this effect (Kemp, 1990), this correction is considered biased as it was based on overestimated Keenleyside flows, as discussed in Section 3.3.

Daily flow data for 1986-1994 were obtained from WSC Station 08ND025, entitled "Revelstoke Project Outflow". Data for 1995-2003 was provided by B.C. Hydro, Burnaby.

Results

Pre- and post-impoundment inflow is shown in Figures 3.2.1(a). The change in flow after completion of Mica Dam in 1974 is evident. The spring peak flow is reduced and replaced with a more variable flow throughout the year. The mean daily pre-impoundment hydrograph shown in Figure 3.2.1(b) has a single large peak of $2,500 \text{ m}^3/\text{s}$ between day 150 and 200 (May 30 to July 19). Inflow gradually declines through the summer and fall until it reaches a low baseline winter flow of approximately $150 \text{ m}^3/\text{s}$. In contrast the mean post-impoundment hydrograph shown in Figure 3.2.1(c) has flow distributed more evenly throughout the year and shows two smaller peaks. Water is first retained during snowmelt in the spring, but once impoundments fill, the tail of the freshet results in an increase in flow during summer. The second peak occurs as water is released during winter at the time of peak hydroelectric demand.

The mean annual pre-impoundment flow for 1955-1964 was $818 \text{ m}^3/\text{s}$. The flow for 1986-1994 is $780 \text{ m}^3/\text{s}$ or 5% lower than the flow for 1955-1964. There are two potential sources for this difference: measurement error and climatic variation. Open river

gauging, such as the station above Steamboat Rapids, is generally considered accurate to 5%. The Revelstoke outflow is based on total power generated and considerable effort generally goes into establishing turbine ratings by the turbine manufacturer. As a result this flow is considered good to 1%. Climatic variation will be examined briefly in Section 3.11.

For the period after the completion of the Mica Dam in 1973 but before the completion of the Revelstoke Dam in 1983, the mean hydrograph (not shown) is similar to that shown in Figure 3.2.2 for 1986-1994. This is expected, as the Revelstoke dam is operated as run-of-the-river, and should have little impact on the shape of the annual hydrograph.

The daily mean Revelstoke outflow for 1997 to 2003 is shown in Figure 3.2.2, along with the mean pre- and post-impoundment hydrographs. Mean seasonal and yearly flows are summarized in Table 3.2.1. The inflow for all seven years generally followed the mean post-impoundment hydrograph. The first four study years (1997-2000) show above average annual inflow, while the last three years (2001-2003) had generally below average inflow. Of the seven study years, the highest flow occurred in 1997 and the lowest in 2001. Focusing on the inflow during the productive season (spring, summer and fall), 1997 and 1999 were well above average, 1998 and 2000 were close to average and 2001, 2002 and 2003 were all well below average, particularly in spring and summer.

Table 3.2.1. Mean seasonal inflow (m³/s) from Revelstoke Dam.

Season	Winter*	Spring	Summer	Fall	Year*
	Nov21-Apr10	Apr11-Jun15	Jun16-Sep21	Sep22-Nov20	Nov21-Nov20
Mean*	736	620	1063	593	779
1997	733 (0%)	697 (+12%)	1166 (+10%)	1087 (+83%)	901 (+16%)
1998	853 (+16%)	690 (+11%)	1022 (-4%)	839 (+41%)	866 (+11%)
1999	663 (-10%)	669 (+8%)	1198 (+13%)	1053 (+78%)	872 (+12%)
2000	735 (-0.2%)	671 (+8%)	1105 (+4%)	873 (+47%)	845 (+8%)
2001	734 (-0.3%)	555 (-11%)	694 (-35%)	627 (+6%)	673 (-14%)
2002	730 (-0.7%)	493 (-21%)	781 (-27%)	900 (+52%)	729 (-6%)
2003	855 (+16%)	515 (-17%)	856 (-19%)	616 (+4%)	754 (-3%)

* For example, winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year flow for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean flows are for 1986-1994.

3.3 Outflow (Qout).

The outflow from Arrow is the discharge through the Hugh Keenleyside Dam. Discharge from the Keenleyside Dam takes place from four vertically gated overflow sluices with a crest elevation of 424.9 m and eight tunnel ports with sill elevation of 411.5 m, with four ports on the north side of the sluices and four on the south side (Ketchum, 1990).

Construction of a diversion channel and powerhouse at Keenleyside Dam began in March 1999 and was completed in 2002. The 1,280 m concrete lined approach channel diverts

water around the Keenleyside Dam to the power plant located 400 m downstream of the dam.

Methods

There are two sources of WSC outflow data. The first is WSC station 08NE002, entitled "Columbia River at Castlegar" which was operational from 1913-1915 and 1961-1972. This record spans the construction of the Keenleyside Dam completed in 1967. This station is located approximately 7.5 km downstream of the Dam, just above Norns Creek, which is about one kilometer above the confluence with the Kootenay River. This station is a good representation of flow at the Keenleyside Dam because the Columbia River between the Keenleyside Dam and this station drains only ~30 km². The second source of outflow data is that computed from the Keenleyside operational record, reported by WSC as station 08NE126 entitled "Arrow Lakes Reservoir Outflow" from 1973 onward.

Both of these flows were reviewed by B.C. Hydro in the early 1990's (Ketchum, 1990 and May, 1994). This review was prompted by concerns that the flow from the Keenleyside Dam was overestimated during high discharge. The review was primarily based on a water balance between the Keenleyside discharge, the Kootenay River, which joins the Keenleyside discharge at Castlegar, and the downstream flow measured at Birchbank. Figure 3.3.1 shows the location of these stations. Each of these three flows was evaluated. Confidence in the Birchbank flow is high, as the river bottom at this gauging station is rock. Birchbank is an international gauging station and the stage-discharge rating curve is checked by both WSC and the U.S. Geological Survey and has not changed since 1961. The Kootenay River flow was found consistent by comparing the flow from the Brilliant Dam and the sum of the discharges from the Corra Linn, the Kootenay Canal and the Slocan River, see Ketchum (1990) for detail. This review concluded that the reported flow from the Keenleyside Dam was about 5% higher than actual and that this overestimation occurred primarily during high flow conditions.

In 1992, after a reexamination of scale models (May, 1994) a new set of equations was used to calculate the Keenleyside discharge. However, this set over corrected and underestimated the discharge. After further study, a final correction was applied in February 1993. As a result, the WSC Arrow Lakes Reservoir Outflow should be considered an overestimate before 1992, an underestimate in 1992 and accurate after 1993.

This review also found that measurement at the WSC station "Columbia River at Castlegar" was affected by high backwater levels during high discharge from the Kootenay River which joins the Columbia River about 1 kilometer downstream.

Corrected flows, for WCS station "Columbia River at Castlegar" for 1961-1972 and for WSC station "Arrow Lakes Reservoir Outflow" for 1973-1990 were obtained from K. Ketchum, B.C. Hydro, Burnaby. The data at the station "Columbia River at Castlegar" was corrected by reducing the flow by 4.7% or a mean of 58 m³/s. The Arrow Lakes Reservoir Outflow for 1973-1990 was corrected by reducing the flow by 3.4-5.5%, or a

mean of 52 m³/s. Additional study is currently underway to improve Arrow outflow data quality in conjunction with construction of the power project on Keenleyside Dam (Stan Matthews, Power Supply Resource Management, B.C. Hydro, Burnaby).

Data for 1997-2003 were provided by B.C. Hydro, Burnaby. Reported is total release from the project, both power and non-power.

Results

The Columbia River flow near the Hugh Keenleyside Dam is shown in Figure 3.3.2(a). The change in flow due to the completion of the Hugh Keenleyside Dam in 1967 is clearly visible. The spring peak is reduced and month to month variability is increased. The mean daily pre-impoundment hydrograph given by the corrected daily data for the station "Columbia River at Castlegar" for 1961-1966 is shown in Figure 3.3.2(b). The mean annual outflow for this period was 1,151 m³/s. The post-impoundment hydrograph given by the corrected daily data for the Keenleyside discharge for 1973-1990, is shown in Figure 3.3.2(c). The mean annual outflow for this period was 1,079 m³/s.

Similar to that seen for the pre-impoundment inflow at Revelstoke, the pre-impoundment outflow shows a dramatic spring peak of 4,000 m³/s which declines through summer and fall until it reaches a low winter baseline of around 200 m³/s. Post-impoundment outflow shows flow distributed more evenly throughout the year with minor peaks in summer and winter.

Table 3.3.1. Mean seasonal outflow (m³/s) from Hugh Keenleyside Dam.

Season	Winter* Nov21-Apr10	Spring Apr11-Jun15	Summer Jun16-Sep21	Fall Sep22-Nov20	Year* Nov21-Nov20
Mean*	1126	674	1388	903	1078
1997	1234 (+10%)	695 (+3%)	1829 (+32%)	1296 (+44%)	1306 (+21%)
1998	1556 (+38%)	486 (-28%)	1285 (-7%)	852 (-6%)	1174 (+9%)
1999	1336 (+19%)	651 (-3%)	1649 (+19%)	1215 (+35%)	1277 (+18%)
2000	1404 (+25%)	694 (+3%)	1558 (+12%)	1014 (+12%)	1253 (+16%)
2001	1302(+16%)	951 (+41%)	1037 (-25%)	916(+1%)	1104 (+2%)
2002	846 (-25%)	484 (-28%)	1389 (0%)	1383 (+53%)	1014 (-6%)
2003	1047 (-7%)	442 (-34%)	1346 (-3%)	1236 (+37%)	1049 (-3%)

* Winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year flow for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean flows are for 1973-1990.

The Keenleyside outflow for 1997 to 2003 is given in Figure 3.3.3, together with the mean pre- and post-impoundment hydrographs. The mean seasonal and yearly flows are summarized in Table 3.3.1. The flows from 1997 to 2003 generally followed the mean post-impoundment hydrograph. Annual outflow was well above average in 1997, 1999 and 2000 and about average in the other years. In 1998, flow was below average throughout the productive period (spring, summer and fall). In both 2002 and 2003 spring flow was below average, with summer close to average, similar to that observed in

1998. However, in 2002 and 2003, outflow increased significantly in the fall. In contrast, spring flow was very high in 2001, despite low Revelstoke and local inflow.

3.4 Local Metered Stream Flow

Of the rivers and streams entering Arrow, not all have been monitored by Water Survey Canada; for those that have been monitored see Appendix 3.3. The sum of all local metered stream flow into Arrow results in a flow of $187 \text{ m}^3/\text{s}$ from a drainage area of $4,940 \text{ km}^2$. This represents only 57% of the total local inflow computed in Section 3.7. Only seven local inflows are currently metered: the Illecillewaet River, the Whatshan discharge and Beaton, Kuskanax, Barnes, Inonoaklin and Deer Creeks. The mean flow for these seven is $78 \text{ m}^3/\text{s}$, which represents 24% of the local flow. The Illecillewaet River will serve as an example of monitored tributary inputs, as follows.

Methods.

Flow of the largest local river, Illecillewaet, was metered at Greeley, and daily flow data for 1963-1994 was obtained for WSC station 08NE013, entitled “Illecillewaet at Greeley”. Data for 1995-2001 was provided by B.C. Hydro, Burnaby. Data for 2002 and 2003 was provided by Water Survey Canada. The data from B.C. Hydro had not undergone quality control. In B.C. Hydro records anomalous peaks in flow are evident during winter: peaks of this sort are not found in any of the WSC winter data. For 1997, missing data (3 days through the year and blocks after day 313) were linearly interpolated, and anomalous winter peaks were removed by replacing day 1-70 with the mean flow. In 1998, missing data from 333-340 was linearly interpolated and anomalous winter flows during days 5-30 and 355-365 was removed by replacement with mean values. In 1999, most of July was missing (days 198-215, Jul 5-Aug 8) and this was replaced with the mean. Missing data from days 36-58 and 281-284 was linearly interpolated. Anomalous winter flow from days 0-21 was replaced with the mean. In 2000, daily averages were computed from hourly data. The 2000 hourly data contained many missing hourly values, especially in summer. Daily averages were computed if 12 or more hourly values existed for a given day. The flow for the occasional missing day was linearly interpolated. In 2000, anomalous winter flows during days 344-366 was removed by replacement with mean values. In 2001, anomalous winter flow was replaced with mean values for day 1-69 and day 354-365 onward and missing data through the year were linearly interpolated.

Results

Figure 3.4.1(a) shows the flow for 1963-1994. The mean daily hydrograph for Illecillewaet, shown in Figure 3.4.1(b) has the same character as the pre-impoundment flows of the both the Columbia at Revelstoke and at Castlegar, with a peak in spring of $160 \text{ m}^3/\text{s}$ tapering through summer and fall to a baseline winter flow of around $10 \text{ m}^3/\text{s}$. For the Illecillewaet at Greeley, the mean annual outflow for 1963-1994 was $52.6 \text{ m}^3/\text{s}$.

For 1997 to 2003, the daily flow of the Illecillewaet at Greeley is shown in Figure 3.4.2 along with the daily mean flow for 1963-1994. Mean seasonal and yearly flows are summarized in Table 3.4.1. Even though flow in 1997, 1999 and 2000 was at or below average for the first part of spring, the flow in summer and the average flow for the year were above average. In contrast, in 1998, flow was above average in early spring but flow through the remainder of the year was below average. In 2001 flow remained below average throughout the year. In 2002, a late spring was followed by above average summer flow, while in 2003, a late spring was followed by below average summer flow.

Table 3.4.1. Mean seasonal flow (m³/s) for the Illecillewaet River at Greeley.

Season	Winter* Nov21-Apr10	Spring Apr11-Jun15	Summer Jun16-Sep21	Fall Sep22-Nov20	Year* Nov21-Nov20
Mean*	10.2	90.7	105	25.8	52.7
1997	10.6 (+3%)	108 (+19%)	108 (+3%)	48.6 (+88%)	60.5 (+15%)
1998	11.0 (+7%)	105 (+15%)	77.6 (-26%)	14.9 (-42%)	46.5 (-12%)
1999	9.1 (-11%)	76.3 (-16%)	133 (+27%)	37.8 (+46%)	59.1 (+12%)
2000	15.1 (+45%)	81 (-11%)	119 (+14%)	27.3 (+6%)	57(+8%)
2001	9.8 (-4%)	76 (-17%)	85 (-19%)	22 (-16%)	44 (-17%)
2002	10.0 (-3%)	84 (-7%)	121 (+15%)	20 (-24%)	55 (+4%)
2003	9.6 (-6%)	91 (0%)	84 (-19%)	41 (+58%)	50 (-6%)

- Winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year flow for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean flows are for 1963-1994.

3.5 Lake and Reservoir Levels

Methods

The measurement of lake and reservoir level is summarized in Table 3.5.1. Daily data were obtained from WSC. For 1995-2000, hourly data for Nakusp, Fauquier and the Keenleyside forebay were provided by B.C. Hydro, Burnaby. Anomalous data in the B.C. Hydro records were replaced with interpolated values: small blocks of data with a large offset occurred a couple of times a year and were probably the result of instrument servicing. Hourly data were averaged to daily values.

Results

Figure 3.5.1(a) shows the water level of the Lower Arrow given by the WSC stations “Lower Arrow Lake at Needles” and “Arrow Lakes Reservoir at Fauquier”. Figures 3.5.1(b) and (c) shows the mean daily pre-impoundment water level for 1930-1965 and the mean daily post-impoundment water level for 1970-1994, respectively. Note that Needles is located at essentially the same place along the lake/reservoir as Fauquier with Needles on the west side and Fauquier on the east (Figure 1.1). Comparison of these figures, both plotted with the same scale, shows the increase in variability of the Arrow reservoir level after impoundment.

Table 3.5.1. Summary of water level measurement.

WSC Station	Station Name	Years	Filename base
Historic			
BC 08NE038	UPPER ARROW LAKE AT ARROWHEAD	1930-1968	lupah
BC 08NE068	UPPER ARROW LAKE AT BEATON	1946-1946	lupbe
BC 08NE107	ARROW RESERVOIR AT SHELTER BAY	1969-1974	lshel
BC 08NE045	UPPER ARROW LAKE AT NAKUSP	1922-1969	lupna
BC 08NE046	LOWER ARROW LAKE AT NEEDLES	1930-1968	llone
Present			
BC 08NE103	ARROW RES. AT HUGH KEENLEYSIDE DAM	1969-1997	lhkdm
	Reported by WSC to 1988 only.		
BC 08NE102	ARROW RESERVOIR AT FAUQUIER	1969-1997	lfauq
BC 08NE104	ARROW RESERVOIR AT NAKUSP	1969-1997	lnaku

Table 3.5.2 compares pre-and post-impoundment lake and reservoir levels for the Lower Arrow.² Before impoundment, lake level reflected inflow: during spring melt, lake level peaked and during summer and fall lake levels gradually declined to a steady winter level. Construction of the Hugh Keenleyside Dam resulted in both an increase in the mean water level of 12.5 m and an increase in the mean annual water level variation from 8 to 15 m.

Table 3.5.2. Comparison of pre- and post-impoundment lake and reservoir levels

	Pre-impoundment	Post-impoundment
Station	Lower Arrow Lake At Needles	Arrow Reservoir At Fauquier
Years	1930-1965	1985-1994
Water level variation, m:		
Maximum	11.4	19.6
Mean	8.0	15.5
Maximum water level, m	428.5 (Jun 11/48)	440.6 (Oct 6/86)
High water level, mean, m	425.4 +/- 1.3	438.5 +/- 2
Mean water level, m	419.8	432.4
Low water level, mean, m	417.4 +/- 0.2	423.0 +/- 2
Minimum water level, m	417.1 (Mar 25/44)	421.1 (Apr 18/92)
Normal full pool 440.13 m. Minimum pool 420 m. (BC Hydro Keenleyside web site.)		

² Results from Fauquier in the Lower Arrow will be used for the entire Arrow Reservoir. The mean water level for 1986-1994 for Fauquier (Lower Arrow) is 432.37 m and for Nakusp (Upper Arrow) is 432.43 m, a difference of 6 cm. Larger differences are expected for the mean low and minimum water levels due to riverine flow through the narrows.

Before impoundment, the mean water level was close to the mean pre-impoundment low water level: in other words, water levels remain low through most of the year with a peak in spring. In contrast, the post-impoundment mean water level is closer to the mean post-impoundment high water level: water levels remain high throughout most of the year with a drop in water level in late winter. Thus, before impoundment, spring flows briefly covered a partially vegetated flood zone whereas after impoundment winter release exposes a non-vegetated and considerably larger draw-down zone.

Figure 3.5.2 shows the 1997 to 2003 Fauquier and Nakusp water levels located in the Lower and Upper Arrow, respectively. Mean seasonal and yearly flows are summarized in Table 3.5.3. The water levels generally follow the Fauquier post-impoundment mean. From 1997 to early 2001, water levels were generally higher than average, but seasonal means were generally within 2 m of average. In 2001, from May onward, the water levels were very unusual, up to 10 m below average, and remained low until spring 2002. These low water levels in 2001 occurred after a winter of exceptionally low snow pack.* The low water levels are highlighted in Fig. 3.5.1a. In 2002 and 2003, early summer water levels were normal. However, lake levels in 2002 and 2003 dropped more rapidly than usual through mid-summer and fall, resulting in near average outflow despite both low Revelstoke and local inflows. This rapid summer-fall decline in 2002 and 2003 also resulted in below average water levels in fall and early winter

Table 3.5.3. Mean seasonal water level (m) at Fauquier.

Season	Winter** Nov21-Apr10	Spring Apr11-Jun15	Summer Jun16-Sep21	Fall Sep22-Nov20	Year* Nov21-Nov20
Mean**	429.1	427.5	437.0	436.3	432.1
1997	428.7 (-0.4)*	429.0 (+1.5)	439.0 (+2.0)	437.3 (+1.0)	432.9 (+0.8)
1998	431.7 (+2.6)	429.2 (+1.7)	437.7 (+0.7)	437.3 (+1.0)	433.8 (+1.7)
1999	430.4 (+1.3)	427.0 (-0.5)	438.2 (+1.2)	436.8 (+0.5)	433.0 (+0.9)
2000	431.1 (+2.0)	428.2 (+0.7)	438.0 (+1.0)	436.1 (-0.2)	433.3 (+1.2)
2001	430.3 (+1.2)	423.4 (-4.1)	428.7 (-8.3)	426.2 (-10.1)	428.0 (-4.1)
2002	424.4 (-4.7)	428.4 (+0.9)	437.4 (+0.4)	432.2 (-4.1)	429.9 (-2.2)
2003	427.0 (-2.1)	430.9 (+3.4)	437.5 (+0.5)	432.0 (-4.3)	431.3 (-0.8)

* Bracketed values give water level difference (m) from the mean.

** Winter level for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year level for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean levels are for 1970-1994.

In all seven years the water level in Lower Arrow was essentially the same as that in Upper Arrow. Some water level difference occurred around day 90 in both 1998 and 1999, around day 140 in 2001 and around day 15 in 2002. A difference between the post-impoundment water levels can occur when water levels are low in combination with high flow through the narrows. As an example, the water levels for 1991 (Figure 3.5.3) show a significant difference between Upper and Lower Arrow levels from days 75-150.

* It also occurred after a period of exceptionally high electricity prices in California (Oct 2000-June 2001) but whether this factor contributed to reduced water levels is not known.

In 1991, separation between the Upper and Lower Arrow began when water levels dropped below 428 m above datum. In general, the water level at which separation begins will also depend on the flow rate through the narrows.

3.6 Flow to Storage (Qstor)

The storage flow is here defined as the flow of water to and from storage in the Arrow reservoir. If Qstor is positive the reservoir level rises and water is stored while the reverse is true for negative values.

Methods

A storage-elevation curve provided by K. Ketchum, B.C. Hydro, Burnaby is shown in Appendix 3.2 and is used to calculate the storage flow as the reservoir level changes. The storage flow is here calculated from the Fauquier water levels. The water level was center differenced, with storage flow on day i , determined by the mean daily water level difference between days $i+1$ and $i-1$. Namely, the volume of the reservoir for a given day i , $V(l_i)$, is determined from the mean daily water levels, l_i , and the volume change during day i , is estimated as follows: $(V(l_{i+1}) + V(l_i))/2 - (V(l_i) + V(l_{i-1}))/2$.

Results

Figure 3.6.1(a) shows the post-impoundment storage flow for 1970-2003. The mean daily flow for 1973-1990 is shown in Figure 3.6.1(b). The storage flow for 1997 to 2003 is given in Figure 3.6.2. Water is stored (flow to storage with Qstor positive) during spring and early summer as water levels rise. There is a small flow from storage during late summer and fall and this flow from storage increases during winter as reservoir levels drop, in preparation to receive new spring runoff. Note the reduced storage flow in spring-summer 2001.

3.7 Computing the Local Flow (Qloc).

Introduction

Local inflow is any inflow except that from the Columbia River at the site of the Revelstoke Dam. The local inflow is composed of inflow from local rivers and streams, inflow from the Whatshan Reservoir and inflow from direct precipitation to the reservoir surface. The local inflow will be determined from a water balance as detailed below.

As discussed in Section 3.4, the currently metered streams and rivers represent only 20% of the local inflow. As a result the local inflow, as computed in this section, will be used to compute the nutrient loads in Chapter 9. The local inflow will be evaluated in Section 3.8 and the local flow will be divided between regions of the Arrow basin in Section 3.9.

Equation for the local flow

The local flow is here defined as any water flow that enters Arrow other than the inflow at the site of Revelstoke Dam. The local flow is determined by the water balance,

$$Q_{in} + Q_{loc} = Q_{out} + Q_{stor}$$

where;

Q_{in} Revelstoke Project Outflow,
 Q_{loc} Local inflow,
 Q_{out} Flow out from the Keenleyside Dam,
 Q_{stor} Flow to storage.

It should be noted that Q_{loc} is the small difference between relatively large quantities (Q_{in} , Q_{out} and Q_{stor}) and therefore Q_{loc} is subject to considerable error.

Mean annual local flow

Before computing the daily local flow, the annual local flow is examined as follows. Mean annual local flow computed from the mean annual inflow, outflow and storage flow is shown in Table 3.7.1, for both Arrow Lakes Reservoir and Kootenay Lake.

For Arrow Lakes Reservoir, the local drainage area accounts for 28% of the total drainage area above the Keenleyside Dam and the local inflow accounts for 31% of the total flow through Keenleyside. Two examples are given for the Arrow Lakes Reservoir, showing the differences that result from averaging over different periods. There are two possible sources for these differences, either errors or climatic variability. The Illecillewaet at Greeley for the first period 1973-1990 (52.0 m³/s) was 6% lower than that for the second period 1986-90, 95-97 (55.3 m³/s). Compare this to a 9% decrease in Q_{loc} , between these two periods. Thus, it appears that a good part of the variance is accounted for by climate.

The storage flow, Q_{stor} , is expected to be zero for means over many years. This is the case for 1973-1990 (Table 3.7.1.), but for shorter means a non-zero Q_{stor} results from the water level change between the start and end of the averaging period. For example, the mean annual Q_{stor} for 1986-1994 is -11.7 m³/s. However, during this time the water level dropped from 434.83 m on Jan 1/86 to 427.71 m on Dec 31/94 with a volume loss of 3,243 Mm³, which over 9 years corresponds to a flow of -11.4 m³/s.

Data for Kootenay Lake are shown in Table 3.7.1 for comparison. Kootenay Lake has three arms: the North, South and West Arms. The North and South Arms form the main basin of Kootenay Lake. Flow drains out of Kootenay Lake along the West Arm. The local inflow to the main basin of Kootenay Lake accounts for 13% of the total inflow to the main basin. This is substantially smaller than the 31% for Arrow Lakes Reservoir. Note, however, that this comparison depends on the definition of the local flow. For example, in Kootenay Lake, the Lardeau River is considered part of the main inflow: the

Lardeau joins the outflow from the Duncan Dam to form the Lower Duncan River which then enters the North Arm of Kootenay Lake. It could be argued that the main inflow to Arrow Lakes Reservoir should be the flow entering the main basin of Upper Arrow at Arrowhead.

Table 3.7.1. Mean annual local flow determined from water balance

ARROW LAKES RESERVOIR: 1973-1990		Area km ²	Flow m ³ /s	Yield ⁵ m/yr
Inflow	Mica Dam ⁴	21,000	586	0.88
	Between Mica and Revelstoke Dam	5,410	163	0.95
Qin	Columbia R. above Steamboat 1973-85; Revelstoke Project Outflow 1986-90	26,410 ¹	749	0.93
Qout	Corrected Arrow Lakes Reservoir Outflow 1973-1990	36,500 ²	1080	0.93
Qstor	Storage Flow		+2	
Qloc	Local Inflow to Arrow	10,100	333	1.12
	Qloc/Qout	28%	31%	

ARROW LAKES RESERVOIR: 1986-1990,1995-1997⁶		Area km ²	Flow m ³ /s	Yield ⁵ m/yr
Qin	Revelstoke Project Outflow	as above	785.7	
Qout	Corrected Arrow Reservoir Outflow		1,148.6	
Qstor	Storage Flow		+13.5	
Qloc	Local Inflow to Arrow		376.4	
	Qloc/Qout		31%	

KOOTENAY LAKE		Area km ²	Flow m ³ /s	Yield ⁵ m/yr
Inflow ³	Libby Dam	24,450	352	0.45
	Drainage to Kootenai R. between Libby Dam and South Arm	10,860	143	0.42
	Total Kootenai R. to South Arm	35,310	495	0.44
	Duncan and Lardeau to North Arm (Duncan 100 ⁷ m ³ /s, Lardeau 81 m ³ /s)	4,590	181	1.24
Outflow ³	Total Inflow:	39,900	676	0.53
	Corra Linn	45,600	805	0.56
	Minus Drainage to West Arm	1,090	30	0.87
	Total Outflow from North, South Arms	44,510	775	0.55
Qloc	Local Inflow to North and South Arms	4,610	99	0.67
	Qloc/Qout	10 %	13%	

Notes to Table 3.7.1:

1. Area for station "Columbia R. above Steamboat Rapids" plus 10 km²; see Section 3.2.
2. Area for station "Columbia R. at Castlegar" minus 30 km²; see Section 3.3.
3. All Kootenay data is from Daley *et. al.* (1981, p10).
4. From B.C. Hydro: http://eww.bchydro.bc.ca/html/lib_comp_psupp_columbia.html. Compare WSC station 08ND007 entitled "Columbia River above Nagle Creek" located just below the Mica Dam site with drainage area of 21,500 km² and the mean flow for 1947-1983 of 567 m³/s.

5. Yield or “effective” precipitation (m/yr) is $[\text{flow (m}^3/\text{s)} \times 31.5575] / [\text{area (km}^2)]$, where $31.5575 \text{ m/yr} = (1 \text{ m}^3/\text{s}) / (1 \text{ km}^2)$. See also Section 3.9.
6. This period was chosen to use the relatively more accurate Revelstoke discharge data from 1986 and because the corrected Arrow discharge is not currently available for 1991-1994.
7. Duncan R. below Duncan Dam, 08NH126, 1964-1986. Lardeau is the difference, $181^3 - 100 = 81 \text{ m}^3/\text{s}$. The B.C. Hydro web site⁴ reports the Duncan flow as $102 \text{ m}^3/\text{s}$.

In that case, the Illecillewaet would be considered a part of the main inflow rather than a part of the local flow as it enters the riverine reach between the Revelstoke Dam and Arrowhead. In Section 3.9 below, the local flow into this riverine section is estimated as $130 \text{ m}^3/\text{s}$. Thus, considering the flow at Arrowhead as the main inflow results in the local inflow to the rest of the reservoir being 17% which is more comparable to Kootenay. However in this work the local inflow will continue to be defined as all flow other than the Revelstoke dam outflow.

Daily local flow

Methods.

Daily values for the local flow into the Arrow Lakes Reservoir were computed using the equation given above for 1973-2003. Daily values of Q_{stor} were determined from the Fauquier water level as discussed in Section 3.7. Q_{out} consisted of daily discharge from the Hugh Keenleyside Dam described in Section 3.3: corrected data was used for 1973-1990 and 1994-2001 and uncorrected data for 1991-1993. Q_{in} consisted of daily flow data from the WSC station 08ND011 (Columbia River above Steamboat Rapids) for 1970-1985 and the Revelstoke Project Outflow for 1986-2001, as described in Section 3.2.

Results

Local flow to the Arrow Lakes Reservoir for 1973 to 2003 is shown in Figure 3.7.1(a). The 8 year mean from 1986-1990 and 1995-1997 is shown in Figure 3.7.1(b). The average local flow for this period was $376.4 \text{ m}^3/\text{s}$.

Local flow for 1997 to 2003 is given in Figure 3.7.2. Mean seasonal and yearly flows are summarized in Table 3.7.2. Note that Q_{loc} is highly variable, as it is a difference between large values. Negative values of the local flow correspond to a local drain rather than a local source of water, which is erroneous. Negative flows generally occur next to large positive flows: smoothing of the daily data results in a physical hydrograph (smoothed data not shown). The local flow generally follows that of the Illecillewaet (Section 3.4). While early spring flows for 1997 and 1999 were average, both had above average local flow for the rest of the year, with 1997 particularly high. In contrast, 1998 had above average local flow in early spring but reduced local flow through late spring and summer that resulted in considerably reduced flow for the year. In 2000, local flow was close to average with minor variation about the average from one season to the next. In 2001, local flow was considerably below average throughout the year. In 2002 and 2003, local flows were generally less than average though not as low as 2001. Note the

late spring in 2001, 2002 and 2003, followed by a pulse of runoff at the end of May (Fig. 3.6.2).

Table 3.7.2. Mean seasonal local inflow (m³/s).

Season	Winter*	Spring	Summer	Fall	Year*
	Nov21-Apr10	Apr11-Jun15	Jun16-Sep21	Sep22-Nov20	Nov21-Nov20
Mean*	165	749	522	227	376
1997	168 (+2%)	953 (+27%)	677 (+30%)	314 (+39%)	471 (+25%)
1998	166 (+1%)	748 (0%)	327 (-37%)	94.9 (-58%)	303 (-20%)
1999	142 (-14%)	680 (-9%)	728 (+39%)	244 (+8%)	413 (+10%)
2000	175 (+6%)	710 (-5%)	594 (+14%)	152 (-32%)	380 (+1%)
2001	108 (-34%)	576 (-23%)	384 (-26%)	146 (-36%)	273 (-28%)
2002	138 (-16%)	651 (-13%)	584 (+12%)	122 (-46%)	348 (-8%)
2003	118 (-28%)	648 (-13%)	389 (-26%)	237 (+5%)	306 (-19%)

* Winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year flow for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean flows are for 1986-1990, 1995-1997.

3.8 Evaluation of the Local Flow

Is the local flow reasonable? Unreasonable local flow during winter was one of the primary reasons that B.C. Hydro reevaluated the Keenleyside discharges in the early 1990s. This section will first compare the hydrograph of the local flow to that of the local rivers and streams. Second, an estimate of the error in the local flow will be given.

Comparison of hydrographs

Figures 3.8.1 and 3.8.2 show a variety of mean hydrographs, plotted with constant area under the curve. The spring runoff begins first in the Inonoaklin Creek on the Lower Arrow. This is expected since the climate warms progressively from Castlegar to Revelstoke. Spring runoff begins next in the Kuskanax Creek, at Nakusp, on the southern end of the Upper Arrow. The Kuskanax curve looks like the Inonoaklin curve displaced by 10 to 20 days. Spring runoff begins last for the Illecillewaet, which reaches up into glacial fields in the Roger's Pass area. The shape of the Illecillewaet is different than that of the Inonoaklin and Kuskanax with a larger tail through late summer. Unlike the Inonoaklin and Kuskanax, the Illecillewaet has a substantial glacial melt component that sustains the flows through late summer and into early fall. Glacial melting is sensitively controlled by the albedo of the glacier. During late summer and early fall the glacier has low albedo and high melting rates, supplying much of the runoff encountered by fish spawning in early September. However, on the first snowfall, the albedo of the glacier is increased and melting abruptly halts (Dr. Mindy Brugman, Columbia Mountain Institute, pers. comm.).

The computed local flow shown in Figure 3.8.1 has a shape which resembles a composite of the glacially augmented Illecillewaet flow and that of the Kuskanax and Inonoaklin.

However, the local flow is higher during winter. The cause of this higher winter flow is examined as follows.

The winter component of the local flow can be divided into three parts:

1. the fraction of the winter flow that comes from tributary inflow,
2. the fraction of the winter flow that comes from known sources, namely direct precipitation to the water surface and flow from the Whatshan Reservoir, and
3. the remainder which will be considered error.

Appendix 3.4 details the first two in order to determine the remainder. For the years 1986-90, 95-97 the remainder is 11% of the local flow and for 1997 the remainder is 3%. Thus from the examining the winter flow the error in the local flow is order 3-11%.

Error estimate for the local flow

As seen from discrepancies in the mean winter flow, the error in the local flow appears to be 3-11%. A second way of approaching an error estimate for the local flow is to estimate the measurement errors.

Measurement error can be expressed as the error in a daily value or the error in longer-term averages. Clearly the local flow has a large daily error as represented by the noise in the unsmoothed hydrograph. The error in hourly and daily flows for both the Revelstoke and Arrow discharges is probably on order of 5%, while the bias or error in longer term means is probably on order of 1%, (K. Ketchum, pers. comm.) The error in the storage flow will not be evaluated here.³ The mean Q_{in} and Q_{out} for day 1-75 are 710 and 1350 m³/s, respectively. An error of 1% for both would give rise to an error on order of 20 m³/s or 6% in the local flow. In conclusion the error for Q_{loc} will be considered to be order 6%-11%.⁴

3.9 Division of the local flow between regions in the Arrow basin

Calculation of the nutrient load to each of the upper and lower basins individually requires that the local flow be divided between the two. In this section the local flow will be divided into four distinct geographical regions on the basis of mean stream yields for each region.

³ Error in the storage flow is not dominated by error in water level measurement. Using the Nakusp water levels rather than those from Fauquier makes at most a 0.3% difference in the annual mean of the local flow for each given year from 1973-1990.

⁴ Local flows computed here were also compared to smoothed local flow data computed by B.C. Hydro based on the corrected Keenleyside discharges and obtained from K. Ketchum, B.C. Hydro, Burnaby. The hydrographs of both local flows follow each other in detail, and the difference between the two is flat point-alternating noise. The mean of the B.C. Hydro local flow for 1986-90,95-97 is 357 m³/s. Differencing on a year by year basis and averaging gives the difference between these two local flows as 19 +/- 15 m³/s or 5% of Q_{loc} .

The four regions of the Arrow Lakes Reservoir

The local inflow was divided into four regions:

1. **Revelstoke Reach** the riverine section between Revelstoke and Arrowhead;
2. **Beaton Arm** an inlet at the north end of the Upper Arrow, here defined as waters to the northeast of a line between Arrowhead and Storm Point (also known as Northeast Arm);
3. **Mainstem, Upper Arrow** is the remainder of the Upper Arrow. The southern boundary of the Upper Arrow is chosen at the north end of the narrows, following a natural drainage boundary, 4.5 km upstream of the Arrow Park Cable ferry;
4. **Lower Arrow**, from the southern boundary of the Upper Arrow to the Keenleyside Dam. The narrows are here considered part of the Lower Arrow.

The drainage and water surface areas of these four regions are given in Table 3.9.1, and were determined from the 1:250,000 topographical maps using a digitizing tablet, computer and appropriate software, accurate to within 3%. The local drainage area determined in this way compares within 0.1% of that reported by WSC⁵, and the water surface area compares within 2% of that determined from the storage-elevation curve.⁶

Table 3.9.1. Characteristics of the Arrow Lakes Reservoir regions

Name	Drainage Area km ²	Water Surface km ²	Estimated Yield m/yr	Flow m ³ /s	Percent of local flow	Percent of total flow
Revelstoke Reach	2,620	70	1.56	130	40%	12.1%
Beaton Arm	1,270	31	1.50	60.4	19%	5.6%
Main stem Upper A.	2,070	206	1.12	73.4	23%	6.9%
Upper Arrow	5960	307		264	82%	24.7%
Lower Arrow	3,650	191	0.49	56.7	18%	5.3%
Total	9,610	498		321		

Drainage and water surface area from topographic map with narrows included in the Lower Arrow.

Precipitation near the reservoir

A simple division of the local flow by drainage area assumes that the precipitation to all parts of the local drainage area is the same. This is not appropriate, however, as precipitation increases substantially from Castlegar to Revelstoke. As will be seen below, the near shore precipitation is also not an appropriate criteria for dividing the

⁵ The total drainage area for the Arrow Reservoir, which includes the water surface area, is 10,110 km². This compares well with the area of 10,100 km² estimated from drainage areas reported by WSC as shown in Table 3.7.1. (The extremely good agreement is considered fortuitous.)

⁶ The water surface on the topographic map is marked "Max 1437ft" which is the mean high water level of 438 m. Assume that the shoreline on the topographic map indicates the shoreline during mean high water. The area of the reservoir determined from the topographic maps is 498 km². This is within 2% of the water surface area of 510 km² determined from the storage-elevation curve for 438 m (Appendix 3.2).

local flow as it does not reflect rainfall in the mountains. In the next subsection, stream yield will be used to divide the local flow.

Mean yearly precipitation at four gauging sites is shown in Table 3.9.2. Rain records at Castlegar are shown for reference and differ considerably from those at the Keenleyside Dam. While the dam is only 8 km east of Castlegar, the dam and the Arrow Lakes Reservoir lie in a valley distinct from that of Castlegar. Note also that all of these rain gauges lie in the valley, close to the reservoir. Note the large increase in precipitation from Fauquier to Nakusp.

Table 3.9.2. Annual temperature and precipitation at five sites along Arrow¹

	Revelstoke. A	Nakusp	Fauquier	Castlegar BCHP Dam	Castlegar A
Years	1969-90	1961-90	1961-90	1969-90	1961-90
Mean daily temp. (C)	6.7	7.3	7.5	8.5	8.3
Degree-day below 0°C	479	299	300	NA	302
Days with Max Temp >0	312	324	323	NA	325
Rainfall (mm)	612	642	506	481	533
Snowfall (mm)	445	216	169	116	225
Precipitation (mm)	950	859	676	597	732
Insolation (h)	1598	NA	NA	NA	1859

1. Canadian Climate Normals, (1993).

Mean stream yield to each region

Streamflow data also provides a measure of precipitation. The effective precipitation will be defined as the mean annual streamflow divided by the drainage area and is given in units of m/yr. The effective precipitation is also known as the ‘stream yield’. Effective precipitation for all of the metered streams in the Arrow drainage basin is given in Appendix 3.2. Effective precipitation to the Upper Arrow is almost 3 times as high as that to the Lower Arrow. This dramatic difference is not reflected in the valley rain gauge data. This implies that precipitation in the mountain headwaters of the local streams and rivers is substantially higher than the precipitation near the reservoir.

The effective precipitation for each of the four drainage areas is given in Table 3.9.1 and was determined as follows:

1. Revelstoke Reach. The Illecillewaet (1.4 m/yr) accounts for nearly half of the drainage area to the Revelstoke Reach. The other half of the drainage area is taken to have an effective precipitation which is the mean of the Akolkolex (1.6 m/yr), Cranberry (1.5 m/yr) and Jordan (2.0 m/yr).
2. Beaton Arm. The Incomappleux (1.7 m/yr) accounts for 80% of the area draining into Beaton Arm. The remainder of the drainage area lies close to the arm and will be considered similar to Beaton Creek (0.78 m/yr).

3. Main stem Upper Arrow. Two thirds of the drainage area to the main stem of the Upper Arrow is considered similar to the Kuskanax (1.33 m/yr), which is the only large river into the main stem to have been metered by WSC. The remaining third is considered an average of Hill Creek at Mill Bridge Road (0.70 m/yr) and Brouse Creek (0.71 m/yr).
4. Lower Arrow. The arithmetic mean is taken of all streams into the Lower Arrow for which it was possible to determine an effective precipitation (0.49 m/yr).

Recall that only half of the total local flow has been metered and a variety of assumptions are made in determining the effective precipitation to each drainage area. As a check, the effective precipitation was multiplied by the drainage area to give the effective streamflow for each region: these flows are given in Table 3.9.1. The sum of these streamflows is 320m³/s, which is comparable to the mean local flow of 333 m³/s found in section 3.7 for 1973-1990.

Allocation of local flows to basins

The local flow to each region will be computed as the fraction of the total local flow using the percentages shown in Table 3.9.1. The local flow to the Upper Arrow, Qlocup, is defined to be the sum of the local flows to the Revelstoke Reach, Beaton Arm and the main stem Upper Arrow. Qlocup is 82% of the local stream flow to the Arrow Lakes Reservoir.

Using a fraction of the total local flow to represent the local flow into each basin assumes that the hydrograph of the flow into a given sub-basin has the same shape as the hydrograph for the total local flow. This is not the case as discussed in Section 3.8. For example the true hydrograph for the Lower Arrow would begin earlier and have less of a tail than that of the hydrograph of the total local flow, Qloc. Nevertheless a fraction of Qloc will be used as the local flow to each sub-basin in what follows as further refinement is not likely warranted.

3.10 Flow through the narrows

Conservation of water for both the Upper and Lower Arrow gives the following two equations,

$$\begin{aligned} Q_{nar} + Q_{storup} &= Q_{in} + Q_{locup} \\ Q_{out} + Q_{storlo} &= Q_{nar} + Q_{loclo} \end{aligned}$$

where;

Qnar	Flow through the Narrows
Qin	Inflow from the Revelstoke Dam
Qout	Outflow from the Keenleyside Dam
Qstor	Storage Flow (rising water level corresponds to a positive Qstor)
Qstorup	Storage flow to the Upper Arrow

	Qstorlo	Storage flow to the Lower Arrow
Qloc	Local flow (all inflow other than that from the Revelstoke Dam)	
	Qlocup	Local inflow to the Upper Arrow = $0.82 \cdot Q_{loc}$
	Qloclo	Local inflow to the Lower Arrow = $0.18 \cdot Q_{loc}$

Methods

Qin and Qout are used as described in Section 3.7. Qlocup and Qloclo were used as determined in Section 3.9, where the local flow was divided between the Upper and Lower Arrow based on stream yield to each. Qstorup and Qstorlo were determined using the storage-elevation curve discussed in Section 3.6 and detailed in Appendix 3.3. Note the storage-elevation curves include the narrows with Upper Arrow whereas the narrows is here included with Lower Arrow. Using the storage elevation curves results in Qstorup on order 6% ($20 \text{ km}^2 / 334 \text{ km}^2$) higher and Qstorlo 6% lower than would be expected if the narrows were included with Lower Arrow. In the calculation of the narrows flow, the storage flows given by the storage-elevation curves are used as given.

Results

The daily Narrows flow for 1973-2003 is shown in Figure 3.10.1(a) and the mean for 1973-1990 is shown in Figure 3.10.1(b). As expected, the Narrows flow is similar to the post-impoundment inflow and outflow with relatively steady flow through the year and showing a broad increase in flow during both late summer and winter. For comparison, the mean inflow and outflow are plotted with the mean Narrows flow, all averaged over the years 1986-1990, in Figure 3.10.1(c). As expected the Narrows flow generally lies between the inflow and outflow. The narrows flow most resembles the outflow as both local flow and storage in Lower Arrow is smaller than in Upper Arrow. The flow through the Narrows in 1997 to 2003 is shown in Figure 3.10.2. Mean seasonal and yearly flows are summarized in Table 3.10.1. The flows generally follow the mean hydrograph. Note the reduced flow during summer 2001. In 2002 and 2003, the narrows flow (and hence flushing), were slightly less than average in late July-early August, though not reduced as dramatically as in 2001.

Table 3.10.1. Mean seasonal narrows flow (m³/s).

Season	Winter*	Spring	Summer	Fall	Year*
	Nov21-Apr10	Apr11-Jun15	Jun16-Sep21	Sep22-Nov20	Nov21-Nov20
Mean*	963	782	1,380	825	1,020
1997	1,080 (+12%)	879 (+12%)	1,710 (+24%)	1,280 (+55%)	1,250 (+22%)
1998	1,330 (+38%)	708 (-9%)	1,250 (-10%)	864 (+5%)	1,120 (+10%)
1999	1,120 (+16%)	795 (+2%)	1,620 (+17%)	1,200 (+45%)	1,210 (+18%)
2000	1,192 (+24%)	825 (+5%)	1,502 (+9%)	991 (+20%)	1,176 (+15%)
2001	1,112 (+16%)	919 (+17%)	985 (-29%)	835(+1%)	998 (-2%)
2002	830 (-14%)	613 (-22%)	1,277 (-8%)	1,229 (+49%)	977 (-4%)
2003	998 (+4%)	590 (-25%)	1,241 (-10%)	1,056 (+28)%	999 (-2%)

* Winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year flow for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean flows are for 1973-1990.

3.11 Annual stream flow as a climate gauge

Natural stream flow can be used as a gauge of the inter-annual variation in precipitation.

Methods

For convenience, means are here taken over each calendar year rather than from November 21-November 20 as here done for seasonal flows or as September 1 to August 31, as is common. Means any of these periods are similar as flow during the fall and winter is relatively low.

Results

Figure 3.11.1 gives the mean annual local flow for 1973-2003. The bars indicate the local flow computed in Section 3.7 (with data missing for 91-94) and the circles give the local flow from B.C. Hydro.⁴ The climate variability is larger than the error between these two local flows. In the lower section of the plot is shown the data for the Illecillewaet. Clearly, 1997 was a wet year with local flow 25% above average. 1998 local flow was 20% below average. In 1999 local flow was 10% above average and in 2000 the local flow was close to average. El Niño conditions were observed through the 1997-1998 winter and El Niña conditions followed in the summer of 1998. In 2001, local flow was 28% below average the lowest in 8 years. In 2002 local flow was near average and in 2003 local flow was slightly below average.

3.12 Mean and total flow over the seasons

For reference, Table 3.12.1-3 gives the mean flow (m³/s) and the total flow (Mm³=1,000,000 m³) averaged over each limnological season (Section 3.13) in 1997 to 2001 for:

1. local flow (qloc0),

2. Revelstoke project outflow (revpo),
3. flow through the narrows (qnar0), and
4. Arrow reservoir outflow (arro).

Table 3.12.1. Average and total flows over the seasons, 1997.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc097	m ³ /s	168	953	677	314	471
revpo97	m ³ /s	733	697	1,166	1,097	901
qnar097	m ³ /s	1,079	879	1,714	1,278	1,246
arro97	m ³ /s	1,234	695	1,829	1,296	1,306
qloc097	Mm ³	2047	5434	5732	1628	14853
revpo97	Mm ³	8930	3975	9873	5687	28414
qnar097	Mm ³	13145	5012	14513	6625	39294
arro97	Mm ³	15033	3963	15487	6718	41186

* Winter flow for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. This is different to the 1997/98 report (Pieters, 1998) in which winter flow was given for Jan 1-Apr10 and Nov 21-Dec 31, 1997.

Table 3.12.2. Average and total flows over the seasons, 1998.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc098	m ³ /s	166	748	327	95	303
revpo98	m ³ /s	853	690	1,022	839	866
qnar098	m ³ /s	1,329	708	1,250	864	1,119
arro98	m ³ /s	1,556	486	1,285	852	1,174
qloc098	Mm ³	2022	4265	2769	492	9555
revpo98	Mm ³	10392	3935	8653	4349	27310
qnar098	Mm ³	16190	4037	10584	4479	35289
arro98	Mm ³	18956	2771	10880	4417	37023

* Winter flow for 1998 is for Nov. 21, 1997 to Apr. 10, 1998.

Table 3.12.3. Average and total flows over the seasons, 1999.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc099	m ³ /s	142	680	728	244	413
revpo99	m ³ /s	663	669	1198	1,053	872
qnar099	m ³ /s	1,115	795	1,619	1,200	1,206
arro99	m ³ /s	1,336	651	1,649	1,215	1,277
qloc099	Mm ³	1,730	3,878	6,164	1,265	13,024
Revpo99	Mm ³	8,077	3,815	10,144	5,459	27,499
qnar099	Mm ³	13,583	4,533	13,708	6,221	38,032
arro99	Mm ³	16,276	3,712	13,962	6,299	40,271

Winter flow for 1999 is for Nov. 21, 1998 to Apr. 10, 1999.

Table 3.12.4. Average and total flows over the seasons, 2000.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc000	m ³ /s	174	710	594	152	380
revpo00	m ³ /s	734	671	1105	873	845
qnar000	m ³ /s	1,192	825	1,503	991	1,176
arro00	m ³ /s	1,404	694	1,558	1,014	1,253
qloc000	Mm ³	2,135	4,049	5,030	788	12,016
revpo00	Mm ³	9,005	3,826	9,356	4,526	26,672
qnar000	Mm ³	14,624	4,704	12,726	5,137	37,188
arro00	Mm ³	17,225	3,957	13,192	5,257	39,515

* Winter flow for 2000 is for Nov. 21, 1999 to Apr. 10, 2000.

Table 3.12.5. Average and total flows over the seasons, 2001.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc001	m ³ /s	108	576	384	146	273
revpo01	m ³ /s	734	555	694	627	673
qnar001	m ³ /s	1,112	919	985	835	998
arro01	m ³ /s	1302	951	1037	916	1104
qloc001	Mm ³	1,316	3,285	3,251	757	8,609
revpo01	Mm ³	8,942	3,165	5,876	3,250	21,224
qnar001	Mm ³	13,547	5,241	8,340	4,329	31,473
arro01	Mm ³	15,861	5,423	8,780	4,749	34,816

* Winter flow for 2001 is for Nov. 21, 2000 to Apr. 10, 2001.

Table 3.12.6. Average and total flows over the seasons, 2002.

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc002	m ³ /s	138	651	584	122	348
revpo02	m ³ /s	730	493	781	900	729
qnar002	m ³ /s	830	613	1,277	1,229	977
arro02	m ³ /s	846	484	1,389	1,383	1,014
qloc002	Mm ³	1,681	3,712	4,945	632	10,975
revpo02	Mm ³	8,893	2,811	6,613	4,666	22,990
qnar002	Mm ³	10,111	3,496	10,813	6,371	30,811
arro02	Mm ³	10,306	2,760	11,761	7,169	31,978

Winter flow for 2002 is for Nov. 21, 2001 to Apr. 10, 2002.

Table 3.12.7. Average and total flows over the seasons, 2003

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc003	m ³ /s	118	648	389	237	306
revpo03	m ³ /s	855	515	856	616	754
qnar003	m ³ /s	998	590	1,241	1,056	999
arro03	m ³ /s	1,047	442	1,346	1,236	1,049
qloc003	Mm ³	1,438	3,695	3,294	1,229	9,650
revpo03	Mm ³	10,416	2,937	7,248	3,193	23,778
qnar003	Mm ³	12,158	3,364	10,508	5,474	31,504
arro03	Mm ³	12,755	2,520	11,397	6,407	33,081

* Winter flow for 2003 is for Nov. 21, 2002 to Apr. 10, 2003. Values in Tables 3.12.1-7 should be shown to a maximum of 3 significant figures but all place values are given for computational checks.

3.13 Limnological Seasons

Limnological seasons demarcate major periods in the annual hydrologic input, stratification and mixing events within a lake or reservoir, and assist in better understanding and interpreting nutrient loading events and their associated biotic responses within the reservoir. The major limnological seasons selected for Arrow are given in Table 3.13.1.

Table 3.13.1. Limnological seasons

Season	Winter	Spring	Summer	Fall
Date (not leap yr.)	Nov21-Apr10	Apr11-Jun15	Jun16-Sep21	Sep22-Nov20
Julian day	325-365(6), 1-100	101-166	167-264	265-324
No of days/season	141 (142)	66	98	60
Perrin et.al. (1997)	Dec-Apr	May, June	July, Aug	Sep, Nov
Lake level	falling	fast-rising	slow-rising	constant
Outflow	high	low	high	low
Local inflow	very low (base flow)	very high	high	low

Perrin *et. al.* (1997) selected limnological seasons for their study of the phosphorus loads to Duncan reservoir, and Arrow seasons are similar but show some differences, namely:

1. spring was chosen to start earlier as snow melt runoff and reservoir filling has begun by mid-April,
2. summer was chosen to be longer, in order to span the period of greatest biological activity, and
3. fall was chosen to end earlier because December conditions are more like winter than fall, with gradually falling reservoir levels and local rivers at base flow levels.

For computing averages, the start and end of each limnological season is specified by a Julian day, chosen such that noon on January 1st is Julian day 1.5. A table for converting between Julian day and calendar date is given in Appendix 3.1. Because the seasonal averages are defined by Julian day, in a leap year the calendar date of the start and end of the seasons will shift by one day. For example, in a leap year, the end of summer, at Julian day 264, will occur on September 20th rather than September 21st.

3.14 Summary

Flow conditions *during the study period* are summarized as follows (T=Temperature):

1997 ***Highest flow***

Local flow: highest (> 2 standard deviations (σ) above mean)
Spr/Sum/Fall Revelstoke inflow: highest
Spr/Sum/Fall Arrow outflow: highest
Water level: slightly above average

1998 ***Low flow***

Local flow: low (about 1 standard deviation (σ) below mean)
Spr/Sum/Fall Revelstoke inflow: average
Spr/Sum/Fall Arrow outflow: lowest
Water level: close to average
Other: fine summer weather, high air T & surface water T (26°C in Upper Arrow)

1999 ***High flow***

Local flow: high ($> +1\sigma$)
Spr/Sum/Fall Revelstoke inflow: high
Spr/Sum/Fall Arrow outflow: high
Water level: close to average
Other: average water T (18°C); extended low sun and air T from mid Jun-mid Jul

2000 ***Flow slightly lower than average***

Local flow: slightly higher than average
Spr/Sum/Fall Revelstoke inflow: slightly higher than average
Spr/Sum/Fall Arrow outflow: slightly above average
Water level: average
Other: average water T (20 °C); cloudy Jun & sunny Jul

2001 ***Lowest flow***

Local flow: lowest ($< -1\sigma$)
Spr/Sum/Fall Revelstoke inflow: lowest
Spr/Sum/Fall Arrow outflow: below average
Water level: 8-10 m below average; third lowest average levels since 1969; at drawdown level from May onward
Other: low snowpack (~60% normal); higher summer surface water T (21-24 °C).

2002 ***Average flow***

Local flow: average
Spr/Sum/Fall Revelstoke inflow: lower than average
Spr/Sum/Fall Arrow outflow: near average
Water level: average, with above average decline from mid-summer onward

2003 ***Flow slightly below average***

Local flow: slightly lower than average
Spr/Sum/Fall Revelstoke inflow: lower than average
Spr/Sum/Fall Arrow outflow: near average
Water level: average, with above average decline from mid-summer onward

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Figure 3.1.1. Columbia River basin. Adapted from B.C. Hydro (1969).

Figure 3.1.2. Upper Columbia River basin. Adapted from Inland Waters Directorate (1977).

Figure 3.2.1. Main inflow. (a) The Columbia River from WSC station 08ND011 "Columbia River above Steamboat Rapids", 1955-1986 and WSC station 08ND025 "Revelstoke Project Outflow", 1986-2003. Mean pre (b) and post (c) impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.2.2 Main Inflow: Columbia River at the Revelstoke Dam, 1997-2003

Figure 3.2.2. Main inflow, from WSC station 08ND025, “Revelstoke Project Outflow”, 1997-2003 (heavy line). Mean pre-impoundment flow for 1955-1964 (medium line) and mean post-impoundment flow for 1986-1994 (light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.3.1. Map of Columbia Basin around Castlegar. Adapted from Ketchum (1990).

Figure 3.3.2. Outflow. (a) WSC station 08NE002, "Columbia River at Castlegar", 1961-1972 and WSC station 08NE126 "Arrow Lakes Reservoir Outflow", 1973-2003. Both data sets corrected to 1990 by K. Ketchum as described in the text. Mean pre (b) and post (c) impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.3.3 Outflow: Columbia River at the Hugh Keenleyside Dam, 1997-2003

Figure 3.3.3. Outflow from WSC station 08NE126 "Arrow Lakes Reservoir Outflow", 1997-2003 (heavy line). Mean pre-impoundment flow for 1961-1966 (medium line) and mean post-impoundment flow for 1973-1990 (light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.4.1 Illecillewaet River at Greeley

Figure 3.4.1. (a) WSC station 08NE013, “Illecillewaet at Greeley”, 1961-2003. (b) Mean flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.4.2 Illecillewaet River at Greeley, 1997-2003

Figure 3.4.2. WSC station 08NE013, “Illecillewaet at Greeley” for 1997-2003 (heavy line). Mean flow for 1963-1994 (light line) is shown for comparison. See methods for interpolation and replacement of missing data and for replacement of anomalous winter flow: note the replacement of missing data for July 5-August 8, 1999 with the mean flow. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.5.1 Water Level: Lower Arrow

Figure 3.5.1. Water level. (a) WSC station 08NE046, “Lower Arrow Lake at Needles” for 1930-1968 and WSC station 08NE102, “Arrow Lakes Reservoir at Fauquier” for 1969-2003. Mean pre (b) and post (c) impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.5.2 Water levels: Lower Arrow at Fauquier, 1997-2003

Figure 3.5.2. Water levels for WSC station 08NE102 "Lower Arrow at Fauquier" (heavy line) and WSC station 08NE104 "Upper Arrow at Nakusp" (medium line) for 1997-2003. Note the two curves are generally coincident except near day 180 in 1997 when Nakusp data is erroneous and around day 90 and often during drawdown in spring when water levels in Upper Arrow can be slightly higher than Lower Arrow (see text). Mean pre-impoundment water level for 1930-1965 (lower light line) and mean post-impoundment water level for 1970-1994 (upper light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13).

Figure 3.5.3 Upper and Lower Arrow Lake Level, 1991

Figure 3.5.3. 1991 water level for the Lower Arrow at Fauquier (08NE102) and the Upper Arrow at Nakusp (08NE104). The two curves are almost coincident except from day 75 to 150 when the water level in Upper Arrow is slightly higher than in Lower Arrow and flow through the narrows is slightly riverine. The gaps in the Nakusp level near day 140 result from missing data.

Figure 3.6.1 Storage Flow

Figure 3.6.1. Storage flow. **(a)** Storage flow for 1970-2003. **(b)** Mean storage flow for 1973-1990. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.6.2 Storage Flow, 1997-2003

Figure 3.6.2. Storage flow for 1997-2003 (heavy line). Also shown is the mean storage flow for 1973-1990 (light line). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.7.1. Local flow. **(a)** Local flow for 1973-2003. **(b)** Mean local flow for 1986-1990, 1995-1997. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). Local flows below zero are erroneous: see discussion in the text. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.7.2 Local Flow, 1997-2003

Figure 3.7.2. Local flow for 1997-2003 (heavy lines). Also shown in the mean local flow for 1986-1990, 1995-1997 (light lines). Local flows below zero are erroneous: see text for discussion. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.8.1. Selected hydrographs of local inflow plotted with constant area. The area under each curve is 365.25 and the resulting mean flow is 1 m³/s.

Figure 3.8.2. Hydrographs of local inflow plotted with constant area. The area under each curve is 365.25 and the resulting mean flow is 1 m³/s.

Figure 3.10.1 Narrows Flow

Figure 3.10.1. Narrows flow. (a) Narrows flow for 1973-2003. (b) Mean narrows flow for 1973-1990. Mean (heavy line), maximum and minimum (medium lines) and mean $\pm$ one standard deviation (light lines). (c) Comparison of mean Narrows flow (heavy line) mean inflow (medium line) and mean outflow (light line) for 1986-1990. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.10.2 Narrows Flow, 1997-2003

Figure 3.10.2. Narrows flow for 1997-2003 (heavy line). Also shown is the mean local flow for 1973-1990 (light line). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.11.1. (a) Mean annual local flow from 1973 to 2003. Bars represent the mean annual local flow computed in Section 3.7. Circles represent the mean annual flow computed from the smoothed local flow from B.C. Hydro. Horizontal lines mark the mean, the mean plus one standard deviation and the mean minus one standard deviation. **(b)** Mean annual flow for the Illecillewaet. Horizontal lines mark the mean, the mean plus one standard deviation and the mean minus one standard deviation. For convenience, bars are marked with year during this study. Averages done over calendar year; these differ little from averages over the hydrologic year as winter flow are small.

APPENDIX 3.1
CONVERSION BETWEEN DATE AND JULIAN DAY

Table A3.1.1. Conversion between date and Julian day for REGULAR YEAR

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

Julian day is here defined such that noon, Jan 1st is day 1.5.

Table A3.1.2. Conversion between date and Julian Day for LEAP YEAR

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1	32	61	92	122	153	183	214	245	275	306	336
2	2	33	62	93	123	154	184	215	246	276	307	337
3	3	34	63	94	124	155	185	216	247	277	308	338
4	4	35	64	95	125	156	186	217	248	278	309	339
5	5	36	65	96	126	157	187	218	249	279	310	340
6	6	37	66	97	127	158	188	219	250	280	311	341
7	7	38	67	98	128	159	189	220	251	281	312	342
8	8	39	68	99	129	160	190	221	252	282	313	343
9	9	40	69	100	130	161	191	222	253	283	314	344
10	10	41	70	101	131	162	192	223	254	284	315	345
11	11	42	71	102	132	163	193	224	255	285	316	346
12	12	43	72	103	133	164	194	225	256	286	317	347
13	13	44	73	104	134	165	195	226	257	287	318	348
14	14	45	74	105	135	166	196	227	258	288	319	349
15	15	46	75	106	136	167	197	228	259	289	320	350
16	16	47	76	107	137	168	198	229	260	290	321	351
17	17	48	77	108	138	169	199	230	261	291	322	352
18	18	49	78	109	139	170	200	231	262	292	323	353
19	19	50	79	110	140	171	201	232	263	293	324	354
20	20	51	80	111	141	172	202	233	264	294	325	355
21	21	52	81	112	142	173	203	234	265	295	326	356
22	22	53	82	113	143	174	204	235	266	296	327	357
23	23	54	83	114	144	175	205	236	267	297	328	358
24	24	55	84	115	145	176	206	237	268	298	329	359
25	25	56	85	116	146	177	207	238	269	299	330	360
26	26	57	86	117	147	178	208	239	270	300	331	361
27	27	58	87	118	148	179	209	240	271	301	332	362
28	28	59	88	119	149	180	210	241	272	302	333	363
29	29	60	89	120	150	181	211	242	273	303	334	364
30	30		90	121	151	182	212	243	274	304	335	365
31	31		91		152		213	244		305		366
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC

Julian day is here defined such that noon, Jan 1st is day 1.5.

APPENDIX 3.2

WATER SURVEY CANADA STATIONS, FLOWS, DRAINAGE AREAS AND EFFECTIVE PRECIPITATION

Table A.3.2.1. Water Survey Canada Stations in the Arrow Drainage Area

Table A.3.2.1 follows at the end of this appendix.

Notes to Table A3.2.1

Table A3.2.1 includes all Water Survey Canada (WSC) stations for flows in the Arrow Lakes/Reservoir region up to and including 1994. The Table is sorted from north to south with an entry for major communities where they occur along the lake/reservoir.

Mean flows are those given by WSC when data is available over a whole year. However, many of the smaller streamflows have been gauged for only part of a year, typically from spring to fall. In these cases an annual streamflow is estimated and marked “E”. For a missing winter month, the flow from another winter month is used: winter flow is relatively constant. If flow during the spring melt has been metered then the percentages in Table A3.2.2 are used to estimate the annual flow. These percentages were derived from the Kuskanax River and Deer Creek flows which are assumed to be typical for the Upper and Lower Arrow, respectively. In making these estimates it is assumed that all months are of equal length. Table A3.2.3 gives the one letter abbreviation used to indicate month.

- Note 1 Unable to estimate the annual flow as this record is missing data during a substantial part of the spring melt period.
- Note 2 This value is unusually low and is considered erroneous.
- Column “L” Drainage area and flow are included in the sum of the known local flow. See Section 4.4 for discussion.
- Column “M” Metered in 1997.
- Column “Q” Water quality sampling in 1997.

Table A3.2.2. Percentage of mean annual flow represented by record over given months

Months	Fraction of flow Kuskanax River Representative of Upper Arr.	Fraction of flow Deer Creek Representative of Lower Arr.
April-September	85%	87%
May-September	80%	78%
June-September		48%

Table A3.2.3. One letter abbreviation used to indicate month

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
J	F	M	A	Y	U	L	G	S	O	N	D

Table A3.2.4. Drainage areas and estimated flows for rivers and streams sampled in Chapter 6 but not gauged by WSC.

	Drainage Area*	Flow	Yield	Comment
	Km ²	m ³ /s	m/y	
Halfway River	327	13.5	1.3	Assume Yield
St.Leon's Cr.	109	4.5	1.3	Assume Yield
Cape Horn Cr.	39	1.6	1.3	Assume Yield
Slewiskin Cr.	96	3	1	Assume Yield
Mosquito Cr.	410	13	1	Assume Yield
Burton Cr. ^a	311	9.9	1	Assume Yield
Caribou Cr.	232	7.3	1	Assume Yield
Barnes Cr.	201	4	0.63	WSC Flow
Whatshan Discharge	390	7	0.57	WSC Flow
Eagle Cr.	112	1.4	0.4	Assume Yield
Dear Cr.	79	0.85	0.33	WSC Flow
Little Cayuse Cr.	32	0.19	0.24	WSC Flow
Syringa Cr.	22	0.21	0.31	WSC Flow

* Areas for streams not given by WSC were determined as described in Section 3.9.

^a Drainage area includes Snow Cr. (153 km²) as Burton Cr. is sampled below confluence with Snow.

Table A3.2.1. Water Survey Canada Stations in the Arrow Drainage Area

Station	Station Name	Year	L	Drainage Area km ²	Mean Flow m ³ /s	Effective Precip. m/yr	M	Q
	Columbia River Input							
BC08ND025	Revelstoke Project Outflow	1986-1994		NA	779	NA	M	Q
BC08ND011	Columbia River Above Steamboat Rapids.	1955-1986		26,400	796	0.95		
BC08ND002	Columbia River At Revelstoke ⁷	1912-1950		26,700	854	1.01		
BC08ND006	Columbia River At Twelve Mile Ferry ⁸	1948-1968		28,500	929	1.03		
	Local Flow							
BC08ND014	Jordan River Above Kirkup Creek	1963-1988	L	272	17.3	2.01		
BC08ND004	Jordan River Near Revelstoke	1946-1947 1956-1957		350	N1	NA		
BC08ND022	Dolan Creek Above Diversions ⁹	1985-1989 Apr-Sept		NA	0.041	NA		

⁷ Includes Jordan River

⁸ Includes Jordan And Illecillewaet Rivers

	Revelstoke							
BC08ND003	Illecillewaet River Near Revelstoke ¹⁰	1911-1916 Mar-Dec	L	1230	E 52	1.3		Q
BC08ND013	Illecillewaet River At Greeley	1963-1994		1170	52.6	1.42	M	
BC08ND001	Akolkolex River Near Revelstoke	1913-1922 part 1954	L	394	19.9	1.59		Q
BC08NE123	Cranberry Cr. Above B.C. Hydro Intake ¹¹	1980-1986		99.6	4.84	1.53		
	Beaton							
BC08NE001	Incomappleux River Near Beaton	1914-1915 1952-1994	L	1020	55.8	1.73		Q
BC08NE008	Beaton Creek Near Beaton	1952-1994	L	99.5	2.46	0.78		
	Shelter Bay-Galena							
BC08NE124	Hill Creek Above Spawning Channel	1982-1984		15.1	0.691	1.44		
BC08NE120	Hill Creek At Mill Road Bridge	1977-1980	L	28.2	0.623	0.70		
BC08NE121	Hill Creek Near 820 M Contour	1977-1981		17.1	0.471	0.87		
BC08NE035	Strauss Creek Near Nakusp - Not On Chart	1928-1929 May-Sept		NA	-	NA		
BC08NE006	Kuskanax Creek Near Nakusp	1914-1915 1963-1994	L	337	14.2	1.33	M	Q
BC08NE117	Kuskanax Creek At 1040 m Contour	1973-1994		113	5.34	1.49		
BC08NE007	Nakusp Creek Near Nakusp ¹²	1914-1914 Apr-Dec	L	104	E 0.95	0.29		
BC08NE021	Brouse Creek Above Diversions	1924-1929 1975-1986		1.01	0.023	0.71		
BC08NE022	Brouse Creek Near Nakusp (Lower Stn) ¹³	1924-1925 May-Sept		6.22	E 0.01	0.05 Note2		
BC08NE026	Brouse Creek (West Fork) Near Nakusp ¹⁴	1925-1929 May-Sept		4.66	E 0.0038	0.03 Note2		
BC08NE101	Halfway Cr. (West Fork Of Wensley Cr.) Near Nakusp	1968-1975 May-Sept	L	2.07	E 0.043	0.66		
	Boundary Between Upper And Lower Arrow							
BC08NE023	Mauchline Creek Near Arrow Park ¹⁵	1923-1926 Jun-Aug		0.34	Note1	NA		
BC08NE034	Reinecker Creek Near Burton	1928-1929 Apr-Sept	L	3.63	E 0.023	0.19		
	Burton							

⁹ Enters the Columbia from west just before the Illecillewaet, near Revelstoke townsite;
A 0.095, Y 0.233, U 0.047, L 0.016, G 0.01, S 0.016.

¹⁰ Assume Jan and Feb Flows equal that in March

¹¹ Into Columbia between Revelstoke and Upper Arrow

¹² Assume flows For Jan, Feb, March and Dec are equal

¹³ Y 0.039, U 0.031, L 0.009, G 0.009, S 0.011

¹⁴ Y 0.012, U 0.012, L 0.007, G 0.003, S 0.003

¹⁵ Near Mosquito in Narrows

BC08NE005	Caribou Creek Near Burton City ¹⁶	1914-1914 Aug-Dec.		531	Note1	NA		Q
BC08NE050	Pin Creek Near Fauquier	38,39,42 May-Sept	L	0.85	E 0.024	0.89		
	Fauquier-Needles							
BC08NE052	Fauquier Creek Near Fauquier ¹⁷	1938-1939 1942-1944 Apr-Sept	L	9.84	E 0.22	0.71		
BC08NE063	Whatshan River At Needles	1944-1951	L	609	11.2	0.58		
BC08NE078	Whatshan River Near Needles ¹⁸	1950-1965		396	4.22	0.34		
BC08NE077	Barnes Creek Near Needles	1950-1994	L	201	4.01	0.63	M	
BC08NE051	Heart Creek Near Fauquier ¹⁹	1938-1939 May-Sept	L	23.8	E 0.36	0.48		
BC08NE127	Inonoaklin Creek Near The Mouth	1987-1990 Jul-Nov		377	Note1	NA		Q
BC08NE110	Inonoaklin Creek Above Valley Creek	1971-1982 1987-1994		298	3.80	0.40	M	
BC08NE009	Inonoaklin Creek Near Edgewood	1915-1920	L	401	5.00	0.39		
	Edgewood-Applegrove							
BC08NE122	Mackenzie Creek Near 520 M Contour	1977-1981	L	20.7	0.502	0.76		
BC08NE125	Mackenzie Creek Above Fish And Wildlife Diversion	1982-1984		NA	0.533	NA		
BC08NE027	Ferguson Creek Near Edgewood ²⁰	1925-1927 1958-1959 Jun-Sept	L	1.92	E 0.038	0.62		
BC08NE030	McLean Creek Near Edgewood (Not On Chart)	1927-1929 April-Sept		6.99	E 0.016	0.07 Note2		
BC08NE028	Renata Creek Near Renata	1930-1930 Aug-Sept		195	Note1	NA		
	Renata, Deer Park							
BC08NE087	Deer Creek At Deer Park	1958-1994	L	80.5	0.840	0.33	M	
BC08NE082	Cayuse Creek Near Deer Park ²¹	1955-1958 Apr-Sept	L	51.3	0.85	0.52		
BC08NE083	Little Cayuse Creek Near Deer Park	1955-1958 Apr-Sept	L	24.6	0.19	0.24		
	Srynga Creek Park							
BC08NE085	Syringa Creek Near Syringa Creek	1958-1960 Jun-Sept	L	21.5	0.21	0.305		
	Sum Of Known Local Drainage Area And Flow For Stream Records Marked "L"			4936	186.8			

¹⁶ G 5.75, S 3.36, O 4.59, N 9.11, D 10.9

¹⁷ Use 80% (From Kuskanax) to scale to full year flow; A 0.073, Y 0.642, U 1.12, L 0.365, G 0.076, S 0.047

¹⁸ Spot values only for 1957-1965

¹⁹ Use 78% (from Deer Cr.) to scale to full year flow.

²⁰ Not on chart; U 0.111, L 0.045

²¹ A 0.669, Y 4.05, U 3.13, L 0.750, G 0.179, S 0.057

	Outflow							
BC08NE126	Arrow Reservoir Outflow	1973-1994		NA	1170		M	Q
	Arrow Local Flow	73-90		10114	333	1.1		
BC08NE002	Columbia River At Castlegar	1913-1915 1961-1972		36,500	1210	1.05		

Appendix 3.3

STORAGE-ELEVATION CURVE FOR ARROW LAKES RESERVOIR

Table A3.3.1 was adapted from an Excel spreadsheet from K. Ketchum, B.C. Hydro, Burnaby. It is assumed that this storage-elevation curve is based on the corrected Keenleyside discharges, discussed in section 3.3. The elevations, volumes and areas in metric units are calculated from the imperial values. ($\text{Mm}^3 = 1,000,000 \text{ m}^3$)

Table A3.3.1. Storage-elevation curves for Arrow Lakes Reservoir

Volume = $c(1) * (El - c(2)) ** c(3) + c(4) * El + c(5)$

Area = $c(1)*c(3)*(El - c(2))**(c(3)-1) + c(4)$

NB: El in ft, Volume in cfs-days, Area in cfs-days/ft

Equations taken from BCH FLOCAL database

i	c(i): Upper	c(i): Lower
1	5.901562864E+01	2.171048618E+02
2	1.370000000E+03	1.360000000E+03
3	2.143500000E+00	1.639300000E+00
4	2.608000000E+04	1.624000000E+04
5	-3.594333000E+07	-2.240166900E+07

El (ft)	V (Upper)	V (Lower)	V (Total)	A (upper)	A(lower)	A (total)
1378	0.27	1850.21	1850.47	27443.87	18498.52	45942.39
1380	55282.34	39005.61	94287.95	27840.32	18655.89	46496.20
1390	344154.81	229225.70	573380.50	29968.82	19370.77	49339.60
1400	655201.94	426148.72	1081350.66	32262.71	20002.92	52265.63
1410	989788.13	629101.46	1618889.59	34671.05	20579.90	55250.95
1420	1348918.07	837612.37	2186530.44	37168.24	21116.41	58284.65
1430	1733396.36	1051325.04	2784721.40	39738.61	21621.45	61360.06
1440	2143898.24	1269956.64	3413854.88	42371.46	22101.02	64472.49
1444	2315518.91	1358733.21	3674252.12	43440.29	22286.72	65727.01

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El (m)	V(Upper) Mm^3	V(Lower) Mm^3	V(Total) Mm^3	A(Upper) km^2	A(lower) km^2	A(total) km^2
420.014	0.00	4.53	4.53	220.29	148.48	368.77
420.624	135.25	95.43	230.68	223.47	149.75	373.22
423.672	842.00	560.82	1402.82	240.55	155.49	396.04
426.720	1603.00	1042.61	2645.61	258.97	160.56	419.53
429.768	2421.59	1539.14	3960.74	278.30	165.19	443.49
432.816	3300.23	2049.28	5349.51	298.34	169.50	467.84
435.864	4240.89	2572.15	6813.03	318.97	173.55	492.53
438.912	5245.21	3107.04	8352.25	340.11	177.40	517.51
440.131	5665.09	3324.24	8989.34	348.69	178.89	527.58

Table A3.3.2 Surface areas and volumes for some common elevations

El m	El** ft	V(Up) Mm ³	V(Lo) Mm ³	V(Tot) Mm ³	A(Up) km ²	A(Lo) km ²	A(Tot) km ²	Description
441	1147	5970.70*	3480.12*	9450.82*	354.84*	179.94*	534.78*	Datum+7 m
440.6	1445	5829.33	3408.24	9237.57	352.00	179.46	531.46	Post, High
438.5	1438	5105.68	3034.06	8139.74	337.22	176.89	514.12	Post, Mean High
434	1423	3658.17	2250.92	5909.08	306.29	171.10	477.39	Datum
432.4	1418	3176.70	1978.89	5155.59	295.57	168.93	464.50	Post, Mean
428.5	1405	2073.88	1330.87	3404.75	270.16	163.31	433.47	Pre, High
425.4	1395	1266.53	832.06	2098.60	250.86	158.43	409.29	Pre, Mean High
424	1391	921.22	611.91	1533.13	242.48	156.06	398.54	Datum - 10 m
423	1387	681.66	456.73	1138.39	236.65	154.29	390.94	Post, Mean Low
421.1	1381	242.23	166.94	409.17	226.02	150.70	376.72	Post, Low
419.8	1377	-47.11	-27.26	-74.37	219.19	148.03	367.22	Pre, Mean
417.4	1369	-570*	-375.95	-946*	209*	142.34	351*	Pre, Mean Low
417.1	1368	-630*	-418.53	-1049*	207*	141.52	349*	Pre, Low

Areas and volumes include narrow with the Upper Arrow (see Section A3.3.1 below.)

* These values were extrapolated from the given data.

** Elevations rounded to the nearest foot.

A3.3.1 Location of boundary between Upper and Lower Arrow

Where is the location of the boundary between Upper and Lower Arrow, which is implied in the division of storage into upper and lower by the storage-elevation curve? This can be answered by comparing water surface areas, shown in Table A3.3.3.

Compare first the total surface area given by the topographic map (Section 3.9) to that given by the storage-elevation curve. The total area bounded by the shoreline on the 1:250,000 topographic map is 498 km². The topographic map annotates the water surface as "Max 1437±", which is 438.0 m. Assume that the shore shown on the topographic map corresponds to this water level even though this mean high water level and not the highest water level observed (see Table A3.3.2). This assumption is confirmed by the total area given by the storage-elevation curves for 1437 ft, which is within 2% of the area determined from the topographic maps: this percentage is within the error of the digitizer method.

Next, consider the boundary between Upper and Lower Arrow. The area for Upper and Lower Arrow, as determined from the storage-elevation curve, are 27 km² larger and 15 km² smaller, respectively. Thus the storage-elevation curve has the Upper Arrow being larger by a mean difference of 21 km². As the reservoir is approximately 1 km wide at this point, the boundary between the Upper and Lower Arrow is about 20 km downstream, near Burton at the south end of the narrows. Thus the storage elevation curve includes the narrows with the Upper Arrow.

Inclusion of the Narrows with the Upper or Lower Arrow is summarized in Table A3.3.2.

Table A3.3.3. Comparing topographic and storage-elevation surface areas

	Area (km ²) From topographic map	Area (km ²) From storage-elevation at 1437 ft (438.0 m)
Upper Arrow	307	334
Lower Arrow	191	176
Total	498	510

Table A3.3.4. Narrows included with Upper or Lower Arrow?

Discussion	Report Section	Narrows included with:
Surface areas and volumes from the digitized bathymetric charts.	Section 2.2, Tables 2.2 and 2.3 (in Pieters et al. 2003)	Upper Arrow
Area of the drawdown zone.	Section 2.3 (in Pieters et al. 2003)	Upper Arrow
Summary of Upper Columbia lakes and reservoirs; area, volume.	Table 3.1	Lower Arrow
Storage-elevation curve.	Section 3.6, Appendix 3.3	Upper Arrow
Division of local flow into four regions.	Section 3.9	Lower Arrow
Nutrient budget.	Chapter 6	Lower Arrow

APPENDIX 3.4

EVALUATION OF LOCAL FLOW BY EXAMINATION OF MEAN WINTER FLOWS OF TRIBUTARY HYDROGRAPHS

The hydrograph of the computed local flow shown in Figure 3.8.1 has a shape which resembles a composite of the glacially augmented Illecillewaet flow and that of the Kuskanax and Inonoaklin. However, the local flow is higher during winter. The cause of this higher winter flow is examined as follows, and is used to give an error estimate for the local flow.

The winter component of the local flow can be divided into three parts:

1. the fraction of the winter flow that comes from tributary inflow,
2. the fraction of the winter flow that comes from known sources other than tributary flow, namely direct precipitation to the reservoir surface and flow from Whatshan Reservoir, and
3. the remainder which will be considered error.

Section A3.4.1 will show that approximately 40 m³/s of the winter flow can be accounted for by direct precipitation to the reservoir surface and flow from Whatshan Reservoir.

A3.4.1 Known sources of additional local flow during winter

The first source of additional winter flow to the reservoir is direct precipitation to the reservoir surface. Using a mean precipitation of 0.9 m/yr on 500 km² gives 14 m³/s. Rain gauge data (Sect. 3.9) and data for 1997 show similar levels of precipitation.²² Also contributing to the local flow in winter is precipitation on near shore regions, either as rain or as snow which melts within a few weeks. Assuming a near shore region of area comparable to that of the reservoir would give a total flow from direct precipitation of 28 m³/s.

A second source of winter flow is the Whatshan reservoir. The annual mean outflow for Whatshan is 9.3 m³/s. The mean flow from Whatshan in 1997 was 13.3 m³/s and the mean flow for day 1-75 was 12.2 m³/s.

In conclusion, direct precipitation and Whatshan flow contribute approximately 40 m³/s to the local flow.

A3.4.2 Fraction of the local flow unaccounted for by tributary input during winter

To look at the winter flows, a variety of mean hydrographs are shown in Figure 3.8.2, plotted with constant area. In all cases the winter or baseline flow is consistently low,

²² A similar value is obtained by using mean winter precipitation data from four meteorological stations along the reservoir, described in Table 3.9.2. Also the 1997 rainfall for day 1-100 at Greeley, near Revelstoke, applied to the entire water surface gives 17 m³/s, which is also roughly comparable to the mean flow.

and almost constant. The winter flow is characterized by comparing the mean flow for day 1-75 with the mean annual flow. For the natural hydrographs the fraction of the total flow that occurs during winter is approximately constant across all hydrographs, though there are a few exceptions.

Table A3.4.1 summarizes the winter flow data of rivers and creeks to the Arrow Lakes Reservoir, for all cases where winter data exist. For this discussion, the mean of day 1-75 is referred to as winter flow: this period is shorter than the limnological season of winter defined in Section 3.13. For natural hydrographs, the winter flow is, for the most part, 15-20% (mean 17%) of the mean annual flow. The exceptions to this are several smaller creeks marked with brackets in Table A3.4.1. For the years 1986-90, 95-97, the mean winter flow of the local flow is 39% of the mean annual flow. Thus the local flow appears to be high by $39\%-17\%=22\%$, or $83 \text{ m}^3/\text{s}$. Of this, about $40 \text{ m}^3/\text{s}$ is accounted for by direct precipitation and Whatshan. Thus $43 \text{ m}^3/\text{s}$ of the local flow remains unaccounted. This represents an error in the local flow of order 11%.

For 1997, the mean winter flow is 29% of the mean annual flow. Thus the local flow appears to be high by $29\%-17\%=12\%$, or $56 \text{ m}^3/\text{s}$. Of this, approximately $40 \text{ m}^3/\text{s}$ is accounted for by direct precipitation and Whatshan. Thus $16 \text{ m}^3/\text{s}$ of the local flow remains unaccounted in 1997. This represents an error in the local flow of about 3%.

Table A3.4.1. Comparison of mean winter-like flow (day 1-75) to annual flow

Flow Name	Abbr.	Years	Winter Mean m ³ /s	Annual Mean m ³ /s	Winter /Annual Mean
Columbia R. at Steamboat Rapids	colsr1	55-70	150	825	18%
Jordan River above Kirkup Creek	Note 1	63-86	2.37	17.3	14%
Illecillewaet at Greeley	illgr1	63-94	8.45	52.6	16%
Akolkolex R.	akolk1	13-22, 54	3.64	20.1	18%
Incomappleux R.	incob1	14-15, 52-94	9.61	55.7	17%
Beaton Cr. near Beaton	Note 1	52-86	0.96	2.84	(34%)
Hill Cr. at Mill Road Bridge	Note 1	78-80	0.164	0.623	(26%)
Brouse Cr. Above Diversions	Note 1				
Kuskanax Cr.	kuskn1	14-15, 63-94	2.77	14.1	20%
Whatshan River at Needles	Note 1	45-51	3.23	11.2	(29%)
Barnes Cr. Near Needles	Note 1				
MacKenzie Cr. Above Diversions	Note 1	82-84	0.172	0.533	(32%)
Deer Cr. at Deer Park	Note 1	58-86	0.165	0.876	19%
Inonoaklin above Valley Cr.	inonv1	71-94	0.56	3.68	15%
MEAN, exclude values in brackets					17%
Mean Qloc	qloc08	96-90, 95-97	148	376	39% (σ 8%)
1997 Qloc	qloc097	97	134	465	29%

Note 1. Winter flow is the average of the mean January and February flows.

CHAPTER 4

RESPONSE OF PHYSICAL AND CHEMICAL LIMNOLOGY OF ARROW LAKES RESERVOIR TO EXPERIMENTAL FERTILIZATION, YEARS 4 and 5, (2002 and 2003)

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Introduction

Nutrient additions (fertilization) to Arrow Lakes Reservoir began in 1999 to restore lost nutrients from upstream hydroelectric impacts. The lost nutrients led to the oligotrophication of the reservoir, which resulted in declining kokanee populations. The fertilization experiment is modelled after the successful Kootenay Lake fertilization program.

Nutrients have been added to the reservoir in the form of liquid ammonium polyphosphate and urea ammonium nitrate (see Chapter 2 for details) from the end of April through the beginning of September during each year of the experiment. During 2002 and 2003, 52 tonnes of phosphorus (P) and 268 tonnes of nitrogen (N) were added to the reservoir.

This report summarizes the physical, chemical, and chlorophyll a data collected on Arrow Lakes Reservoir in 2002 and 2003. Measurements from previous years are shown in the tables and discussed in relation to 2002 and 2003. Previous years data can be found in Pieters et al. 1998, 1999, 2000, 2001a, 2003 a and b.

Materials and Methods

Water samples for physical and chemical analyses were collected at eight established sampling stations (Fig 1.1) in conjunction with phytoplankton samples (Table 4.1). Stations AR1 through AR4 are located in Upper Arrow, AR5 is located in the old river channel that connected the original Upper and Lower Arrow lakes pre-dam impoundment, and AR6 through AR8 are located in Lower Arrow. Samples were collected one week apart in Lower Arrow and Upper Arrow because of logistics.

Table 4.1. Limnological sampling stations for the Arrow Lakes Reservoir Fertilization Experiment

Site ID	EMS Site No.	Site name	Depth (m)
AR1	E225768	Arrow Lake @ Albert Point	220
AR2	E225769	Arrow Lake @ Ann Point	285
AR3	E225770	Arrow Lake @ Turner Creek	155
AR4	E225771	Arrow Lake @ Slewiskin Creek	75
AR5	E225779	Arrow Lake, downstream Mosquito Creek	50
AR6	E225781	Arrow Lake @ Johnson Creek	145
AR7	E225782	Arrow Lake @ Bowman Creek	155
AR8	E225783	Arrow Lake @ Cayuse Creek	85

In 2002 and 2003, temperature and oxygen profiles were taken from April through November at AR 1-3 and AR 6-8 using a Hydrolab (Surveyor III) probe. Each profile was obtained from a 100-m water column, with measurements taken at approximately one-metre intervals from 0-50 m and at 5-m intervals from 50 to 100 m. Due to instrument malfunction, October and November 2002 profiles were not taken. Temperature and oxygen profiles were also taken during both years at AR 4 and AR 5 at 1-m intervals to 50 m and at 5 m intervals from 50 m to 5 m off the bottom. Bottom depths for AR4 ranged from 45 to 60 m and the bottom depth for AR5 was approximately 50 m (depths ranged depending on the reservoir level within each month). Water transparency was measured at each sampling station using a standard 20-cm Secchi disk.

Water samples were collected at AR 1-8 from January through November using a 2.54-cm (inside diameter) tube sampler to collect an integrated water sample from 0-30 m. A Van Dorn bottle was used to collect hypolimnetic water samples (5 m off the bottom) at stations AR 1-3 and AR 6-8. Water samples were shipped within 24 h of collection to PSC Analytical Services (now Maxxam Analytics, Inc.) in Burnaby, B.C. Samples were analyzed for turbidity, pH, conductivity, total phosphorus (TP), total dissolved phosphorus (TDP), orthophosphate (OP), total nitrogen (TN; Jun – Nov 2003 only), dissolved inorganic nitrogen (DIN), silica, alkalinity, total organic carbon (TOC), and chlorophyll a (Chl a). Prior to shipping to the lab, Chl a samples were prepared by filtering a portion of the integrated water sample through a filter with 0.45 µm pore size. At the lab, the filters were placed in centrifuge tubes with 90% buffered acetone and sonicated to rupture the algal cells and homogenize the filters. Chl a concentrations were then calculated from formulae using the absorbance of the supernatant at specific wavelengths.

In 2003, additional water samples were taken at discrete depths, using a Van Dorn sampling bottle, in the epilimnion of Arrow Lakes Reservoir. Epilimnion samples were obtained from depths of 2, 5, 10, 15, and 20 m for analysis at the lab (as above) of TP, TDP, OP, DIN, Chl a, and silica. Chl a samples were generally analyzed only for depths of 2-15 m. Samples were taken monthly from June to October at AR 2 and AR7 and monthly from August to October at all other stations.

In this report, average measurements from the spring, summer, and fall of 1997-2003 are given for Upper Arrow (AR 1-3) and Lower Arrow (AR 6-8). Seasonal variations of the 2002 and 2003 data are illustrated in the figures of this report. Detailed data and analysis of the 1997-2001 data are available in previous annual reports (Pieters et al. 1998, 1999, 2000, 2003a and 2003b). All data are on file at the BC Ministry of Environment office in Nelson, B.C.

Results and Discussion

Physical limnology

Temperature

Arrow Lakes Reservoir is a monomictic lake, with isothermal temperatures from late fall to early spring and stratification during the summer months. Surface warming began in May and a thermocline was strongly developed by July (Figs. 4.1- 4.8). Surface temperatures were generally warmer in 2003 than in 2002 from May to September. The water began to cool in September in both years. Surface temperatures were generally cooler at AR1 than at the other Arrow stations. This could be due to the influence of inflowing streams, which are generally cooler than the reservoir (Chapter 3 describes stream temperatures). The maximum surface temperature in Upper Arrow was 21.70 °C on July 15, 2002, and 23.34 °C on July 21, 2003, both at station AR2. The maximum surface temperature in Lower Arrow was 18.65 °C on August 06, 2002, and 22.07 °C on August 18, 2003, both at station AR7.

Dissolved Oxygen

Dissolved oxygen profiles in Arrow Lakes Reservoir showed an oxygen-saturated water column throughout the sampling season. Values in Upper Arrow and Lower Arrow ranged from 11 to 19 mg/L in 2002 and 12 to 15 mg/L in 2003 (Figs. 4.9 to 4.16). There was minimal seasonal variation at all sampling stations. This indicates that the reservoir is well oxygenated throughout the year, consistent with oligotrophic systems (Wetzel, 2001).

Redox potential

Measurements of redox potential in 2002 ranged from 30 to 103 mV. These measurements do not correlate with the oxygen data as redox potential should be about 500 mV when there is abundant oxygen (Horne and Goldman, 1994). These data are not included in the report as the probe was probably malfunctioning. In 2003, measurements ranged from 335 to 501 mV in Upper Arrow and from 303 to 513 mV in Lower Arrow. There was an increase of 10 to 40 mV from the surface to 100 m at all stations in both Upper and Lower Arrow during the stratification period.

Secchi depth

The Secchi depth in Upper Arrow ranged from 2.13 m to 16.15 m in 2002 and from 2.74 m to 15.85 m in 2003 (Fig 4.17). The Secchi depth in Lower Arrow ranged from 3.05 m to 11.58 m in 2002 and from 3.05 m to 15.85 m in 2003 (Fig 4.17). Secchi depths were highest in the spring and then declined with the onset of the spring freshet and increasing phytoplankton biomass. Secchi depths increased again during the late fall months in both

years. Averages of spring, summer and fall Secchi depths are similar to the 2001 results (Table 4.2).

Turbidity

Turbidity increased as the season progressed from spring to summer and then decreased again during the fall months (Fig 4.18). This trend coincides with an increase in Secchi depth measurements in 2002 and 2003. There are two possible outliers in the data set, a value of 2.15 NTU in July of 2002 and a value of 1.40 NTU in October of 2003. Spring, summer and fall averages from 1997 through 2003 ranged from 0.10 to 0.82 NTU in Upper Arrow and from 0.22 to 0.59 NTU in Lower Arrow (Table 4.3). The turbidity was highest in the summer of 2001 which coincides with high chlorophyll a biomass and low Secchi depth measurements.

Conductivity

Conductivity or specific conductance ranged from 97 to 144 $\mu\text{S}/\text{cm}$ in Upper Arrow and 99 to 135 $\mu\text{S}/\text{cm}$ in Lower Arrow in 2002. The values ranged from 107 to 145 in Upper Arrow and 102 to 132 $\mu\text{S}/\text{cm}$ in Lower Arrow in 2003 (Fig 4.19). Values were highest in the winter months and decreased slightly as the summer progressed. Conductivity averages showed little variability in spring, summer and fall from 1997 to 2003 (Table 4.4).

Table 4.2. Average Secchi depth (m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	5.91	5.68	7.05	10.72	6.47	9.65
1998	9.50	10.06	10.52	6.54	10.09	9.40
1999	9.42	5.79	8.42	7.04	7.76	9.25
2000	8.66	5.05	8.12	5.76	7.37	8.69
2001	9.27	3.95	9.98	7.52	6.35	9.45
2002	10.90	4.17	8.99	7.04	6.13	7.62
2003	9.12	4.52	7.77	7.92	6.23	9.60

Table 4.3. Average turbidity (NTU) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	0.55	0.53	0.27	0.49	0.36	0.36
1998	0.36	0.54	0.33	0.59	0.32	0.32
1999	0.36	0.79	0.47	0.55	0.47	0.30
2000	0.33	0.58	0.10	0.50	0.40	0.22
2001	0.33	0.82	0.24	0.32	0.56	0.30
2002	0.28	0.70	0.32	0.44	0.52	0.39
2003	0.33	0.58	0.10	0.50	0.40	0.22

Table 4.4. Average conductivity ($\mu\text{S}/\text{cm}$) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	131	109	119	124	106	112
1998	128	115	126	123	112	117
1999	133	108	122	128	104	103
2000	132	119	119	127	109	110
2001	no data	117	120	no data	118	116
2002	136	107	115	125	107	105
2003	132	119	119	127	109	110

Chemical Limnology – 0-30 m integrated samples

Phosphorus

Total phosphorus (TP) ranged from 2 to 6 $\mu\text{g}/\text{L}$ in Upper Arrow and from 2 to 5 $\mu\text{g}/\text{L}$ in Lower Arrow in 2002. The concentrations ranged from 2 to 8 $\mu\text{g}/\text{L}$ in Upper Arrow and from 2 to 9 $\mu\text{g}/\text{L}$ in Lower Arrow in 2003 (Fig. 4.20). Seasonal averages of TP ranged from 2.33 to 7.42 $\mu\text{g}/\text{L}$ from 1997 through 2003 in the entire reservoir (Table 4.5). These results are indicative of an oligotrophic to oligo-mesotrophic lake (Wetzel 2001).

Note: In 2002 and 2003, some total phosphorus results were lower than total dissolved phosphorus results, suggesting there may be a problem with lab analysis of phosphorus.

Total dissolved phosphorus (TDP) ranged from 2 to 9 $\mu\text{g}/\text{L}$ in Upper Arrow and from 2 to 10 $\mu\text{g}/\text{L}$ in Lower Arrow in 2002. The concentrations ranged from 2 to 7 $\mu\text{g}/\text{L}$ in Upper Arrow and from 2 to 7 $\mu\text{g}/\text{L}$ in Lower Arrow in 2003 (Fig. 4.21). Seasonal averages of

TDP ranged from 2.00 to 4.25 µg/L from 1997 through 2003 (Table 4.6). The annual natural load of TDP ranged from 197 tonnes to 95 tonnes from 1997 through 2003 (see Chapter 6). During the years of nutrient additions via fertilizer, the total load of phosphorus (natural load and the fertilizer added together) in the entire reservoir ranged from 147 tonnes to 196 tonnes (see Chapter 2 for fertilizer loading). The highest load of phosphorus occurred in 1997 and the lowest load in 1998; this trend coincided with the highest TDP concentration in 1997 (spring and summer) and the lowest concentration in 1998 (spring and summer) (Table 4.6).

Orthophosphate ranged from 1 to 3 µg/L in both Upper and Lower Arrow in 2002. The concentrations ranged from 1 to 5 µg/L in Upper Arrow and from 1 to 3 µg/L in Lower Arrow in 2003 (Fig. 22). During previous years, orthophosphate was at or below 1 µg/L (Pieters et al. 2003). Some of the orthophosphate results in 2002 and 2003 were higher than total phosphorus; this indicates there was a problem with analyses at the laboratory.

Table 4.5. Average total phosphorus (µg/L) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	4.00	7.42	6.00	4.95	6.00	3.00
1998	2.33	2.83	3.00	2.44	3.67	3.83
1999	4.25	4.58	5.25	3.89	4.78	4.67
2000	4.58	6.42	3.63	4.00	6.89	4.83
2001	4.08	4.25	2.25	3.00	3.67	2.67
2002	2.83	2.75	2.63	2.44	3.33	3.00
2003	2.39	3.00	3.13	2.89	2.44	3.25

Table 4.6. Average total dissolved phosphorus ($\mu\text{g/L}$) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	3.13	4.25	3.00	3.50	3.33	2.00
1998	2.00	2.08	2.00	2.22	2.33	2.33
1999	2.42	2.58	2.00	2.22	3.11	3.00
2000	2.17	2.67	2.38	2.56	2.67	2.17
2001	2.00	2.33	2.00	2.44	2.22	2.00
2002	3.71	3.08	2.63	2.67	3.89	3.67
2003	2.58	3.25	2.00	2.89	2.44	3.25

Nitrogen

Total Nitrogen (TN) concentrations ranged from 110 to 370 $\mu\text{g/L}$ in Upper Arrow and from 100 to 210 $\mu\text{g/L}$ in Lower Arrow (Fig 4.23) in 2003. However, the 370 $\mu\text{g/L}$ result in Upper Arrow may be an outlier. There were no seasonal trends in the 2003 data from June through November. TN data were not collected in 2002.

Ammonia concentrations were at or near the detection limit of 5 $\mu\text{g/L}$, except for the following: at stations AR3 and AR4, the concentration was 10 $\mu\text{g/L}$ in August 2002; at station AR3, the concentration was 9 $\mu\text{g/L}$ in August 2003 and at station AR4, the concentration was 25 $\mu\text{g/L}$ in August 2003.

Dissolved inorganic nitrogen ($\text{DIN} = \text{NH}_3 + \text{NO}_3 + \text{NO}_2$) concentrations ranged from 94 to 203 $\mu\text{g/L}$ in Upper Arrow and from 63 to 184 $\mu\text{g/L}$ in Lower Arrow during 2002. The concentrations ranged from 56 to 185 $\mu\text{g/L}$ in Upper Arrow and 44 to 196 $\mu\text{g/L}$ in Lower Arrow in 2003 (Fig 4.24). DIN concentrations have decreased from results in previous years. Summer averages of DIN have decreased from 156 $\mu\text{g/L}$ in 2000 to 112 $\mu\text{g/L}$ in Upper Arrow in 2003 and 89 $\mu\text{g/L}$ in Lower Arrow in 2003 (Table 4.7). These results suggest that Arrow could be becoming nitrogen limited in the surface waters during the summer months. The natural load of DIN to the Arrow system ranged from 7200 tonnes in 1997 to 4500 tonnes in 2003; these results coincide with the decrease in DIN measurements from water samples taken in the reservoir during this period. During the years of nutrient additions via fertilizer, the total load of nitrogen (natural load and the fertilizer added together) in the entire reservoir ranged from 7632 tonnes in 1999 to 4732 tonnes in 2003.

Table 4.7. Average dissolved inorganic nitrogen ($\mu\text{g/L}$) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	162	147	130	119	130	112
1998	155	121	114	117	119	99
1999	142	152	137	123	118	144
2000	153	156	122	129	117	104
2001	201	154	140	192	128	117
2002	159	134	153	133	89	120
2003	138	112	136	141	55	90

Silica

Silica concentrations ranged from 2.3 to 3.6 mg/L in Upper Arrow and from 2.0 to 4.5 mg/L in Lower Arrow in 2002. Concentrations ranged from 2.4 to 4.5 mg/L in Upper Arrow and from 2.0 to 4.6 mg/L in Lower Arrow in 2003. Silica was always well above 0.5 mg/L, which is considered the limiting concentration for diatoms (Wetzel, 2001). During 2002, concentrations decreased in August, and during 2003, concentrations decreased in the summer months (Fig. 4.27). There was no trend from 1997 to 2003 in spring, summer, or fall averages. However, average silica for the summer months in Upper Arrow in 2001 was lower than the average values from all other years (Table 4.8).

Table 4.8. Average silica (mg/L) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	3.94	3.95	4.46	3.72	3.92	3.75
1998	3.83	3.13	3.16	3.78	3.34	3.33
1999	3.63	3.40	3.49	4.20	3.67	3.50
2000	3.93	3.67	3.10	4.52	3.64	2.87
2001	3.81	2.71	3.21	4.09	2.60	2.55
2002	3.57	3.03	3.21	4.08	3.18	3.28
2003	3.99	3.15	3.40	4.09	2.49	3.13

Alkalinity

Alkalinity is the buffering capacity of the carbonate system in water (Wetzel, 2001). Alkalinity in Upper and Lower Arrow decreased through the summer during 2002 and 2003 and then increased during the fall (Fig. 4.26). In 2002, alkalinity ranged from 42 to 60 mg CaCO₃/L in Upper Arrow and from 41 to 58 mg CaCO₃/L in Lower Arrow. In 2003, the results ranged from 44 to 81 mg CaCO₃/L in Upper Arrow and 42 to 59 mg CaCO₃/L in Lower Arrow (Fig. 4.26). Seasonal averages remained uniform from year to year between 1998 and 2003, except during the summer of 2001 where alkalinity was lower than other years by 10 to 20 mg CaCO₃/L in Upper Arrow (Table 4.9).

Table 4.9. Average alkalinity (mg CaCO₃/L) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	no data	no data	no data	no data	no data	no data
1998	59	53	57	57	50	48
1999	59	47	50	57	46	44
2000	57	52	53	54	48	48
2001	no data	34	53	no data	52	52
2002	58	45	48	54	47	44
2003	57	49	51	55	46	47

pH

pH is the negative log of the hydrogen-ion concentration (Horne and Goldman, 1994). During 2002, the pH ranged from 7.40 to 8.10 in Upper Arrow and from 6.90 to 8.00 in Lower Arrow. During 2003, the pH ranged from 7.60 to 8.10 in Upper Arrow and from 7.00 to 8.00 in Lower Arrow. Seasonal averages are listed in Table 10, which shows that the pH level has been consistent between years, except in summer 2001 where the pH was slightly lower than other years.

Table 4.10. Average pH (pH units) (0-30 m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	7.92	7.87	7.92	7.96	7.95	7.90
1998	7.93	7.84	7.87	7.94	7.96	7.84
1999	7.96	7.92	7.40	7.99	7.94	7.25
2000	7.84	7.80	7.58	7.84	7.80	7.59
2001	7.69	7.51	7.64	7.69	7.52	7.67
2002	7.64	7.94	7.66	7.91	7.91	7.28
2003	7.83	7.89	7.70	7.54	7.93	7.90

Chlorophyll a

Chlorophyll a (Chl a) is the primary photosynthetic pigment in algae (Wetzel, 2001). Chl a ($\mu\text{g/L}$) ranged from 0.5 to 4.2 $\mu\text{g/L}$ in Upper Arrow and from 0.5 to 4.6 $\mu\text{g/L}$ in Lower Arrow in 2002. The values ranged from 0.5 to 7.5 $\mu\text{g/L}$ in Upper Arrow and from 0.5 to 8.9 $\mu\text{g/L}$ in Lower Arrow in 2003 (Fig. 4.28). In 2002, a filamentous green algae (*Ulothrix elongatum*) contributed to 50 % of the total phytoplankton biomass in September (see Chapter 7), which coincides with higher concentrations of Chl a (Fig. 4.28). During 2003, *Fragilaria* sp. were dominant in both basins, with large peaks occurring in September and October (see Chapter 7), coincident with high concentrations of Chl a in the same months (Fig. 4.28). Average summer Chl a was higher in 2002 and 2003 than in previous years (Table 4.11). Results from 2001 showed problems with the analysis at the lab; however, an additional set of Chl a analyses were completed in conjunction with primary production work, and concentrations were higher than the lab results (Pieters et al. 2003).

Table 4.11. Average chlorophyll a concentrations (0-30 m) in spring (Apr-Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2003.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	2.80	2.46	1.54	1.45	2.32	1.73
1998	2.43	0.97	0.94	1.53	1.30	1.00
1999	0.90	1.48	1.11	1.53	1.34	2.35
2000	1.46	2.19	1.58	1.36	1.40	1.92
2001	1.21	1.77	1.20	2.13	1.64	1.12
2002	2.25	3.10	2.65	2.81	3.19	1.70
2003	1.48	3.85	1.70	1.19	4.17	4.48

Discrete depth sampling in 2003

Nitrate concentrations decreased significantly below 25 µg/L (which is the concentration where nitrate is considered limiting to phytoplankton; (Wetzel, 2001) between June and July at AR2 and AR7 (Fig. 4.28).

Nitrogen to phosphorus ratios are used as a measure to determine nutrient limitation in lakes. Ratios less than 10 (by weight) indicate nitrogen limitation and ratios greater than 10 to 15 indicate phosphorus limitation (Downing and McCauley, 1992; Horne and Goldman, 1994). Ratios decreased from 55:1 to 6:1 in the upper depths between June and July at AR2 and from 38:1 to 6:1 in the upper depths between June and July at AR7. Ratios at AR 3, 4, 5, 6, and 8 were all less than 10 in August and had increased by September (Fig. 4.29). These results coincide with low nitrate concentrations during these months, with the exception of AR8 where nitrate increased but dissolved phosphorus also increased (Fig. 4.30).

These results indicate that the nitrogen to phosphorus blends of fertilizer added to the reservoir need to be fine tuned and closely monitored in upcoming years. Vertical profiles were also taken as a component of the primary production work in 2001, and the results indicated nitrogen limitation in the upper depths of AR2 in July and September and in the upper depths at AR7 in August.

Chl a results varied between months and stations (Fig. 4.31). Chl a concentrations were higher during the fall months, especially in Lower Arrow, which coincide with phytoplankton biomass increases (see Chapter 7).

Hypolimnion samples

Turbidity

Turbidity ranged from 0.12 to 0.42 NTU in Upper Arrow and 0.13 to 0.48 NTU in Lower Arrow in 2002. The results ranged from 0.10 to 0.94 NTU in Upper Arrow and from 0.05 to 0.46 NTU in Lower Arrow in 2003 (Fig. 4.32). There was slight variation between months and sampling dates in both years, except for a possible outlier of 0.94 NTU at AR2 in April of 2003.

Conductivity

Conductivity ranged from 131 to 148 µs/cm in Upper Arrow and 123 to 134 µs/cm in Lower Arrow in 2002. The results ranged from 134 to 149 µs/cm in Upper Arrow and from 125 to 136 µs/cm in Lower Arrow in 2003 (Fig 4.33). Conductivity was slightly lower at Lower Arrow stations in both years.

Phosphorus

Total phosphorus ranged from 2 to 6 µg/L in Upper Arrow and from 2 to 11 µg/L in Lower Arrow in 2002. The results ranged from 2 to 16 µg/L in Upper Arrow and from 2 to 8 µg/L in Lower Arrow in 2003 (Fig. 4.34).

Total dissolved phosphorus ranged from 2 to 7 µg/L in Upper Arrow and from 2 to 6 µg/L in Lower Arrow in 2002. The results ranged from 2 to 9 µg/L in Upper Arrow and from 2 to 8 µg/L in Lower Arrow in 2003 (Fig 4.35).

Orthophosphate concentrations ranged from 1 to 4 µg/L in Upper Arrow and from 1 to 7 µg/L in Lower Arrow in 2002. The concentrations ranged from 1 to 7 µg/L in Upper Arrow and from 1 to 3 µg/L in Lower Arrow in 2003 (Fig. 4.36).

The results indicate that the hypolimnion is not becoming phosphorus-enriched as a result of nutrient addition.

Nitrogen

Total nitrogen concentrations ranged from 180 to 260 µg/L in Upper Arrow and from 190 to 290 µg/L in Lower Arrow in 2003 (Fig. 4.37). Concentrations were slightly higher in September in Lower Arrow. Samples were not analyzed for total nitrogen in 2002.

Ammonia concentrations were at or near the detection limit of 5 µg/L during 2002 except at station AR4, where the concentration was 37 µg/L in November and at station AR8 where the concentration was 16 µg/L in August. Concentrations were at or near the detection limit during 2003 except at station AR4 where the concentration was 16 µg/L in August.

Dissolved inorganic nitrogen concentrations ranged from 148 to 360 µg/L in Upper Arrow and from 150 to 209 µg/L in Lower Arrow in 2002. The results ranged from 120 to 216 µg/L in Upper Arrow and from 160 to 200 µg/L in Lower Arrow in 2003 (Fig. 4.38). There was minimal variation between sampling dates and stations, except in 2003 where the concentration was 360 µg/L in March 2003 at AR6. All results are indicative of typical oligotrophic systems.

Silica

Silica concentrations ranged from 3.4 to 4.4 mg/L and from 2.8 to 5.6 mg/L in Lower Arrow in 2002. Concentrations ranged from 2.9 to 5 mg/L in Upper Arrow and from 3.4 to 4.6 mg/L in Lower Arrow in 2003 (Fig. 4.39). Concentrations slightly increased during the summer and fall months in 2002. Results remained uniformly distributed amongst stations and depths in 2003.

Alkalinity

Alkalinity concentrations ranged from 56 to 63 mg CaCO₃/L in both Upper and Lower Arrow in 2002. The concentrations ranged from 55 to 64 mg CaCO₃/L in Upper Arrow and from 51 to 60 mg CaCO₃/L in Lower Arrow in 2003 (Fig 4.40). Concentrations were slightly higher in Upper Arrow in 2003.

pH

pH ranged from 7.5 to 8.2 pH units in Upper Arrow and from 7.0 to 8.0 pH units in Lower Arrow in 2002. The results ranged from 7.7 to 8.1 in Upper Arrow and from 7.1 to 8.0 in Lower Arrow in 2003. These are similar to the epilimnion results.

Conclusions

Arrow Lakes Reservoir is oligotrophic to mesotrophic according to nutrient and chlorophyll a concentrations from the 0-30 m integrated measurements. The additional discrete-depth sampling in 2003 indicated that the system became nitrogen limited at depths of 2, 5, and 10 m between June and July (low nitrate concentrations and low nitrogen to phosphorus ratios). Chlorophyll a concentrations were higher than in the previous years of fertilization, consistent with the phytoplankton results in 2002 and 2003. The discrete-depth results indicated an increase in biomass between June and July, which coincides with the low nitrogen to phosphorus ratios during the same time.

Recommendations

Vertical profiles of nutrients, as conducted with the discrete-depth sampling in 2003, are required to assess the nutrient concentrations in the upper depths of the reservoir. This information assists with changes to weekly nutrient loading from fertilizer.

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Figure 4.1. Temperature profiles, April to November, station AR1, 2002 and 2003.

Figure 4.2. Temperature profiles, April to November, station AR2, 2002 and 2003.

Figure 4.3. Temperature profiles, April to November, station AR3, 2002 and 2003.

Figure 4.4. Temperature profiles, April to November, station AR4, 2002 and 2003.

Figure 4.5. Temperature profiles, April to November, station AR5, 2002 and 2003.

Figure 4.6. Temperature profiles, April to November, station AR6, 2002 and 2003.

Figure 4.7. Temperature profiles, April to November, station AR7, 2002 and 2003.

Figure 4.8. Temperature profiles, April to November, station AR8, 2002 and 2003.

Figure 4.9. Dissolved oxygen profiles, April to November, station AR1, 2002 and 2003.

Figure 4.10. Dissolved oxygen profiles, April to November, station AR2, 2002 and 2003.

Figure 4.11. Dissolved oxygen profiles, April to November, station AR3, 2002 and 2003.

Figure 4.12. Dissolved oxygen profiles, April to November, station AR4, 2002 and 2003.

Figure 4.13. Dissolved oxygen profiles, April to November, station AR5, 2002 and 2003.

Figure 4.14. Dissolved oxygen profiles, April to November, station AR6, 2002 and 2003.

Figure 4.15. Dissolved oxygen profiles, April to November, station AR7, 2002 and 2003.

Figure 4.16. Dissolved oxygen profiles, April to November, station AR8, 2002 and 2003.

Figure 4.17. Seasonal Secchi disk depths, 2002 and 2003.

Figure 4.18. Seasonal turbidity, 0-30 m integrated samples, 2002 and 2003.

Figure 4.19. Seasonal conductivity, 0-30 m integrated samples, 2002 and 2003.

Figure 4.20. Seasonal total phosphorus, 0-30 m integrated samples, 2002 and 2003.

Figure 4.21. Seasonal total dissolved phosphorus, 0-30 m integrated samples, 2002 and 2003.

Arrow - OrthoPhosphate

Arrow - Ortho Phosphate

Figure 4.22. Seasonal orthophosphate, 0-30 m integrated samples, 2002 and 2003.

Figure 4.23. Seasonal total nitrogen, 0-30 m integrated samples, 2003 (no samples were collected in 2002).

Figure 4.24. Seasonal dissolved inorganic nitrogen, 0-30 m integrated samples, 2002 and 2003.

Arrow - Dissolved Reactive Silica

Arrow - Dissolved Reactive Silica

Figure 4.25. Seasonal soluble reactive silica, 0-30 m integrated samples, 2002 and 2003.

Figure 4.26. Seasonal alkalinity, 0-30 m integrated samples, 2002 and 2003.

Arrow - Chlorophyll a

Arrow - Chlorophyll a

Figure 4.27. Seasonal chlorophyll *a*, 0-30 m integrated samples, 2002 and 2003.

Figure 4.28. Discrete depth nitrate-nitrogen profiles, 2003.

Figure 4.29. Discrete depth nitrogen:phosphorus ratios (weight:weight), 2003.

Figure 4.30. Discrete depth total dissolved phosphorus, 2003.

Figure 4.31. Discrete depth chlorophyll *a*, 2003.

Figure 4.32. Seasonal discrete turbidity, hypolimnion samples, 2002 and 2003.

Figure 4.33. Seasonal discrete conductivity, hypolimnion samples, 2002 and 2003

Arrow - Total Phosphorus (hypolimnion)

Arrow - Total Phosphorus (hypolimnion)

Figure 4.34. Seasonal discrete total phosphorus, hypolimnion samples, 2002 and 2003.

Figure 4.35. Seasonal discrete total dissolved phosphorus, hypolimnion samples, 2002 and 2003.

Figure 4.36. Seasonal discrete orthophosphate, hypolimnion samples, 2002 and 2003.

Arrow - Total Nitrogen (hypolimnion)

Figure 4.37. Seasonal discrete total nitrogen, hypolimnion samples, 2003 (no samples were collected in 2002).

Figure 4.38. Seasonal discrete dissolved inorganic nitrogen, hypolimnion samples, 2002 and 2003.

Figure 4.39. Seasonal discrete silica, hypolimnion samples, 2002 and 2003.

Figure 4.40. Seasonal discrete alkalinity, hypolimnion samples, 2002 and 2003.

CHAPTER 5

ARROW LAKES RESERVOIR RIVER AND STREAM CHEMISTRY, 2002 and 2003

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Introduction

This chapter reports on the water chemistry data collected during 2002 and 2003 from select tributary inputs to Arrow Lakes Reservoir, including the Columbia River and five smaller streams, and from the reservoir's outflow, the Columbia River. The Columbia River inflow site was at Revelstoke, and the outflow site was below the Keenleyside dam at Rialto Creek. These data are used to determine the nutrient budget to Arrow Lakes Reservoir in Chapter 6.

Materials and Methods

During 2002 and 2003, seven stream and river sites were sampled. The number of tributary streams sampled decreased to 6 from 10 in previous years due to reduced funding. The tributaries sampled in 2002 and 2003 were Columbia River at Revelstoke, Illecillewaet River, Kuskanax River, Incomappleux River, Burton Creek, and Deer Creek. The Columbia River outflow from Arrow Lakes Reservoir was also sampled at Rialto Creek. The Columbia River stations were sampled monthly throughout the year, and the five tributary streams were sampled monthly from the beginning of April through the beginning of October. Deer Creek was also sampled once in May and once in August. Additional streams were sampled twice a year prior to 2002, but in both 2002 and 2003, Deer Creek was the only stream sampled due to decreased funding.

Water was taken from the side of the river or stream with a bucket, and samples were then collected immediately from this water. The temperature in the bucket was measured with a handheld thermometer immediately after collection from the river or stream and again prior to sample collection. Samples were shipped within 24 h of collection to PSC Analytical Services (now Maxxam Analytics, Inc.) in Burnaby, B.C. Samples were kept in a cooler on ice prior to shipping.

In both 2002 and 2003, the following parameters were analyzed: nitrate- and nitrite-nitrogen, total dissolved phosphorus, total phosphorus, conductivity, and pH. In 2002, ammonia-nitrogen and orthophosphate were also analyzed, but these parameters were eliminated in 2003. Orthophosphate was not analyzed in 2003, because concentrations in previous years were at or below detection for most samples. Ammonia was eliminated from analyses because of cost as well as previous results indicating that ammonia only contributed approximately 10% to the overall dissolved inorganic nitrogen load to Arrow Lakes Reservoir. However, ammonia was measured at the two Columbia River sites during January to March, 2003.

Chapter 3 (Hydrology) includes details on the percentage of total inflow that the listed tributaries contribute to Arrow Lakes Reservoir.

Results

Nitrogen

During the 2002 sampling period, concentrations of ammonia ranged from 5 to 95 µg/L for the Columbia River at Revelstoke, from 5 to 90 µg/L for the Illecillewaet River, from 5 to 19 µg/L for Burton Creek, and from 5 to 13 µg/L for the Columbia River at Rialto Creek (Fig. 5.1). In both the Incomappleux River and the Kuskanax River, ammonia was consistently 5 µg/L. Deer Creek was sampled only twice (May and August) in 2002 and the concentration of ammonia was 5 µg/L each time. Table 5.1 lists averages of ammonia from select stream and river locations for 1997 through 2003.

Concentrations of nitrate- and nitrite-nitrogen ranged from 56 to 194 µg/L for the Columbia River at Revelstoke, from 51 to 413 µg/L for the Illecillewaet River, from 23 to 454 µg/L for the Incomappleux River, from 25 to 155 µg/L for the Kuskanax River, from 6 to 151 µg/L for Burton Creek, and from 14 to 171 µg/L for the Columbia River at Rialto Creek (Fig. 5.2). Table 5.2 lists averages of nitrate- and nitrite-nitrogen from select stream and river locations for 1997 through 2003.

Ammonia-nitrogen and nitrate- and nitrite-nitrogen make up the total dissolved nitrogen (TDN) component; 90 % of TDN is nitrate. The concentrations of TDN were higher during 2002 than 2003, which was most likely due to 2002 having a larger snowpack than 2003. The highest concentrations of TDN occurred in the spring, and TDN then decreased through the summer and fall periods (Table 5.3). The spring result is the average concentration from April 11 to June 15, summer is the average concentration from June 16 to September 21, and fall is the average concentration from September 22 to November 20. Chapter 6 discusses the TDN loads to Arrow Lakes Reservoir.

Table 5.1. Average ammonia concentrations (µg/L) from select stream and river locations for 1997–2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	5.5	6.8	17.6	8.6	5.4	9.5
1998	5.1	7.6	6.6	8.6	10.0	16.9
1999	5.0	5.4	5.4	8.4	8.7	7.1
2000	7.0	12.1	5.3	5.7	7.0	7.1
2001	6.5	14.0	8.3	5.2	6.2	8.8
2002	15.0	16.2	5.0	5.0	7.1	5.4
2003	9.7*	NS	NS	NS	NS	8.3*

* only sampled Jan, Feb, and Mar; NS = not sampled

Table 5.2. Average nitrate- and nitrite-nitrogen concentrations ($\mu\text{g/L}$) from select stream and river locations for 1997–2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	153.5	256.2	246.8	79.2	70.9	110.5
1998	133.5	198.3	218.7	81.4	71.2	114.3
1999	144.8	329.9	362.9	106.8	117.8	110.5
2000	155.0	294.8	328.2	106.2	92.6	123.0
2001	139.2	208.9	248.3	75.4	68.6	113.7
2002	147.2	245.3	262.1	80.6	67.9	100.5
2003	127.6	197.7	210.6	60.1	53.4	107.5

Table 5.3. Average total dissolved nitrogen ($\text{NH}_3 + \text{NO}_2 + \text{NO}_3$) concentrations ($\mu\text{g/L}$) in sampled stream and river locations for spring, summer, and fall, 2002 and 2003. Spring = Apr 11 – Jun 15; Summer = Jun 16 – Sep 21; and Fall = Sep 22 – Nov 20 (these dates coincide with the data presented in Chapter 3).

Stream	Spr 02	Sum 02	Fall 02	Spr 03	Sum 03	Fall 03
Columbia River at Revelstoke	160	193	142	136	147	112
Illecillewaet River	414	149	102	345	74	83
Incomappleux River	440	136	149	343	89	120
Kuskanax River	133	38	99	79	24	59
Burton Creek	119	36	11	77	21	65
Columbia River at Rialto	129	65	65	117	53	66

Phosphorus

In most cases, orthophosphate concentrations were close to the detection limit of $1 \mu\text{g/L}$ except for a few individual samples (Fig. 5.3). Concentrations of total dissolved phosphorus varied from 2 to $9 \mu\text{g/L}$ in the Columbia River at Revelstoke, from 2 to $10 \mu\text{g/L}$ in the Illecillewaet River, from 2 to $6 \mu\text{g/L}$ in the Incomappleux, from 2 to $8 \mu\text{g/L}$ in the Kuskanax River, from 2 to $10 \mu\text{g/L}$ in Burton Creek and from 2 to $10 \mu\text{g/L}$ in the Columbia River at Rialto Creek during the sampling period (Fig. 5.3). Table 5.3 lists the annual average total dissolved phosphorus concentration from select stream and river samples for 1997–2003.

Total phosphorus concentrations varied from 2 to $17 \mu\text{g/L}$ in the Columbia River at Revelstoke, from 2 to $51 \mu\text{g/L}$ in the Illecillewaet River, from 2 to $63 \mu\text{g/L}$ in the Incomappleux, from 2 to $45 \mu\text{g/L}$ in the Kuskanax River, from 2 to $54 \mu\text{g/L}$ in Burton Creek, and from 2 to $20 \mu\text{g/L}$ in the Columbia River at Rialto Creek during the sampling period. Table 5.4 lists the annual average total phosphorus concentration from select

stream and river samples from 1997-2003. There is no definite trend between seasons for total dissolved phosphorus or total phosphorus (Tables 5.6, 5.7). However, the summer results were slightly higher in 2002, and a few stream and river locations had higher concentrations during the summer period in 2003. Chapter 6 discusses phosphorus loading to Arrow Lakes Reservoir.

Table 5.4. Average total dissolved phosphorus ($\mu\text{g/L}$) concentrations from select stream and river locations for 1997-2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	3.8	4.7	3.8	5.7	6.0	3.7
1998	2.3	3.1	2.2	3.6	3.0	3.0
1999	2.5	3.0	3.2	3.9	4.8	2.6
2000	2.4	4.2	3.4	5.6	5.2	2.9
2001	2.9	3.3	2.6	2.6	2.7	2.2
2002	3.8	4.3	3.7	5.0	3.4	4.0
2003	3.8	3.7	2.7	3.8	3.5	3.3

Table 5.5. Average total phosphorus concentrations ($\mu\text{g/L}$) from select stream and river locations for 1997-2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	7.5	49.6	68.3	9.0	18.9	9.1
1998	4.1	31.2	51.3	6.9	10.0	6.8
1999	4.5	40.1	67.8	10.9	19.1	6.2
2000	3.6	19.0	47.4	6.8	12.2	5.4
2001	3.4	14.3	26.0	3.3	2.9	5.5
2002	4.1	14.0	9.6	4.2	3.7	3.2
2003	4.3	9.6	21.1	9.5	12.6	5.5

Table 5.6. Average total dissolved phosphorus concentrations ($\mu\text{g/L}$) in sampled stream and river locations for spring, summer, and fall, 2002 and 2003. Spring = Apr 11 – Jun 15; Summer = Jun 16 – Sep 21; and Fall = Sep 22 – Nov 20 (these dates coincide with the data presented in Chapter 3).

Stream	Spr 02	Sum 02	Fall 02	Spr 03	Sum 03	Fall 03
Columbia River at Revelstoke	2.8	3.8	5.0	4.2	3.7	2.0
Illecillewaet River	3.8	4.2	7.0	3.0	4.0	3.0
Incomappleux River	3.8	4.2	2.0	3.0	2.2	2.0
Kuskanax River	4.8	6.0	3.0	3.0	4.2	2.0
Burton Creek	3.0	3.8	4.0	3.4	4.0	2.0
Columbia River at Rialto	3.5	6.2	2.0	3.8	2.5	2.0

Table 5.7. Average total phosphorus concentrations ($\mu\text{g/L}$) in sampled stream and river locations for spring, summer, and fall, 2002 and 2003. Spring = Apr 11 – Jun 15; Summer = Jun 16 – Sep 21 and Fall = Sep 22 – Nov 20 (these dates coincide with the data presented in Chapter 3).

Stream	Spr 02	Sum 02	Fall 02	Spr 03	Sum 03	Fall 03
Columbia River at Revelstoke	3.0	4.0	3.0	6.5	3.7	2.0
Illecillewaet River	9.0	17.5	20.0	9.0	11.5	7.0
Incomappleux River	3.0	18.8	3.0	31.5	19.8	2.0
Kuskanax River	3.2	5.2	3.0	17.0	5.0	2.0
Burton Creek	3.2	4.2	4.0	24.7	2.0	6.0
Columbia River at Rialto	2.7	3.2	4.0	9.5	3.5	2.0

Conductivity

In 2002, conductivity ranged from 77 to 170 $\mu\text{S/cm}$ in the Columbia River at Revelstoke, from 97 to 161 $\mu\text{S/cm}$ in the Illecillewaet River, from 75 to 145 $\mu\text{S/cm}$ in the Incomappleux River, from 57 to 176 $\mu\text{S/cm}$ in the Kuskanax River, from 31 to 105 $\mu\text{S/cm}$ in Burton Creek, and from 91 to 123 $\mu\text{S/cm}$ in the Columbia River at Rialto Creek (Fig. 5.5). In 2003, conductivity ranged from 86 to 154 $\mu\text{S/cm}$ in the Columbia River at Revelstoke, from 85 to 182 $\mu\text{S/cm}$ in the Illecillewaet River, from 63 to 162 $\mu\text{S/cm}$ in the Incomappleux River, from 17 to 66 $\mu\text{S/cm}$ in the Kuskanax River, from 32 to 104 $\mu\text{S/cm}$ in Burton Creek, and from 106 to 125 $\mu\text{S/cm}$ in the Columbia River at Rialto Creek (Fig. 5.5). Conductivity generally decreased through the spring and then increased again in mid to late summer. These results follow the same trend as previous years (Pieters et al. 2003b). Table 5.5 lists the annual averages of conductivity from select stream and river locations.

Table 5.8. Average conductivity ($\mu\text{S}/\text{cm}$) from select stream and river locations for 1997-2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	120.0	109.2	92.9	32.7	66.9	114.7
1998	133.7	104.1	90.9	39.0	65.4	117.9
1999	124.9	121.3	97.9	38.4	53.8	117.2
2000	132.7	121.6	102.4	32.1	60.4	111.9
2001	134.0	127.6	102.6	44.4	74.6	122.8
2002	123.4	116.0	103.3	37.1	63.8	113.0
2003	132.1	118.1	95.3	40.0	61.0	117.9

pH

The pH of select stream and river locations ranged from 6.6 to 8.1 during 2002 and 2003 (Fig. 5.6). The results were within the range of averages from previous years (Table 5.6).

Table 5.9. Average pH from select stream and river locations for 1997–2003.

Year	Inflows to Arrow Lakes Reservoir					Outflow Columbia River at Rialto
	Columbia River at Revelstoke	Illecillewaet River	Incomappleux River	Kuskanax River	Burton Creek	
1997	7.88	8.01	7.88	7.30	7.66	7.94
1998	7.89	7.93	7.84	7.32	7.58	7.86
1999	7.88	8.01	7.88	7.34	7.52	7.95
2000	7.89	7.90	7.83	7.23	7.60	7.78
2001	7.99	7.89	7.76	7.52	7.73	7.89
2002	7.77	7.87	7.91	7.26	7.66	7.75
2003	7.87	7.91	7.72	7.36	7.56	7.77

Temperature

Temperature was measured throughout the 2002 and 2003 sampling seasons in all stream and river locations, except for the Columbia River at Revelstoke and the Illecillewaet River. Variations in temperature were similar to other years, except in 2003 in Burton Creek and Kuskanax Creek, where the peaks occurred in August with temperatures of 13.6 °C and 16.3 °C, respectively. Temperature variations by year are listed in Pieters et al. (1998, 1999, 2000, 2003a, 2003b).

Conclusions

Average nitrate and nitrite concentrations during 2003 were lower than in previous years. This could be a result of low snow pack and therefore less flow. The Illecillewaet and Incomappleux rivers tended to have higher concentrations of nitrate, nitrite, and total phosphorus than the other sampled stream and river locations.

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Figure 5.1. Ammonia concentrations in select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

Figure 5.2. Nitrate concentrations in select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

Figure 5.3. Phosphorus concentrations (OP = orthophosphate and TDP = total dissolved phosphorus) in select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

Figure 5.4. Total phosphorus concentrations, select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

Figure 5.5. Specific conductivity, select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

Figure 5.6. pH (pH units), select rivers and streams, Arrow Lakes Reservoir, 2002 and 2003.

CHAPTER 6

NUTRIENT BUDGET OF ARROW LAKES RESERVOIR, 2002 and 2003

by

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Introduction

Concern over the dramatic decline in kokanee, a land locked sockeye salmon (*Oncorhynchus nerka*), resulted in a comprehensive study of the Upper and Lower Arrow which began in April 1997. This component of the study gives estimates of the nutrient inputs (loads) to the Arrow Reservoir in 2002 and 2003.

Arrow Lakes Reservoir and Kootenay Lake are naturally oligotrophic, with low rates of primary productivity. Mountain lakes of this region are primarily phosphorus (P) limited though nitrogen (N) concentrations can decline in late summer in some lakes to suggest possible co-limitation at certain times. In Arrow Lakes Reservoir and Kootenay Lake, the upstream impoundments have resulted in reduction in ambient nutrient concentration or oligotrophication, reducing an already naturally low level of production.

There are several causes of reservoir, lake and stream oligotrophication (Stockner et al. 2000) but among the more relevant to this discussion are the following:

1. Trapping of nutrients by upstream impoundments or dams which has, for example, occurred in Kootenay and other lakes (Ashley *et al.* 1997a; Ney, 1996);
2. Increases in lake level and increases in lake level variation have also been reported as causing oligotrophication. For example, Milbrink and Holmgren (1981) implicate the wide lake level variations in Lake Anjan as causing oligotrophication due to a reduction in littoral zone fauna and faster deposition of phosphorus to the deeper parts of the lake;
3. Blockage of the 'anadromous nutrient pump.' In many BC lakes, pacific salmon return to spawn and die in the autumn depositing marine N & P in lakes and streams. Salmon carcass contributions to historic nutrient loads have ranged from 15 to 50% of the total phosphorus (TP) load (Stockner and MacIsaac, 1996). Reduction in the number of returning salmon has resulted in oligotrophication of many of these lakes (Stockner 2003, Stockner et al. 2000, Larkin and Slaney, 1997);
4. Levels of productivity can also change as a result of changes in the nutrient pathway through the lake due, for example, to changes in the natural hydrograph or as a result of climate change. Climate changes, particularly global warming, can cause oligotrophication by altering seasonal hydrographs and changing circulation patterns e.g. from dimictic to warm-monomictic. This change accentuates nutrient limitation in the epilimnion, changes food web structure and productivity (Stockner, 1997).

The primary aim of this project is to estimate the present nutrient load to the Arrow Lakes Reservoir. This input will be compared to estimates from previous years and with Kootenay Lake.

6.2 Introduction: Kootenay Lake

As Kootenay Lake forms the backdrop to this work on the Arrow Lakes Reservoir, the history of phosphorus loading to Kootenay Lake is briefly traced. In contrast to the Arrow Lakes Reservoir, where little limnological work had been done prior to 1997, Kootenay Lake is one of the most studied lakes in British Columbia (e.g. Daley, et al. 1981, Ashley et al. 1997a,b).

Kootenay Lake is unusual with its outflow occurring mid-lake from the West Arm. Outflow has been regulated by the Corra Linn Dam since 1939, however impoundment has only resulted in an increase in mean lake level of 2.4 m. Annual drawdown is 3 m. The major inflows into Kootenay Lake are both subject to impoundment: the Duncan Dam (1967) regulates 63% of the lower Duncan River entering the North Arm and the Libby Dam (1973) regulates 71% of the Kootenai River entering the South Arm. As a result 56% of the inflow to Kootenay Lake is regulated. For comparison, the Arrow Lakes experienced a mean lake level increase of 12.5 m with the construction of the Hugh Keenleyside Dam in 1967 to create the Arrow Lakes Reservoir. The pre-impoundment mean lake level variation of 8 m increased to 15 m. Of the inflow to Arrow Lakes Reservoir, 70% is regulated.

The area of Kootenay Lake is $\sim 400 \text{ km}^2$; that of Arrow Lakes Reservoir is $\sim 500 \text{ km}^2$. The flow through the Kootenay Lakes is $780 \text{ m}^3/\text{s}$; that through the Arrow Lakes Reservoir, $1,080 \text{ m}^3/\text{s}$. Flows, water levels and surface areas are detailed in Chapter 3.

The story of nutrients in Kootenay Lake is complicated by two factors: the introduction of mysid shrimp, *Mysis relicta*, in 1949 and the construction of a fertilizer plant near Kimberly in 1953, upstream of what would be the Libby reservoir (see Figure 3.1.1). The discharge from the fertilizer plant resulted in a large load of phosphorus to Kootenay Lake. The production of this plant doubled and tripled in 1962 and 1965, respectively, before pollution controls were progressively implemented from 1969 to 1979 and the plant was closed in 1987 (Lekstrum et al. 1994).

The load of total phosphorus (TP) to Kootenay Lake is shown in Figure 6.1 (Lekstrum et al. 1994; 1980-96 from Larkin 1998). The TP load is divided by the lake surface area to facilitate comparison with Arrow Lakes Reservoir. Note first the estimated historic load. This estimate of historic load was determined by working back from estimated retentions of the present impoundments.¹ A peak in phosphorus loading in the late 1960's is

¹ The estimated historic load to Kootenay Lake was determined by using an estimated TP retention of 90% for the Libby Dam, and an estimated increase in TP retention of 40% after construction of the Duncan Dam. Load was assumed proportional to flow volume. The historic load was estimated by working back from the mean 1980-96 load of Larkin (1998).

Retentions for Duncan is based on Perrin et al. (1996). They report the present retention of the Duncan Dam based on a comprehensive set of data collected in 1994-95. They also estimated the retentions of the original Duncan Lake and Koocanusa reservoir using two empirical models. The results from the

evident. Subsequent to the implementation of pollution control and to the construction of the Duncan and Libby Dams, the load of phosphorus drops below the estimated historic load in the 1980s. Finally, fertilization of Kootenay Lake began in 1992 (Ashley et al. 1997a,b) and the total load, including that of the fertilizer is shown by the dashed line in Figure 6.1. While fertilizer was applied to the North Arm, all loads are here calculated on a lake wide basis. Note that fertilizer phosphorus load is in the form of liquid ammonium polyphosphate, which is of immediate biological availability. Thus the effect of a given fertilizer load will be substantially greater than the effect of a similar TP load, depending on the fraction of the TP that is biologically available.² This issue of comparing different types of phosphorus will be noted again, further in the chapter.

These four features of the phosphorus load – historic levels, a peak in the late 1960's, the drop below historic level in the 1980's and the subsequent fertilization – are echoed in the number of kokanee returning to spawn at Meadow Creek in the North Arm of Kootenay Lake shown in Figure 11.12. The Meadow Creek spawning channel was opened in 1967 to compensate for spawning grounds lost above the Duncan Dam. While the data is partial, a peak in returns is evident in the early 1970's. Unfortunately, the increase in the number and size of kokanee through the 1960's was incorrectly ascribed to the introduction of mysid shrimp, which were thought to be acting as a food supplement for the kokanee³. This resulted in the introduction of mysid shrimp in several hundred lakes throughout western North America and Scandinavia (Martin and Northcote, 1991). However, because of their translucence and their daily migration to very deep water during the day, rather than being a good source of food for the kokanee, the mysid shrimp have instead proven to be a competitor for biological productivity.

Turning to the 1980's, a drop in kokanee escapement is evident. Note that there can be significant yearly variability in kokanee number because of the average 4 years for spawner return. For example, the return in 1972 is over double the return of their parent class in 1968. In contrast, 1986-1991 saw an unbroken decline in numbers through several year classes.

Subsequent to fertilization, an increase in spawner returns was observed. Of continuing concern are the mysid shrimp: biological modeling has suggested that mysids would out-compete kokanee for the increased productivity resulting from fertilization (Walters et al.

empirical models underestimate the present retentions of the Duncan Reservoir. Retention of Koocanusa Reservoir is taken to be that of the Duncan Reservoir. A nutrient budget of Koocanusa Reservoir would provide more accurate retention values.

² In this report "fraction of load that is biologically available" refers not only to the fraction of chemical species that are ultimately of biological availability but also refers to the rate of availability.

³ While the kokanee in the main basin were not increasing in size as a result of mysids, the kokanee in the West Arm were benefiting from mysids because of the unique hydraulic conditions found there. Mysids, entrained from the main basin into the West Arm, were unable to avoid predation from kokanee because of the relatively shallow depths.

The mysid shrimp were originally introduced as an intermediate sized food for rainbow trout. As these trout grow they switch from eating *Daphnia*, a zooplankton, to eating the much larger kokanee fry (L. Thompson, pers. comm.).

1991). However, mysid populations have declined through the initial years of fertilization with slight increases in the last few years. The reason for the initial decline is not currently understood (Ashley et al. 1997b).

6.3 Introduction: Arrow Lakes Reservoir

Spawner estimates for the Upper and Lower Arrow are shown in Figures 11.1 and 11.2. As with returns during the late 1980's in Kootenay Lake, the number of Arrow returns in the 1990's, show a steady decrease across year classes. It is this decline which triggered the comprehensive study of the Arrow Lakes Reservoir.

Note that the number of fish returning to spawn is lower in the Arrow Lakes Reservoir than in Kootenay Lake, both historically and at present. This, as well as other biological indicators of productivity, suggest that the productivity of the Arrow Lakes Reservoir is generally lower than that of Kootenay Lake. One step to understanding changes in productivity is to examine loading to the Arrow Lakes Reservoir.

6.4 Nutrient Load: methods

Nutrient loads to the Arrow Lakes Reservoir and component Upper and Lower Arrow basins were estimated for 2002 and 2003 using flow and nutrient data presented in Chapters 3, 4 and 5.

Loading was calculated for the following variables:

1. total dissolved phosphorus (TDP),
2. particulate phosphorus ($PP=TP-TDP$),
3. total phosphorus (TP),
4. dissolved inorganic nitrogen ($DIN=NH_3+N_2+N_3$).

Methods

From 1997 to 2001, inflow, outflow and 8 major tributaries were sampled 10-16 times through the year (intensively sampled tributaries) and 9 additional tributaries were sampled twice (Table 6.4.1; see for detail Pieters et al 1998, 1999, 2001, 2003a, 2003b). As a result of budgetary constraints in 2002 and 2003, the number of intensively sampled tributaries was reduced from 8 to 4 (Table 6.4.1), and only one additional tributary was sampled (Deer Cr.). Also, measurement of ammonia and orthophosphate (OP) were discontinued in 2003. Ammonia and OP were consistently low over the previous six years.

Table 6.4.1 shows the intensively sampled rivers and streams. In 2002, 4 streams were discontinued reducing the sampling from 54 to 40% of annual *local* inflow or reducing the sampling from 86 to 82% of the *total* flow into Arrow Lakes Reservoir. For the intensively monitored rivers and streams, sample collection from April to October captured approximately 75% of the flow in each stream, which peaks during snow melt in spring. The Revelstoke inflow and Arrow Lakes Reservoir outflow were sampled

throughout the year, see Chapter 5 for detail. Flow through the Narrows is sampled almost monthly at station AR5; see Chapter 4 for details.

The nine to fifteen samples on the intensively monitored rivers and streams (Chapter 5) were interpolated and extrapolated⁴ to year round daily values. Sample concentrations at or below detection level were considered at detection level.

Loading and export were computed by multiplying daily flow data by the daily concentration values and summing over each season and over one year. In order to assess the nutrient load supplied to the lake for production in the spring, summer and fall of, e.g. 2002, the nutrient budget was computed for November 21, 2001 to November 20, 2002 with winter from November 21, 2001 to April 10, 2002.⁵ (Limnological seasons are defined in Section 3.13.)

Table 6.4.1. Intensively sampled streams, 1997-2003

Region	Tributary	Flow m ³ /s	% of local inflow	% of total inflow	Sampled 1997- 2001	Sampled 2002, 2003
Inflow	Columbia River at Revelstoke	750		69.4	√	√
Revelstoke Reach	Illecillewaet	53	15.9	4.9	√	√
	Akolkolex	20	6.0	1.9	√	
Beaton Arm	Incomappleux	56	16.8	5.2	√	√
Upper Arrow	Kuskanax	14	4.2	1.3	√	√
Lower Arrow	Mosquito	3.9	3.9	1.2	√	
	Burton	3.0	3.0	0.9	√	√
	Caribou	2.2	2.2	0.7	√	
	Inonoaklin	1.5	1.5	0.5	√	
Outflow	Columbia R. below Keenleyside Dam	1080			√	√

Local river and stream data were used as follows:

1. **Revelstoke Reach:** The Revelstoke Reach is a big part of the local drainage to the Arrow system, receiving 40% of the local flow. Of the local flow to the Revelstoke Reach itself, the Illecillewaet represents about 40% and the Akolkolex

⁴ Extrapolation was not required in 1998 through 2002 as data from before and after these years were available. Extrapolation was done by extending the first and last measurements. This extrapolation was evaluated by ensuring that plots of the daily nutrient concentrations appeared reasonable. An alternate extrapolation, using mean sample concentration, is discussed in Appendix 9.2.

⁵ Because of limited data, the 1997 nutrient budget was estimated from January 01, 1997 to December 31, 1997 and winter was defined as January 01 to April 10, 1997 and November 21 to December 31, 1997. See Pieters et al. (1998).

15%. The Illecillewaet and Akolkolex are similar in character with high TP, low TDP (3-4 ug/L), high nitrate (250-300 ug/L N) and low ammonia (5-10 ug/L N).

In the nutrient budget for 1997-2001, the Illecillewaet River was taken to represent half of the local drainage area to the Revelstoke Reach and the other half of this area was assumed to be similar in character to the Akolkolex River. During this time, the interpolated daily nutrient concentrations for the Illecillewaet and Akolkolex were averaged. In 2002 & 2003, the Illecillewaet is taken to represent the entire drainage. To compute the load the average concentration was then multiplied by 40% of the daily value of the local flow. (See Table 3.9.1 for the fraction of local flow to each region.)

2. **Beaton Arm:** The Incomappleux accounts for 80% of the drainage to Beaton Arm. It is assumed that the remaining local inflow to Beaton Arm is similar in nutrient concentration to the Incomappleux. The daily nutrient concentration for the Incomappleux River is multiplied by 19% of the daily value of the local flow.
3. **Mainstem Upper Arrow:** The only intensively monitored flow to the mainstem of Upper Arrow is Kuskanax Creek representing 16% of the local drainage to the Upper Arrow mainstem. In terms of nutrients, the additional streams sampled on the east side of Upper Arrow in previous years were similar to Kuskanax Cr. (Halfway River, St Leon, Cape Horn and Slewiskin Creeks; 28% of local drainage to mainstem Upper Arrow; see Chapter 8, Pieters et al 2003b). Two large systems on the west side of Upper Arrow (Pingston and Fosthall Creeks) have not been sampled. In summary, Kuskanax Creek concentrations are generally representative of 44% of the local drainage to mainstem Upper Arrow and Kuskanax Creek is assumed to be representative of the balance. Kuskanax Creek concentrations are multiplied by 23% of the local flow.
4. **Lower Arrow:** For 1997-2001, the arithmetic mean is taken of interpolated daily concentrations for Mosquito, Burton, Caribou and Inonoaklin Creeks representing 37% of the drainage to Lower Arrow. In 2002 and 2003, only Burton Creek was sampled. Comparison of the 1997-2001 mean concentrations, suggest values for Burton Creek be multiplied by 0.8 for TDN, 1.3 for TDP and 2.7 for TP, in order to correct for the missing streams. The resulting stream concentrations are then multiplied by 18% of the local flow.

For discussion of other Lower Arrow streams sampled twice in 2001 and previous years, see Chapter 8 Pieters et al (2003b). Small tributaries to the south end of Lower Arrow are characterized by lower nitrate and higher TDP concentrations.

5. **Narrows:** Flow through the narrows represents export from the Upper Arrow and import to the Lower Arrow. Reverse flow through the narrows is unlikely (see Chapters 4 and 5, Pieters et al. 1998). The 0-30 m integrated sample

concentrations⁶ at Station AR5 were used as representative of the narrows and were interpolated and extrapolated to daily values and multiplied by the narrows flow.

The only stream data collected during winter are samples for the Revelstoke inflow, Narrows flow and Arrow outflow. Outside of these measurements, the winter loadings are the result of the interpolated data. To emphasize its speculative character, the winter data is italicized in Appendix 6.1.

Data correction

As discussed below there are two components to the nutrient budget: (1) the nutrient load and (2) the nutrient balance giving estimates of retention. Correction of data that affect nutrient load has been kept to a minimum. However some adjustment of outflow data has been required to provide more realistic retentions. The retentions are generally a small difference between the larger load and export, and hence subject to considerable error (see below). Problems with the estimates of retention also result from generally high nutrient concentrations in the Keenleyside outflow (occurring both before and after construction began near the dam in the spring of 1999). This problem was addressed by omission of selected outflow data. For changes see Appendix 6.4.

Data presentation

Consider the load of TDP shown in Appendix 6.1. Three tables are given, providing budgets for the upper, lower and total reservoir. All units are in 1,000 kg/season. Double lines indicate sums or differences. For example, the local load to Upper Arrow is first given for each sub-region. These values are summed to give the local load to all of the Upper Arrow. In turn, this local load is summed with that from the Revelstoke outflow to give the total load to the Upper Arrow. Finally the export through the narrows is subtracted from the total load to give the retention. The percentage retained is $100 \times (\text{import} - \text{export}) / \text{import}$.

Error estimate

A comprehensive analysis of all measurement errors and assumptions is beyond the scope of this report. Instead, Appendix 6.2 briefly examines the effect on TDP of a change in a few of the main underlying assumptions. In this case the total annual load appears to be accurate to about 10% and errors for loads by region and season are generally around 10%, but may be as high as 35%. The percentage retention for the total reservoir is accurate to about 35%. However, the error in the seasonal and sub-basin (Upper and Lower Arrow) retentions indicate that they are not likely meaningful.

⁶ Narrows samples are 0-30 m in name only as the depth at AR5 is ~13m below datum.

6.5 Nutrient load: results and discussion

6.5.1 Phosphorus

Orthophosphate

Orthophosphate (PO_4^{-3} , here OP), also known as soluble reactive phosphorus (SRP), was at or below the detection level for most of the river and narrows samples in 2002.⁷ (In 2003, measurement of OP was discontinued). Low OP is consistent with phosphorus-limited oligotrophic conditions where OP is expected to be utilized immediately by biological activity.

Total and Particulate Phosphorus

Total phosphorus (TP) is the usual measure of phosphorus input to a lake or reservoir. For example, Vollenweider (1968) developed his loading models on the basis of TP/Chlorophyll, and more recently Lekstrum et al. (1994) used TP to model loading to Kootenay Lake.

Total phosphorus is composed of two fractions, total dissolved phosphorus (TDP) and particulate phosphorus (PP), where $\text{TP} = \text{TDP} + \text{PP}$. Two samples are taken: TP is determined from an unfiltered sample and TDP is determined from the filtrate through a $0.45\ \mu\text{m}$ filter. PP is then computed as the difference between TP and TDP and represents the particulate form larger than $0.45\ \mu\text{m}$.

Mean concentrations of TP, TDP and PP are shown for all rivers and streams in Figure 6.2 monitored in 2002 & 2003. As in previous years, the particulate load in the Revelstoke inflow and Arrow outflow are generally low due to settling. In contrast, the load from local streams has a large component of PP. As in previous years, Kuskanax Creek is an exception with a relatively small load of PP, though Burton Creek also shows low PP in 2002. Most of the PP load to the Arrow Lakes Reservoir settles on entering the reservoir, and the mean concentration of PP in the water column is only $1.5 \pm 1.0\ \mu\text{g/l}$ in 2002 (0-30 m samples). The large concentration of PP in the local streams entering the Arrow Lakes Reservoir confounds comparison of TP load between Arrow and other lakes.

Particulate phosphorus in streams and rivers typically occurs in a variety of forms that can be broadly grouped as: a) phosphorus in organic structures, b) phosphorus adsorbed

⁷ There were 20 values of orthophosphate not at or below detection level in the intensively sampled rivers and streams in 2002, similar to previous years. Note that sampling of the Illecillewaet takes place approximately 1 km downstream of the Revelstoke Sewage Treatment Plant discharge. The Revelstoke plant provides secondary treatment for a population of about 8,000. This source may account for the very slightly elevated mean level of observed OP.

on particles, such as clays, and c) phosphorus as a mineral component of fine rock fragments (Forsberg 1989). Particulate phosphorus in organic form consists of organic matter having entered the stream, such as leaves and needles, which are in varying states of decomposition. Particulate organic matter also results from growth in the streams, e.g. periphyton. Weathering of phosphorus from rock fragments (apatite) is extremely slow, especially for igneous bedrock indigenous to the drainage. It is likely that PP entering Arrow Lakes Reservoir will play a minor role in biological processes, and most will settle from the water column and be sequestered in surficial sediments. Because of the steep sided character of the reservoir this material would be deposited relatively deep in the reservoir. As the water column remains oxygenated year round, the flux of phosphorus from the sediments is inhibited.

Total Dissolved Phosphorus

Mean annual TDP concentrations in streams for 2002 and 2003 were close to average, unlike 2001 when TDP values were low (during lowest flow of study period) or 1997 when TDP values were high (during highest flow of study period). Stream TDP values in 2003 were slightly lower than in 2002, reflecting the slightly below average local flow in 2003.

Tributary contributions of TDP generally increase from north to south in the Arrow system. The Revelstoke inflow, Illecillewaet, Akolkolex and Incomappleux Rivers all have mean TDP values of 2-4 µg/l. The Kuskanax has mean TDP values of 3-6 µg/l, and Mosquito, Caribou and Burton Creeks have means of 3-7 µg/l. Inonoaklin Creek was usually slightly higher with a mean TDP concentration ranging from 4-10 µg/l for 1997-2001. The Inonoaklin watershed includes a relatively large component of agricultural lands. Finally TDP in Deer, Little Cayuse and Syringa Creeks varied from 8-14 µg/l from 1997-2000 (with slightly lower values in 2001). It is not known whether this increase in TDP is representative of the southern end of the Lower Arrow or is a result of the anthropogenic activity specific to these creeks (e.g. agriculture, septic fields) though it shows no signs of elevated nitrogen that would likely accompany these.

Comparison of TDP between the Upper and Lower Arrow

Comparison of areal loads entails assumptions discussed in Appendix 6.3. While comparison is made between Upper and Lower Arrow (this section) and with Kootenay Lake (next section), these assumptions should be borne in mind.

To start, Table 6.5.1 summarizes the load of TDP from local flow to each basin. In contrast to the increase in TDP concentration from north to south, there is a decrease in local water inflow from north to south, i.e. 82% of local flows go to Upper Arrow. As seen in Table 6.5.1, the Upper Arrow receives more local load per square meter of surface area than the Lower Arrow.

However, when the main inflows are included (namely, the inflow from Revelstoke Dam into the Upper Arrow and inflow from the Narrows into the Lower Arrow) the Lower Arrow generally receives a higher areal load of TDP than the Upper Arrow (Table 6.5.2). While this is consistent with biological data suggesting that the Lower Arrow is more productive than Upper Arrow (see previous reports), the significance of the higher areal load to Lower Arrow is questionable as it results, in part, from the export of TDP of low biological availability from the Upper Arrow into Lower Arrow.

Table 6.5.1. TDP load from *local* inflow

	Revelstoke Reach	Beaton Arm	Mainstem Up. Arrow	Upper Arrow	Lower Arrow	Total
Area ⁸ , km ²	69.9	31.2	205.6	307	191	498
Load, 1,000 kg/yr 1997	26	11	20	57	20	77
Load, 1,000 kg/yr 1998	10	4	7	21	7	28
Load, 1,000 kg/yr 1999	13	7	11	31	12	43
Load, 1,000 kg/yr 2000	17	8	16	40	16	56
Load, 1,000 kg/yr 2001	10	4.4	5.6	20	5.1	25
Load, 1,000 kg/yr 2002	17	7	10	34	8	42
Load, 1,000 kg/yr 2003	15	5	7	26	6	32
Load, mg/m ² /yr 1997	380	340	100	187	105	155
Load, mg/m ² /yr 1998	143	128	34	68	37	56
Load, mg/m ² /yr 1999	186	224	54	101	63	86
Load, mg/m ² /yr 2000	240	250	76	131	82	112
Load, mg/m ² /yr 2001	143	141	27	65	27	50
Load, mg/m ² /yr 2002	245	224	49	111	42	85
Load, mg/m ² /yr 2003	209	147	34	85	32	65

⁸ Using areas from Table 3.9.1 at mean high water level, with narrows included in Lower Arrow.

Consider the load of TDP in 1997 (Table 6.5.2). Why, was the TDP load to the Upper Arrow ($580 \text{ mg/m}^2/\text{yr}$) and to the Lower Arrow ($870 \text{ mg/m}^2/\text{yr}$) higher than the load to the whole reservoir ($390 \text{ mg/m}^2/\text{yr}$)? In computing the load to the whole reservoir the nutrient flux through the narrows is not considered. However, in computing the nutrient load to the Lower Arrow, the nutrient flow through the narrows is the main input. Thus nutrients which flow through the Upper Arrow are double counted as they flow pass the narrows and enter the Lower Arrow.

Comparison with Kootenay Lake

In comparison with Kootenay Lake, the assumptions in areal load should be kept in mind (Appendix 6.3). Nevertheless, a brief comparison is given here.

Previous work on Kootenay Lake has focused on TP (e.g. Larkin, 1998). Table 6.5.3 compares the TP load to the Arrow Lakes Reservoir during the study period to the load of TP to Kootenay Lake from the Duncan and Kootenay Rivers. The average TP load is similar, as is the variability. Note that the TP load for Kootenay Lake does not include the local inflow to Kootenay Lake, where the local inflow is smaller (13%) than it is for Arrow Lakes Reservoir (31%).

The TDP load to Kootenay Lake is estimated⁹ to be $260 \text{ mg/m}^2/\text{yr}$. The mean TDP load to Arrow Lakes Reservoir during the study period is comparable to that estimated for Kootenay Lake. However, the productivity of Kootenay Lake is generally considered higher than that of Arrow. The discrepancy between TDP load and productivity may be due to an underestimate of the Kootenay load (the estimate is based on limited data), due to a TDP load with higher bioavailability to Kootenay Lake or due to differences in nutrient pathway through the lakes.

⁹ The TDP load of the Lower Duncan River (4100 kg/yr) and the Lardeau River (3300 kg/yr) are from 1994-95, Perrin et al. (1996). The TDP load of the Kootenay R. was estimated by averaging 53 values of [TDP] from the Kootenai R. at Creston, EMS station 0200013, covering the period 11/83-3/88. The resulting mean [TDP] was multiplied by $495 \text{ m}^3/\text{s}$. In addition a TDP load from local flow, of 50 mg/m^2 , was estimated by assuming that the [TDP] of the local flow into Kootenay Lake had a [TDP] of $6.4 \text{ } \mu\text{g/l}$, similar to that entering the Lower Arrow.

Table 6.5.2. Natural TDP load to basins

	Upper Arrow	Lower Arrow	Total
Area, km ²	307	191	498
Total Load, 1,000 kg/yr 1997	177	166	197
Total Load, 1,000 kg/yr 1998	87	104*	94
Total Load, 1,000 kg/yr 1999	105	96	117
Total Load, 1,000 kg/yr 2000	108	127*	123
Total Load, 1,000 kg/yr 2001	90	85	95
Total Load, 1,000 kg/yr 2002	108	75	116
Total Load, 1,000 kg/yr 2003	138	72	144
Load, mg/m ² /yr 1997	580	870	390
Load, mg/m ² /yr 1998	283	544	198
Load, mg/m ² /yr 1999	342	503	235
Load, mg/m ² /yr 2000	350	662	247
Load, mg/m ² /yr 2001	293	445	191
Load, mg/m ² /yr 2002	352	393	233
Load, mg/m ² /yr 2003	450	377	289

*That this is higher than the total is due to error in calculating flux of TDP through the narrows.

For comparison, fertilization added 52.8 MT of P to Upper Arrow. Dividing by the area of the Upper Arrow mainstem, 192 km², gives 270 mg P/m²/yr. Alternatively, dividing by the total area, 498 km², gives 106 mg P/m²/yr.

Table 6.5.3. Comparison of Arrow and Kootenay natural phosphorus load

	TP mg/m²/yr	TDP mg/m²/yr
Local Flow 1997	1,330	150
Revelstoke 1997	390	240
Total Arrow 1997	1,730	390
Local Flow 1998	460	60
Revelstoke 1998	250	130
Total Arrow 1998	710	190
Local Flow 1999	1,040	90
Revelstoke 1999	250	150
Total Arrow 1999	1,280	240
Local Flow 2000	530	110
Revelstoke 2000	230	140
Total Arrow 2000	760	250
Local Flow 2001	210	50
Revelstoke 2001	150	140
Total Arrow 2001	360	190
Local Flow 2002	240	85
Revelstoke 2002	250	150
Total Arrow 2002	490	235
Local Flow 2003	270	65
Revelstoke 2003	260	225
Total Arrow 2003	530	290
Total Arrow Average 97-03	840±490	250±60
Kootenay Lake	820±450 ¹⁰	Est. 260 ⁹

¹⁰ Mean TP load for 1997-2003 from Duncan and Kootenay Rivers (Binsted, & Ashley, 2006). The mean TP load for 1980-2003 was 730 ±320, slightly lower with less variability.

6.5.2 Nitrogen

Dissolved Ammonia

The detection level for dissolved ammonia (NH_3) is 5 $\mu\text{g/l}$. Streamflow NH_3 concentrations typically range from the detection level of 5 $\mu\text{g/l}$ to 10 $\mu\text{g/l}$, with a few larger values.

Dissolved Nitrite and Nitrate

Dissolved nitrate is the predominant ion (>90%). Nitrate values were well above detection levels (2 $\mu\text{g/l}$). The Revelstoke inflow had a mean nitrate concentration of 148 and 128 $\mu\text{g/l}$ in 2002 and 2003 respectively, close to the 7-year mean of 143 $\mu\text{g/l}$. Unlike TDP, which increased in the local streams and rivers from north to south, nitrate decreases from north to south. The Illecillewaet, Akolkolex and Incomappleux Rivers had mean concentrations around 250-300 $\mu\text{g/l}$, while the Kuskanax, Mosquito, Caribou and Burton Creeks ranged from means of 60-130 $\mu\text{g/l}$. Inonoaklin Creek and other southern creeks had means of 25 $\mu\text{g/l}$ of nitrate or less.

Dissolved Inorganic Nitrogen

Dissolved Inorganic Nitrogen (DIN) or Total Dissolved Nitrogen (TDN) is here defined as the sum of ammonia, nitrite and nitrate: $\text{DIN}=\text{TDN}=\text{NH}_3+\text{NO}_2+\text{NO}_3$. As the values of ammonia and nitrite are generally low, DIN is predominately nitrate. In 2002 and 2003, the total load of DIN to the Arrow Lakes Reservoir was 5.3×10^6 and 4.5×10^6 kg N compared with TDP load of 116×10^3 and 144×10^3 kg P, respectively. The N:P ratio of the annual load is ~40:1 (weight ratio) or ~90:1 (atomic ratio), providing very strong support for overall phosphorus limitation of autotrophic production in the Arrow system.

Table 6.5.4. Natural load of DIN (nitrate and ammonia) to the Arrow system

Year	DIN 1,000 kg
1997	7,200
1998	5,600
1999	7,400
2000	7,300
2001	4,700
2002	5,300
2003	4,500
Average 97-03	6,000±1,200

The load of DIN to Arrow is summarized in Table 6.5.4. For comparison, the fertilizer adds 232,000 kg N, in 2003, 268,000 kg N was added. During low flow years (e.g. 2001 & 2003), lower loading of natural DIN results from both lower DIN concentrations in stream inflow and from lower flow volumes. During these years, the natural concentrations of DIN available at the surface in spring are reduced and may have

contributed to nitrogen co-limitation observed e.g. in 2001 (Pieters et al 2003b, Chapter 7 and 15).

6.6 Additional sources and sinks of phosphorus

Atmospheric

In a review, Ahl (1988) noted that atmospheric deposition of phosphorus varies from 5-7 kg P/km²/yr in Northern Canada, Finland and Sweden (Abisko area), 11-15 kg P/km²/yr for forest and tundra areas in the USSR, 24-53 kg P/km²/yr for Central Canada, and 20-80 kg P/km²/yr over England. Assuming that Arrow is a remote region with a deposition rate of 6 kg P/km²/yr, gives a phosphorus load of 3,000 kg/yr over the 500 km² surface area of the reservoir. This is 0.3% of the 1997 TP load or 1.5% of the 1997 TDP load to the system.¹¹

Upper Arrow dust control program

Severe dust storms in the town of Revelstoke have resulted from the early spring exposure and drying of large, unvegetated areas after the typical 15 m drawdown of the Arrow Lakes Reservoir. These exposed areas are located in the "Revelstoke Reach", the narrow riverine section between Revelstoke and Arrowhead. The exposed soils/sediments are susceptible to erosion by the prevailing north/south winds along the old river channel. After evaluating a variety of solutions, the method of choice has been to spread fall rye seed with fertilizer, using an agricultural seed drill with disk, pulled behind a tractor. This ensures that the rye seed and fertilizer are delivered together below the surface of the soil (broadcast delivery of seed and fertilizer was found to be ineffective). The resulting rapid growth of the fall rye inhibits dust formation. Above certain elevations, this growth of rye has provided cover for the establishment of native littoral fauna some of which has begun to survive the annual flooding (Carr et al. 1993; Percell 1997; Dave Percell, B.C. Hydro, Revelstoke, personal communication).

Since 1991, between 1,900 and 2,500 acres of fall rye were seeded each year. In 1997, 2,490 acres (10 km²) was seeded with 95 lbs of rye and 50 lbs of 19-23-15 fertilizer/acre¹², from April 7-28. The reservoir was at maximum drawdown at the end of March, and seeding proceeded immediately following snow melt. Three islands of 150 acres were also fertilized by airplane with 100 lbs of rye and 75 lbs of fertilizer per acre. In total, this corresponds to the application of 5,890 kg P to the littoral slope of Upper Arrow. Good germination was observed. Subsequent flooding of seeded areas began in May and was complete by the end of June when the reservoir reached full pool. Many

¹¹ Perrin et al. (1996) installed a dust-fall collection flask at the Duncan weather station near the Duncan Dam. From monthly analyses of TP they estimated atmospheric nutrient load to the Duncan Reservoir, that "was extremely small, producing only 30g [sic] of P added to the entire reservoir over the year." With a reservoir surface area of 75 km², this gives a deposition of 0.4gP/km²/yr much less than the deposition rates reported in Ahl (1988) for remote areas.

¹² Assumed to be N-P₂O₅-K₂O, % by weight.

fish were observed along and within these drawdown regions, as they flooded (Dave Percell, personal communication). As this fertilizer is delivered below the soil surface, and as good germination and growth was observed, it is likely that little of this P was immediately available to the reservoir biota during flooding. Nevertheless, raised levels of fertilizer in the soils may eventually be mobilized into the water column during flooding of the river channel.

Until 2001, the seeding program was confined to the Revelstoke Reach above Arrowhead. In 2001 additional seeding was done below Arrowhead for the first time (Dean den Biesen, B.C. Hydro, Castlegar, personal communication). Seeding was done between 1,408 and 1,444 ft (429.1 to 440.1 m). As the reservoir topped out at 1,411 ft (430 m), little of this area was flooded in 2001.

Table 6.6.1 summarizes the seeding program application (data courtesy of Brian Gadbois, B.C. Hydro, Revelstoke). In conclusion, fertilization of the drawdown zone south of Revelstoke provided a potential load of 4,500-7,800 kg P in 1997-2000. In 2001 more fertilizer was applied but most of the fertilized area was not subsequently flooded due to low water levels. For 1997-2000, the load is e.g. 2-4% of the total load of TDP to the Arrow Lakes Reservoir in 1997, but it is difficult to assess how much of the phosphorus enters the reservoir biota.

Table 6.6.1. Upper Arrow dust control program

Year	Area Seeded (acres)	Area Seeded (km²)	Total Fall Rye (lbs)	Total Fertilizer 19/23/15 (lbs)	Fertilizer Type	P* (kg)
1997 ground	2,490	10.1	236,550	124,500	19/23/15	5,700
1997 air	150	0.6	15,000	11,250		500
1997 total	2,640	10.7	251,550	135,750		6,200
1998	2,736	11.1	273,600	116,500	19/23/15	5,300
1999	1,983.5	8.0	198,350	99,180	19/23/15	4,500
2000	2,450	9.9	245,000	168,750	19/23/15	7,700
2001 above Arrowhead	4,130	16.7	358,300	350,600	16/20/12 + 7% S	13,900
2001 below Arrowhead	1,437	5.8	-	143,700		5,700
2001 total	5567	22.5	-	494,300		19,600
2002	459	1.9	-	45,900	16/20/12+ 7% S	1,800
2003	2,347	5.5	-	138,884	16/20/12+ 7% S	5,500

* (124,500 lbs of 19/23/15)*(23% P₂O₅)*(44% P/P₂O₅)*(1kg/2.2lbs)=5700 kg P.

Residential sources

The two largest communities within the drainage basin of Arrow Lakes Reservoir are Revelstoke (population 8,300) and Nakusp (population 1,700). To estimate the potential load of phosphorus from residential sources consider the population of the remaining communities to be 3,000. With 1 kg P/year/person this basin population could potentially contribute 13,000 kg P/yr. The total load of TDP to the Arrow Lakes Reservoir was 197,000 kg in 1997. Thus, the local population could potentially add about 7% to the present TDP load to the Arrow Lakes Reservoir.

Revelstoke's sewage treatment plant is located approximately 1 km upstream of the sampling site for the Illecillewaet River. Depending on the discharge schedule, the Illecillewaet samples may include the contribution from this source. In Nakusp, sewage undergoes an extended aeration process and then exfiltrates into an alluvial basin near Kuskanax Creek. Monitoring of nitrates in test wells shows no influence of the lagoon on nearby groundwater (John Janzen, personal communication, Public Works, Nakusp). It is therefore unlikely that P from either Revelstoke or Nakusp will contribute significantly to the Arrow P load.

Anadromous salmon

In the Columbia River basin, anadromous salmon were reported as far north as Columbia Lake. An adult salmon of 2.5 kg weight returns about 12 g P (Stockner and MacIsaac 1996). Assuming a hypothetical return of 1 million anadromous salmon to local streams of the Arrow Lakes Reservoir, and assuming that each carries 12 g P would result in a P load of 12,000 kg/yr. This corresponds to 1.4% of the TP load or 6.3% of the TDP load to the Arrow Lakes Reservoir. Note that the phosphorus load of the salmon is in an organic form and is likely to be of higher biological availability than the natural load of TP or TDP.

Fishing

Commercial or recreational fishing is not an important loss of P to the Arrow system.

6.7 Conclusion

The load of TP to the Arrow Lakes Reservoir in 2002 and 2003 was below average but above the minimum set during the low flow in 2001 (Table 6.5.3). In contrast, the load of TDP was close to average in both 2002 and 2003 at 116 and 144 metric tons, respectively. The load of nitrogen in 2002 and 2003 was 5,300 and 4,500 metric tons of DIN, respectively. Low orthophosphate (OP) and high N:P ratios for a portion of the year indicate general phosphorus-limited oligotrophic conditions. However, results from the discrete profiles in 2003 indicate that the upper epilimnetic depths become nitrogen limited for a portion of the year (see Chapter 4).

Comparison of load to Arrow with that to Kootenay is tentative as the concept of areal loading is at the limit of applicability in these river-like reservoirs with high flow through (Appendix 6.3). Comparison of fish populations and other biological indicators of productivity suggest that in previous years productivity of the Arrow Lakes Reservoir was substantially lower than that of Kootenay Lake (see previous reports). However, averaged over the study period, the Arrow Lakes Reservoir received a similar load of TP and TDP as Kootenay Lake (though Kootenay TP load did not include local inflow and Kootenay TDP load was based on limited data). The reason that this load of TP and TDP to Arrow does not result in productivity comparable to Kootenay could include lower biological availability of the phosphorus load to Arrow than to Kootenay or differing nutrient pathways through the reservoir or through the food web.

A comparison of Arrow to a wide range of lakes can be made using chlorophyll *a* and total phosphorus as done by Vollenweider (1976), see Figure 6.3. The abscissa is the [TP] of the water column in $\mu\text{g/l}$ (mg/m^3) as predicted from the loading using a statistical model for retention (see Vollenweider, 1976 for detail). Here the mean observed 0-30 m [TP] will be used, namely 5.5 $\mu\text{g/l}$ for Arrow (1997) and 4.7 $\mu\text{g/l}$ for Kootenay Lake (mean of 1992-95).¹³ Mean chlorophyll *a* for both Arrow (1997) and Kootenay (1992-95) are an average of 0-30 m samples for all stations from April-November and are 2.2 and 2.7 $\mu\text{g/l}$, respectively.¹⁴ Both Arrow and Kootenay fall within the expected range and both are oligotrophic.

In Figure 6.4, Arrow Lakes Reservoir is compared to a series of lakes from Vancouver Island, which provide examples of high flushing, salmon bearing systems (Stockner and Shortreed 1985; J. Stockner, unpublished). Based on a comparison of chlorophyll *a*¹⁵, Figure 6.4 suggests that the effective surface layer [TP] is $\approx 2.7 \mu\text{g/l}$ in Arrow, a reduction from the observed mean values of 3-6 $\mu\text{g/l}$ seen in the surface layer (0-30m samples). (For Kootenay Lake the suggested [TP] is $\approx 3.5 \mu\text{g/l}$, a 25% reduction from the 4.7 $\mu\text{g/l}$ observed.) This suggests the phosphorus load to Arrow is of lower bio-availability.

Another way to approach bio-availability is to consider, for example, 2003 where a total of 144,000 kg phosphorus as TDP entered the Arrow Lakes Reservoir in $33.9 \times 10^9 \text{ m}^3$ of inflow. This corresponds to an average TDP inflow concentration of 4.3 $\mu\text{g/l}$. The average in-lake [TDP] is 2.4 $\mu\text{g/l}$ (0-30 m samples). Part of this in-lake concentration results from the minimum detection level of 2 $\mu\text{g/l}$; all values at and below the detection limit were set to the detection limit. Ignoring the bias created by the detection limit, the difference between the inflow and in-lake concentrations, $4.3 - 2.4 = 1.9 \mu\text{g/l}$, is a rough

¹³ Mean 0-30m [TDP] is 3.3 $\mu\text{g/l}$ for Arrow and 3.4 $\mu\text{g/l}$ for Kootenay (1992-95).

¹⁴ On Arrow, for comparison, mean Chl *a* was 2.2, 1.3, 1.5, 1.6, NA, 2.6 and 2.8 $\mu\text{g/l}$ for 1997 to 2003, respectively.

¹⁵ As with the comparison of phosphorus loads, this comparison of chlorophyll *a* implies a variety of assumption and should be made with caution. The major difficulty inherent in comparing chlorophyll *a* is variable zooplankton grazing. For example, a series of lakes in the Yukon which lack planktivores, show reduced chlorophyll *a* levels as a result of high zooplankton populations (Shortreed and Stockner, 1986).

measure of the natural TDP taken up. This suggests that, the bias from the detection limit notwithstanding, there is a fraction of in-lake TDP that is of low biological availability.

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Figure 6.1. Load of total phosphorus to Kootenay Lake. See Section 6.2. (x axis is year)

Figure 6.2 TP = TDP+ PP for 2002 and 2003

Figure 6.2. Arithmetic mean of river and stream sample concentrations for total phosphorus (TP), total dissolved phosphorus (TDP) and particulate phosphorus (PP=TP-TDP) concentrations. See Section 6.5.1.

Figure 6.3. Adapted from Vollenweider (1966). The units on the x-axis are mg/m^3 ($\mu\text{g}/\text{l}$). See Section 6.7 for further detail.

Figure 6.4. Comparison of average Chlorophyll *a* and average surface layer total phosphorus concentration. The line is fit to the Vancouver Island Lakes only ($R^2=0.83$). See Section 6.7 for further detail.

APPENDIX 6.1

LOAD TO ARROW LAKES RESERVOIR

Notes:

- All units in 1,000 kg/season. Namely 4.9 indicates 4,900 kg over the given season.
- Last line of each table is percent retention.
- Winter is italicized as it is based on limited data, see text.
- Double lines within a table indicate a sum or difference of previous lines.
- Negative retentions generally reflect error in the estimate of retention, see Section 6.4.

Table A6.1.1 Load of Total Dissolved Phosphorus (1000 kg), 2002

UPPER ARROW AS A UNIT: TDP	<i>WIN</i>	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	2.7	5.8	6.9	1.8	17.1
Load to Beaton Arm	0.9	2.2	3.7	0.3	7.0
Load to Mainstem Upper Arrow	1.3	2.9	5.3	0.5	10.0
Load from Local Flow to Upper Arrow	4.8	10.9	15.9	2.5	34.1
Load from Revelstoke Dam	20.8	8.2	22.4	22.0	73.5
Load to Upper Arrow	25.6	19.1	38.2	24.6	107.6
Load through Narrows	21.7	7.8	21.6	15.6	66.8
Retention in Upper Arrow	3.9	11.3	16.6	9.0	40.8
Retention in Upper Arrow (percent)	15	59	43	37	38

LOWER ARROW AS A UNIT: TDP	<i>WIN</i>	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	0.8	2.9	4.0	0.4	8.1
Load through Narrows	21.7	7.8	21.6	15.6	66.8
Load to Lower Arrow	22.5	10.8	25.6	16.0	74.9
Export from Keenleyside Dam	15.7	6.9	30.6	21.4	74.5
Retention in Lower Arrow	6.8	3.9	-5.0	-5.4	0.4
Retention in Lower Arrow (percent)	30	37	-19	-34	0.5

ARROW RES. AS A UNIT: TDP	<i>WIN</i>	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	5.6	13.8	19.8	2.9	42.2
Load from Revelstoke Dam	20.8	8.2	22.4	22.0	73.5
Total Load to Arrow Reservoir	26.4	22.1	42.2	25.0	115.7
Export from Keenleyside Dam	15.7	6.9	30.6	21.4	74.5
Retention	10.7	15.2	11.7	3.6	41.1
Retention (percent)	41	69	28	14	36

Table A6.1.2 Load of Particulate Phosphorus (1000 kg), 2002

UPPER ARROW AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	7.8	12.7	22.8	2.8	46.2
Load to Beaton Arm	3.2	0.9	8.3	0.6	12.9
Load to Mainstem Upper Arrow	0.4	1.4	2.4	0.0	4.2
Load from Local Flow to Upper Arrow	11.3	14.9	33.6	3.4	63.3
Load from Revelstoke Dam	25.6	1.9	8.4	13.6	49.5
Load to Upper Arrow	36.9	16.8	41.9	17.1	112.8
Load through Narrows	19.3	0.0	0.0	0.4	19.7
Retention in Upper Arrow	17.6	16.8	41.9	16.6	93.0
Retention in Upper Arrow (percent)	48	100	100	98	83

LOWER ARROW AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	2.3	5.1	6.0	0.4	13.8
Load through Narrows	19.3	0.0	0.0	0.4	19.7
Load to Lower Arrow	21.6	5.1	6.0	0.8	33.5
Export from Keenleyside Dam	12.2	3.4	12.4	12.9	40.9
Retention in Lower Arrow	9.3	1.7	-6.4	-12.0	-7.4
Retention in Lower Arrow (percent)	43	33	-107	-1419	-22

ARROW RES. AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	13.6	20.0	39.6	3.9	77.1
Load from Revelstoke Dam	25.6	1.9	8.4	13.6	49.5
Total Load to Arrow Reservoir	39.2	22.0	48.0	17.5	126.6
Export from Keenleyside Dam	12.2	3.4	12.4	12.9	40.9
Retention	27.0	18.5	35.5	4.6	85.7
Retention (percent)	69	85	74	26	68

Table A6.1.3 Load of Total Phosphorus (1000 kg), 2002

UPPER ARROW AS A UNIT: TP	<i>WIN</i>	<i>SPR</i>	<i>SUM</i>	<i>FALL</i>	<i>TOT</i>
Load to Revelstoke Reach	<i>10.5</i>	18.5	29.7	4.6	63.3
Load to Beaton Arm	<i>4.0</i>	3.0	12.0	0.8	19.9
Load to Mainstem Upper Arrow	<i>1.7</i>	4.3	7.7	0.5	14.2
Load from Local Flow to Upper Arrow	<i>16.1</i>	25.8	49.4	6.0	97.4
Load from Revelstoke Dam	<i>46.4</i>	10.1	30.8	35.6	123.0
Load to Upper Arrow	<i>62.5</i>	36.0	80.2	41.6	220.3
Load through Narrows	<i>41.0</i>	7.8	21.6	16.0	86.5
Retention in Upper Arrow	<i>21.5</i>	28.1	58.6	25.6	133.8
Retention in Upper Arrow (percent)	<i>34</i>	78	73	62	61

LOWER ARROW AS A UNIT: TP	<i>WIN</i>	<i>SPR</i>	<i>SUM</i>	<i>FALL</i>	<i>TOT</i>
Load from Local Flow to Lower Arrow	<i>3.0</i>	8.1	10.0	0.8	21.9
Load through Narrows	<i>41.0</i>	7.8	21.6	16.0	86.5
Load to Lower Arrow	<i>44.1</i>	15.9	31.6	16.9	108.4
Export from Keenleyside Dam	<i>27.9</i>	10.3	43.0	34.3	115.4
Retention in Lower Arrow	<i>16.1</i>	5.6	-11.4	-17.4	-7.0
Retention in Lower Arrow (percent)	<i>37</i>	36	-36	-103	-7

ARROW RES. AS A UNIT: TP	<i>WIN</i>	<i>SPR</i>	<i>SUM</i>	<i>FALL</i>	<i>TOT</i>
Total Local Load to Arrow Reservoir	<i>19.2</i>	33.9	59.4	6.8	119.3
Load from Revelstoke Dam	<i>46.4</i>	10.1	30.8	35.6	123.0
Total Load to Arrow Reservoir	<i>65.6</i>	44.0	90.2	42.5	242.2
Export from Keenleyside Dam	<i>27.9</i>	10.3	43.0	34.3	115.4
Retention	<i>37.7</i>	33.7	47.2	8.2	126.8
Retention (percent)	<i>57</i>	77	52	19	52

Table A6.1.4 Load of Total Dissolved Nitrogen
TDN = NH₃ + NO₂ + NO₃ (1000 kg), 2002

UPPER ARROW AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	167.7	584.6	305.9	28.3	1086.5
Load to Beaton Arm	60.8	277.9	139.0	18.7	496.3
Load to Mainstem Upper Arrow	25.1	94.6	43.3	15.0	177.9
Load from Local Flow to Upper Arrow	253.5	957.1	488.2	61.9	1760.8
Load from Revelstoke Dam	1183.4	444.8	1110.9	710.2	3449.4
Load to Upper Arrow	1437.0	1401.9	1599.1	772.1	5210.2
Load through Narrows	1823.4	462.0	1087.0	911.2	4283.6
Retention in Upper Arrow	-386.4	939.9	512.1	-139.0	926.6
Retention in Upper Arrow (percent)	-27	67	32	-18	18

LOWER ARROW AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	15.4	61.9	26.3	4.1	107.7
Load through Narrows	1823.4	462.0	1087.0	911.2	4283.6
Load to Lower Arrow	1838.8	523.9	1113.3	915.3	4391.3
Export from Keenleyside Dam	1461.7	353.5	725.0	688.8	3228.9
Retention in Lower Arrow	377.1	170.4	388.3	226.5	1162.4
Retention in Lower Arrow (percent)	21	33	35	25	27

ARROW RES. AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	268.9	1019.0	514.5	66.1	1868.5
Load from Revelstoke Dam	1183.4	444.8	1110.9	710.2	3449.4
Total Load to Arrow Reservoir	1452.3	1463.8	1625.4	776.3	5317.9
Export from Keenleyside Dam	1461.7	353.5	725.0	688.8	3228.9
Retention	-9.3	1110.3	900.5	87.5	2089.0
Retention (percent)	-1	76	55	11	39

Table A6.1.5 Load of Total Dissolved Phosphorus (1000 kg), 2003

UPPER ARROW AS A UNIT: TDP	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	3.6	4.1	5.4	1.5	14.6
Load to Beaton Arm	0.9	1.9	1.4	0.5	4.6
Load to Mainstem Upper Arrow	1.4	3.0	1.9	0.6	6.9
Load from Local Flow to Upper Arrow	6.0	8.9	8.7	2.5	26.1
Load from Revelstoke Dam	61.2	10.2	33.4	6.7	111.5
Load to Upper Arrow	67.2	19.1	42.1	9.2	137.7
Load through Narrows	27.0	6.7	21.0	10.9	65.7
Retention in Upper Arrow	40.2	12.4	21.1	-1.8	71.9
Retention in Upper Arrow (percent)	60	65	50	-19	52

LOWER ARROW AS A UNIT: TDP	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	1.4	2.6	1.5	0.6	6.2
Load through Narrows	27.0	6.7	21.0	10.9	65.7
Load to Lower Arrow	28.5	9.4	22.6	11.5	71.9
Export from Keenleyside Dam	43.8	8.9	22.8	23.4	98.9
Retention in Lower Arrow	-15.4	0.4	-0.2	-11.8	-27.0
Retention in Lower Arrow (percent)	-54	5	-1	-103	-38

ARROW RES. AS A UNIT: TDP	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	7.4	11.5	10.3	3.1	32.3
Load from Revelstoke Dam	61.2	10.2	33.4	6.7	111.5
Total Load to Arrow Reservoir	68.7	21.7	43.7	9.8	143.8
Export from Keenleyside Dam	43.8	8.9	22.8	23.4	98.9
Retention	24.8	12.8	20.9	-13.6	44.9
Retention (percent)	36	59	48	-139	31

Table A6.1.2 Load of Particulate Phosphorus (1000 kg), 2003

UPPER ARROW AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	2.8	9.8	7.7	2.2	22.5
Load to Beaton Arm	0.1	22.5	10.4	0.0	33.1
Load to Mainstem Upper Arrow	0.5	5.6	2.7	0.1	8.8
Load from Local Flow to Upper Arrow	3.3	37.9	20.8	2.3	64.4
Load from Revelstoke Dam	13.4	6.2	0.0	0.0	19.6
Load to Upper Arrow	16.7	44.1	20.8	2.3	84.0
Load through Narrows	12.1	3.8	12.3	5.8	34.0
Retention in Upper Arrow	4.6	40.4	8.5	-3.5	50.0
Retention in Upper Arrow (percent)	28	92	41	-152	60

LOWER ARROW AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	1.5	28.5	4.2	2.9	37.2
Load through Narrows	12.1	3.8	12.3	5.8	34.0
Load to Lower Arrow	13.7	32.3	16.5	8.8	71.2
Export from Keenleyside Dam	4.4	12.0	10.4	-9.7	17.0
Retention in Lower Arrow	9.3	20.3	6.1	18.5	54.2
Retention in Lower Arrow (percent)	68	63	37	211	76

ARROW RES. AS A UNIT: PP	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	4.9	66.4	25.0	5.2	101.6
Load from Revelstoke Dam	13.4	6.2	0.0	0.0	19.6
Total Load to Arrow Reservoir	18.3	72.6	25.0	5.2	121.2
Export from Keenleyside Dam	4.4	12.0	10.4	-9.7	17.0
Retention	13.9	60.6	14.6	15.0	104.2
Retention (percent)	76	84	59	286	86

Table A6.1.3 Load of Total Phosphorus (1000 kg), 2003

UPPER ARROW AS A UNIT: TP	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	6.4	13.9	13.1	3.7	37.1
Load to Beaton Arm	1.0	24.4	11.8	0.5	37.7
Load to Mainstem Upper Arrow	1.9	8.5	4.7	0.6	15.7
Load from Local Flow to Upper Arrow	9.3	46.8	29.6	4.8	90.5
Load from Revelstoke Dam	74.6	16.4	33.4	6.7	131.1
Load to Upper Arrow	84.0	63.2	62.9	11.5	221.7
Load through Narrows	39.2	10.5	33.3	16.8	99.7
Retention in Upper Arrow	44.8	52.8	29.6	-5.3	121.9
Retention in Upper Arrow (percent)	53	83	47	-46	55

LOWER ARROW AS A UNIT: TP	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	2.9	31.1	5.8	3.5	43.4
Load through Narrows	39.2	10.5	33.3	16.8	99.7
Load to Lower Arrow	42.1	41.6	39.1	20.3	143.1
Export from Keenleyside Dam	48.2	20.9	33.2	13.6	115.9
Retention in Lower Arrow	-6.1	20.7	5.9	6.7	27.2
Retention in Lower Arrow (percent)	-14	50	15	33	19

ARROW RES. AS A UNIT: TP	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	12.3	78.0	35.3	8.3	133.9
Load from Revelstoke Dam	74.6	16.4	33.4	6.7	131.1
Total Load to Arrow Reservoir	86.9	94.4	68.7	15.0	265.0
Export from Keenleyside Dam	48.2	20.9	33.2	13.6	115.9
Retention	38.7	73.4	35.5	1.4	149.1
Retention (percent)	45	78	52	9	56

Table A6.1.8 Load of Total Dissolved Nitrogen
TDN = NH₃ + NO₂ + NO₃ (1000 kg), 2003

UPPER ARROW AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Load to Revelstoke Reach	107.3	410.5	106.2	42.8	666.7
Load to Beaton Arm	61.8	205.5	62.8	28.5	358.6
Load to Mainstem Upper Arrow	41.2	67.5	21.9	17.9	148.5
Load from Local Flow to Upper Arrow	210.3	683.5	190.8	89.3	1173.8
Load from Revelstoke Dam	1393.0	417.3	1019.9	377.3	3207.5
Load to Upper Arrow	1603.3	1100.7	1210.7	466.6	4381.3
Load through Narrows	1937.4	385.4	784.6	594.9	3702.3
Retention in Upper Arrow	-334.1	715.4	426.0	-128.3	679.0
Retention in Upper Arrow (percent)	-21	65	35	-28	16

LOWER ARROW AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Load from Local Flow to Lower Arrow	15.6	37.6	12.9	12.4	78.6
Load through Narrows	1937.4	385.4	784.6	594.9	3702.3
Load to Lower Arrow	1953.0	423.0	797.6	607.3	3780.9
Export from Keenleyside Dam	2068.0	296.7	651.6	515.6	3531.9
Retention in Lower Arrow	-115.0	126.3	146.0	91.7	249.0
Retention in Lower Arrow (percent)	-6	30	18	15	7

ARROW RES. AS A UNIT: TDN	WIN	SPR	SUM	FALL	TOT
Total Local Load to Arrow Reservoir	225.9	721.1	203.7	101.7	1252.4
Load from Revelstoke Dam	1393.0	417.3	1019.9	377.3	3207.5
Total Load to Arrow Reservoir	1618.9	1138.3	1223.6	479.0	4459.9
Export from Keenleyside Dam	2068.0	296.7	651.6	515.6	3531.9
Retention	-449.1	841.6	572.0	-36.6	928.0
Retention (percent)	-28	74	47	-8	21

APPENDIX 6.2

ERROR ESTIMATE FOR TDP LOAD

A comprehensive analysis of all measurement errors and assumptions is beyond the scope of this report. Instead, we briefly examine the effect on TDP of a change in a few of the main underlying assumptions. This is done for the 1997 TDP load as done in the year 1997/98 report (Pieters et al. 1998) and is here provided for reference.

Consider the effect of the following "variations" on the 1997 load of TDP shown in Table A6.2.1:

0. No change.
1. Extrapolate using the mean concentration rather than the first and last values.
2. Use only every other sample. (Keep the first, delete the second). This reduces the total number of stream samples from 93 to 51. This reduces the number of samples per stream from 5-11 to 3-6.
3. Reduce the local flow and Arrow discharge by 25 m³/s. (No compensating adjustment was made to the narrows flow.)
- A. Rather than calculating the load by multiplying the daily flow by the daily interpolated concentration, simply multiply the arithmetic mean of the concentrations for a given season (Appendix 8.3, 1997/98 report) by the flow volume over that season (Section 3.12).

Table A6.2.1 Change to 1997 TDP loads for variations

Variation		0	1	2	3	A	%
LOADS:							
Local load to the Upper Arrow	yr	57	55	56	54	55	5%
Load from Revelstoke reservoir	yr	120	108	108	nc	110	10%
Load through Narrows	yr	146	158	146	nc	148	8%
Local load to the Lower Arrow	yr	20	18.5	21	19	18	15%
Export from Arrow	yr	163	148	163	160	156	9%
Total load to the Upper Arrow	yr	177	163	164	174	165	8%
Total load to the Lower Arrow	yr	166	177	168	165	166	7%
Total load	yr	197	181	185	193	183	8%
Total load	spr	51	47	50	50	-	8%
Total load	sum	63	63	58	62	-	8%
Total load	fal	24	26	18	23	24	33%
RETENTIONS:							
% retention in the Upper Arrow	yr	17	3	11	16	10	82%
% retention in the Lower Arrow	yr	2	16	3	3	6	700%
% retention in the total reservoir	yr	17	18	12	17	15	35%

Notes to Table A6.2.1:

- The column marked “%” gives the percentage variation, (max. value - min. value)*100/(value in column "0").
- All units are 1000 kg except the percentage retention.
- Values which did not change, and were not expected to change, are marked “nc”.

Consider first the loads. The error in the load, given in the last column of Table A6.2.1, should not be considered accurate on a case by case basis, but should rather be seen as indicative. The mean error in the loading is 11%. Note, that the larger error in the fall load resulted from the removal of one moderately high point in the Revelstoke inflow (Nov. 3). While removal of this one point also resulted in a reduction in the annual load, the effect of this one point on the annual load is smaller than its effect on the fall load. Thus, in general, the error is expected to be larger when considering either local regions or shorter periods of time. The largest variation in load resulted from the change in the method of extrapolation of the data to the entire year (variation "1"). Much of this extrapolation will be reduced after 1997 as water column sampling and sampling of the Revelstoke inflow and Arrow Lakes Reservoir outflow will be available from throughout the year. (In 1997 sampling began in late April). Note that variation "A" does quite well in determining the total load. This would be the case if there was little correlation between flow rate and nutrient concentration. (Nevertheless, there may be some seasonal variation in TDP concentration.)

The error in the percentage retention is substantially higher than the error in the load: retention is a small difference of the large loads. For example, take the load and export of the Upper Arrow and vary it by $\pm 10\%$: this varies the retention from a maximum of 32% to a minimum of -1% . From the large error, it is clear that it has not been possible to determine the retention of the Upper and Lower Arrow individually. Also the error in the retention for given seasons is expected to be higher (not shown) because of the increased error in the loads of loads to individual seasons. However, the retention for the total reservoir is around $17\% \pm 6\%$, indicative of a low residence, high flushing system. Changes in the method of extrapolation (variation "1") had the largest effect on the retentions of the Upper and Lower Arrow. Reduced extrapolation may provide improved retention estimates for these sub-basins.¹⁶

In conclusion, the total annual load appears to be accurate to about 11% and errors for loads by region and season are generally around 11%, but may be as high as 33%. The percentage retention for the total reservoir is accurate to about 35%, and the retentions for the upper and Lower Arrow are considered inaccurate and therefore not meaningful.

¹⁶ While the sampling period beginning in April captured most of the period of spring melt and hence sampled most of the local inflow, the 1997 sampling period did not capture the substantial inflow, outflow and narrows flow that occur during winter as a result of winter drawdowns.

APPENDIX 6.3

DISCUSSION OF AREAL LOAD

One goal of computing the nutrient load (kg/yr) to the Arrow Lakes is comparison of the present load to the historic (pre-impoundment) load. Another is comparison of nutrient load between lakes/reservoirs and between years. Can the apparent higher productivity of the Lower Arrow be explained by a higher nutrient load to that part of the Arrow system? How does the load to the Arrow Lakes Reservoir compare to Kootenay Lake? The usual way of making such comparisons is to compute an areal load ($\text{mg/m}^2/\text{yr}$), namely nutrient load (kg/yr) divided by the surface area of the lake/reservoir (km^2). In this appendix the limitations of the areal load concept are discussed.

The following assumptions are implicit in an areal load:

1. Dividing the load by the surface area of the lake/reservoir, rather than dividing by the volume of the lake/reservoir, assumes that the load is distributed over a surface layer of the lake/reservoir and not mixed through the whole volume;
2. The water layer receiving the load is a 'stirred reactor', namely the load is stirred uniformly over the surface layer;
3. The load is consumed locally.

Do these three assumptions hold for the Arrow Lakes Reservoir? As discussed below the answer is,

1. somewhat,
2. not really,
3. no.

A brief discussion of each assumption is sketched below.

1. Once the reservoir stratifies in spring, the river and stream inflow forms an interflow between the warm surface layer and the colder hypolimnion. This period lasts for a substantial fraction of the year and captures a good fraction of the Revelstoke inflow and most of the local inflow. However, nutrients carried by this inflow, need to make their way to the euphotic zone and this depends on the mixing between the interflow and the overlying thermal layer, characterization of which requires further investigation. Nevertheless, for a substantial part of the year, the nutrient inputs are not mixed through the whole volume of the reservoir and enter in or near the surface layer.
2. Clearly the surface of the reservoir is not a stirred reactor. As discussed in the previous paragraph there is some question about the vertical mixing of the nutrient inputs from an interflow layer into the euphotic zone of the surface layer. Beside this question of vertical mixing there is also the question of horizontal mixing. The Arrow Lakes is part of a river and there is a substantial flow through the reservoir. During summer, this river flow is transported primarily through the surface layer as indicated by current meter records (Chapter 4, Pieters et al. 1998). Thus nutrients are generally swept downstream.

3. If a first lake receives twice the areal load as a second, the nutrient load concept at its simplest implies that the productivity will also be double. For this to hold, double the nutrients need be consumed in the first lake. In the Arrow system, nutrients are not consumed locally. This could be the result of phosphorus of low biological availability or of nutrients not finding their way to the euphotic zone.

In conclusion, the Arrow system is not a static pool of water, where added nutrients are consumed to produce local productivity, but rather a system that is being flushed with nutrients of low biological availability. The above limitations should be borne in mind when using areal loads for these systems.

APPENDIX 6.4

DATA CORRECTION

From 1997 to 2001, lake and stream chemistry samples were analyzed by the Pacific Environment Science Center (PESC), 2645 Dollarton Highway, North Vancouver. Starting in 2002, these samples were analyzed by PSC Analytical Services, 8577 Commerce Court, Burnaby.

Load data. Load data was adjusted as follows:

- Two unusually high values of TDP of 32 µg/l for the Illecillewaet on Sept. 3/97 and of 18 µg/l for the Arrow outflow on Nov. 3/97 were both reduced to 3 µg/l.
- Period of extended missing data was linearly interpolated to mean values to 5 and 150 and for NH₃, NN, respectively (2001).
- Values of TP and TDP were switched when TDP was greater than TP. Note there were numerous values of TDP>TP, particularly in 2002 and 2003. This may be symptomatic of uncertainties in measuring nutrient values so close to the detection limit. If this is the case, switching TDP and TP when TDP>TP introduces a slight downward bias on TDP. Switching of TDP and TP when TDP>TP is done here to be consistent with previous work. A number of high values of in-lake, Revelstoke, and Arrow outflow TDP and TP of exactly 100 µg/l were excluded in 2002 and 2003. The following exceptionally high values in 2002 and 2003 were excluded: TP 215 µg/l to Burton Cr. (5/26/2003), NH₃ 95 µg/l to Columbia at Revelstoke (6/19/2002) and NH₃ 115 µg/l to Kuskanax Cr. (10/7/2002).

Outflow data. As discussed below, nutrient retention is subject to higher error, as it is a difference between a load and an export. In a nutrient balance, a larger quantity enters or loads the system, a smaller quantity is exported and the balance is retained. However, the export of more nutrient than is imported results in a negative retention which is not generally expected. The difference can be small, and the natural variability in sampling will result in considerable error (Appendix 6.2).

For the Arrow outflow many of the mean nutrient concentrations were unusually high compared to mean in-lake concentrations for both the surface (0-30 m integrated) and deep (>0 70 m) samples as summarized in Table 6.4.1. Inflow between Station AR8 and the Keenleyside Dam is unlikely to account for this in light of the large volume of water passing through the system. Some of the largest differences between in-lake and outflow concentrations occur in 1997 and 1998 (e.g. 1997 mean TP and 1998 mean NH₃) before construction began on the Keenleyside dam in the spring of 1999.

In the 1997 nutrient budget, the higher export was compensated by a combination of both high local stream concentrations and high local stream flow. This was not the case in 1998, when both local stream concentrations and local stream flow were lower than in 1997. Low import and high export resulted in negative retentions.

As a first attempt to correct the negative retentions, the following Arrow Lakes Reservoir outflow samples were not included in the budget: Nov. 3/97, Dec. 1/97, Jan. 5/98, Feb. 2/98, Apr. 20/98, March 9/98, Nov. 2/98, Dec. 1/98, Oct. 18/99 and Nov. 22/99. High values (7-14 µg/l) of TP (3/7/01, 1/8/01, 2/6/01 and 11/14/01) were reduced to Lower Arrow 2001 average of 3.3 µg/l. Note for duplicate values in the 1999 outflow data, the upstream location at the rock groyne was chosen over the Rialto Creek site (Pieters et al 2003, Appendix 8.1). TP values of 10 µg/l (6/17/2002 and 8/6/2002) were reduced to the value of TDP (3 µg/l) and a TP value of 113 µg/l (11/3/2003) was excluded.

Despite neglecting considerable outflow data, some negative retention values remain. In some cases it may be more appropriate to use in-lake nutrient concentrations. For example, in 2003, the TDP retention for Upper Arrow can be improved by using AR 4 for the narrows to increase export from Upper Arrow, and AR8 for the Arrow outflow to reduced export from Lower Arrow. This does not however, solve the negative retentions observed in 2003. It should be noted that the error analysis suggests that seasonal and sub-basin retentions are not meaningful (Appendix 6.2). Also note that outflow and lake TDP and TP

values are typically very low (2-10 ug/l), have coarse resolution (1ug/l) and are close to the detection limit (2 ug/l).

Table 6.4.1 Arithmetic mean of selected river and reservoir water quality parameters for calendar year.

1997	pH pH unit	RF mg/l	COND uS/cm	NH ₃ µg/l	NN µg/l	OP µg/l	TDP µg/l	TP µg/l
97 revel	7.88	74	120	5.5	154	1.1	3.8	7.5
97 UA 0-30m	7.90	71	118	5.5	141	1.4	3.6	6.0
97 UA >=70m	7.90	86	140	6.1	149	1.2	3.2	5.0
97 narro	7.90	70	113	5.3	131	1.3	3.7	6.0
97 LA 0-30m	7.94	69	113	5.8	116	1.1	3.0	5.0
97 LA >=70m	7.91	79	133	5.5	151	1.1	2.7	3.5
97 arro	7.94	71	115	9.5	111	1.2	3.7	9.1
1998	pH	RF	COND	NH ₃	NN	OP	TDP	TP
98 revel	7.89	83	134	5.1	134	1.0	2.3	4.1
98 UA 0-30m	7.88	73	125	5.3	133	1.1	2.4	3.1
98 UA >=70m	7.83	82	142	5	161	1.1	2.3	2.9
98 narro	7.92	75	122	5.2	120	1.0	2.3	3.3
98 LA 0-30m	7.91	70	119	6.4	110	1.1	2.3	3.6
98 LA >=70m	7.86	78	130	5.1	161	1.0	2.5	3.6
98 arro	7.86	75	118	16.9	114	1.2	3.0	6.8
1999	pH	RF	COND	NH ₃	NN	OP	TDP	TP
99 revel	7.88	77	125	5	144.8	1.1	2.5	4.5
99 UA 0-30m	7.82	75	124	6.1	141	1.0	2.3	4.3
99 UA >=70m	7.84	85.7	141	5.2	153	1.0	2.3	4.2
99 narro	7.82	73	121	6.3	137	1.0	2.2	3.9
99 LA 0-30m	7.81	71	116	6.9	124	1.0	2.6	4.1
99 LA >=70m	7.78	81	133	5.5	161	1.0	2.5	3.8
99 arro	7.95	69	117	7.1	110.5	1.4	2.6	6.2
2000	pH	RF	COND	NH ₃	NN	OP	TDP	TP
00 revel	7.89	77.1	132.7	7.0	155.0	1.0	2.4	3.6
00 UA 0-30m	7.75	NA	126	6.3	143	1.0	2.4	4.8
00 UA >=70m	7.84	NA	138	5.6	150	1.0	2.6	3.7
00 narro	7.76	80.0	121	9.9	139	1.0	2.6	4.6
00 LA 0-30m	7.75	NA	118	8.9	115	1.0	2.4	5.1
00 LA >=70m	7.79	NA	131	7.0	158	1.0	2.6	4.3
00 arro	7.78	72.2	118	7.1	123.0	1.8	2.9	5.4
2001	pH	RF	COND	NH ₃	NN	OP	TDP	TP
01 revel	7.99	NA	134.0	6.5	139	1.0	2.9	3.4
01 UA 0-30m	7.58	NA	118*	10.1	123*	1.0	2.2	4.0
01 UA >=70m	7.67	NA	142*	6.4	167*	1.0	2.3	3.2
01 narro	7.75	NA	120.3*	10.4	112*	1.0	2.6	4.1
01 LA 0-30m	7.66	NA	121*	6.6	149*	1.0	2.4	3.3
01 LA >=70m	7.61	NA	133*	5.7	184*	1.0	2.3	2.4
01 arro	7.89	NA	122.8	8.8	114	1.2	2.2	5.5

2002	pH	RF	COND	NH ₃	NN	OP	TDP	TP
02 revel	7.78	-	123	8.5	147.7	1.5	3.5	4.6
02 UA 0-30m	7.79	-	121.6	5.1	148.3	1.3	2.5	3.1
02 UA >=70m	7.92	-	140.7	5.1	175.5	1.6	2.5	3.2
02 narro	7.71	-	118.4	5	134.9	1.3	2.4	2.9
02 LA 0-30m	7.87	-	115.7	4.8	119.8	1.7	2.9	3.2
02 LA >=70m	7.81	-	128.7	5.4	167.2	1.8	2.5	3.4
02 arro	7.75	-	113	5.4	100.5	1.2	2.5	4.5

2003	pH	RF	COND	NH ₃	NN	OP	TDP	TP
03 revel	7.9	-	132	9.7	127.6	1.3	3.7	4.4
03 UA 0-30m	7.812	-	126.7	5.6	130.1	1.5	2.4	3.9
03 UA >=70m	7.85	-	143.1	5.4	167.4	1.4	2.3	3.1
03 narro	7.81	-	123.4	5.2	107.5	1.7	2.0	2.9
03 LA 0-30m	7.77	-	117.8	5.0	101.1	1.2	2.3	3.3
03 LA >=70m	7.76	-	130.5	5.0	166.6	1.4	2.5	4.7
03 arro	7.8	-	117.9	8.3	107.5	2.7	3.2	5.7

1. 'revel', 'narro' and 'arro' refer to the Columbia River at **Revel**stoke, the **Narrows** (AR5) and the **Arrow** Lakes **Reservoir** **Outflow**, respectively. UA and LA refer to Lower and Upper Arrow in-lake samples, either an average of all integrated 0-30 m samples or an average of all samples >=70 m.
 2. These means are for the given calendar years while the budget is for Nov. 21 to Nov. 20.
 3. See Pieters et al, Appendix 8.1 for river name and water quality parameter abbreviations.
 4. Data assembled from Table 7.1, Table 8.1 and Appendix 8.3 in the reports for respective years.
- * missing Apr-Jul 2001.

CHAPTER 7

PHYTOPLANKTON RESPONSE TO EXPERIMENTAL FERTILIZATION, ARROW LAKES RESERVOIR, YEARS 4 and 5 (2002 and 2003)

by

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2002

Introduction

Background & objectives

Arrow Lakes Reservoir is a large, narrow BC interior, fjord-type hydroelectric system, created over 30 years ago by impounding the Columbia River at the outlet of Lower Arrow Lake. The reservoir prior to the commencement of fertilization was ultra-oligotrophic, with low concentrations of total dissolved phosphorus (TDP), low phyto- and zooplankton biomass, and declining fish production (Pieters et al. 1998). Fisheries studies in the reservoir document the decline in pelagic kokanee populations (*Oncorhynchus nerka*) over the past several decades, and it is hypothesized that one of the contributing factors may be low primary production or 'oligotrophication', i.e. severe nutrient depletion caused by reservoir aging and compounded by construction of a recent upstream hydroelectric reservoir - Revelstoke Dam (Pieters et al. 1998, 1999).

As part of a continuing study to document the productive status of the reservoir, a 6th year of the Arrow Lakes Reservoir Monitor Program (ALRMP) was funded, together with a 4th year of fertilizer application to the northern sector of the Upper Arrow basin. One component of the multidisciplinary program was a 6th year of phytoplankton monitoring to ascertain their response to a 4th year of nutrient supplementation, and to examine population variation during the 4th year of nutrient enrichment. Results from year 2002 will permit commentary on observed changes in phytoplankton biomass, species composition and succession between untreated (1998) and treated years (1999-2002).

Study limitations

As a caveat it should be noted that the number of stations sampled (8), the sampling frequency (monthly) and effort (1 sample/station, depth-integrated 0-20m) only provide a 'first approximation' of phytoplankton population abundance, biomass, diversity and spatiotemporal variability in the large and complex Arrow Lakes Reservoir. As in the past, no attempts were made in year 2002 to further examine vertical population structure by discrete sampling, i.e. examine species composition of deep biomass (chlorophyll) peaks. Thus interpretations of phytoplankton population trends reported here are based on only two variables, **Abundance** (cells/mL) of genera and their respective taxonomic Classes, and **Biomass** (mm³/L) or bio-volume of genera and Classes. Thus this report should be considered more as 'overview' of current phytoplankton population 'trends' after 4 yrs of nutrient addition rather than a synthesis of the phytoplankton community dynamic. I have attempted to provide a 'best' interpretation of the apparent seasonal population trends without the support of additional data, e.g. chlorophyll, nutrients, primary production; therefore results, by necessity, are preliminary and somewhat speculative.

Methods

Sampling

A single, depth integrated (0-20m) sample from each of 8 monitoring stations (AR 1-8) along a north/south axis of Arrow Lakes Reservoir were obtained monthly from April to October, 2002. Each phytoplankton sample was preserved within in acid Lugol's iodine preservative until enumerated. Stations 1-3 were representative of pelagic conditions in the larger, deep upper basin, i.e. 'old' Upper Arrow Lake, while Stations 6-8 represented the smaller, Lower Arrow Lake basin, i.e. 'old' Lower Arrow Lake. Stations 4 and 5 were located in the 'Narrows' region of the reservoir, a moderately shallow region of the old Columbia River channel that connected 'old' Upper and Lower Arrow lakes. These stations represent conditions in what can best be described as a 'transition' zone between the two, deeper 'old' lake basins (Pieters et al. 1998, 1999).

Enumeration

Prior to quantitative enumeration the samples were gently shaken for 60 seconds, carefully poured into 25 mL settling chambers and allowed to settle for a minimum of 24 hr. Counts were done using a Carl Zeiss inverted phase-contrast plankton microscope. Counting followed a 2-step process: 1. Micro-phytoplankton (20-200 μ), e.g. diatoms, dinoflagellates, and filamentous blue-greens, within several random fields (5 -10) were enumerated at 250X magnification, and 2. phytoplankton within or touching a 10 to 15 mm transect line were counted at 1560X magnification. This high magnification scan permitted quantitative enumeration of minute (<2.0 μ m) autotrophic picoplankton cells (0.2-2.0 μ m) [Class Cyanophyceae], and also of small auto-, mixo- and heterotrophic nano-flagellates (2.0-20.0 μ m) [Classes Chrysophyceae and Cryptophyceae]. In total between 250-300 cells were consistently enumerated in each sample to assure statistical accuracy (Lund et al. 1958). The compendium of Canter-Lund & Lund (1995) was used as the taxonomic reference. The phytoplankton species and bio-volume list used for the computation of population and class bio-volume estimates for Arrow Lakes Reservoir in 2001 appear in Appendix Table 1.

Results

[Salient results from year 2002 phytoplankton monitor are presented and discussed, and when appropriate, results are compared with basin summaries from previous years (Table 7.1- 7.3, & Figs. 7.1-7.5).]

Basin summaries, seasonal trends 2002 (Table 1, Appendix Figs. 7.1 & 7.2)

In year 2002 there was more spatiotemporal variability in phytoplankton biomass and abundance than in 2001. As was observed in 2001, the largest populations occurred at stations in the Narrows (AR 4 & 5) most notably at AR5, while lowest densities were noted at AR6-8 in the Lower Basin (Table 1.). In the first 2 years of fertilization a clear north/south gradient developed.

Table 7.1. Phytoplankton abundance and biovolume by basin in Arrow Lakes Reservoir 2002.

	Upper Basin	'Narrows'	Lower Basin	Whole Reservoir
	Stations 1-3	Station 4,5	Stations 6-8	Stations 1-8
Abundance (Cells/mL)	5,141	5,211	3,952	4,713
Biovolume (mm ³ /L)	0.56	0.60	0.39	0.51

due largely to a strong spring and early summer increase of pico-cyanobacteria and μ flagellates and later large increases of colonial diatoms at Upper basin stations closest to the region of fertilizer application, e.g. AR1 and 2. But in the 3rd year of treatment (2001) there was no clear north/south gradient, and phytoplankton populations were much larger than in previous years. The 4th year of treatment seemed to restore the north/south density gradient with considerably lowered population sizes and biomass in Lower Arrow. In 2002 the striking growth response of diatom populations did not occur as early and was of lesser magnitude than was seen in 2001. The major 'new' occurrence in the seasonal succession was the marked growth response in August and September in the Upper basin and narrow region of a filamentous green alga – *Ulothrix elongatum*, a species heretofore rarely observed in Arrow Lakes Reservoir. *Ulothrix* contributed up to 50% of the total phytoplankton biomass by mid-September at several of the Upper Arrow and 'narrows' stations (AR1-5), but was infrequently observed, i.e. rare, at Lower Arrow stations (AR6-8).

Figure 7.1. Biomass of diatoms and *Ulothrix* (Chlorophyte) Arrow Upper Basin (AR2) in 2002.

There was greater among station variability in phytoplankton abundance and biomass in Arrow in 2002 than was observed in 2001, but large colonial diatoms remained the major contributors to total biomass at all stations in Arrow from July to October in 2002 albeit at lower abundance than in 2001. Year 2000 was cited as the year of '**diatom return**,' to Arrow with moderate sized autumnal populations noted at most all stations, and Year 2001 was cited as the year of '**diatom ascendancy**' with large populations at all station from July to October and peak densities in September, most profoundly so at AR 5. Year 2002 can be cited as the year of '**Chlorophyte ascendancy**'.

In summary, the most striking changes in phytoplankton populations in 2002 were the continued suppression of pico-cyanobacteria populations in spring and early summer, a return to moderate population densities of μ flagellates, a reduction in the size and duration of populations of colonial diatoms, and the striking emergence of *Ulothrix* and other colonial 'green' algae in the Upper basin stations. Certainly the most unusual feature of the phytoplankton community response to fertilization in 2002 was the sudden occurrence of *Ulothrix* coincident with the decline of diatoms. Such a large response by filamentous 'greens' has not been seen in fertilized coastal or interior sub-alpine lakes before (Stockner & Shortreed 1994, Stockner & MacIsaac 1996).

Trends in groups and species in 2002

In the two control years without fertilization - 1997 and 1998, populations of *Synechococcus* sp., a small pico-cyanobacteria were numerically dominant at all Arrow stations, and their dominance continued through the first 2 years of fertilization. But in 2001 the 3rd year of treatment, picoplankton populations were greatly reduced, and for the first time populations of μ flagellates began to decline as well, but colonial diatoms exhibited a remarkable growth response at all stations, notably by species of *Fragilaria* and populations of *Diatoma elongatum* with a large peak in September and October. In 2002, the 4th year of fertilization, the most intriguing feature sudden occurrence of *Ulothrix* in the Upper basin and the decline of diatom prominence in the Lower basin.

The largest *Fragilaria* populations in 2002 were seen at station AR 5 in the 'narrows' where populations peaked at > 10,000 cells/mL. In both 2001 and 2002 major species were chiefly colonial forms, e.g. *Fragilaria crotonensis*, *F. acus* cf. *actinastroides*, but 2 additional colonial species - *Diatoma elongatum* and *Asterionella formosa* were also major contributors to the diatom blooms of 2002.

Apart from the major late-summer growth response by Chlorophytes, i.e. *Ulothrix elongatum* and *Planctonema* sp., other phytoplankton groups were minor players in the seasonal growth response in 2002. Dinoflagellates, (e.g. *Peridinium* and *Gymnodinium*) contributed little to total biomass or abundance and as previously noted, μ -flagellate populations were similar in biomass and abundance to populations noted in 2001, with dominant genera being *Dinobryon*, *Chryptomonas*, *Chromulina*, *Chrysochromulina*, *Keprion*, and *Rhodomonas*.

In summary, 2002 was a year of smaller populations of phytoplankton throughout the Arrow Lakes, when compared to abundances observed in 2001, and there were notable changes in the seasonal successional pattern in 2002, the most striking being the diminishment of abundance of colonial diatoms in both basins, but especially in the Lower basin, and the rapid rise of filamentous ‘greens’ (e.g. *Ulothrix*) in the Upper basin community from Aug to October.

Biomass and abundance from 1997- 2002 (Fig. 7.2, Tables 7. 2 & 7.3, Appendix Figs. 7.3-7.6)

It is informative to compare phytoplankton responses of the 4 years of treatment with the 2 control years 1997-98. During the first year of treatment the most significant phytoplankton response was the large increase in the picoplankter *Synechococcus*. The major impact of the second year was the large autumn diatom increase, while the third year’s biggest surprise was the magnitude and spatial extent of the huge colonial *Fragilaria* spp. and *Diatoma elongatum* maximum. In 2002, the 4th year of treatment, the filamentous green (*Ulothrix elongatum*) arrived and contributed significantly to total biomass. Taken in totality, the 3rd fertilization year (2001) produced the largest phytoplankton response seen to date in the reservoir, year 4 (2002) the next largest, and years 1 (1999) and 2 (2000) the lowest (Fig. 7.2, Table 7.2). Arrow Lakes Reservoir after 4 years of treatment has on average a greater abundance of phytoplankton than Williston Reservoir, but has less biomass and abundance than neighboring ‘untreated’ Okanagan Lake (Table 7.3).

Table 7.2. Average phytoplankton abundance/biovolume in Arrow Lakes Reservoir by sector, 1997- 2001.

Abundance (Cells·mL ⁻¹)	Year	Upper Basin	'Narrows'	Lower Basin	Whole Reservoir
		Stations 1-3	Station 4,5	Stations 6-8	Stations 1-8
1 st control year	1997	4,440	6,945	6,200	5,725
2 nd control year	1998	4,265	3,798	3,879	4,004
1 st Treated year	1999	5,853	4,175	5,428	5,274
2 nd Treated year	2000	5,352	5,174	4,760	5,086
3 rd Treated year	2001	5,761	7,551	5,665	6,173
4 th Treated year	2002	5,141	5,211	3,952	4,713
Biovolume (mm ³ /L)		Stations 1-3	Station 4,5	Stations 6-8	Stations 1-8
1 st control year	1997	0.30	0.58	0.54	0.46
2 nd control year	1998	0.25	0.28	0.30	0.31
1 st Treated year	1999	0.23	0.26	0.36	0.29
2 nd Treated year	2000	0.46	0.45	0.45	0.46
3 rd Treated year	2001	0.60	0.84	0.62	0.67
4 th Treated year	2002	0.56	0.60	0.39	0.51

Table 7.3. Phytoplankton abundance and biomass in Okanagan Lake and Williston and Arrow reservoirs.

	Year	Arrow Reservoir	Williston Reservoir	Okanagan Lake
Abundance (Cells·mL ⁻¹)	1997	5,725	----	----
	1998	4,004	----	----
	1999	5,274	4,675	5,252
	2000	5,086	4,596	5,010
	2001	6,173	----	4,377
	2002	4,713	----	5,345
Biovolume (mm ³ ·L ⁻¹)	1997	0.46	----	----
	1998	0.31	----	----
	1999	0.29	0.32	0.77
	2000	0.46	0.26	0.69
	2001	0.67	----	0.75
	2002	0.51	----	0.80

Figure 7.2. Phytoplankton biomass and abundance in Arrow Lakes Reservoir 1997-2002.

Discussion

Year 2002 is the 6th year of phytoplankton enumeration in the reservoir and the 4th year of fertilization, and some profound changes have occurred in phytoplankton community structure and in the relative abundance of species. For example in untreated or control years 1997 and 1998 the phytoplankton community was characterized as a microbial dominated community, one typical of ultra-oligotrophic lakes, one well adapted to low nutrient conditions and reliant upon 'recycled' nutrients supplies (Weisse & Stockner 1993). These microbial communities are typically dominated by very small-celled autotrophic picoplankters (*Synechococcus* spp.) and μ flagellates together with heterotrophic grazers – nano-flagellates, ciliates and rotifers (Stockner 1981, 1987). Large-celled species such as dinoflagellates, desmids and colonial diatoms were always present in Arrow, but never abundant prior to fertilization. The first year of Arrow fertilization in 1999 brought a striking response from the microbial picoplankton community, but spatially the response was limited to the zone of influence of application, i.e. within the northern sector of Upper Arrow basin (AR 1 & 2). The next 2 years of treatment resulted in a major increase of colonial diatoms that heralded 'the return of the diatoms.' But unlike previous years, major phytoplankton responses were seen for the first time in both basins, and were now pronounced both in the narrows and throughout the Lower basin. These large autumnal diatom increases in Arrow were interpreted as the first indication by the community of the presence of a more nutrient-rich epilimnetic environment, one that is more typically found in more productive oligotrophic interior BC lakes like Kootenay (fertilized years) or Okanagan Lake (Rae et al. 1997, Stockner, in Andrusak et al. 2000). The return of the diatoms to the system in 2000 and 2001 was considered a clear indication that enrichment of Arrow was working well and that spatially the zone of influence had begun to spread throughout the entire reservoir (Stockner, In Pieters et al. 2000). The 3rd year of fertilization in 2001 was remembered as the year of '**diatom ascendancy**,' with huge populations for protracted periods dominating the phytoplankton community, a condition that has seldom been seen in more pristine, untreated oligotrophic lakes (Stockner & Northcote 1974, Stockner & MacIsaac 1996). The '**green**' **ascendancy** seen in 2002 is equally noteworthy, in that it was again an inedible, filamentous species that gained pre-eminence. Unfortunately, there is a downside to supremacy of colonial diatoms in 2001 and both diatoms and 'greens' in 2002 related to food quality. Most all of these dominant species from cell-clusters or colonies, e.g. long chains, stars, etc., that are morphological adaptations that prevent them from rapidly sinking out of the euphotic zone and also prevents grazing by most zooplankton species, i.e. they are inedible. Thus the proliferation of colonial species in late summer must be viewed as a carbon 'sink' within the pelagic ecosystem or Arrow Lakes Reservoir, and if maintained for protracted periods, could potentially short circuit carbon flows to pelagic fish (Pieters et al. 2000). Evidence suggests that most colonial diatoms are immune from grazing pressure, and also show a strong growth response to phosphorus additions (Stockner 1987).

Figure 7. 3. Diatom density at Upper (AR3) and Lower (AR6) Arrow basins in 2001 and 2002.

Figure 7.4. Fragilaria Species abundance by station Arrow Lakes Reservoir 2001 and 2002.

But in 2002 their population densities were nearly 2-fold lower than in 2001 (see Figs. 7.3 & 7.4), and this may be related to 2002 being a moderately high-water year while 2001 was a low-water year. It seems the magnitude of the Arrow reservoir phytoplankton response in a given year may well be coupled to hydrologic cycles, e.g. inflow volume, strength of stratification, current speed between Upper and Lower basin as well as nutrient additions (Pieters et al. 2000). It is apparent that with the continued dominance of diatoms and now *Ulothrix* within the phytoplankton community that the Arrow ecosystem is experiencing an increased ‘carry-over’ effect from over-wintering pelagic biomass between treated years, and it is likely that ambient nutrient concentrations will very gradually increase with each successive year of fertilization until a new turnover equilibrium is achieved (Stockner and Shortreed 1985, Stockner and MacIsaac 1996).

But Arrow will remain an ‘oligotrophic’ ecosystem because the major inflow is largely from nutrient-poor, Revelstoke Reservoir discharge and the carbon retention within the system is very high, thus enabling the reservoir to annually re-equilibrate to a low-nutrient status after winter flushing/filling.

Conclusions

The return of substantial autumn diatom populations to the plankton community of Upper Arrow Lakes Reservoir in year 2000; their ascendancy to dominance in both basins in 2001 and the ascendancy of filamentous ‘greens’ in 2002 sends a signal that ambient nutrient concentrations are gradually rising and more productive pelagic conditions are annually re-occurring in the reservoir. The co-dominance of potentially ‘inedible’ diatoms (*Fragilaria* spp. and *Diatoma*) and now ‘greens’ (*Ulothrix*) in the pelagic of Arrow in 2002 suggests that the pelagic ecosystem may soon be short-circuiting efficient energy flows to juvenile kokanee, and instead owing to high deposition and carbon retention rates may be enhancing benthic or profundal communities by increased sedimentation of carbon, i.e. increased benthic-pelagic coupling. But present high levels of carbon production may easily sustain both benthic and pelagic food webs, too soon to predict but time will tell!

Recommendations

1. Studies of phytoplankton responses should continue so as to monitor the impact of fertilization in 2003, tracking the *Fragilaria* spp. and *Ulothrix* co-dominance response seen in 2002. Similar studies should be done on zooplankton changes, e.g. species composition, density, size, fecundity, etc., in light of the possibility that more carbon may be tied-up in inedible species (sinks) and unavailable to zooplankton.
2. A more detailed examination of the vertical structure of phytoplankton populations is warranted in light of observations that deep chlorophyll plates occur in the reservoir in mid-summer. We need to know the composition of these plates, i.e. are they composed of the inedible *Fragilaria* spp. and *Diatoma elongatum*?
3. Are the large phytoplankton responses now seen at the ‘Narrows’ stations a result of advection from the more productive Upper Arrow basin or entrainment (upwelling at the sill)? We currently have a poor level of understanding of the dynamics of the pelagic phytoplankton community in Arrow Lakes Reservoir and further studies of reservoir physics and biotic plankton responses are needed.
4. Finally, sampling of the 8 stations should be on successive days, not broken by a 2-week period between completion of the series, i.e. several times in 2002, AR5-8 would be sampled on one day, then 2 weeks later AR1-4 would be sampled. This schedule makes interpretation of treatment response difficult! As was done in 2002, phytoplankton sampling must continue on until the middle of November or as close to fall turnover as possible. Valuable information is lost if sampling stops in early October, as was the case in 2001. Spring sampling should start as soon as ice leaves the system.

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Appendix Table 7. 1. Arrow Reservoir Phytoplankton species, codes and biovolumes.

Code	Class	Bvol.	Genus & Species
<i>Bacillariophytes - diatoms</i>			
AM	Bacillariophyte	80	Achnanthes sp
AY	Bacillariophyte	100	Asterionella formosa var1
AZ	Bacillariophyte	120	Asterionella formosa var2
CP	Bacillariophyte	200	Cocconeis sp.
CU	Bacillariophyte	500	Cyclotella bodanica
CZ	Bacillariophyte	350	Cyclotella comta
CJ	Bacillariophyte	350	Ceratoneis sp.
CS	Bacillariophyte	150	Cyclotella stelligera
CW	Bacillariophyte	50	Cyclotella glomerata
CT	Bacillariophyte	150	Cyclotella sp
CM	Bacillariophyte	500	Cymbella sp. (large)
CO	Bacillariophyte	250	Cymbella sp.
DF	Bacillariophyte	150	Diatoma sp.
EV	Bacillariophyte	250	Eunotia sp.
FF	Bacillariophyte	80	Fragilaria construens
FC	Bacillariophyte	120	Fragilaria crotonensis
FG	Bacillariophyte	100	Fragilaria capucina
GG	Bacillariophyte	750	Gomphonema sp.
MD	Bacillariophyte	350	Aulicoseira distans
MI	Bacillariophyte	200	Aulicoseira italica
MJ	Bacillariophyte	250	Aulicoseira granulata
MZ	Bacillariophyte	350	Aulicoseira sp.
NV	Bacillariophyte	500	Navicula sp.
NZ	Bacillariophyte	200	Nitzschia sp.
RC	Bacillariophyte	50	Rhizosolenia sp.
SH	Bacillariophyte	500	Stephanodiscus hantschii.
SE	Bacillariophyte	1500	Stephanodiscus sp.
SN	Bacillariophyte	100	Fragilaria acus
SO	Bacillariophyte	150	Fragilaria angustissima
SU	Bacillariophyte	1000	Fragilaria ulna
SS	Bacillariophyte	500	Suriella
SR	Bacillariophyte	250	Fragilaria sp.
PI	Bacillariophyte	2000	Pinnularia sp.
TF	Bacillariophyte	500	Tabellaria fenestrata
TB	Bacillariophyte	500	Tabellaria flocculosa
DL	Bacillariophyte	250	Diploneis sp.
<i>Chryso-Cryptophyte flagellates</i>			
BS	Chryso-cryptophyte	200	Bitrichia sp.
CH	Chryso-cryptophyte	250	Chilomonas sp.
XX	Chryso-cryptophyte	20	Chromulina sp1
CA	Chryso-cryptophyte	150	Chroomonas acuta
YO	Chryso-cryptophyte	500	Chryptomonas sp.
CC	Chryso-cryptophyte	75	Chrysochromulina sp.
DN	Chryso-cryptophyte	150	Dinobryon sp1
DO	Chryso-cryptophyte	200	Dinobryon sp2
KA	Chryso-cryptophyte	50	Kephyrion sp.
IS	Chryso-cryptophyte	200	Isthmochloron
MH	Chryso-cryptophyte	500	Mallomonas sp1
MG	Chryso-cryptophyte	700	Mallomonas sp2
SX	Chryso-cryptophyte	75	Stenokalyx
YZ	Chryso-cryptophyte	15	Small microflagellates
OC	Chryso-cryptophyte	250	Ochromonas sp.

PT	Chryso-cryptophyte	100	Pseudokephrion sp.
PP	Chryso-cryptophyte	150	Pseudopedinella sp.
CI	Chryso-cryptophyte	75	Chrysoikos sp.
SY	Chryso-cryptophyte	700	Synura
RO	Chryso-cryptophyte	100	Rhodomonas sp.
CF	Chryso-cryptophyte	250	Chrysidiastrium

Dinophytes

GY	Dinophyte	500	Gymnodinium sp1
GZ	Dinophyte	1500	Gymnodinium sp2
CE	Dinophyte	5000	Ceratium
PJ	Dinophyte	350	Peridinium sp1
PK	Dinophyte	700	Peridinium sp2

Chlorophytes

XC	Chlorophyte	80	Ankistrodesmus sp.
CX	Chlorophyte	150	Coccomyxa sp.
CL	Chlorophyte	500	Coelastrum sp.
CN	Chlorophyte	500	Cosmarium sp.
CK	Chlorophyte	200	Crucigenia sp.
XU	Chlorophyte	700	Crucigeniella apiculata
DI	Chlorophyte	900	Dichtyosphaerium
LA	Chlorophyte	30	Langerheimia
EL	Chlorophyte	250	Elakatothrix sp3
EU	Chlorophyte	2500	Euglena
GO	Chlorophyte	500	Gonium
OO	Chlorophyte	500	Oocystis sp.
SI	Chlorophyte	60	Scenedesmus sp.
SD	Chlorophyte	1500	Staurodesmus sp.
QD	Chlorophyte	250	Quadrigula
UL	Chlorophyte	700	Ulothrix
CD	Chlorophyte	150	Closteriopsis
MO	Chlorophyte	200	Monoraphidium
NE	Chlorophyte	350	Nephrocytium
ST	Chlorophyte	1000	Staurastrum sp.
PL	Chlorophyte	350	Planctonema sp.
PA	Chlorophyte	1000	Planctosphaeria
PS	Chlorophyte	100	Paulschultzia sp.
CB	Chlorophyte	20	Chlorella
KI	Chlorophyte	50	Kirchneriella sp.
PE	Chlorophyte	1000	Pediastrum sp.
PA	Chlorophyte	1500	Pandorina sp.
TE	Chlorophyte	50	Tetradron
VO	Chlorophyte	4000	Volvox
XI	Chlorophyte	700	Xanthidium

Cyanophytes

AC	Cyanophyte	900	Anabaena circinalis
AH	Cyanophyte	100	Aphanothecae sp.
MS	Cyanophyte	20	Merismopedia sp.
ZN	Cyanophyte	20	Oscillatoria sp2
ZO	Cyanophyte	350	Oscillatoria limnetica

Appendix Figure 7.3. Phytoplankton biovolume stations AR1-4, Arrow Lakes Reservoir 1998-2002.

Appendix Figure 7.4. Phytoplankton biovolume stations AR5-8, Arrow Reservoir 1998-2002.

Appendix Figure 7.5. Phytoplankton abundance stations AR1-4, Arrow Reservoir 1998-2002.

Appendix Figure 7.6. Phytoplankton abundance stations AR5-8, Arrow Reservoir 1998-2002.

2003

Introduction

Background & objectives

Arrow Lakes Reservoir is a large, narrow BC interior, fjord-type hydroelectric system, created over 30 years ago by impounding the Columbia River at the outlet of Lower Arrow Lake. The reservoir prior to the commencement of fertilization was ultra-oligotrophic, with low concentrations of total dissolved phosphorus (TDP), low phyto- and zooplankton biomass and declining fish production (Pieters et al. 1998). Fisheries studies in the reservoir document the decline in pelagic kokanee populations (*Oncorhynchus nerka*) over the past several decades, and hypothesized that one of the contributing factors may be low primary production or 'oligotrophication', a severe nutrient depletion caused by reservoir aging (i.e. nutrient trapping, sedimentation) that has been further exacerbated by construction of Revelstoke Dam and its associated impoundment - Revelstoke Reservoir (Pieters et al. 1998, 1999).

As part of a continuing study to document the productive status of the reservoir, a 7th year of the Arrow Lakes Reservoir Monitor Program (ALRMP) was funded, together with a 5th year of fertilizer application to the northern sector of the Upper Arrow basin in 2003. One of the key components of the monitor program continues to be the assessment of phytoplankton populations at 8 stations along a north/south axis and their response to nutrient supplementation. In 2003 for the *first time* in the program, additional discrete depth phytoplankton samples were obtained to examine spatiotemporal vertical population variations during nutrient enrichment. Results from 2003 will permit further commentary on observed changes in phytoplankton biomass, species composition and succession between untreated 1 untreated (1998) and 5 treated years (1999-2003).

Study limitations

As a caveat it should be noted that the number of stations sampled (8), the sampling frequency (monthly) and effort (1 sample/station, depth-integrated 0-20m) only provide a 'first approximation' of phytoplankton population abundance, biomass, diversity and spatiotemporal variability in this large reservoir. However in year 2003 with limited discrete depth sampling we have a first look at vertical population variance among stations and through a partial season to ascertain whether species composition, abundance or biovolume varies significantly with depth, and whether deep biomass peaks are prevalent in Arrow Lakes Reservoir in summer and fall, i.e. deep chlorophyll layers. Interpretations of phytoplankton population trends reported here are based on only two variables, **Abundance** (cells/mL) of genera and their respective taxonomic Classes, and **Bio-volume** (mm³/L) or biomass of genera and Classes. Thus this report should be considered more as an 'overview' of current phytoplankton population 'trends' in Arrow after 5 yrs of nutrient addition rather than a synthesis of the more complex phytoplankton community dynamic within the reservoir which will follow with more discrete depth sampling in 2004. I have attempted to provide a 'best' interpretation of the seasonal

population trends without the support of additional data, e.g. chlorophyll, nutrients, primary production; therefore results are by necessity preliminary and somewhat speculative.

Methods

Sampling

A single, depth integrated 0-20m tube-sample from each of 8 monitoring stations (AR 1-8) along a north/south axis of Arrow Lakes Reservoir were obtained monthly from April to November, 2003. Vertical sampling consisted of discrete-depth VanDorn samples taken from 2, 5, 10, 15 and 20 m depths at stations 2 and 7 from June to October and from stations 1,3,4,5,6, and 8 from August to October. Each phytoplankton sample was preserved in acid Lugol's iodine preservative until enumerated. Stations 1-3 were representative of pelagic conditions in the larger, deeper upper basin, i.e. 'old' Upper Arrow Lake, while Stations 6-8 represented the smaller, Lower Arrow Lake basin, i.e. 'old' Lower Arrow Lake. Stations 4 and 5 were located in the 'Narrows' region of the reservoir, a moderately shallow region of the old Columbia River bed channel that connected 'old' Upper and Lower Arrow lakes. These stations represent conditions in what can best be described as a 'transition' zone of mixing between the two 'old' lake basins (Pieters et al. 1998, 1999).

Enumeration

Prior to quantitative enumeration the samples were gently shaken for 60 seconds, carefully poured into 25 mL settling chambers and allowed to settle for a minimum of 8 hrs. Counts were done using a Carl Zeiss inverted phase-contrast plankton microscope. Counting followed a 2-step process: 1. Micro-phytoplankton (20-200 μ), e.g. diatoms, dinoflagellates, and filamentous blue-greens, within several random fields (5 -10) were enumerated at 250X magnification, and 2. phytoplankton within or touching a 10 to 15 mm transect line were counted at 1560X magnification. This high magnification scan permitted quantitative enumeration of some minute (<2.0 μ m) autotrophic picoplankton cells (0.2-2.0 μ m) [Class Cyanophyceae], and also of small auto-, mixo- and heterotrophic 'micro'- or nano-flagellates (2.0-20.0 μ m) [Classes Chrysophyceae and Cryptophyceae]. In total between 250-300 cells were consistently enumerated in each sample to assure statistical accuracy (Lund et al. 1958). The compendium of Canter-Lund & Lund (1995) was used as the taxonomic reference. The phytoplankton species and bio-volume list used for the computation of population and class bio-volume estimates for Arrow Lakes Reservoir in 2003 appears in Appendix Table 1.

Results

[Salient results from year 2003 phytoplankton monitor are presented and discussed, and where appropriate, results are compared with basin summaries from previous years (Table 7.4- 7.7, & Figs. 7.5-7.10).]

Basin summaries, seasonal trends 2003 (Table 7.4, Appendix Figs. 7.7 & 7.8)

In year 2003 there was less spatiotemporal variability in phytoplankton biomass and abundance than occurred either in 2001 or 2002. As previously noted the largest populations were seen at stations in the Upper Basin (AR 1-3) and most notably so in the Narrows (AR 4-5), while lowest densities were noted at AR6-8 in the Lower Basin (Table 1). During the first 2 years of fertilization a well defined north/south gradient developed due largely to a strong spring and early summer increase of pico-cyanobacteria and μ flagellates and later to large increases of colonial diatoms at Upper basin stations closest to the region of fertilizer application, e.g. AR1 and 2. But in the 3rd year of treatment (2001) there was no clear north/south gradient, and

Table 7.4. Phytoplankton abundance and biovolume by basin in Arrow Lakes Reservoir 2003.

	Upper Basin	'Narrows'	Lower Basin	Whole Reservoir
	Stations 1-3	Station 4,5	Stations 6-8	Stations 1-8
Abundance (Cells/mL)	6,807	7,282	4,976	6,239
Biovolume (mm ³ /L)	0.65	0.81	0.59	0.67

phytoplankton populations at most stations were on average *much* larger than seen in previous years and dominated by large colonial diatoms. e.g. *Fragilaria* spp., *Diatoma elongatum*. The 4th year (2002) of treatment seemed to partially restore the north/south density gradient but with noticeably lower population densities and biomass at Lower Arrow stations, and there were fewer diatoms and more filamentous greens. In 2002 the large diatom growth response seen in 2001 did not occur as early nor was it as large. But in 2003, the 5th year of treatment there was a striking 'return to dominance' by diatoms, most notably by *Fragilaria* spp, *Diatoma elongatum* and *Asterionella formosa*. The major diatom 'bloom' occurred earlier in 2003, commencing in late June and early July instead of in August and September in 2002. The large bloom of the filamentous green *Ulothrix elongatum* in the Upper Arrow and at the 'narrows' stations (AR1-5) was conspicuous by its almost complete absence in 2003 (see Fig. 7.5), and when present it was only a minor component of the phytoplankton community at all stations throughout the growing season. There was less among station variability in both phytoplankton abundance and biomass in Arrow in 2003 than occurred in 2002, and in July large colonial diatoms, notably *Fragilaria* spp. *Diatoma* and *Asterionella* remained the major contributors to total biomass at all stations in Arrow.

In summary, Year 2000, the 2nd year of fertilization was cited as the year of '**diatom return**,' to Arrow with moderate sized autumnal populations noted at most all stations for the first time since monitoring began - 1997; Year 2001 was the year of '**diatom**

ascendancy' to become predominant components of the phytoplankton community throughout the season, with large populations at all station from July to October; Year 2002 became the year of '**Chlorophyte ascendancy**' with large populations of *Ulothrix elongatum* in late-summer and a concurrent noticeable decline of diatom populations; and Year 2003 must be cited as the year of '**diatom recurrence**' with striking increases again of large populations of colonial diatoms, most notably *Fragilaria* spp. now dominant in *both* basins of Arrow. The abrupt decline of *Ulothrix* coincident with the re-ascendancy of diatoms in 2003 was one of the most striking shifts in phytoplankton populations yet seen over the past 5 treatment years.

Figure 7.5. Biomass of diatoms and Ulothrix (Chlorophyte) Arrow Upper Basin (AR2) in 2002 & 2003.

Trends in groups and species in 2003

In the two control years without fertilization - 1997 and 1998, populations of *Synechococcus* sp., a small pico-cyanobacteria were numerically dominant at all Arrow stations, and their dominance continued through the first 2 years of fertilization. But by 2001 the 3rd year of treatment, picoplankton populations were greatly reduced, and for the first time populations of μ flagellates began to decline as well, but colonial diatoms exhibited a remarkable growth response at all stations, notably by *Fragilaria crotonensis*, *F. acus* and *Diatoma elongatum* with a large peak occurring in September and October. In 2002, the 4th year of fertilization, the most intriguing feature was the rapid and

unexpected occurrence of *Ulothrix* in the Upper Arrow basin concurrent with a slight decline of diatom densities in both Arrow basins. The largest *Fragilaria* populations in 2001 occurred at station AR 5 in the ‘narrows’ where populations peaked at > 10,000 cells/mL. In both 2001 and 2002 major species were chiefly colonial forms, e.g. *Fragilaria crotonensis*, *acus* cf. *actinastroides*, but 2 additional colonial species - *Diatoma elongatum* and *Asterionella formosa* were also major contributors to the diatom blooms of 2001. In 2003 *F. crotonensis* declined in importance and was replaced by large populations of the ‘star-cluster’ colonies of *F. acus* cf. *actinastroides*, and peak densities of > 5000 cells/mL in the Upper basin and about 4000 cells/mL in the Lower basin.

Apart from the major diatom recurrence throughout much of the active growth period, other phytoplankton groups were minor players in the seasonal treatment response in 2003. Dinoflagellates, e.g. *Peridinium* and *Gymnodinium* contributed little to total biomass or abundance and as previously noted the μ -flagellate populations were similar in biomass and abundance to patterns noted in 2001 and 2002, with dominant genera being *Dinobryon*, *Chryptomonas*, *Chromulina*, *Chrysochromulina*, *Kephyrion*, and *Rhodomonas*.

In summary, Year 2003 was another year characterized by the rapid and prolific growth response of colonial diatoms, and the abrupt decline of the filamentous green – *Ulothrix*. There were some notable changes in the seasonal successional pattern in 2003, the most striking being the diminishment of *Fragilaria crotonensis* and rise of *F. acus* cf. *actinastroides* in both basins, but noticeably so in the Lower Arrow basin.

Figure 7.6. Seasonal abundance of *Fragilaria crotonensis*, *F. acus* and other diatoms in Arrow from 2000-2003.

Biomass and abundance from 1997- 2003 (Fig. 7.7, Tables 7.6 & 7.7, Appendix Figs. 7.10-7.13)

It is informative to compare phytoplankton responses of the 5 years of treatment with the 2 control years 1997-98. As previously noted - the first year of treatment increased populations of the picoplankter *Synechococcus*, while the second year saw large autumnal diatom increases. The surprise in the third year was the magnitude and extensive spatiotemporal distribution of colonial diatoms *Fragilaria* spp. and *Diatoma elongatum*, and in the fourth year the sudden burst of *Ulothrix elongatum* populations, while in the fifth year no major surprise, only a recurrence of colonial diatoms most notably *F. acus*. Taken in totality as a reservoir seasonal averages: the 5th (2003) and 3rd (2001) fertilization years produced the largest phytoplankton responses seen to date in the reservoir, while the 1st, 2nd, and 4th years all produced similar, lower responses to nutrient additions. Arrow Lakes Reservoir after 5 years of treatment has *on average* produced a greater abundance of phytoplankton than Williston Reservoir, but less phytoplankton abundance and biomass than neighboring 'untreated' Okanagan Lake (Table 7.7).

Table 7.6. Average phytoplankton abundance/biovolume in Arrow Lakes Reservoir by sector, 1997- 2003.

Abundance (Cells·mL ⁻¹)	Year	Upper Basin Stations 1-3	'Narrows' Station 4,5	Lower Basin Stations 6-8	Whole Reservoir Stations 1-8
1 st control year	1997	4,440	6,945	6,200	5,725
2 nd control year	1998	4,265	3,798	3,879	4,004
1 st Treated year	1999	5,853	4,175	5,428	5,274
2 nd Treated year	2000	5,352	5,174	4,760	5,086
3 rd Treated year	2001	5,761	7,551	5,665	6,173
4 th Treated year	2002	5,141	5,211	3,952	4,713
5 th Treated year	2003	6,807	7,282	4,976	6,239

Biovolume (mm ³ /L)		Stations 1-3	Station 4,5	Stations 6-8	Stations 1-8
1 st control year	1997	0.30	0.58	0.54	0.46
2 nd control year	1998	0.25	0.28	0.30	0.31
1 st Treated year	1999	0.23	0.26	0.36	0.29
2 nd Treated year	2000	0.46	0.45	0.45	0.46
3 rd Treated year	2001	0.60	0.84	0.62	0.67
4 th Treated year	2002	0.56	0.60	0.39	0.51
5 th Treated year	2003	0.65	0.81	0.59	0.67

Table 7.7. Phytoplankton abundance and biomass in Okanagan Lake and Williston and Arrow reservoirs.

	Year	Arrow Reservoir	Williston Reservoir	Okanagan Lake
Abundance (Cells·mL ⁻¹)	1997	5,725	----	----
	1998	4,004	----	----
	1999	5,274	4,675	5,252
	2000	5,086	4,596	5,010
	2001	6,173	----	4,377
	2002	4,713	----	5,345
	2003	6,239		4,658
Biovolume (mm ³ ·L ⁻¹)	1997	0.46	----	----
	1998	0.31	----	----
	1999	0.29	0.32	0.77
	2000	0.46	0.26	0.69
	2001	0.67	----	0.75
	2002	0.51	----	0.80
	2003	0.67	----	0.85

Figure 7.7. Phytoplankton biomass and abundance in Arrow Lakes Reservoir 1997-2003.

Discussion

Year 2003 is the 7th year of phytoplankton enumeration in the reservoir and the 5th year of fertilization, and some profound changes have occurred in phytoplankton community structure and in the relative abundance of species. For example in untreated or 'control' years (1997, 1998) the phytoplankton community was characterized largely as a microbial community, typically found in fast-flushing ultra-oligotrophic lakes and well

adapted to low ambient nutrient conditions and heavily reliant upon ‘recycled’ nutrient supplies (Stockner 1986, Weisse & Stockner 1993). These microbial communities are dominated by small, single celled autotrophic picoplankters (*Synechococcus* & *Synechocystis* spp.) and free-living heterotrophic bacteria and by phototrophic μ flagellates together with heterotrophic grazers – nano-flagellates, ciliates and rotifers (Stockner 1981,1987). Large-celled species such as dinoflagellates, desmids and colonial diatoms are large blue greens that are more typical of more productive lakes, e.g. Okanagan, were infrequently seen and never abundant in Arrow prior to fertilization. The first year of Arrow fertilization in 1999 brought a striking growth response from the microbial picoplankton community, but spatially the initial response was limited to the northern sector of Upper Arrow basin (AR 1-3), the primary zone of influence of Ferry application. The next 2 years of treatment resulted in a major increase of colonial diatoms that heralded ‘the return of the large diatoms’ to Arrow Lakes Reservoir. But unlike the pattern seen in previous years, a notable response was seen for the first time seen in the Lower basin extending to the dam forebay. These first large autumnal diatom increases in Arrow were interpreted as the first recognizable signal by the phytoplankton community of persistent occurrence of a more nutrient-rich epilimnetic environment, one that is more typically found in more productive oligotrophic interior BC lakes like Kootenay (fertilized years) or Okanagan lakes (Rae et al. 1997, Stockner, in Andrusak et al. 2000). Said another way, by the end of the 2nd year the consensus was that the nutrient enrichment of Arrow was working well, and that spatially the zone of influence was not longer restricted to the Upper basin, but had begun to spread throughout the entire reservoir (Pieters et al. 2001). The 3rd year of fertilization in 2001 was the year of ‘diatom ascendancy,’ with huge populations for protracted periods dominating the phytoplankton community, a condition seldom seen in more pristine, untreated oligotrophic lakes (Stockner & Northcote 1974, Stockner & MacIsaac 1996), and concern was growing about the possibilities of producing ‘inedible’ carbon sinks. The ‘green ascendancy’ in 2002 was equally noteworthy, in that it again was an inedible, filamentous species that gained pre-eminence, and Year 2003 with the recurrence of diatoms was a repeat of 2001 with the reservoir showing a very high biomass of ‘inedible’ *Fragilaria* spp. compared to 2002 (Fig. 7.8). The marked change in phytoplankton diatom abundance in Arrow is well illustrated in figure 7.9. Unfortunately, there is a downside to the sustained supremacy of colonial diatoms in 2001, 2002, and 2003 that is directly related to food quality. Most of the dominant species form either cell-clusters or colonies, e.g. long chains, stars, ladders, etc., that are morphological adaptations that prevent them from rapidly sinking out of the euphotic zone but also prevent grazing by most herbivorous zooplankton species, i.e. their morphology renders them ‘inedible’.

Figure 7.8. *Fragilaria* spp. abundance by station Arrow Lakes Reservoir in 2002 and 2003.

Figure 7.9. Diatom density at Upper Arrow (AR2) basin and Narrows (AR5) in 1999 and in 2003.

Among causal factors influencing abundance and distribution of phytoplankton it appears that climatic variability may be one of the more important variables, acting indirectly on phytoplankton by affecting nutrient supply, dispersal, dilution and transport (advection), etc. Year 2003 (Fragilaria year) was a low-water year while 2002 (Ulothrix year) was a moderately high-water year while 2001 (Fragilaria year) was a low-water year. It seems sensible to suggest that the magnitude of the Arrow Lakes Reservoir phytoplankton response in a given year may well be coupled to hydrologic cycles, e.g. inflow volume, strength of stratification, current speed and advection between Upper and Lower basins (Pieters et al. 2000), and as well to nutrient additions and the seasonal variance in the ratio of available P to available N (DIN:TDP ratio). It is apparent that with the continued dominance of diatoms within the phytoplankton community in 2003 that the Arrow ecosystem is experiencing an increased ‘carry-over’ effect from over-wintering pelagic biomass between treated years, and it is likely that ambient nutrient concentrations will gradually rise in successive years of fertilization, more rapidly in dry years with lower flushing and greater retentiveness (Stockner and Shortreed 1985, Stockner and MacIsaac 1996).

But Arrow will in one sense be protected from ‘over enrichment’ because the major Columbia River inflow is nutrient-poor coming from the Revelstoke Reservoir discharge,

and further the carbon retention within the Arrow system is very high, thus enabling the reservoir to annually re-equilibrate to a lower nutrient status during high-water years but less so during low-water years.

Conclusions – 2003 Monitor

The return of large diatom populations to the plankton community of Upper Arrow Lakes Reservoir in year 2003 and their dominance in both sends a strong signal that ambient nutrient concentrations are continuing to rise and productive pelagic conditions are annually re-occurring in Arrow Lakes Reservoir. The dominance of the ‘inedible’ colonial diatoms (*Fragilaria* spp., *Asterionella formosa*, and *Diatoma elongatum*) in the pelagic of Arrow in 2003 suggests that the ecosystem is already short-circuiting efficient energy flows to juvenile kokanee by reducing their forage base – zooplankton. Because of the high deposition rate, enhanced carbon retention may now be supporting benthic/profundal communities i.e. increased benthic-pelagic coupling. In 2004 it may be necessary to alter both frequency and doses of weekly loads of N & P to slow the advance of inedible diatom population growth.

Phytoplankton distribution patterns in 2003

AR2 (June – October)

Abundance (Append. Fig. 7.11)

There were high phytoplankton densities (>11,000 cells/mL) at the surface (2 m) in June with a gradual decline to <5,000 cells/mL at 20 m. No subsurface peaks in profile, with flagellates and small coccoid green algae the dominant groups. Peak phytoplankton densities occurred in July with > 12,000 cells/mL at 2 and 5 m and abruptly declining to <4,000 at 15 and 20 m depths. Diatoms increased in July to share co-dominance with flagellates, while coccoid greens showed major declines at all depths. The August profile of abundance was similar to the June profile with the major exceptions being; 1: the peak (>10,000 cells/mL) occurred at 5 m instead of 2 m as seen in June, and 2. diatoms were clearly the dominant group with flagellates and greens showing marked declines. The mid-September profile showed peaks at 2 m with a gradual decline to 20 m. Densities (<5,000 cells/mL) were markedly reduced from previous months highs, and diatoms and flagellates shared co-dominance. There was further reduction in abundance in the October profile with lowest densities (<2,000 cells/mL) at 15 and 20 m depths and slightly higher densities at 5 and 10 m.

Biomass (Append. Fig. 7.15).

Not surprisingly, biomass profiles in many respects were similar to abundance profiles. The only differences were that owing to the large cell size of diatoms and small cell size of coccoid greens that diatoms were more predominant in all profiles. Peak biomass occurred in July and August profiles with peaks at 2 and 5 m. September and June profiles were similar with respect to total biomass but diatoms were more dominant in

September than in June. By October biomass was at its lowest level with little variation with depth, and diatoms making little or no contribution to total biomass.

AR7 (June – October)

Abundance (Append. Fig. 7.11).

Greatest densities occurred at the surface (2 m) and next highest at 10 m. Microflagellates were the major contributor to biomass in June and diatoms were not common, but by July they were dominant at all depths to 10 m where a small peak ($> 10,000$ cells/mL) occurred. In August from 2 m to 10 m densities had markedly declined to $< 5,000$ cells/mL, with a sub-surface peak at 15 and 20 m of $> 6,000$ cells/mL, and diatoms were again the major component of the community. Both September and October profiles were similar with low phytoplankton densities ($< 4,000$ cells/mL) equally distributed among major groups. Densities in both profiles tended to be higher between 5-15 m and lowest at 2 and 20 m.

Biomass (Append. Fig. 7.15).

Flagellates were the primary contributor to biomass in June with peak values at 2 m, declining to less than half surface values at 5 m, then increasing at 10 m before declining to low values at 20 m. July profile showed high biomass from surface to 10 m with a small peak at 10 m, then gradually declining to the lowest values at 20 m. Diatoms were clearly dominant at all depths followed by dinoflagellates and flagellates. In August lowest values occurred at the surface increasing to a noticeable peak at 15 m and a secondary peak at 20 m. Diatoms were again the primary contributor to biomass at all depths. In both September and October profiles that were no major peaks and total biomass values were similar to June values, with a equal distribution of biomass among groups with the exception being a large contribution by dinoflagellates in October at depths from 5-20 m.

AR1 (August – October)

Abundance (Append. Fig. 7.12).

The mid-August profile showed abundance peaks ($> 10,000$ cells/mL) at 2 and 5 m and abruptly declining to $< 3,000$ at 10 m and $< 2,000$ at 15 and 20 m. Diatoms were dominant followed by flagellates. A marked decline of abundance of all groups characterized the mid-September profile that showed gradually declining abundance with increasing depth. Diatoms were most prevalent followed by flagellates. By October total abundance was even lower ($< 3,000$ cells/mL) with few diatoms present and flagellates and small autotrophic picoplankters as major contributors to total abundance.

Biomass (Append. Fig. 7.16).

Profiles of biomass mirrored abundance profiles. The August profile showed peak biomass at 2 and 5 m ($>1.0 \text{ mm}^3/\text{L}$) with about a 6-fold decline occurring at 10, 15 and 20 m depths with diatoms making the greatest contribution. In September the biomass peak was at 2 m ($>0.9 \text{ mm}^3/\text{L}$) declining to less than half this value at 10 m and then to very low levels at 15 and 20 m. Diatoms were major contributors along with dinoflagellates and flagellates. By the end of October biomass was very low ($<0.25 \text{ mm}^3/\text{L}$) at all depths with little difference among depths.

AR3 (August – October)

Abundance (Append. Fig. 7.12).

Peak phytoplankton abundance in August occurred at 5 m depth ($>12,000 \text{ cells/mL}$) but abundance exceeded 9,000 cells/mL at all other depths except 20 m where values were $>7,000$. Diatoms were major contributors followed by flagellates and pico-cyanobacteria. By mid-September densities at all depths were $<4,000 \text{ cells/mL}$ and the vertical profile was nearly uniform with diatoms and flagellates the major contributors. In October densities at all depths were about 3,000 cells/mL and little variation with depth was noted.

Biomass (Append. Fig. 7.16).

Biomass profiles were very similar to abundance profiles. In August peak biomass ($>1.4 \text{ mm}^3/\text{L}$) occurred at 5 m and diatoms were clearly the major contributor to total biomass at all depths followed by flagellates and dinoflagellates. By September biomass values had fallen to less than half of August totals and there was little difference in depth distribution except for a ‘mini’ peak at 15 m caused by an increased contribution by large dinoflagellates. Diatoms and dinoflagellates were co-dominants at all depths. In October values further declined to seasonal low levels ($0.2 - 0.3 \text{ mm}^3/\text{L}$) and there was little difference among depths apart from a slight increase at 5 m owing to increased chlorophyte abundance.

AR4 (August – October)

Abundance (Append. Fig. 7.13).

High abundance of phytoplankton occurred at all depths to 15 m, with the peak at 5 m ($>12,000 \text{ cells/mL}$) and lowest density at 20 m ($<4.5 \text{ cells/mL}$). Diatoms were clearly dominant followed by flagellates. By September the distribution was more uniform at all depths with a slight peak at 10 m owing to increased flagellate abundance. Flagellates and diatoms were co-dominants. In October densities were very low ($<2,000 \text{ cells/mL}$) flagellates were the most abundance plankter, with all other groups rare, including diatoms!

Biomass (Append. Fig. 7.17).

Biomass profiles were similar to abundance profiles at most all depths and dates. In August peak values were at 5 m depth ($>1.4 \text{ mm}^3/\text{L}$) but were high (>1.0) at 2, 10 and 15 m as well, but <0.6 at 20m. Diatoms were clearly the major contributor at all depths. In September values were markedly lower ($0.6\text{-}0.8 \text{ mm}^3/\text{L}$) than in August and there was a more uniform depth profile and a more equal contribution to biomass by three groups - diatoms, dinoflagellates and flagellates. By October biomass values fell to around $0.3 \text{ mm}^3/\text{L}$ and the depth profile was basically uniform with all groups making a contribution.

AR5 (August – October)

Abundance (Append. Fig. 7.13).

In August phytoplankton abundance was moderately high at all depths with a peak ($>10,000 \text{ cells/mL}$) at 5 m and minimum at 20 m ($<6,500 \text{ cells/mL}$). Diatoms were dominant at all depths followed by flagellates. Overall abundance was lower in September with a small surface peak at 2 m of about $6,500 \text{ cells/mL}$, and at remaining depths density averaged about $4,000 \text{ cells/mL}$. Surprisingly, flagellates were the predominant group followed by diatoms and cyanobacteria. By October densities at all depths were $<4,000 \text{ cells/mL}$ and greatest abundance occurred at 2 and 5 m depths. Cyanobacteria were the dominant group, especially in the surface, followed by flagellates and diatoms.

Biomass (Append. Fig. 7.17).

Biomass profiles showed a similar depth distribution pattern to abundance on all dates. The August profile was quite similar from 2-20 m with highest values at 5, 10 and 15 m ($>1.2 \text{ mm}^3/\text{L}$). Diatoms were clearly the dominant contributor to biomass at all depths followed by dinoflagellates and flagellates. By September values had slightly diminished and there was a peak at 10 m ($>1.0 \text{ mm}^3/\text{L}$) and dinoflagellates and flagellates were co-dominants, followed by diatoms and cyanobacteria. By the end of October values were at seasonal low levels ($<0.25 \text{ mm}^3/\text{L}$) at all depths except at the surface ($>0.35 \text{ mm}^3/\text{L}$). The depth profile was uniform from 5-20 m and all major groups except Chlorophytes contributed to the total.

AR6 (August – October)

Abundance (Append. Fig. 7.14).

In August abundance was $>10,000 \text{ cells/mL}$ at all depths except 20 m where it was substantially less ($>4,000 \text{ cells/mL}$), and a peak density of $12,000 \text{ cells/mL}$ occurred at 5 m. Diatoms were dominant at all depths followed by flagellates. By mid-September densities averaged about $4,000 \text{ cells/mL}$ and the profile was nearly uniform with the exception of a small maximum at 10 m. Flagellates were now the predominant group

followed by diatoms and dinoflagellates. By late-October the profile was uniform and cell abundance at all depths was <2,000 cells/mL and comprised mostly of flagellates.

Biomass (Append. Fig. 17.18).

The biomass profiles mirrored the abundance profiles. In August biomass was high in the surface layer (2-15 m) averaging about 1.2 mm³/L, and peaking at >1.4 mm³/L at 5m. At 20 m biomass was less than half of surface values (< 0.6 mm³/L). Diatoms were clearly dominant at all depths and followed by about equal densities of flagellates and dinoflagellates. With the exception of a small biomass peak at 10 m, the September profile was nearly uniform albeit with much lower values than in August. Diatoms were no longer dominant, supplanted by dinoflagellates and flagellates as major contributors.

AR8 (August – October)

Abundance (Append. Fig. 7.14).

In August phytoplankton abundance in surface layers to 15 m exceeded 8,000 cells/mL with a minor peak at 5 m (>10,000 cells/mL). At 20 m densities were about 6,000 cells/mL. Diatoms were the dominant group at all depths followed by flagellates. Densities dropped to <5,000 cells/mL in September at all depths except the surface (2 m) where they exceeded 7,000 cells/mL. Apart from the 2 m surface peak the profile was nearly uniform with increasing depth. Flagellates were the dominant group followed by diatoms and dinoflagellates. By mid-October densities had fallen to about 2,000 cells/mL except in the surface where they were slightly higher – 3,500 cells/mL. Cyanobacteria and flagellates were the predominant groups.

Biomass (Append. Fig. 7.18).

Phytoplankton biomass was surprisingly uniform at all depths in August, exceeding 1.0 mm³/L at all depths and showing minor peaks (>1.2 mm³/L) at 5, 10 and 15 m. Diatoms were dominant at all depths followed by dinoflagellates and flagellates. In September values declined slightly to < 0.8 mm³/L at all depth except in the surface (0.9) and at 10 m where they were >1.0 mm³/L. Dinoflagellates and flagellates were dominant groups followed by diatoms. By mid-October the profile was nearly uniform and biomass was <0.3 at all depths except at 2 m where it was slightly higher. Flagellates, dinoflagellates and diatoms were the major groups at all depths.

Conclusions – Vertical distribution

The partial seasonal sampling of a vertical phytoplankton distribution series has quite clearly shown that there are marked differences among depths, stations and dates, and that these differences seem to be most clearly defined in June, July and August, the height of the active growth period, but less apparent in the autumn when deep-mixing periods serve to coalesce any perceptible vertical differences. Subsurface biomass and abundance peaks appeared to be most prevalent in July and August, a period when colonial diatom densities were greatest and surface waters most stably stratified. Further,

there was a tendency for the Lower basin of Arrow to show greater phytoplankton biomass at deeper depths later in the season than the Upper basin as best illustrated by comparing AR2 to AR7 in both September and October profiles (see Append. Figs. 11 and 15). Not surprisingly, the greatest plankton abundance and biomass first accumulates in the Upper basin in late June and early July but this large 'wall' of plankton biomass seems restricted to the upper 10 -15 m of the water column, but within a month or so is advected by strong currents to the 'narrows,' where mixing and active transport sends populations to Lower basin stations AR6-. It was clear that phytoplankton populations in Lower Arrow in moderately high abundance extend to greater vertical depth (20 m) than in the Upper basin. Perhaps the shallowness of the 'narrows' serves as an *in situ* 'chemostat,' providing the requisite mixing to inject 'new' nutrient and actively transport abundant phytoplankton biomass into the surface layer (epilimnion) of the Lower basin. Finally, from this preliminary look at vertical patterns one can conclude that there were neither indications of a resilient sub-surface accumulation of phytoplankton at any station sampled nor did the of the major groups show distinct depth preferences. Said another way, though there were differences in abundance and biomass within the 20 m water column, there were no strong signals of any major shifts in community composition with depth, i.e. pico-cyanobacteria restricted to deep plates, diatoms sinking to the metalimnion to form plates, dinoflagellates only at mid-depth, etc.

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Recommendations

1. Studies of phytoplankton responses should continue so as to monitor the impact of fertilization in 2004, tracking the *Fragilaria* spp. response seen in 2003. Similar studies should be continued on zooplankton changes, e.g. species composition, density, size, fecundity, etc., in light of the possibility that more carbon may be tied-up in inedible species (sinks) and unavailable to zooplankton.
2. A detailed examination of the vertical structure of phytoplankton populations through all seasons and at all stations must continue in 2004. We need to know the how difference between basins in depth distribution and abundance and biomass evolve. Further we need to track the abundance of edible and inedible plankters through the seasons.
3. Are the large phytoplankton responses now seen at the 'Narrows' stations a result of advection from the more productive Upper Arrow basin or entrainment (upwelling at the sill)? We currently have a poor level of understanding of the dynamics of the pelagic phytoplankton community in Arrow Lakes Reservoir and further studies of reservoir physics and phytoplankton responses are needed.

4. **(Important Point!)** Finally, sampling of the 8 stations should be on successive days, not broken by a 2-week period between completion of the series, i.e. several times in 2003 AR5-8 would be sampled on one day, then 2 weeks later AR1-4 would be sampled. This schedule makes interpretation of treatment response difficult and provides equivocal results! As was done in 2003, phytoplankton sampling must continue on until the middle of November or as close to fall turnover as possible. Valuable information is lost if sampling stops in early October.

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Appendix Table 1. Arrow Reservoir Phytoplankton species, codes and biovolumes.

Code	Class	Bvol.	Genus & Species
<i>Bacillariophytes - diatoms</i>			
AM	Bacillariophyte	80	Achnanthes sp
AY	Bacillariophyte	100	Asterionella formosa var1
AZ	Bacillariophyte	120	Asterionella formosa var2
CP	Bacillariophyte	200	Cocconeis sp.
CU	Bacillariophyte	500	Cyclotella bodanica
CZ	Bacillariophyte	350	Cyclotella comta
CJ	Bacillariophyte	350	Ceratoneis sp.
CS	Bacillariophyte	150	Cyclotella stelligera
CW	Bacillariophyte	50	Cyclotella glomerata
CT	Bacillariophyte	150	Cyclotella sp
CM	Bacillariophyte	500	Cymbella sp. (large)
CO	Bacillariophyte	250	Cymbella sp.
DF	Bacillariophyte	150	Diatoma sp.
EV	Bacillariophyte	250	Eunotia sp.
FF	Bacillariophyte	80	Fragilaria construens
FC	Bacillariophyte	120	Fragilaria crotonensis
FG	Bacillariophyte	100	Fragilaria capucina
GG	Bacillariophyte	750	Gomphonema sp.
MD	Bacillariophyte	350	Aulicoseira distans
MI	Bacillariophyte	200	Aulicoseira italica
MJ	Bacillariophyte	250	Aulicoseira granulata
MZ	Bacillariophyte	350	Aulicoseira sp.
NV	Bacillariophyte	500	Navicula sp.
NZ	Bacillariophyte	200	Nitzschia sp.
RC	Bacillariophyte	50	Rhizosolenia sp.
SH	Bacillariophyte	500	Stephanodiscus hantschii.
SE	Bacillariophyte	1500	Stephanodiscus sp.
SN	Bacillariophyte	100	Fragilaria acus
SO	Bacillariophyte	150	Fragilaria angustissima
SU	Bacillariophyte	1000	Fragilaria ulna
SS	Bacillariophyte	500	Suriella
SR	Bacillariophyte	250	Fragilaria sp.
PI	Bacillariophyte	2000	Pinnularia sp.
TF	Bacillariophyte	500	Tabellaria fenestrata
TB	Bacillariophyte	500	Tabellaria flocculosa
DL	Bacillariophyte	250	Diploneis sp.
<i>Chryso-Cryptophyte flagellates</i>			
BS	Chryso-cryptophyte	200	Bitrichia sp.
CH	Chryso-cryptophyte	250	Chilomonas sp.
XX	Chryso-cryptophyte	20	Chromulina sp1
CA	Chryso-cryptophyte	150	Chroomonas acuta
YO	Chryso-cryptophyte	500	Chryptomonas sp.
CC	Chryso-cryptophyte	75	Chrysochromulina sp.
DN	Chryso-cryptophyte	150	Dinobryon sp1
DO	Chryso-cryptophyte	200	Dinobryon sp2
KA	Chryso-cryptophyte	50	Kephyrion sp.
IS	Chryso-cryptophyte	200	Isthmochloron
MH	Chryso-cryptophyte	500	Mallomonas sp1
MG	Chryso-cryptophyte	700	Mallomonas sp2
SX	Chryso-cryptophyte	75	Stenokalyx
YZ	Chryso-cryptophyte	15	Small microflagellates
OC	Chryso-cryptophyte	250	Ochromonas sp.

PT	Chryso-cryptophyte	100	Pseudokephrion sp.
PP	Chryso-cryptophyte	150	Pseudopedinella sp.
CI	Chryso-cryptophyte	75	Chrysoikos sp.
SY	Chryso-cryptophyte	700	Synura
RO	Chryso-cryptophyte	100	Rhodomonas sp.
CF	Chryso-cryptophyte	250	Chrysidiastrum

Dinophytes

GY	Dinophyte	500	Gymnodinium sp1
GZ	Dinophyte	1500	Gymnodinium sp2
CE	Dinophyte	5000	Ceratium
PJ	Dinophyte	350	Peridinium sp1
PK	Dinophyte	700	Peridinium sp2

Chlorophytes

XC	Chlorophyte	80	Ankistrodesmus sp.
CX	Chlorophyte	150	Coccomyxa sp.
CL	Chlorophyte	500	Coelastrum sp.
CN	Chlorophyte	500	Cosmarium sp.
CK	Chlorophyte	200	Crucigenia sp.
XU	Chlorophyte	700	Crucigeniella apiculata
DI	Chlorophyte	900	Dichtyosphaerium
LA	Chlorophyte	30	Langerheimia
EL	Chlorophyte	250	Elakatothrix sp3
EU	Chlorophyte	2500	Euglena
GO	Chlorophyte	500	Gonium
OO	Chlorophyte	500	Oocystis sp.
SI	Chlorophyte	60	Scenedesmus sp.
SD	Chlorophyte	1500	Staurodesmus sp.
QD	Chlorophyte	250	Quadrigula
UL	Chlorophyte	700	Ulothrix
CD	Chlorophyte	150	Closteriopsis
MO	Chlorophyte	200	Monoraphidium
NE	Chlorophyte	350	Nephrocytium
ST	Chlorophyte	1000	Staurostrum sp.
PL	Chlorophyte	350	Planctonema sp.
PA	Chlorophyte	1000	Planctosphaeria
PS	Chlorophyte	100	Paulschultzia sp.
CB	Chlorophyte	20	Chlorella
KI	Chlorophyte	50	Kirchneriella sp.
PE	Chlorophyte	1000	Pediastrum sp.
PA	Chlorophyte	1500	Pandorina sp.
TE	Chlorophyte	50	Tetraedron
VO	Chlorophyte	4000	Volvox
XI	Chlorophyte	700	Xanthidium

Cyanophytes

AC	Cyanophyte	900	Anabaena circinalis
AH	Cyanophyte	100	Aphanothecae sp.
MS	Cyanophyte	20	Merismopedia sp.
ZN	Cyanophyte	20	Oscillatoria sp2
ZO	Cyanophyte	350	Oscillatoria limnetica

Appendix Figure 7.7. Phytoplankton abundance by station, Arrow Lakes Reservoir May-November 2003.

Appendix Figure 7.8. Phytoplankton biovolume by station, Arrow Lakes Reservoir May-November 2003.

Appendix Figure 7.9. Phytoplankton biovolume Arrow Lakes Reservoir AR1-8 from 1998-2003.

Appendix Figure 7.10. Phytoplankton abundance Arrow Lakes Reservoir AR1-8 from 1998-2003.

Appendix Figures 7.11. Arrow Phytoplankton 2003, Vertical Profiles - abundance (Cells/mL).

Appendix Figures 7.12. Arrow Phytoplankton 2003, Vertical Profiles - abundance (Cells/mL).

Appendix Figures 7.13. Arrow Phytoplankton 2003, Vertical Profiles - abundance (Cells/mL).

Appendix Figures 7.14. Arrow Phytoplankton 2003, Vertical Profiles - abundance (Cells/mL).

Appendix Figure 7.15. Arrow Phytoplankton 2003, Vertical Profiles – Biomass (mm³/L)

Appendix Figure 7.17. Arrow Phytoplankton 2003, Vertical Profiles – Biomass (mm³/L)

Appendix Figure 7.18. Arrow Phytoplankton 2003, Vertical Profiles – Biomass (mm^3/L)

CHAPTER 8

ZOOPLANKTON RESPONSE TO EXPERIMENTAL FERTILIZATION ARROW LAKES RESERVOIR, YEARS 4 and 5 (2002 and 2003)

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Introduction

The study of Arrow Lakes Reservoir macrozooplankton (length >150 µm) started in 1997, as part of a multidisciplinary project to restore Arrow Lakes Reservoir kokanee. Water quality in the reservoir has been influenced by anthropogenic changes including the construction of dams during the last 70 years. Upstream reservoirs have acted as nutrient traps resulting in oligotrophication of Arrow Lakes Reservoir and reduction of all trophic levels, declining fish stocks. After positive results of a fertilization project in Kootenay Lake (Ashley et al. 1999; Wright et al. 2002a, 2002b, 2002c), an initial two-year study of limnology and trophic status of Arrow Lakes started in 1997 (Pieters et al. 1998; Pieters et al. 1999), followed by a five-year fertilization experiment initiated in 1999 (Pieters et al. 2000, 2003a, 2003b). Changes in zooplankton composition, density and biomass during the study period show positive trends toward more productive conditions.

Methods

Samples have been collected monthly at six stations (AR 1 - 3, AR 6 - 8), from April to November in 2002 and 2003 (Fig. 1.1). From 1997 through 2001, samples had been collected from April to October, but in 2002 the sampling season was lengthened to include a November sample. In 2002 samples were collected from 11 April to 19 November, and in 2003 from 7 April to 17 November, using a Clarke-Bumpus sampler. At each of the stations three replicate oblique tows were made. The net had 153 µm mesh and was raised from a depth of 40 to 0 m, at a boat speed of 1 m s⁻¹. Tow duration was 3 min, with approximately 2,500 L of water filtered per tow. The exact volume sampled was estimated from the revolutions counted by the Clarke-Bumpus flow meter. The net and flow meter were calibrated before and after the sampling seasons. All calibrations were done in a flume at the Civil Engineering Department at the University of British Columbia.

Collected zooplankton samples were rinsed from the dolphin bucket into a 100 µm filter to remove excess lake water, then preserved in 70% ethanol. Zooplankton samples were analyzed for species density, biomass (estimated from empirical length-weight regressions, McCauley 1984), and fecundity. Samples were re-suspended in tap water filtered through a 74 µm mesh and sub-sampled using a four-chambered Folsom-type plankton splitter. Splits were placed in gridded plastic petri dishes and stained with Rose Bengal to facilitate viewing with a Wild M3B dissecting microscope (at up to 400X magnification). For each replicate, organisms were identified to species level and counted until up to 200 organisms of the predominant species were recorded. If 150 organisms were counted by the end of a split, a new split was not started. The lengths of 30 organisms of each species were measured for use in biomass calculations, using a mouse cursor on a live television image of each organism. Lengths were converted to biomass (µg dry-weight) using empirical length-weight regression from McCauley (1984). The number of eggs carried by gravid females and the lengths of these individuals were recorded for use in fecundity estimations.

Rare species, e.g., *Leptodiaptomus sicilis*, were counted and measured as “Other Copepods” or “Other Cladocerans ” as appropriate. Zooplankton species were identified with reference to Pennak’s taxonomic keys (Pennak 1989), and Wilson’s keys were also

referred to for the identification of the calanoid copepods (Wilson 1959). Note that in 1997 sampling began in May, hence April data were absent from the 1997 annual averages.

Results

Species Present

During the seven years of the study, four calanoid copepod species have been identified in the samples from the Arrow Lakes Reservoir (Table 8.1). *Epischura nevadensis* (Lillj.), and *Leptodiaptomus ashlandi* (Marsh) were observed in all seven years. *Onychodiaptomus hesperus* (Wilson and Light) was observed in 1997 and 1998, but was rare. In 1998, 1999, 2000, 2001, 2002 and 2003 *Leptodiaptomus sicilis* was also seen, although rarely. One cyclopoid copepod species, *Diacyclops bicuspidatus thomasi* (Forbes), was seen in all seven years.

Table 8.1. List of zooplankton species identified in Arrow Lakes Reservoir 1997-2003.

Species	1997	1998	1999	2000	2001	2002	2003
Cladocera							
<i>Alona sp.</i>		r					
<i>Ceriodaphnia reticulata</i>	r	r	r	r	r	r	r
<i>Chydorus sphaericus</i>		r	r	r	r	r	r
<i>Daphnia galeata</i>	+	+	+	+	+	+	+
<i>Daphnia pulex</i>	+	+	+	+	+	+	+
<i>Daphnia longispina</i>	+	+	+	+	+	+	+
<i>Diaphanosoma brachiurum</i>	r				r	r	+
<i>Bosmina longirostris</i>	+	+	+	+	+	+	+
<i>Holopedium gibberum</i>		r				r	
<i>Leptodora kindti</i>	+	+	+	+	+	+	+
<i>Polyphemus pediculus</i>	r	r					
<i>Scapholeberis mucronata</i>	r	r	r	r	r	r	r
<i>Sida crystallina</i>							r
Copepoda							
<i>Diacyclops bicuspidatus</i>	+	+	+	+	+	+	+
<i>Epischura nevadensis</i>	+	+	+	+	+	+	+
<i>Leptodiaptomus ashlandi</i>	+	+	+	+	+	+	+
<i>Leptodiaptomus sicilis</i>		r	r	r	r	r	+
<i>Onychodiaptomus hesperus</i>	r	r					

^r rarely seen species

Of the thirteen species, cladocera was present in the Arrow Lakes Reservoir during the studied period (Table 8.1). Seven species were present in the samples in all seven studied

years: *Ceriodaphnia reticulata* (Jurine), *Daphnia galeata mendotae* (Birge), *Daphnia pulex* (Leydig), *Daphnia longispina* (O.F.M.), *Bosmina longirostris* (O.F.M.), *Leptodora kindti* (Focke), and *Scapholeberis mucronata* (O.F.M.). Other rare species such as *Diaphanosoma brachyurum* (Liéven), *Polyphemus pediculus* (L.), *Holopedium gibberum* (Zaddach), *Chydorus sphaericus* (O.F.M.), *Sida crystallina* (O.F.M.) and *Alona* sp. were observed sporadically. *Daphnia* spp. were not identified to species for density counts in any of the seven years.

In all seven years the zooplankton population composition has remained similar in both Arrow basins. The predominant copepods in the Arrow Lakes Reservoir were *L. ashlandi*, and *D. bicuspidatus thomasi*. The cladocerans *Daphnia* spp., and *B. longirostris* were common in all seven years.

Density and Biomass

The zooplankton density in 2002 and 2003 was numerically dominated by copepods which averaged 91% and 74% in Upper and 89% and 81% in Lower Arrow. *Daphnia* spp. comprised 2% and 3% in 2002, while in 2003 it comprised 3% and 6% in Upper and Lower Arrow respectively. Cladocerans other than *Daphnia* comprised of 7% and 8% in 2002 and 23% and 12% in 2003 respectively (Fig.8.1). Copepods were the most abundant zooplankton at each station in all seven years studied. They dominated during the entire sampling season in 2002 and 2003, with populations peaking in July-August. Copepods were comprised of calanoids and cyclopoids, during the entire sampling season. In all seven years studied cyclopoids dominated in both Upper and Lower Arrow. The calanoid population was more abundant in Upper Arrow than in Lower Arrow, while the cyclopoid population had a higher density in Lower Arrow than in Upper Arrow (Fig. 8.2).

Total zooplankton density in Upper Arrow increased significantly from 1997 through 2003 except for a slight decrease in 2002 (Fig. 8.3a, Table 8.2). The seasonal average zooplankton density (April to November) in Upper Arrow was 11.10 individuals·L⁻¹ in 2002 while in 2003 it was 16.78 individuals·L⁻¹. *Daphnia* spp. density increased from 1997 to 1999, then in 2000 declined and remained at less than 1 individual·L⁻¹ up to 2003. Other cladocerans fluctuated in density from 1997 to 2003. (Fig.8.3b).

Zooplankton density in Lower Arrow was greater than in Upper Arrow during the entire study period (Fig. 8.3c, Table 8.2). In Lower Arrow, the total zooplankton density increased from 1997 to 2003 with a slight decrease in 2001. A similar pattern was seen for copepods (Fig. 8.3c), while the density of *Daphnia* spp. and other cladocera decreased in 2002 at 0.55 and 1.55 individuals·L⁻¹ and increased again in 2003 at 1.80 and 3.45 individuals·L⁻¹ in Lower Arrow (Table 8.2). The seasonal average zooplankton density in 2002 and 2003 (April to November) in Lower Arrow was 20.30 individuals·L⁻¹ and 28.43 individuals·L⁻¹ respectively. The proportion of cladocerans (including *Daphnia* spp.) fluctuated during the seven studied years from about 21% in 1997 and 1998, 28% in 1999, 26% in 2000, 31% in 2001, 10% in 2002, to 18% in 2003. As in Upper Arrow, the proportion of *Daphnia* spp. to the total zooplankton density in Lower Arrow increased until 1999, then decreased in the next three years, declining to only 3% in 2002 and 6% in 2003.

Table 8.2. Seasonal average density and biomass of zooplankton in Upper and Lower Arrow in 1997-2003. Values from Kootenay and Okanagan Lake are shown for comparison. Values are seasonal averages, calculated for samples collected between May and October in 1997, April and October 1998-2001, and April and November 2002-2003. Density is in units of individuals/L, and biomass is in units of µg/L.

	Lake	1997	1998	1999	2000	2001	2002	2003
Total Density	Upper Arrow	3.78	6.23	9.15	11.38	13.77	11.10	16.78
	Lower Arrow	10.48	8.9	14.29	23.94	14.75	20.30	28.43
	Kootenay	19.83	20.27	17.76	24.42	31.11	30.76	36.20
	Okanagan	22.00	8.00	22.2	21.11	16.66	15.69	14.43
Copepod Density	Upper Arrow	2.30	4.39	6.99	10.04	11.25	10.11	12.47
	Lower Arrow	8.28	7.01	10.31	17.84	10.15	18.20	23.18
	Kootenay	18.20	18.21	16.89	22.07	24.04	28.15	30.90
	Okanagan	21.1	7.4	20.76	20.36	15.84	15.21	13.67
Other Cladoceran Density*	Upper Arrow	0.63	0.92	0.63	0.55	1.71	0.76	3.80
	Lower Arrow	1.11	0.39	0.95	1.50	2.57	1.55	3.45
	Kootenay	1.13	1.17	0.48	1.47	6.09	1.71	3.47
	Okanagan	0.46	0.2	0.9	0.29	0.61	0.31	0.28
<i>Daphnia</i> spp. Density	Upper Arrow	0.15	0.92	1.53	0.8	0.81	0.23	0.48
	Lower Arrow	1.06	1.50	3.04	4.6	2.03	0.55	1.80
	Kootenay	0.51	0.89	0.39	0.88	0.98	0.89	1.82
	Okanagan	0.25	0.11	0.54	0.47	0.21	0.17	0.48
Total Biomass	Upper Arrow	7.73	28.63	44.55	33.04	34.02	19.22	29.45
	Lower Arrow	30.56	47.89	71.57	107.41	55.97	37.26	71.58
	Kootenay	30.82	46.76	31.68	50.53	70.82	59.14	90.72
	Okanagan	N/A	N/A	59.79	58.02	43.19	35.28	42.00
Copepod Biomass	Upper Arrow	4.41	7.85	12.4	17.01	19.53	14.45	18.24
	Lower Arrow	11.46	10.85	17.56	27.03	18.32	24.70	31.47
	Kootenay	23.29	28.93	24.58	34.34	40.36	41.07	48.29
	Okanagan	N/A	N/A	41.9	41.8	34.8	28.92	27.00
Other Cladoceran Biomass**	Upper Arrow	0.95	1.67	0.94	0.92	2.15	1.16	4.58
	Lower Arrow	1.75	2.99	1.26	1.78	3.88	3.36	5.32
	Kootenay	1.96	3.91	1.46	3.78	14.44	4.83	9.51
	Okanagan	N/A	N/A	4.25	2.01	2.65	1.86	1.05
<i>Daphnia</i> spp. Biomass	Upper Arrow	2.37	19.1	31.21	15.12	12.34	3.61	6.63
	Lower Arrow	17.36	34.05	52.75	78.59	33.77	9.20	34.79
	Kootenay	5.57	13.92	5.65	12.41	16.02	13.24	32.92
	Okanagan	N/A	N/A	13.65	14.21	5.74	4.50	13.95

*Values do not include *Daphnia* spp. density.

**Values do not include *Daphnia* spp. biomass.

Total zooplankton and *Daphnia* spp. biomass in Lower Arrow increased from 1997 to 2000, - reaching 107.41 µg/L and 78.59 µg/L, respectively. In the next two years total zooplankton and *Daphnia* spp. biomass decreased significantly to 37.26 µg/L and 9.20 µg/L, respectively. In 2003, the density of zooplankton and *Daphnia* spp. slightly increased. There was also a slight increase in biomass (Table 8.2, Fig. 8.4a). Biomass of copepods and other Cladocera fluctuated during the studied period, with an increased trend from 1997 to 2003. In Upper Arrow, the fluctuation of biomass in all zooplankton categories (total, copepod, cladoceran, *Daphnia* spp.) had a similar trend to Lower Arrow. The decrease of total zooplankton biomass in both Upper and Lower Arrow was due to significant decreases in the biomass of *Daphnia* spp., and other cladocerans with larger individual size compared to copepods. Biomass was greater in Lower Arrow than in Upper Arrow during the study period across all categories (Fig. 8.4b, c). In Upper Arrow, *Daphnia* spp. made up 31%, 67%, 70%, 46%, 36%, 19% and 22% of the total zooplankton biomass from 1997 to 2003. Over the same period *Daphnia* spp. made up 57%, 71%, 74%, 73%, 60%, 25% and 49% of the total zooplankton biomass in Lower Arrow (Fig. 8.5).

In comparison to other BC lakes, zooplankton density and biomass in Kootenay Lake fluctuated and did not show a steady increase across years (Table 8.2). Total density in Kootenay Lake was higher than in either of the Arrow basins in each year of the Arrow study. In 2000 zooplankton densities in Kootenay Lake and Lower Arrow were similar. In 2001 zooplankton density in Kootenay Lake was more than twice as high as zooplankton density in either Arrow basin, in 2002 zooplankton density was three times higher in Kootenay Lake than in Upper Arrow and one half times higher than in Lower Arrow, and in 2003 the density was twice as high in Kootenay Lake than in Upper Arrow. However, total biomass in Kootenay Lake was less than that of Lower Arrow in each year from 1998 to 2000 and less than that of Upper Arrow in 1999.

These differences are due to the greater proportion of *Daphnia* spp. in the Arrow Lakes Reservoir zooplankton, since individual *Daphnia* have much greater biomass than individuals of most other zooplankton species in these lakes. However, from 2001 onward total zooplankton biomass in Kootenay Lake increased significantly in comparison to the previous years and was almost double that of Upper Arrow in 2001 and three times higher in 2002 and 2003. In 2002 there was a decrease of zooplankton biomass in Kootenay Lake but production was still higher than in either Upper or Lower Arrow. In 2003 *Daphnia* spp. biomass in Kootenay Lake increased significantly in comparison to the previous years. The biomass was equivalent to Lower Arrow but exceeded Upper Arrow biomass more than five times.

In Okanagan Lake both density and biomass of most zooplankton categories resulted in a decreasing trend over the course of the study period. In 2003 total zooplankton, copepods and *Daphnia* density in Okanagan Lake were similar to the values from Upper Arrow, while biomass of the same categories were similar to those from Lower Arrow. Density and biomass of other Cladocera were less than the density and biomass in Upper and Lower Arrow.

Seasonal and Along-Lake Patterns

The seasonal development of zooplankton density and biomass was similar in Upper and Lower Arrow during 2002 and 2003 (Fig. 8.6-7). Copepods predominated numerically during the entire season, however, in July the density and biomass of *Daphnia* spp. and other cladocerans began to increase in both basins. Cladocerans were present during the entire sampling season with significant numbers in both basins from July to September, while *Daphnia* spp. density and biomass reached their peak in August-September. In previous years, *Daphnia* spp. made up the majority of the biomass from July to October in both Upper and Lower Arrow. During 2002 and 2003 in Lower Arrow, *Daphnia* biomass prevailed in August and September. . The years 2003, 2002, 2001 and 1997 were late-season years, with cladocerans and *Daphnia* spp. first becoming numerous in August. Conversely, 1998 was an early-season year, in which cladocerans and *Daphnia* spp. began to bloom in June. In 1999 and 2000 the bloom of cladocerans in both basins started in July, and *Daphnia* spp. were present until October.

During 2002, peak total zooplankton density occurred in September in Upper Arrow with 23.90 individuals·L⁻¹ and in July in Lower Arrow with 40.37 individuals·L⁻¹ (Table 8.3). The peak total zooplankton biomass also occurred in September at 47.79 µg/L in Upper Arrow and in August at 79.51 µg/L in Lower Arrow. *Daphnia* spp. biomass reached its peak in September with 18.82 and 42.42 µg/L in Upper and Lower Arrow respectively (Table 8.3). In 2003 peak total zooplankton density occurred in August in Upper Arrow at 43.15 individuals·L⁻¹ and in July in Lower Arrow with 78.60 individuals·L⁻¹ (Table 8.3). The peak total zooplankton biomass took place in August at 78.76 µg/L in Upper Arrow and in September at 176.89 µg/L in Lower Arrow. *Daphnia* spp. biomass get to its peak in August at 28.02 µg/L and in September at 135.21 µg/L in Upper and Lower Arrow respectively (Table 8.3). During the first five years of the study, peaks in density tended to occur at the same time in both basins (e.g. peak density occurred in August of 1997 and 2001, July of 1999 and 2000, and June 1998), while in 2002 and 2003 peaks in density in two basins were one or two months apart (in 2003 in Upper Arrow the peak density occurred in August, while in Lower Arrow it occurred in July). Biomass peaks in the upper and lower basins tended to coincide, or be only a month apart. At times there was a one month delay between the density and biomass peak, due to the increase in *Daphnia* spp. density following the copepod density peak, and the large body size of individual daphnids.

Along the length of the Upper Arrow (Stations 1-3) and the Lower Arrow (Stations 6-8) , zooplankton densities tended to be higher in the Lower basin during the entire 2002 and 2003 season except in November 2002 and June 2003 (Table 8.3). The pattern for biomass was similar to density (Table 8.3). This was particularly pronounced in August and September, when the biomass of *Daphnia* spp. was very high at the Lower Arrow stations. From July onward each year, biomass trends along the two basins were largely driven by the development of *Daphnia* spp., since *Daphnia* make up the majority of zooplankton biomass during this period.

Table 8.3. Monthly average density and biomass of zooplankton in Upper and Lower Arrow in 2002 and 2003. Density is in units of individuals/L, and biomass is in units of $\mu\text{g/L}$.

Density 2002		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	1.58	1.22	7.10	18.76	15.76	19.94	7.81	8.67
	Daphnia	0.00	0.00	0.02	0.10	0.39	1.26	0.08	0.03
	Other Cladocera*	0.01	0.01	0.15	1.35	1.63	2.71	0.19	0.03
	Total Zooplankton	1.59	1.24	7.27	20.21	17.79	23.90	8.08	8.73
Lower Arrow	Copepoda	3.66	10.16	16.02	35.84	33.03	21.85	17.71	7.33
	Daphnia	0.00	0.00	0.00	0.06	1.98	2.16	0.24	0.00
	Other Cladocera*	0.02	0.22	1.07	4.47	3.91	2.08	0.57	0.03
	Total Zooplankton	3.68	10.38	17.09	40.37	38.92	26.08	18.52	7.36
Density 2003		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	1.88	1.92	6.85	30.57	25.11	14.20	10.58	8.68
	Daphnia	0.00	0.00	0.03	0.25	2.23	1.27	0.03	0.00
	Other Cladocera*	0.03	0.17	2.54	7.44	15.81	4.11	0.30	0.02
	Total Zooplankton	1.91	2.09	9.42	38.26	43.15	19.57	10.91	8.70
Lower Arrow	Copepoda	3.40	9.19	8.01	68.48	32.07	23.29	24.16	16.81
	Daphnia	0.00	0.00	0.00	0.56	5.71	6.87	1.10	0.15
	Other Cladocera*	0.02	0.20	0.60	9.56	8.41	4.07	4.33	0.45
	Total Zooplankton	3.42	9.39	8.60	78.60	46.19	34.23	29.58	17.41
Biomass 2002		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	2.66	2.32	14.08	23.03	23.67	24.79	10.53	14.52
	Daphnia	0.00	0.00	0.40	1.15	6.85	18.82	1.32	0.32
	Other Cladocera**	0.01	0.02	0.35	1.97	2.14	4.18	0.59	0.05
	Total Zooplankton	2.67	2.34	14.83	26.15	32.66	47.79	12.43	14.89
Lower Arrow	Copepoda	6.15	15.06	23.73	48.61	40.11	29.85	25.10	9.03
	Daphnia	0.00	0.00	0.00	0.50	26.59	42.42	4.01	0.05
	Other Cladocera**	0.03	0.32	1.92	6.45	12.81	4.44	0.92	0.04
	Total Zooplankton	6.18	15.37	25.65	55.55	79.51	76.71	30.02	9.12
Biomass 2003		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	2.42	2.22	15.44	37.36	33.82	20.94	15.79	17.91
	Daphnia	0.05	0.00	1.12	4.11	28.02	19.05	0.68	0.00
	Other Cladocera**	0.04	0.30	3.59	9.60	16.93	5.74	0.42	0.03
	Total Zooplankton	2.52	2.52	20.15	51.07	78.76	45.73	16.89	17.94
Lower Arrow	Copepoda	4.82	13.81	17.19	77.15	43.00	35.40	38.73	21.64
	Daphnia	0.00	0.00	0.00	7.55	114.40	135.21	19.03	2.10
	Other Cladocera**	0.03	0.32	0.77	15.87	11.19	6.28	7.57	0.55
	Total Zooplankton	4.84	14.13	17.96	100.57	168.59	176.89	65.33	24.30

*Values do not include *Daphnia* spp. density.

**Values do not include *Daphnia* spp. biomass.

Zooplankton Fecundity

Fecundity features of the four most common zooplankton species *L. ashlandi*, *D. bicuspidatus thomasi*, *Daphnia spp.* and *B. longirostris* were studied during the seven years period.

L. ashlandi females were gravid from July to November 2002 and from June to November 2003 in Upper and Lower Arrow (Fig. 8.8). The proportion of females that were gravid was highly variable, as in previous years, and was always below 0.5, except in September 2002 and October 2003 in Lower Arrow when it was 1. In previous years from 1997-2002, there was a trend for females in the Upper basin to carry slightly more eggs than in the Lower basin, or to carry the same number of eggs as it was in 1999 and 2001. However in 2003, the proportion of gravid females in Upper Arrow was significantly lower, and females carried less eggs than in the Lower basin. During the sampling season 2002 (April - November) *L. ashlandi* females carried an average of 9.65 and 8.35 eggs per gravid female, while in 2003 it was 9.05 and 10.92 eggs per gravid female in Upper and Lower Arrow respectively (Table 8.4). The number of eggs per water volume averaged 0.11 eggs·L⁻¹ in Upper Arrow and 0.13 eggs·L⁻¹ in Lower Arrow in 2002, and 0.07 eggs·L⁻¹ in Upper Arrow and 0.45 eggs·L⁻¹ in Lower Arrow in 2003. The number of eggs per capita (number of eggs per individual of species) averaged 0.05 eggs·individual⁻¹ in both of the basins in 2002, and 0.02 eggs·individual⁻¹ and 0.21 eggs·individual⁻¹ in 2003 in Upper and Lower Arrow respectively. There were no consistent differences in any of the fecundity measures in the two basins across years.

Table 8.4. Fecundity data for *L. ashlandi* in Upper and Lower Arrow 1997-2003. Values are seasonal averages, calculated for samples collected between May and October in 1997, between April and October 1998-2001, and between April and November in 2002-2003.

Fecundity Measure	Basin	1997	1998	1999	2000	2001	2002	2003
Proportion of gravid females	Upper Arrow	0.17	0.10	0.15	0.14	0.15	0.08	0.03
	Lower Arrow	0.18	0.09	0.18	0.09	0.07	0.12	0.14
# Eggs per gravid Female	Upper Arrow	11.91	11.22	11.00	11.85	8.20	9.65	9.05
	Lower Arrow	10.46	8.58	10.99	8.91	8.55	8.35	10.92
# Eggs per Litre	Upper Arrow	0.24	0.17	0.56	0.80	0.35	0.11	0.07
	Lower Arrow	0.08	0.17	0.28	0.15	0.10	0.13	0.45
# Eggs per Capita	Upper Arrow	0.19	0.13	0.17	0.19	0.07	0.05	0.02
	Lower Arrow	0.11	0.10	0.25	0.07	0.04	0.05	0.21

D. bicuspidatus thomasi females were gravid throughout the sampling period in 2002. The proportion of females that were gravid did not show a distinct peak during the season in Lower basin, while in the Upper basin at all three stations peak occurred in July (Fig. 8.8). From April to November the proportion of gravid females averaged 0.14 in Upper Arrow, and 0.12 in Lower Arrow (Table 8.5). As in previous years, there was no consistent trend in number of eggs per female along the lakes. The seasonal averages were 15.54 and 16.17 eggs per gravid female in Upper and Lower Arrow. During the sampling season the number

of eggs per water volume averaged 2.46 and 3.05 eggs·L⁻¹ in Upper and Lower Arrow respectively. The number of eggs per capita averaged 0.35 and 0.29 eggs·individual⁻¹ in the two basins during this period. The highest proportion of females that were gravid in 2003 occurred in June and September in both basins (Fig. 8.8). From April to November the proportion of gravid females averaged 0.15 in Upper Arrow, and 0.16 in Lower Arrow (Table 8.5).

Table 8.5. Fecundity data for *D. bicuspidatus thomasi* in Upper and Lower Arrow 1997-2003. Values are seasonal averages, calculated for samples collected between May and October in 1997, between April and October 1998-2001, and between April and November in 2002-2003.

Fecundity Measure	Basin	1997	1998	1999	2000	2001	2002	2003
Proportion of gravid females	Upper Arrow	0.33	0.18	0.13	0.13	0.13	0.14	0.15
	Lower Arrow	0.34	0.13	0.13	0.12	0.11	0.12	0.16
# Eggs per gravid Female	Upper Arrow	16.49	15.41	18.18	16.24	16.87	15.54	16.81
	Lower Arrow	14.07	14.49	14.05	14.61	17.70	16.17	15.37
# Eggs per Litre	Upper Arrow	1.48	1.57	2.45	2.65	3.76	2.46	4.24
	Lower Arrow	4.20	1.46	3.26	3.50	2.62	3.05	4.90
# Eggs per Capita	Upper Arrow	0.71	0.61	0.61	0.50	0.55	0.35	0.73
	Lower Arrow	0.61	0.36	0.44	0.43	0.37	0.29	0.55

There was no consistent trend in the number of eggs per female in the two basins. The seasonal averages were 16.81 and 15.37 eggs per gravid female in Upper and Lower Arrow, respectively. The number of eggs per gravid female was consistently higher in Upper than in Lower Arrow from 1997-2000 as well as in 2003. In 2001 and 2002 it changed patterns and was higher in Lower Arrow (Fig. 8.9).

During the sampling season the number of eggs per water volume averaged 4.24 and 4.9 eggs·L⁻¹ in Upper and Lower Arrow respectively. The number of eggs per capita averaged 0.73 and 0.55 eggs·individual⁻¹ in the two basins during this period. The number of eggs per capita was higher in Upper Arrow in all years studied except in 2002 when it was higher in Lower Arrow.

Daphnia spp. gravid females had a late season in the Arrow Lakes Reservoir in 2002 as well as in 2003. In 2002 they were observed from August to November in Lower Arrow Lake while in Upper Arrow Lake they started to appear as early as June. In 2003 they were observed from July to October in both basins. In 1998 and 1999 *Daphnia* spp. gravid females were seen as early as April, in 2000 they did not appear until May, in 1997 until June, in 2001 until July and in 2002 until June. The proportion of females that were gravid in 2002 and 2003 was variable across the season, but tended to be consistently higher from July toward the end of the season (Fig. 8.10). In 2002 the proportion of gravid females averaged 0.15 and 0.16, and in 2003 0.21 and 0.12 in Upper and Lower Arrow respectively (Table 8.6).

Table 8.6. Fecundity data for *Daphnia spp.* in Upper and Lower Arrow 1997-2003. Values are seasonal averages, calculated for samples collected between May and October in 1997, April and October 1998-2001, and April and November in 2002-2003.

Fecundity Measure	Basin	1997	1998	1999	2000	2001	2002	2003
Proportion of gravid females	Upper Arrow	0.16	0.14	0.10	0.16	0.21	0.15	0.21
	Lower Arrow	0.23	0.12	0.10	0.12	0.12	0.16	0.12
# Eggs per gravid Female	Upper Arrow	3.33	2.76	3.64	4.33	3.40	3.13	2.42
	Lower Arrow	2.65	1.84	2.23	2.10	1.78	2.31	2.20
# Eggs per Litre	Upper Arrow	0.08	0.22	0.47	0.67	0.47	0.13	0.27
	Lower Arrow	0.44	0.25	0.31	0.53	0.54	0.22	0.60
# Eggs per Capita	Upper Arrow	0.54	0.44	0.44	0.69	0.82	0.50	0.51
	Lower Arrow	0.66	0.28	0.37	0.33	0.23	0.37	0.30

The number of eggs per gravid female of *Daphnia spp.* (Fig. 8.11) and the number of eggs per capita was consistently higher in Upper Arrow than in Lower Arrow during all years, but for the other fecundity measures there were no consistent differences. The seasonal average number of eggs per gravid female was 3.13 and 2.31 eggs per gravid female in 2002, and 2.42 and 2.20 eggs per gravid female in 2003 in Upper and Lower Arrow respectively. During the sampling season the number of eggs per water volume averaged 0.13 and 0.22 eggs·L⁻¹ in 2002, and 0.27 and 0.60 eggs·L⁻¹ in 2003. The number of eggs per capita averaged 0.50 and 0.37 eggs·individual⁻¹ in 2002, and 0.51 and 0.30 eggs·individual⁻¹ in 2003 in the two basins.

B. longirostris gravid females were observed from April to November in 2002 and 2003. In 2003 as well as in 1998 and 2002 gravid females were observed as early as April, although in other study years they did not appear until May (Fig. 8.10). The proportion of gravid females in 2002 was higher from April to August in Upper Arrow, and from May-June and October-November in Lower Arrow (Fig. 8.10). In 2002 the proportion of gravid females averaged 0.27 and 0.26 in Upper and Lower Arrow respectively (Table 8.7). The number of eggs per gravid female of *B. longirostris* tended to be higher in Upper Arrow (Fig. 8.11). The seasonal averages were 2.27 and 2.12 eggs per gravid female in Upper and Lower Arrow respectively. Across the sampling season the number of eggs per water volume averaged 0.43 and 0.48 eggs·L⁻¹ and the number of eggs per capita averaged 0.55 and 0.57 eggs·individual⁻¹ in the two basins. In 2003 the proportion of gravid females averaged 0.21 and 0.19 in Upper and Lower Arrow respectively (Table 8.7). As in previous years, the number of eggs per gravid female of *B. longirostris* tended to be higher in Upper Arrow (Fig. 8.11). The seasonal averages were 2.03 and 1.96 eggs per gravid female, the number of eggs per water volume averaged 1.40 and 0.92 eggs·L⁻¹ and the number of eggs per capita averaged 0.43 and 0.38 eggs·individual⁻¹ in the two basins. The number of eggs per gravid female and the number of eggs per capita were higher in Upper Arrow than in Lower Arrow during all years, but the proportion of gravid females and number of eggs per water volume did not show consistent differences in two basins across years.

Table 8.7. Fecundity data for *B. longirostris* in Upper and Lower Arrow 1997-2003. Values are seasonal averages, calculated for samples collected between May and October in 1997, April and October 1998-2001, and April and November in 2002-2003.

Fecundity Measure	Basin	1997	1998	1999	2000	2001	2002	2003
Proportion of gravid females	Upper Arrow	0.18	0.33	0.20	0.22	0.24	0.27	0.21
	Lower Arrow	0.24	0.22	0.19	0.07	0.13	0.26	0.19
# Eggs per gravid Female	Upper Arrow	2.52	2.51	2.82	2.72	2.18	2.27	2.03
	Lower Arrow	2.22	2.28	2.40	2.36	1.81	2.12	1.96
# Eggs per Litre	Upper Arrow	0.20	0.36	0.31	0.42	0.76	0.43	1.40
	Lower Arrow	0.21	0.08	0.03	0.08	0.21	0.48	0.92
# Eggs per Capita	Upper Arrow	0.49	0.85	0.64	0.70	0.48	0.55	0.43
	Lower Arrow	0.48	0.56	0.40	0.17	0.28	0.57	0.38

Discussion

Zooplankton density in 2002 and 2003, as well as in the previous study years, indicated higher densities in Lower Arrow than in Upper Arrow. In both basins total zooplankton density was the highest in comparison to previous years. Copepods and other Cladocera (mainly tiny specimens such as *Bosmina* sp.) had distinct peaks, higher than in previous years, while *Daphnia* was not present in higher numbers particularly in Upper Arrow. This density shift in favour to smaller cladocerans is mirrored in a weak biomass increase. In Upper Arrow total zooplankton biomass decreased from 1999 to 2002, and in 2003 increased slightly, while in Lower Arrow there was a decreasing trend from 2000-2002. In Lower Arrow *Daphnia* made up the majority of biomass throughout the study period except in 2002, while in Upper Arrow from 2000-2003 copepods had a much higher ratio in total zooplankton biomass.

Different factors such as climatic conditions, changes in availability of grazeable algae, or changes in *Mysis relicta* and kokanee abundance may have made conditions more favourable for *Daphnia* spp. in the Arrow Lakes Reservoir in some years. In 1999 and 2000 with the addition of fertilizer to Upper Arrow (and subsequent transport of additional nutrients into Lower Arrow), it may have made conditions even more favourable for *Daphnia* population growth. However in 2001 and 2002 the composition of the zooplankton community changes in favour to smaller cladocerans causing a significant decrease in biomass. In 2003 both density and biomass increased slightly in both basins, with the same similar trend of an increased number of smaller cladocerans. These changes have likely been due to a combination of predation and climatic changes. It is notable that zooplankton abundance has increased despite the increase in abundance of kokanee salmon, a major zooplankton predator, in the basins during the same time period. Estimated kokanee numbers for Upper and Lower Arrow combined were 2.12, 4.37, 4.89, 8.06, 16, 20 and 11.6 million in 1997, 1998, 1999, 2000, 2001, 2002 and 2003 respectively (see Chapter 10). There was a four-five fold increase in kokanee abundance since the nineties and up to a ten fold increase since 1997 (the lowest Arrow Lakes Reservoir kokanee abundance estimate on

record). The decrease in zooplankton density in 2002 could be explained by the sharp increase in kokanee numbers and heavy grazing pressure on zooplankton populations. Furthermore, the abundance of *M. relicta*, another predator of zooplankton, also increased during the period from 1997-2000 in both basins, from approximately 50 to 200 individuals·m⁻² (Fig. 8.12). In 2003, *M. relicta* abundance in the Upper Arrow remained close to 300 individuals·m⁻² keeping predation pressure on larger zooplankton such as *Daphnia* and having an impact on its density and biomass. In the Lower Arrow mysids abundance decreased from 259 individuals·m⁻² in 2001 to 158 individuals·m⁻² and 101 individuals·m⁻² in 2002 and 2003, which could explain a growth in *Daphnia* abundance and biomass in Lower Arrow. (see Chapter 9).

Changes in zooplankton density and biomass in the fertilized years, suggest that the system was shifting towards more productive conditions. With the increasing trend in zooplankton density at the beginning of the fertilization in 1999 and a density decrease in the fourth year, the situation is similar to that of Kootenay Lake during the first period of fertilizer loading when zooplankton densities increased from 1992 to 1994 and then decreased in 1995. A possible explanation for the higher *Daphnia* density and biomass in Arrow Lakes Reservoir during the first five years of study is that there was not a high predation pressure on zooplankton by higher mysids densities as in Okanagan Lake and higher kokanee densities as in Kootenay. Also, Kootenay Lake contained approximately twice the density of *M. relicta* as seen in the Arrow Lakes Reservoir between 1997 and 1999 (Wright et al. 2002a, 2002b, 2002c). However, in 2000-2002 mysid density in Arrow Lakes Reservoir was similar to that in Kootenay Lake, and in 2003 the mysid population in Arrow Lakes was twice the density of mysids in Kootenay (see Table 9.1). Since *Daphnia* is the preferred prey of both kokanee and mysids, predation may be suppressing the standing stock biomass of *Daphnia*, despite potentially high zooplankton productivity. In addition to predation, other factors such as changes in the availability of grazeable algae as well as climatic conditions may also affect zooplankton density and biomass.

Acknowledgements

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Figure 8.1. Seasonal average density composition of zooplankton in Upper Arrow (top) and Lower Arrow (bottom) 1997-2003.

Figure 8.2. Density of calanoid and cyclopoid zooplankton in Arrow Lakes Reservoir, 1997-2003.

a. Seasonal average density of total zooplankton, Upper and Lower Arrow, 1997-2003.

b. Seasonal density of zooplankton in Upper Arrow, 1997-2003.

c. Seasonal density of zooplankton in Lower Arrow, 1997-2003.

Figure 8.3. Zooplankton density in Arrow Lakes Reservoir, 1997-2003 (a,b,c).

a. Seasonal biomass of zooplankton in Upper and Lower Arrow, 1997-2003.

b. Seasonal biomass of zooplankton in Upper Arrow, 1997-2003.

c. Seasonal biomass of zooplankton in Lower Arrow, 1997-2003.

Figure 8.4. Zooplankton biomass in Arrow Lakes Reservoir, 1997-2003 (a,b,c).

Figure 8.5. Seasonal average biomass of zooplankton in Upper Arrow (top) and Lower Arrow (bottom), 1997-2003.

Figure 8.6. Density of cladoceran and copepod zooplankton in Arrow Lakes Reservoir, 1997-2003.

Figure 8.7. Biomass of cladoceran and copepod zooplankton in Arrow Lakes Reservoir, 1997-2003.

Figure 8.8. Proportion of gravid females of two species of Copepoda found in Arrow Lakes Reservoir, 1997-2003.

Figure 8.9. Number of eggs per gravid female in two species of Copepoda found in Arrow Lakes Reservoir, 1997-2003.

Figure 8.10. Proportion of gravid females of two species of Cladocera found in Arrow Lakes Reservoir, 1997-2003.

Figure 8.11. Number of eggs per gravid female in two species of Cladocera found in Arrow Lakes Reservoir, 1997-2003.

Figure 8.12. Seasonal average density of *Daphnia* sp. and *M. relicta* in Upper Arrow (top) and Lower Arrow (bottom), 1997-2003.

CHAPTER 9

MYSID RESPONSE TO EXPERIMENTAL FERTILIZATION, ARROW LAKES RESERVOIR, YEARS 4 and 5 (2002 and 2003)

by

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Introduction

The study of mysids (*Mysis relicta*) in Arrow Lakes Reservoir started in 1997, as part of a multidisciplinary project to restore kokanee stocks. Water quality and kokanee in the reservoir has been influenced by anthropogenic changes over the last 70 years, including the introduction of *M. relicta* in 1968. The release of mysids interfered with the established food webs and impacted benthic, phytoplankton, zooplankton and fish communities. Mysids feed on zooplankton and are in direct competition with kokanee for preferred zooplankton prey. A two-year study of limnology and the trophic status of Arrow Lakes Reservoir started in 1997 (Pieters et al. 1998; Pieters et al. 1999). It was followed by a six-year fertilization experiment initiated in 1999 (Pieters et al. 2000, Pieters et al. 2003a, 2003b).

Methods

Samples of mysids from Arrow Lakes Reservoir were collected monthly from January to December, at six stations (AR 1 - 3, 6 - 8). Sampling was done at night, around the time of the new moon, to decrease the chance of mysids seeing and avoiding the net. Three vertical hauls were done at each station, with the boat stationary, using a 1 m² square-mouthed net with 1,000 µm primary mesh net, 210 µm terminal and 100 µm bucket. Two hauls were made in deep water (central and west or east location) and one haul was made in shallow water, within 0.5 nautical miles from either the west or east shore. The net was raised from the lake bottom with a hydraulic winch at 0.3 m s⁻¹. The contents of the bucket were rinsed into a filter to remove excess lake water, then preserved in 100% denaturated alcohol (85% ethanol, 15% methanol).

Samples have been analyzed for density, biomass (estimated from an empirical length-weight regression, Lasenby 1977), life history stage and maturity (Reynolds 1972). The life history stages identified were: juvenile, immature male, mature male, breeding male, immature female, mature female, brooding female (brood pouch full of eggs or embryos), disturbed brood female (brood pouch not fully stocked with eggs, but at least one egg or embryo left to show that female had a brood) and spent female (brood pouch empty, no eggs or embryos remaining).

Samples were re-suspended in tap water filtered through a 74 µm mesh filter, placed in a plastic petri dish and viewed with a Wild M3B dissecting microscope at up to 160X magnification. All mysids in each sample were counted, and had their life history stage and maturity identified. The body lengths (tip of rostrum to base of telson) of up to 30 individuals of each stage and maturity were measured, for use in biomass calculations, using a mouse cursor on a live television image of each organism. Fecundity of brooding females was estimated by removing and counting of eggs or embryos from the female brood pouch.

Results

Abundance and Biomass

Sampling of *Mysis* began in January and continued until December in each year from 1998 to 2003, so all annual average values represent a twelve month period, in comparison with the eight months sampled in 1997 (May-December). The annual average mysid density and biomass at the deep stations were consistently higher in Lower Arrow from 1997 to 2001 (Fig. 9.1, Tab. 9.1). In 2002 and 2003 the pattern changed and mysid density increased in Upper Arrow. Both density and biomass in Upper Arrow increased progressively in each successive year from 1997 to 2003, except in 2001-2002 when stagnation in growth of mysid population was noticed. In Lower Arrow the mysid density and biomass increased from 1997 to 2001, and in the next two years both parameters decreased to levels similar to the prefertilization period.

From 1997 to 2003, densities in both Arrow Lakes Reservoir basins were generally below 500 individuals·m⁻² at both deep and shallow sites throughout the year (Fig. 9.2). However, from 2000 to 2003 this level was exceeded more often than in previous years, particularly from May to August. During the studied period, there was a trend of higher mysid densities at the deep stations in Lower Arrow in late spring (May-June) and early fall (September). In Upper Arrow the peak density was recorded in summer (June-July). During this same period, mysid densities at the shallow stations tended to be higher in both reservoirs during the summer (June-August).

Peak monthly values were usually recorded in June-July at the shallow stations, mainly due to a higher number of immature males and females (Fig. 9.3 and 9.4). At the deep sites there were usually two density peaks during the year, the first in May-June (the highest density of juveniles, Fig. 9.5 and 9.6) and the second in August-October, mainly due to higher densities of immature males and females. There was no clear gradient of increasing density along the length of the lakes during 1997 and 1998. From 1999 to 2002 there was a weak tendency toward higher densities at station AR7 in Lower Arrow. However in 2003, the status changed and mysid density resulted in a distinct peak in Upper Arrow at station AR3. (Fig. 9.7, annual averages from deep sites only) The highest seasonal mysid abundance at a deep site in 2002 was observed at station AR7 in Lower Arrow with 1084 ind/m² (mainly juveniles) while in 2003 was found at station AR3 in Upper Arrow with 2458 ind/m² (mainly immature females and males). The highest seasonal abundance of mysids at a shallow site in 2002 occurred at AR 2 in Upper Arrow with 1916 ind/m² (mainly immature females and males), while in 2003 at station AR1 in Upper Arrow with 450 ind/m² (mainly immature females and males).

Throughout the year in 1997 and 1998 mysid biomass was generally below 1000 mg·m⁻² at all stations (Fig. 9.8). Likewise, in the period from 1999 to 2003 biomass was below 1000 mg·m⁻² at both deep and shallow stations in both basins from January to May. From June 1999 onward biomass at some deep and shallow stations exceeded 1000 mg·m⁻², with occasional values exceeding 2000 mg·m⁻² in September, October, and November. From 2000-2003 values frequently exceeded 1000 mg·m⁻² during the summer and fall. At the

shallow site of station AR2 in Upper Arrow biomass increased significantly, exceeding 9000 mg·m⁻² in August 2000, 8000 mg·m⁻² in July 2001, and 13900 in June 2002. However, while there was a trend toward higher biomass at shallow stations in Upper Arrow, this was not the situation in Lower Arrow (Fig. 9.9 and 9.10). Through the first five years studied there was a tendency toward an increase in biomass at deep sites in both Upper and Lower Arrow (Fig. 9.11 and 9.12). Unlike previous years, deep sites in Upper and Lower Arrow resulted in a decreasing trend in 2002. In 2003, a further decrease of biomass was recorded in Lower Arrow while in Upper Arrow at station AR3 biomass increased, exceeding 14500 mg·m⁻². Immature males and females made up the majority of mysid population at the time, although mature females also contributed to the biomass increase.

Table 9.1. Annual average density and biomass of *Mysis relicta* in Upper and Lower Arrow 1997-2003. Values are for deep stations only, calculated for samples collected between May and December in 1997, and between January and December 1998-2003. Density is in units of individuals·m⁻², and biomass is in units of mg·m⁻².

	Lake	1997	1998	1999	2000	2001	2002	2003
Total Density (individuals·m ⁻²)	Upper Arrow	32	71	116	195	195	185	286
	Lower Arrow	63	99	134	223	259	158	101
	Kootenay	173	146	195	201	273	125	85
	Okanagan	N/A	N/A	184	310	338	201	237
Total Biomass (mg·m ⁻²)	Upper Arrow	154	268	544	816	855	782	1560
	Lower Arrow	263	450	712	1030	1063	598	597
	Kootenay	N/A	N/A	1133	1111	1592	835	607
	Okanagan	N/A	N/A	2188	2266	3361	1385	2151

In comparison to other BC Lakes annual average density of mysids in the Arrow Lakes Reservoir from 1997 to 1999 was approximately half the density observed in Kootenay Lake in those years (Table 9.1). Likewise, mysid biomass in the Arrow Lakes Reservoir was about half that of Kootenay Lake in 1999. However, from 2000 to 2003 densities and biomass in Lower Arrow was similar to Kootenay Lake results. During 2002 and especially in 2003, mysid production was higher in Upper Arrow than in Kootenay Lake. Okanagan Lake mysid density and biomass was higher than in either Upper or Lower Arrow or Kootenay Lake, except in 2003 when mysid density in Upper Arrow increased to 286 individuals·m⁻² exceeding values in all other studied lakes (Lasenby et al. 1998, 1999; Ashley et al. 1999; Wright et al. 2002a, 2002b, 2002c; Andrusak et al. 2001).

Life Stages and Fecundity

The mysid population in Arrow Lakes Reservoir has been comprised of slightly more females than males. Density of developmental stages of *M. relicta* at deep sites is shown in Fig. 9.5 and 9.6. From January to March in both years 2002 and 2003, low numbers of individuals were seen (mostly immature males and females), however, brooding females

were consistently present. From April to July the majority of individuals were juveniles, with increasing proportions of both immature males and females. From July to September the proportion of immature and mature males and females continued to increase, but very few breeding males or brooding females were observed. From October to December very few juveniles were observed, but mature and breeding males were common. Mature and brooding females were also common, and some spent females were observed. The pattern of seasonal development at the deep stations in 2002 and 2003 was very similar to that observed in previous years.

Timing of the progression through the development stages at the shallow sites was similar to the deep sites (Fig. 9.3 and 9.4). However, in most months, the proportion of mature and breeding/brooding individuals was much lower at the shallow sites compared to the deep sites. Brooding females were not seen at shallow sites in 2003 sampling season, most individuals were juveniles, immature males and females. From April to June juveniles dominated the distribution. From July to October immature males and females predominated. In November and December immature males and females were present, and some mature males and females were observed. Breeding males were rarely seen, despite being common at the deep sites during this period. In Upper Arrow during the 2002 season, the number of juveniles was much lower than in previous years, while the number of juveniles and immature males and females in 2003 was less than in previous years.

In 2002 and 2003, mature females were more likely to be gravid from late fall through to spring (January to May, and from November to December (Fig. 9.13a. data from deep sites only). Similar trends were observed in previous years, except in the summer of 1999 when gravid females were consistently present in samples in both Upper and Lower Arrow. During January to March (the peak months) of 2002, 33-86% of mature females were gravid, with the exception of Stations AR1 and AR2, where the highest percentages of females were gravid in March. This proportion declined in summer, as spent females died off, and rose in the fall, as the new cohort matured. By December, 57-82% of females were gravid with the exception of Station AR2 and AR8. Generally at the beginning of the 2002 season, (February to March) females in Lower Arrow were more likely to be gravid as well as in the late summer and through the fall, but at the end of the season, (in December) the number of gravid females was higher in Upper Arrow. During January to March (the peak months) of 2003, 30-87% of mature females were gravid, with the exception of Station AR8, where in February no gravid females were present. The highest percentages of females were gravid in January. This proportion declined in summer, as spent females died off, and rose in the fall, as the new cohort matured. By December, 33-80% of females were gravid. Generally there were no consistent differences in the two basins during the 2003 season.

The seasonal average number of eggs per gravid female in 2002 was 13 and 14 eggs per gravid female while in 2003 was 15 and 16 eggs per gravid female in Upper and Lower Arrow, respectively. At the beginning of the 2002 season the number of eggs per gravid female differed slightly in the two basins. (Fig. 9.12 b.). Gravid females were not present in Lower Lake only in July, while in Upper Lake gravid females started to appear again in October. During the fall-winter season number of eggs per gravid female was significantly higher in Lower than in Upper Arrow Lake. During the 2003 season, the number of eggs per

gravid female fluctuated from 9 to 23. The number of eggs per gravid female was slightly higher in Lower Arrow. (Fig. 9.13b.). Gravid females were not present only in August 2003.

Discussion

The annual average mysid density and biomass data in 2002 and 2003 (deep stations) suggests that Upper Arrow became more productive than Lower Arrow, in comparison to previous years where productivity was higher in Lower Arrow from 1997 to 2001. The trend of higher mysid productivity in Upper basin started in 2002 and continued in the 2003 season. This annual pattern was not produced by a consistent gradient in density in Upper Arrow or Lower Arrow during the year. Rather, densities were uneven along the length of the reservoir, but averaged over the course of the year, resulted in a greater density in Upper Arrow.

The number of juvenile and immature mysids at the near-shore areas of Upper Arrow was much higher than in Lower Arrow in all seven years of study. This resulted in an along-lake pattern of higher density and biomass in Upper Arrow relative to Lower Arrow (Note: this pattern is for shallow, near-shore stations, and is the opposite of the pattern for deep stations). In 2002 and 2003 density and biomass decreased at both shallow and deep sites in Lower Arrow, while in Upper Arrow in 2002 at deep sites a slight decrease of density and biomass occurred, followed by an increase in 2003.

In comparison to other oligotrophic lakes in British Columbia that have been studied, Arrow Lakes Reservoir in the pre-fertilization period had a low mysid density. Since 1999, when the fertilization experiment started, mysid densities increased, reaching a level similar to that of more productive lakes. In 2002 a decrease of both density and biomass occurred in all three Lakes: Arrow, Kootenay and Okanagan. Mysid biomass in Arrow Lakes Reservoir was lower than in Kootenay or Okanagan Lake, but density was higher than in Kootenay Lake. In 2003 an increase in Upper Arrow and Okanagan Lake occurred, while further decrease of both density and biomass in Lower Arrow as well as in Kootenay was recorded.

Annual average fecundity measures have similar trends in both Upper and Lower Arrow. Mysids in Arrow Lakes Reservoir are most actively breeding from October to May. In 2002, the number of gravid females was higher in Lower Arrow during the spring, late summer and fall, and only in January and December more gravid females were present in Upper Arrow. In 2003, the number of gravid females did not differ in Upper and Lower Arrow, but females in Lower Arrow were most likely to carry more eggs than those in Upper Arrow.

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Figure 9.1. Annual average density (top) and biomass (bottom) of *M. relicta* in Arrow Lakes Reservoir, 1997-2003.

Figure 9.2. Monthly average density of *M. relicta* at shallow and deep sites in Upper and Lower Arrow, 1997-2003.

Figure 9.3. Density of developmental stages of *M. relictus* at shallow sites in Upper Arrow, 1997-2003.

Figure 9.4. Density of developmental stages of *M. relictus* at shallow sites in Lower Arrow, 1997-2003.

Figure 9.5. Density of developmental stages of *M. relicta* at deep sites in Upper Arrow, 1997-2003. **Note:** graph AR3 in different scale.

Figure 9.6. Density of developmental stages of *M. relictus* at deep sites in Lower Arrow, 1997-2003.

Figure 9.7. Annual average density (top) and biomass (bottom) along Arrow Lakes Reservoir, 1997-2003.

Figure 9.8. Monthly average biomass of *M. relicta* at shallow and deep sites in Upper and Lower Arrow, 1997-2003.

Figure 9.9. Biomass of developmental stages of *M. relicta* at shallow sites in Upper Arrow, 1997-2003.

Figure 9.10. Biomass of developmental stages of *M. relicta* at shallow sites in Upper Arrow, 1997-2003.

Figure 9.12. Biomass of developmental stages of *M. relicta* at deep sites in Lower Arrow, 1997-2003.

a. Monthly average proportion of gravid females in Upper and Lower Arrow, 1997-2003.

b. Monthly average number of eggs per gravid female in Upper and Lower Arrow, 1997-2003.

Figure 9.13. Fecundity features of *M. relicta* in Arrow Lakes Reservoir.

CHAPTER 10

KOKANEE HYDROACOUSTIC AND TRAWL SURVEYS, ARROW LAKES RESERVOIR FERTILIZATION EXPERIMENT YEARS 4 and 5 (2002 and 2003)

by

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Introduction

Kokanee salmon (*Oncorhynchus nerka*) are an ecologically important species in many of the large lakes of British Columbia. They occupy primarily pelagic habitat 10-60 m in depth and avoid the littoral and shallow areas. Kokanee are considered as a valuable sport fish by anglers, and provide the primary forage for larger predators such as rainbow trout (*Oncorhynchus mykiss*) and bull trout (*Salvelinus confluentus*). Management of kokanee has become a high priority in the Arrow Lakes Reservoir due to downward trends seen in stock monitoring indicators and the growing concern of local anglers.

Four indicators are currently being used to monitor kokanee in the Arrow Lakes Reservoir: acoustic surveys, trawl sampling, spawner counts and angler surveys. Acoustic and trawl surveys similar in design to those used on Kootenay and Okanagan lakes were initiated in 1988 and 1989, respectively. Acoustic surveys were conducted primarily to monitor kokanee distribution and abundance. Trawl surveys were designed to provide information on species composition, abundance and age structure of kokanee. Results of these and other surveys are summarized for the Arrow Lakes Reservoir in Sebastian et al. (2000). Trawl and acoustic surveys have shown varying rates of decline throughout the reservoir since 1994. Spawner counts declined from 630,000 in 1990 to less than 100,000 1997. Angler surveys have suggested a reduction in the catchability and abundance of kokanee from the early to late 1990s in Upper Arrow.

In 1996, a multidisciplinary project was proposed to determine if fertilization was a viable option to restore kokanee in Arrow Lakes Reservoir (Pieters et al., 1998). The study, which commenced in 1997, was modelled after the Kootenay Lake fertilization experiment (Ashley et al., 1993) and included a detailed limnological, hydrological and biological assessment of the reservoir. The standard fall monitoring of kokanee using acoustic and trawl surveys has been included as part of the larger investigation along with some additional surveys to establish baseline (pre-fertilization) kokanee distributions earlier in the season. This report summarises results of acoustic and trawl surveys conducted in October 2002 during year 4 of fertilization.

Methods

Hydroacoustic sampling

Complete night-time surveys of the pelagic habitat in Arrow Lakes Reservoir were conducted during October 5-7 concurrent with the annual trawl survey. Pelagic habitat for kokanee surveys was defined as habitat where water depth was greater than 20 meters depth at the time of survey (Pennak 1964). Acoustic surveys each consisted of 18 standard transects, 10 in the upper basin and 8 in the lower basin (Figure 10.1). Transect 18 was added to fill a gap at the top of Lower Arrow basin in 2000, and it is felt that the addition of this transect does not disrupt the trend of previous data. The 2002 survey also included 2 transects (numbers 19 and 20) in the shallow habitat between the two basins

just below the “Narrows” to assess presence and relative abundance of fish. Note the “Narrows” were too shallow, as the deepest part of the channel was less than 15m deep at the time of survey and was above the typical night time kokanee layer.

All surveys were conducted using standard methods as outlined in Sebastian et al. (1995a) using a Simrad model EY200P operating at 70 kHz. The transducer was towed on a planer alongside the boat at a depth of 1.5 m and data was collected continuously along survey lines at 1-2 pings s^{-1} while cruising at 2 $m s^{-1}$. False bottom echoes necessitated a slower ping rate (0.5-1.0 pings s^{-1}) for many of the transects. The data was converted to digital format stored on a PC computer and backed-up on Sony Digital Audio Tape (DAT). Navigation was by radar and 1:40,000 Canadian Hydrographic Service chart. The Simrad system was calibrated in the field at the beginning of each survey in both the upper and lower basins. Field calibrations were conducted by collecting target strength data from a copper sphere suspended in the center of the echosounder beam at 15-20 m from the transducer. The received signal level was adjusted to -39.1 dB which corresponds to the known strength of the sphere at 70 kHz (Appendix 10.1).

The Simrad 70 kHz survey data were digitised and then analyzed using the Hydroacoustic Data Acquisition System (HADAS) program version 3.98 by Lindem (1991). The HADAS statistical analysis performed a function similar to manual counting to determine the number of targets per unit area by depth stratum. Habitat was stratified by 5 meter depth layers and then further stratified into relatively homogeneous zones within each basin. Regression through origin of echo counts on areas sampled produced mean density and standard error values for each stratum used to develop abundance estimates (Appendix 10.4). A Monte Carlo Simulation procedure was used to determine the maximum likelihood estimates and bounds for each zone and again for the combined zones using 30,000 iterations per run. Pelagic habitat stratum areas were adjusted based on the reservoir water level at the time of the survey as outlined in Appendix 10.4 and Appendix 10.6. Mean fish densities were calculated by dividing the abundance estimates by the surface area of limnetic habitat at the time of survey. In addition, the HADAS estimated fish size distribution using a statistical deconvolution based on Craig and Forbes (1969). The resulting acoustic size distribution was used to proportion the fish population into two size classes representing age 0 fish and age 1-3 fish, respectively.

Fork lengths of trawl caught fish were converted to the same acoustic scale using Love's (1977) empirical relation and compared to acoustic size distributions in order to verify the age cut-off for the two size groups (Appendix 10.2). Since it was not possible to distinguish between age 1, 2 and 3 fish using acoustic data, the proportions of these age groups could only be based on trawl catches.

Trawl sampling

A standard trawl survey of the pelagic habitat (>20m depth) in the Arrow Reservoir was conducted during the nights of October 7-12, 2002. The survey design and sampling techniques were consistent with the kokanee stock monitoring that has been conducted

annually on the Arrow Lakes Reservoir since 1989 (Sebastian et al, 1995b). Three trawls were conducted at each site. Three trawl stations were located within each of the two main basins during October (Figure 10.1). Stepped-oblique trawls ensured a representative sample of fish was attained from each depth strata where fish were observed on the echosounder. The net was fished for 16 minutes over consecutive 5 m depth layers from beneath the observed fish layer to a few meters above the layer. The trawl net used was a 15 meter long beam trawl with a 5m by 5m square opening towed at 0.8 m s^{-1} . The net consisted of graduated mesh panels from 10 cm (stretched mesh) at the head bar to 0.6 cm at the cod end. Net depths were estimated from the cable angle and the length of cable deployed. A geographic positioning system (GPS) was used to determine distances travelled and resulting boat speed and trawl sample volumes.

Captured fish were kept on ice until processed the following morning. The species, fork length, weight, distinguishing marks (e.g. fin clips), scale code and stage of maturity were recorded. The trawl surveys provide species verification for the acoustic survey, an index of kokanee abundance, age structure and size-at-age. Using length correction factors suggested by Sebastian et al. (1995b), kokanee lengths were adjusted to an October 1 standard enabling growth comparisons with previous fall surveys (Appendix 10.3).

Results and Discussion

Water levels and habitat area

Reservoir levels during the October survey were approximately 7m below full pool. The area of limnetic habitat (>20m depth) was estimated at 19,613 ha in Upper Arrow and 9,567 ha in Lower Arrow (Appendix 10.6). The 7 meter draw-down in October reduced the area of limnetic habitat by 2% in Upper Arrow and 6% in Lower Arrow compared to full pool areas.

Trawl Catches

Trawl sampling confirmed that the large majority of fish observed at depth on the echosounder were kokanee during the October 2002 survey. A total of 443 kokanee and 3 pygmy whitefish were captured. Combined catches in Upper and Lower Arrow suggested an approximate age contribution of 60% age 0, 26% age 1 and 13% age 2 kokanee (Table 10.1). Compared with Upper Arrow, catch rates in Lower Arrow were slightly higher for age 0 and 1 kokanee but nearly 2.5 times higher for age 2 fish indicating their densities were higher.

Table 10.1. Kokanee catch statistics from the October trawl survey in 2002.

Basin	Station	Hauls	Age 0	age 1	age 2	Age 3	Total
Upper Arrow	T1 Albert Pt.	3	76	30	12		118
	T2 Halfway R.	3	18	3	3		24
	T3 Nakusp	3	35	21	2		58
	Total of Upper	9	129	54	17		200
	<i>Percent (%) by age</i>		65	27	8		100
Lower Arrow	T4 Johnston Cr.	3	39	7	13		59
	T5 Bowman Cr.	3	41	13	14		68
	T6 Cayuse Cr.	3	59	41	15	1	116
	Total of Lower	9	139	61	42	1	243
	<i>Percent (%) by age</i>		57	25	17	0.5	100
Total Arrow	Both basins	18	268	115	59	1	443
	<i>Percent (%) by age</i>		60.5	26.0	13.3	0.2	100

Fish size and age

Age interpretations in this report were based on fish length and scale interpretation. Differences in fish size at age were evident between Upper and Lower Arrow basins so length frequency distributions have initially been shown separately (Figures 10.2). The mean length-at-age for Upper Arrow kokanee in October were estimated at 54, 124 and 178 mm for age 0, 1 and 2 fish respectively (Table 10.2). In Lower Arrow the mean length-at-age were 57, 121, 195 and 208 mm for age 0, 1, 2 and 3 fish respectively.

As in 2001, the length frequencies were unimodal for age 0 and age 2 kokanee in 2002 making age analyses relatively straight forward (Fig. 10.2). Age 1 size distributions were again bimodal and were typical of other kokanee populations. Trends in mean length at age from trawl sampling showed that growth rates achieved a maximum in 1999 during the first year of fertilization while the total numbers of kokanee remained relatively low. As the numbers of kokanee increased to 20 million in 2001 growth rates declined and by 2002 the mean length-at-age had declined to pre-fertilization levels (Fig. 10.3). The decrease in mean length-at-age during 2002 represents a return to some of the lowest pre-fertilization growth rates observed in this reservoir.

Table 10.2. Kokanee size statistics from the October trawl survey, 2002.

Survey time	Basin	Station	age 0	age 1	age 2	age 3
October 2002	Upper Arrow	Ave. length (mm)	54	124	178	
		Length range (mm)	39-80	76-145	164-193	
		Standard deviation	6.4	19.8	8.1	
		Sample size (n)	129	54	17	
	Lower Arrow	Ave. length (mm)	57	121	195	208
		Range (mm)	44-68	87-173	178-230	
		Standard deviation	4.8	24.7	9.1	
		Sample size (n)	139	61	42	1

Age at maturity

There was considerable size overlap between age 2 fish (based on scale ages) caught in the trawl and the spawners returning to Hill Creek in 2002 indicating a strong likelihood of age 2 spawners again in 2002 (Fig. 10.4). A second mode of spawners at 24cm may represent a weaker age 3 component of the 2002 spawners. Compared with the 2001 estimate of 50% age 2 spawners based on their bi-modal length distribution, it would appear that there has been a further shift in the age of maturity from age 3 to age 2. It may be possible to verify this shift in average age at maturity with otolith interpretation. An increase in the numbers of spawners returning in 2001 and 2002 may be partly a result of the shift in age at maturity since fertilization began.

Fish Density distributions

Kokanee density ranged from 300 – 1450 fish·ha⁻¹ in October in Upper Arrow compared with 300–1000 fish·ha⁻¹ the previous year. Both fry and age 1-3 kokanee density was higher in the upper half of the basin at sites 1-5 (i.e, Beaton Arm and the Shelter Bay area). The most notable change since fertilization was the low number of age 1-3 fish·ha⁻¹ in the middle of the basin from Halfway River south to Nakusp at only 100 fish·ha⁻¹ (Fig. 10.5; Appendix 10.5). These densities were more typical of pre-fertilization densities in the same area. Compared to Upper Arrow, kokanee densities were again higher and more variable in Lower Arrow. Similar to 2001 the small basins between the Narrows and Lower Arrow had very high fry densities at 1300–3100 fish·ha⁻¹. In the main part of Lower Arrow kokanee fry densities were comparable to Upper Arrow but age 1-3 densities were notably higher. This was supported by trawl sampling which indicated that age 2 fish were more abundant in Lower Arrow. This too was typical of Lower Arrow which historically has been more productive than Upper Arrow particularly for older larger kokanee. Basin mean densities for October were 651 and 856 fish·ha⁻¹ for Upper and Lower Arrow, respectively (Table 10.4).

The vertical distribution of fish can be important when quantifying fish with hydroacoustic gear. Fish near the bottom or the surface make it more difficult to get reliable estimates of total abundance. The vertical density distributions in October 2002 showed a definite night-time fish layer present in both basins (Figs. 10.6 and 10.7), with the majority of both fry and larger fish in both basins found between 20-30m depth. This was an ideal depth for quantifying fish using a downward looking towed transducer. Similar to previous fall suveys, the fish appeared to be slightly deeper in Lower Arrow suggesting a deeper thermocline in Lower Arrow at the time of survey. In both basins there was only a slight tendency for age 0 fish to be found shallower than age 1-3 fish.

Abundance estimates

Kokanee abundance in the Arrow Lakes Reservoir was estimated at 20.1 million (18.1 – 23.2) and was very similar to the October 2001 estimate of 20.0 million (Table 10.3). The

relative contribution of 12.5 million from Upper Arrow was slightly lower than in 2001 although differences were not statistically significant.

Table 10.3. Maximum likelihood abundance estimates (MLE) and statistical bounds (95% C.L.) for Arrow Lakes Reservoir kokanee during October 2001 and 2002.

Location	Statistic	October 2001	October 2002
Upper Arrow	MLE in millions (range: 95% C. L.)	13.4 (12.2-14.6)	12.5 (11.3-13.6)
Lower Arrow	MLE in millions (range: 95% C. L.)	6.5 (5.5-7.52)	7.7 (5.9-9.6)
Arrow Reservoir (total basin)	MLE in millions (range: 95% C. L.)	20.0 (18.3-21.4)	20.1 (18.1-22.3)

Although age 0 fish were relatively abundant in 2002 the number of fry did not increase in proportion to the number of spawners in 2001. Fry proportions in 2002 were lower than 2001 and were indicative of a stable rather than building population. The apparent levelling off of the upward trend in fish abundance since fertilization began may indicate that Arrow Lakes Reservoir has reached a new capacity for the current state of nutrient restoration (Fig. 10.8). The second consecutive year of declining growth rates in Upper Arrow Lakes Reservoir may in fact be evidence that capacity has been exceeded at the current abundance of 20 million kokanee. Another measure of fertilization success may be biomass of kokanee spawners produced since there may be no added biological benefit for prey species in production of more kokanee if the size and fecundity continues to decline.

Acoustic size analysis

Single beam de-convolution techniques were used in these surveys to separate kokanee into two size groups corresponding to age 0 and age 1-3 fish, respectively. The peak size of trawl caught age 0 fish, converted to acoustic units using Love's (1977) empirical formula, were -50 decibels (dB) in October, and were similar to the peak fry size (-53dB) suggested by the acoustic data (Fig. 10.9).

Trawl sampling indicated that fry size ranged from 39 to 80mm in October (Table 10.2) and suggested a cut-off of about -47dB for separating age 0 from the larger age 1-3 fish. This cut-off appeared to be reasonable for both Upper and Lower Arrow acoustic size distributions (Fig 10.10). In fact, the proportions of fry (to total fish) suggested by the acoustic cut-off method and the raw trawl catches were remarkably similar (Table 10.4). The acoustic size distributions between the two basins were also quite similar but suggested that there were slightly higher proportions of larger fish in Lower Arrow (Fig.

10.10). This was consistent with trawl catches which caught more age 2 fish in Lower Arrow and showed a slightly higher proportion of age 1-3 fish than in the Upper basin.

Table 10.4. Kokanee proportion, abundance and mean density by age group for Upper and Lower Arrow Lakes Reservoir during October 2002.

Location	Age group	Proportion (by age)		Abundance and density	
		Acoustic (%)	Trawl (%)	Number (millions)	Density (Fish/ha) ¹
Upper Arrow	Age 0	65	65	8.76	457
	Age 1-3	35	35	3.71	194
	Total	100	100	12.47	651
Lower Arrow	Age 0	59	57	4.80	536
	Age 1-3	41	43	2.87	320
	Total	100	100	7.67	856
Total Arrow ²	Age 0			13.56	
	Age 1-3			6.58	
	Total			20.14	

1. Mean basin densities were based on reservoir area at the average depth of the fish layer (Figure 10.7).

2. Total abundance for combined reservoirs are based on Monte Carlo estimates for individual basins.

Recommendations:

1. Continue monitoring kokanee distribution and abundance by size (age) groups using annual acoustic surveys during fall.
2. Continue monitoring kokanee growth (i.e., mean length-at-age) from trawl sampling as near to October 1 as sampling schedules permit.
3. Continue annual spawner enumeration in both Upper and Lower Arrow tributaries.
4. Continue biological sampling of spawners at Hill Creek to determine kokanee size distributions, mean size and fecundity. Some additional monitoring of spawner size distributions in Lower Arrow streams would be informative as well.

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Figure 10.1. Arrow Lakes Reservoir showing hydroacoustic transects and trawl station locations for surveys conducted in October of 2002.

Figure 10.2. Length-frequency of trawl caught kokanee by age in a) Upper and b) Lower Arrow Lakes Reservoir during October 2002.

Figure 10.3. Trends in kokanee mean length at age for a) Upper Arrow and b) Lower Arrow Lakes Reservoir based on trawl caught fish from 1989-2002. Note trawl fish lengths have been corrected to October 1. Upper Arrow spawners obtained from Hill Creek Spawning Channel.

Figure 10.4. Kokanee length-frequency distributions by age for trawl caught fish in Arrow Lakes Reservoir and returning spawners to Hill Creek for 2002.

Figure 10.5. Density distributions of age 0 and age 1-3 kokanee by transects from the October 2002 acoustic survey. Note: transects are in order from north to south (Number 18 is a new transect at the upper end of Lower Arrow; Numbers 19 and 20 are located in Reach 2 just below the Narrows).

Figure 10.6. Vertical distribution of kokanee densities by transects from the October 2002 acoustic survey. Transects 1-18 are shown as these are used to develop population estimates. Densities are given for subsequent 5m bins, namely the depth marked 20 m gives the density from 20-25m.

Figure 10.7. Proportions of age 0 and age 1-3 kokanee by depth from 2002 acoustic surveys.

Figure 10.8. Kokanee abundance estimates (all ages) for Arrow Lakes Reservoir (combined upper and lower basins), Upper and Lower Arrow from annual fall acoustic surveys, 1988-2002.

Figure 10.9. Comparison of fish size distributions from acoustic and trawl surveys on Arrow Lakes Reservoir in October 2002. Note: Love's (1977) dorsal-aspect formula used to convert fish size in mm to the acoustic scale (decibels).

Figure 10.10. Acoustic strength (length) distribution of kokanee in Upper and Lower Arrow Lakes Reservoir in October 2002.

APPENDIX 10.1 Equipment and Data Processing Specifications

a) Echosounder Specifications and Field Settings:

Description	SIMRAD EY200P-P
transducer type	Single beam 70 kHz
beam angle	11.6 degree
receiver gain	3 (0 dB)
pulse width (msec)	0.3
ping rate (p/sec)	medium (1.5)
time varied gain	40 log r
TVG range (m)	2 to 66
Attenuation	-15 dB
Power	1/1
Calibration	2 min. AC tone
Tape recorder	Sony TCD-D10
Record volume	3.5 fixed

b) Data Processing Specifications

Description	HADAS version 3.98
Interface gain	calibration tone to intersect 2 volts at 50 milliseconds
Threshold	minimum detectable target approximately - 65 dB
Field calibrations	Date, peak sphere voltage, sphere depth and threshold used for survey Oct. 5, 2002 Upper Arrow 3800mV, sphere at 20m., threshold 200mV Oct. 7, 2002 Lower Arrow 3800mV, sphere at 20m., threshold 200mV
Lab calibration	July 8 1998, Applied Physics Laboratory UWA

APPENDIX 10.2 Love's (1977) empirical relation of fish length to acoustic target strength

$$TS = 19.1 \log_{10}(L) - 0.9 \log_{10}(F) - 62 \text{ where } TS = \text{target strength in decibels (dB),}$$

$$L = \text{length in cm and } F = \text{frequency in kHz}$$

HADAS size class (db) ¹	Acoustic size range (dB)		Fish length range ² (mm)	
-35	-35	-33.1	317	500+
-38	-38	-35.1	221	317
-41	-41	-38.1	154	221
-44	-44	-41.1	107	154
-47	-47	-44.1	75	107
-50	-50	-47.1	52	75
-53	-53	-50.1	36	52
-56	-56	-53.1	25	36
-59	-59	-56.1	18	25
-62	-62	-59.1	12	18

1 HADAS was set up to view 30 dB range in 10 size classes of 3 dB

2 from Love's (1977) empirical formula (Dorsal aspect).

APPENDIX 10.3 Kokanee length correction factors for Arrow Lakes Reservoir.

Correction factors for >180 mm fish and for 100-180 mm fish are from Rieman (1992). Correction factors for <100 mm fish were derived from Okanagan Lake trawl samples collected during 1988-93.

Date	> 180 mm	100 - 180 mm	<100 mm	Date	> 180 mm	100 - 180 mm	<100 mm
1-Sep	1.025	1.064	1.090	7-Oct	1.000	1.000	0.982
2-Sep	1.023	1.061	1.087	8-Oct	1.000	1.000	0.979
3-Sep	1.021	1.058	1.084	9-Oct	1.000	1.000	0.976
4-Sep	1.020	1.056	1.081	10-Oct	1.000	1.000	0.973
5-Sep	1.018	1.053	1.078	11-Oct	1.000	1.000	0.970
6-Sep	1.016	1.050	1.075	12-Oct	1.000	1.000	0.967
7-Sep	1.014	1.047	1.072	13-Oct	1.000	1.000	0.964
8-Sep	1.012	1.044	1.069	14-Oct	1.000	1.000	0.961
9-Sep	1.011	1.042	1.066	15-Oct	1.000	1.000	0.958
10-Sep	1.009	1.039	1.063	16-Oct	1.000	1.000	0.955
11-Sep	1.007	1.036	1.060	17-Oct	1.000	1.000	0.952
12-Sep	1.005	1.033	1.057	18-Oct	1.000	1.000	0.949
13-Sep	1.003	1.030	1.054	19-Oct	1.000	1.000	0.946
14-Sep	1.002	1.028	1.051	20-Oct	1.000	1.000	0.943
15-Sep	1.000	1.025	1.048	21-Oct	1.000	1.000	0.940
16-Sep	1.000	1.023	1.045	22-Oct	1.000	1.000	0.936
17-Sep	1.000	1.022	1.042	23-Oct	1.000	1.000	0.933
18-Sep	1.000	1.020	1.039	24-Oct	1.000	1.000	0.930
19-Sep	1.000	1.018	1.036	25-Oct	1.000	1.000	0.927
20-Sep	1.000	1.017	1.033	26-Oct	1.000	1.000	0.924
21-Sep	1.000	1.015	1.030	27-Oct	1.000	1.000	0.921
22-Sep	1.000	1.013	1.027	28-Oct	1.000	1.000	0.918
23-Sep	1.000	1.011	1.024	29-Oct	1.000	1.000	0.915
24-Sep	1.000	1.010	1.021	30-Oct	1.000	1.000	0.912
25-Sep	1.000	1.008	1.018	31-Oct	1.000	1.000	0.909
26-Sep	1.000	1.006	1.015	1-Nov	1.000	1.000	0.906
27-Sep	1.000	1.005	1.012	2-Nov	1.000	1.000	0.903
28-Sep	1.000	1.003	1.009	3-Nov	1.000	1.000	0.900
29-Sep	1.000	1.001	1.006	4-Nov	1.000	1.000	0.897
30-Sep	1.000	1.000	1.003	5-Nov	1.000	1.000	0.894
1-Oct	1.000	1.000	1.000	6-Nov	1.000	1.000	0.891
2-Oct	1.000	1.000	0.997	7-Nov	1.000	1.000	0.888
3-Oct	1.000	1.000	0.994	8-Nov	1.000	1.000	0.885
4-Oct	1.000	1.000	0.991	9-Nov	1.000	1.000	0.882
5-Oct	1.000	1.000	0.988	10-Nov	1.000	1.000	0.879
6-Oct	1.000	1.000	0.985	11-Nov	1.000	1.000	0.876

APPENDIX 10.4A Maximum likelihood estimates and bounds for all fish in October 2002 Arrow Lakes Reservoir surveys based on Monte Carlo Simulations.

October 2002 Systat coefficients for fish >-62 dB in 3 zones (zone 1: transects 1-5+10; zone 2: 6-9; zone 3: transects 11-18)									
Zone	Depth	N	R2	Density	Std Dev	Area	Stratum population	Statistic ¹	Abundance
1	5	5	0.954	25.784	2.836	11539	297,516	LB=	11,310,000
1	10	5	0.932	49.539	6.689	11173	553,481	Upper MLE=	12,470,000
1	15	6	0.922	113.650	14.793	10903	1,239,173	Basin UB=	13,630,000
1	20	5	0.923	200.897	28.917	10672	2,144,009	LB=	5,880,000
1	25	5	0.954	328.124	36.085	10441	3,425,925	Lower MLE=	7,670,000
1	30	5	0.895	131.626	22.491	10210	1,343,864	Basin UB=	9,550,000
1	35	5	0.897	36.714	6.236	9978	366,350	LB=	18,050,000
1	40	5	0.828	11.100	2.527	9747	108,194	Total MLE=	20,120,000
1	45	5	0.583	3.575	1.512	9529	34,068	UB=	22,320,000
1	50	5	0.717	1.999	0.628	9315	18,621		
2	5	3	0.838	15.013	4.660	9282	139,355		
2	10	3	0.961	32.356	4.586	9020	291,837		
2	15	3	0.998	66.407	1.907	8899	590,974		
2	20	3	0.939	80.278	14.428	8815	707,618		
2	25	3	0.999	89.651	1.473	8730	782,647		
2	30	3	0.936	35.314	6.539	8645	305,299		
2	35	3	0.966	9.340	1.242	8561	79,956		
2	40	3	0.981	2.907	0.287	8476	24,640		
3	5	7	0.491	6.481	2.693	10779	69,859		
3	10	7	0.530	10.435	4.011	10274	107,209		
3	15	7	0.822	23.165	4.399	9827	227,633		
3	20	7	0.685	175.532	48.642	9394	1,648,877		
3	25	7	0.710	288.839	75.273	8961	2,588,171		
3	30	8	0.778	226.095	45.588	8528	1,928,048		
3	35	7	0.751	86.190	20.283	8095	697,674		
3	40	7	0.605	27.540	9.090	7662	211,000		
3	45	8	0.568	21.178	6.974	7320	155,022		
3	50	7	0.676	7.983	2.256	7001	55,890		

* Each basin is divided into *zones* for the analysis. Zones are determined using Figure 10.6. Zones typically, though not always, correspond to the Upper and Lower Arrow basins. For example, Beaton Arm, would, in certain years, need to be a separate zone.

Reservoir level elevation was 433m in October, 2002.

Depths indicate upper bounds of 5 meter depth strata.

Areas in October were based on 7m below full pool and 2 m to center of strata (down 9m in total).

¹ Key: LB=Lower bounds, UB=Upper bounds, MLE=Maximum likelihood estimate

APPENDIX 10.4B Maximum likelihood estimates and bounds for big fish (>-47dB) in October 2002 Arrow Lakes Reservoir surveys based on Monte Carlo Simulations.

October 2002 Systat coefficients for fish >-47 dB in 3 zones (zone 1: transects 1-5+10; zone 2: 6-9; zone 3: transects 11-18)									
Zone	Depth	N	R2	Density	Std Dev	Area	Stratum population	Statistic ²	Abundance
1	10	5	0.989	5.239	0.281	11173	58,533	LB=	2,970,000
1	15	5	0.829	23.658	5.353	10903	257,953	Upper MLE=	3,710,000
1	20	5	0.855	85.968	17.680	10672	917,466	Basin UB=	4,420,000
1	25	5	0.794	107.523	27.356	10441	1,122,642	LB=	2,240,000
1	30	5	0.763	42.499	11.837	10210	433,903	Lower MLE=	2,870,000
1	35	5	0.838	10.434	2.297	9978	104,115	Basin UB=	3,620,000
1	40	5	0.640	2.218	0.832	9747	21,619	LB=	5,630,000
1	45	6	0.398	2.041	1.123	9529	19,450	Total MLE=	6,740,000
2	15	3	0.862	9.754	2.764	8899	24,598	UB=	7,620,000
2	20	3	0.987	31.870	2.569	8815	280,921		
2	25	3	0.992	36.814	2.388	8730	321,384		
2	30	3	0.918	12.811	2.698	8645	110,755		
2	35	3	0.836	1.814	0.568	8561	15,529		
2	40	3	0.809	1.219	0.418	8476	10,332		
3	10	7	0.382	0.786	0.408	10274	8,075		
3	15	8	0.45	2.55	1.06	9827	25,038		
3	20	7	0.657	36.278	10.705	9394	340,781		
3	25	7	0.718	116.034	29.703	8961	1,039,734		
3	30	7	0.816	110.45	21.439	8528	941,873		
3	35	7	0.677	39.787	11.217	8095	322,060		
3	40	7	0.758	24.276	5.605	7662	185,993		
3	45	8	0.561	7.043	2.357	7320	51,554		
3	50	7	0.473	2.124	0.915	7001	14,870		

² Key: LB=Lower bounds, UB=Upper bounds, MLE=Maximum likelihood estimate

APPENDIX 10.5 Summaries of fish density (number/ha) by transect for 2002 acoustic analysis.

October 2002			
Transect number	All ages	Age 0	Age 1-3
1	696	533	163
2	1448	1170	277
3	721	480	241
4	1306	611	695
5	873	468	405
6	375	272	103
7	311	222	89
8	440	345	96
9	372	264	108
10	1245	671	575
11	587	425	162
12	731	349	383
13	1662	357	1305
14	473	261	212
15	1238	641	597
16	734	464	270
17	621	262	359
18 ^a	3818	3082	736
19 ^b	1507	1438	69
20 ^b	1606	1340	266

a. Transect No. 18 is new and is used with #11-17 to estimate Lower Arrow abundance

b. Transects 19 and 20 are in Reach 2 below the Narrows and are used for qualitative information only at this time.

APPENDIX 10.6 Habitat areas for kokanee

a) Water level and limnetic habitat areas in Arrow Lakes Reservoir during acoustic surveys

Survey Dates		Water level	Habitat area >20 m depth (km ²)		
Year	Month / day	(m)	Upper Arrow	Lower Arrow	Total
2002	Oct 5-7	433.02	196	96	292

b) Reach map and surface area estimates by Reach at full pool from three different sources: Canadian Hydrographic Series, Pieters (1998) and Fisheries GIS mapbase.

Reach No.	Reservoir description	Hydrographic Charts (digitized) ¹ (ha)	<i>Pieters et al</i> (1998) (ha)	<i>Fisheries</i> Victoria (GIS) ² (ha)
1 and 2	Lower Arrow basin ³	15,493	17,724	17,113
3	Narrows	2,200		3,374
4	Upper Arrow basin ⁴	19,298	30,600	21,327
5	Beaton Arm ⁴	3,284		3,150
6	Revelstoke Reach ("flats")	6,437		6,981
Total		46,712	47,724	51,945

1 These estimates were used for expanding the acoustic/ trawl populations.

2. GIS Applications Unit, Fisheries Victoria used Arcview based on 1:50,000 scale polygons, April, 1999.

3. Includes 3,300 ha of shallow habitat (reach 2) which were not used in acoustic population estimates.

Total Lower Arrow habitat included in acoustic population estimates is 12,193 ha

Note: Narrows and Revelstoke reaches also not included in acoustic estimates (too shallow)

4. Total Upper Arrow acoustic habitat areas include reaches 4 & 5

APPENDIX 10.6 continued

c) Habitat area estimates by depth strata used for acoustic population estimates.

Depth (m) from surface	Revelstoke Reach	Upper Arrow	Narrows	Lower Arrow	Depth (m) from surface	Upper Arrow	Lower Arrow
full pool	6437	22,582	5,500	12,193	41	18,729	8,354
1		22,456		12,092	42	18,665	8,268
2		22,330		11,991	43	18,602	8,181
3		22,205		11,890	44	18,539	8,095
4		22,079		11,789	45	18,476	8,008
5		21,953		11,688	46	18,413	7,921
6		21,827		11,587	47	18,350	7,835
7		21,702		11,486	48	18,286	7,748
8		21,576		11,385	49	18,223	7,662
9		21,450		11,284	50	18,160	7,575
10		21,324		11,183	51	18,068	7,511
11		21,198		11,082	52	17,977	7,447
12		21,073		10,981	53	17,885	7,384
13		20,947		10,880	54	17,794	7,320
14		20,821		10,779	55	17,702	7,256
15		20,695		10,678	56	17,611	7,192
16		20,570		10,577	57	17,519	7,129
17		20,444		10,476	58	17,427	7,065
18		20,318		10,375	59	17,336	7,001
19		20,192		10,274	60	17,244	6,937
20		20,055		10,173	61	17,153	6,874
21		19,992		10,086	62	17,061	6,810
22		19,929		10,000	63	16,969	6,746
23		19,866		9,913	64	16,878	6,682
24		19,803		9,827	65	16,786	6,619
25		19,739		9,740	66	16,695	6,555
26		19,676		9,653	67	16,603	6,491
27		19,613		9,567	68	16,512	6,427
28		19,550		9,480	69	16,420	6,364
29		19,487		9,394	70	16,328	6,300
30		19,424		9,307	71	16,237	6,236
31		19,360		9,220	72	16,145	6,172
32		19,297		9,134	73	16,054	6,109
33		19,234		9,047	74	15,962	6,045
34		19,171		8,961	75	15,870	5,981
35		19,108		8,874	76	15,779	5,917
36		19,045		8,787	77	15,687	5,853
37		18,981		8,701	78	15,596	5,790
38		18,918		8,614	79	15,504	5,726
39		18,855		8,528	80	15,413	5,662
40		18,792		8,441			

Data interpolated from Canadian Hydrographic Service charts: # 3056, 3057 and 3058,
Areas are in Hectares (Ha.); Full pool elevation reference 440.24 m

Introduction

Kokanee salmon (*Oncorhynchus nerka*) are an ecologically important species in many of the large lakes of British Columbia. They occupy primarily limnetic habitat 10-60 m in depth and avoid the littoral and shallow areas. Kokanee are considered as a valuable sport fish by anglers, and provide the primary forage for larger predators such as rainbow trout (*Oncorhynchus mykiss*) and bull trout (*Salvelinus confluentus*). Management of kokanee has become a high priority in the Arrow Reservoir due to downward trends seen in stock monitoring indicators and the growing concern of local anglers.

Four indicators are currently being used to monitor kokanee in the Arrow Reservoir: acoustic surveys, trawl sampling, spawner counts and angler surveys. Acoustic and trawl surveys similar in design to those used on Kootenay and Okanagan lakes were initiated in 1988 and 1989, respectively. Acoustic surveys were conducted primarily to monitor kokanee distribution and abundance. Trawl surveys were designed to provide information on species composition, relative abundance, growth and age structure of kokanee. Results of these and other surveys up to 1998 are summarized for the Arrow Lakes Reservoir in Sebastian et al. (2000). Trawl and acoustic surveys have shown varying rates of decline throughout the reservoir since 1994. Spawner counts declined from 630,000 in 1990 to less than 100,000 in 1997. In 1996, a multidisciplinary project was proposed to determine if fertilization was a viable option to restore kokanee in Arrow Reservoir (Pieters et al., 1998). The study, which commenced in 1997, was modelled after the Kootenay Lake fertilization experiment (Ashley and Thompson, 1993) and included a detailed limnological, hydrological and biological assessment of the reservoir. The standard fall monitoring of kokanee using acoustic and trawl surveys has been included as part of the larger investigation along with some additional surveys to establish baseline (pre-fertilization) kokanee distributions earlier in the season. This report summarises results of acoustic and trawl surveys conducted in September 2003 during year 5 of fertilization.

Methods

Habitat Areas

Habitat area estimates for surface area, limnetic area and for 5 meter depth strata used in developing fish abundance estimates were based on water surface elevation at the time of survey (Appendix 10.7).

Trawl sampling

A standard trawl survey of the limnetic habitat (>20 m depth) in the Arrow Reservoir was conducted during the nights of September 23-29, 2003. The survey design and sampling techniques were consistent with the kokanee stock monitoring that has been conducted annually on the Arrow Reservoir since 1989 (Sebastian et al. 2000). Three trawl stations

were located within each of the two main basins (Fig.10.11) and three trawls were conducted at each station during October. Stepped-oblique trawls ensured a representative sample of fish was attained from each depth strata where fish were observed on the echosounder. The net was fished for 16 minutes over consecutive 5 m depth layers from beneath the observed fish layer to a few meters above the layer. The trawl net used was a 15 meter long beam trawl with a 5 m by 5 m square opening towed at 0.8 m s^{-1} . The net consisted of graduated mesh panels from 10 cm (stretched mesh) at the head bar to 0.6 cm at the cod end. Net depths were estimated from the cable angle and the length of cable deployed. A geographic positioning system (GPS) was used to determine distances travelled and resulting boat speed and trawl sample volumes.

Captured fish were kept on ice until processed the following morning. The species, fork length, weight, distinguishing marks (e.g. fin clips), scale code and stage of maturity were recorded. The trawl surveys provide species verification for the acoustic survey, an index of kokanee abundance, age structure and size-at-age. Using length correction factors suggested by Sebastian et al. (1995b), kokanee lengths were adjusted to an October 1 standard enabling growth comparisons with previous fall surveys (Appendix 10.8).

Hydroacoustic sampling

Complete night-time surveys of the limnetic habitat in Arrow Reservoir were conducted during September 27-29 concurrent with the annual trawl survey. Limnetic habitat for kokanee surveys was defined as habitat where water depth was greater than 20 meters depth at the time of survey (Pennak 1964). Acoustic surveys each consisted of 18 standard transects, 10 in the upper basin and 8 in the lower basin (Fig. 10.11). The 2003 survey also included 2 transects (numbers 19 and 20) in the shallow habitat between the two basins just below the “Narrows” to assess presence and relative abundance of fish. Note: the “Narrows” were too shallow, as the deepest part of the channel was $<15 \text{ m}$ deep at the time of survey, far too shallow for the typical night time kokanee layer.

All surveys were conducted using standard methods as outlined in Sebastian et al. (1995a) using a Simrad model EY200P operating at 70 kHz. The transducer was towed on a planer alongside the boat at a depth of 1.5 m and data was collected continuously along survey lines at 1-2 pings s^{-1} while cruising at 2 m s^{-1} . False bottom echoes necessitated a slower ping rate (0.5-1.0 pings s^{-1}) for many of the transects. The data was converted to digital format stored on a PC computer and backed-up on Sony Digital Audio Tape (DAT). Navigation was by radar and 1:40,000 Canadian Hydrographic Service chart. The Simrad system was calibrated in the field at the beginning of each survey in both the upper and lower basins. Field calibrations were conducted by collecting target strength data from a copper sphere suspended in the center of the echosounder beam at 15-20 m from the transducer. The received signal level was adjusted to -39.1 dB which corresponds to the known strength of the sphere at 70 kHz (Appendix 10.9).

The Simrad 70 kHz survey data were digitised and then analyzed using the Hydroacoustic Data Acquisition System (HADAS) program version 3.98 by Lindem

(1991). The HADAS statistical analysis performed a function similar to manual counting to determine the number of targets per unit area by depth stratum. Habitat was stratified by 5 m depth layers and then further stratified into relatively homogeneous zones within each basin. Regression through origin of echo counts on areas sampled produced mean density and standard error values for each stratum used to develop abundance estimates (Appendix 10.10). A Monte Carlo Simulation procedure was used to determine the maximum likelihood estimates and bounds for each zone and again for the combined zones using 30,000 iterations per run. Limnetic habitat stratum areas were adjusted based on the reservoir water level at the time of the survey as outlined in Appendix 1 and Appendix 4. Mean transect fish densities are summarized in Appendix 14.11. Overall mean basin fish densities were calculated by dividing the abundance estimates by the area of limnetic habitat at the time of survey. In addition, the HADAS estimated fish size distribution using a statistical deconvolution based on Craig and Forbes (1969). The resulting acoustic size distribution was used to proportion the fish population into two size classes representing age 0 fish and age 1-3 fish, respectively.

Fork lengths of trawl caught fish were converted to the same acoustic scale using Love's (1977) empirical relation (Appendix 10.12) and compared to acoustic size distributions in order to verify the age cut-off for the two size groups. Since it was not possible to distinguish between age 1, 2 and 3 fish using acoustic data, the proportions of these age groups could only be based on trawl catches.

Results

Water levels and habitat area

Reservoir levels during the September survey were 6.3 m below full pool. The area of limnetic habitat (>20m depth) was estimated at 19,676 ha in Upper Arrow and 9,653 ha in Lower Arrow (Appendix 10.7). The 6 meter draw-down in September reduced the area of limnetic habitat at full pool by 2% in Upper Arrow and 5% in Lower Arrow compared to full pool areas.

Trawl Catches

Trawl sampling confirmed that the large majority (97%) of fish observed at depth on the echosounder were kokanee during the September 2003 survey. A total of 267 kokanee and 7 pygmy whitefish were captured. Combined catches in Upper and Lower Arrow suggested an approximate age contribution of: 32% age 0, 48% age 1 and 20% age 2 and older kokanee (Table 10.5). Compared with the previous year, catch rates for age 0 fish were much lower in both basins during 2003, suggesting a decline in age 0 abundance, while

Table 10.5. Kokanee catch statistics from the September trawl survey in 2003.

Basin	Station	Hauls	age 0	age 1	age 2	age 3	Total
Upper Arrow	T1 Albert Pt.	3	19	12	7		38
	T2 Halfway R.	3	16	36	7		59
	T3 Nakusp	3	17	37	8		62
	Total of Upper	9	52	85	22		159
	<i>Percent (%) by age</i>		<i>33</i>	<i>53</i>	<i>14</i>		<i>100</i>
Lower Arrow	T4 Johnston Cr.	3	16	7	1		24
	T5 Bowman Cr.	3	1	6	16	2	25
	T6 Cayuse Cr.	3	17	30	12		29
	Total of Lower	9	34	43	29	2	108
	<i>Percent (%) by age</i>		<i>31</i>	<i>40</i>	<i>27</i>	<i>2</i>	<i>100</i>
Total Arrow	Both basins	18	86	128	51	2	267
	<i>Percent (%) by age</i>		<i>32</i>	<i>48</i>	<i>19</i>	<i>1</i>	<i>100</i>

the total catch rate for age 1 and age 2 fish was comparable to those of the previous two years.

Fish size and age

Age interpretations in this report were based on fish length and scale interpretation. Differences in fish size at age were evident between Upper and Lower Arrow basins so length frequency distributions are shown separately (Fig. 10.12). The mean length-at-age for Upper Arrow kokanee in September was estimated at 55, 133 and 168 mm for age 0, 1 and 2 fish respectively (Table 10.6). In Lower Arrow the mean length-at-age was 63, 127, 196 and 213 mm for age 0, 1, 2 and 3 fish respectively. Growth rates for age 0+ and 2+ kokanee were better in Lower Arrow compared to Upper Arrow in 2003 and were comparable to pre-fertilization conditions. The larger average size of age 1+ fish in Upper Arrow, however, appears to be a contradiction, particularly since their numbers were also higher compared with Lower Arrow as indicated by the trawl catches. The length frequency distributions show bimodal size distributions for age 1 fish in both Upper and Lower Arrow. Bimodality is common for age 1 kokanee in many lakes and can possibly be explained by a change in their feeding strategy. Fry typically feed only at dawn and

Table 10.6. Kokanee size statistics from the September trawl survey, 2003.

Survey time	Basin	Station	age 0	age 1	age 2	age 3
September 2003	Upper Arrow	Ave. length (mm)	55	133	168	
		Length range (mm)	36-83	82-168	155-183	
		Standard deviation	12.0	16.8	7.2	
		Sample size (n)	52	85	22	0
	Lower Arrow	Ave. length (mm)	63	127	196	213
		Range (mm)	48-90	95-171	180-215	212-214
		Standard deviation	11.3	22.6	8.0	1.3
		Sample size (n)	34	43	29	2

dusk under the cover of darkness and spend daylight hours deep to avoid predation. Age 2+ fish are required to feed more often so will venture into the epilimnion during the daytime to feed. Length distributions would suggest that the majority of age 1+ fish in Upper Arrow in 2003 had switched to the age 2+ feeding strategy and grew more rapidly than the age 1+ fish in Lower Arrow.

Trends in mean length at age show a levelling off or very slight increase in size for most age groups in 2003 following two years of declining size during 2001 and 2002 (Fig. 10.13). The declining size in 2001 and 2002 was most likely a result of the higher densities of age 1-3 fish following initial fertilization. The levelling off of growth in 2003 may reflect a density growth response since densities of ages 1-3 fish appear to have reached a maximum and have levelled off (Fig. 10.19). If so, it is expected that growth will improve in 2004 as age 1-3 densities decline due to lower fry numbers in 2003.

Age at maturity

There was little size overlap between age 2 fish caught in the trawl in Upper Arrow Reservoir and the spawners returning to Hill Creek in 2003. This suggests that contributions of spawners from Upper Arrow would most likely have been age 3 fish (Fig. 10.14b). The larger size of age 2 fish in Lower Arrow suggests that spawners would most likely be a mix of age 2 and age 3 fish, with a likelihood of more age 2s. Combining spawner lengths from two Lower Arrow streams (Octopus and Deer creeks) show two size groups which largely corresponded to the age 2 and 3 estimates from otolith analysis and also fit well with the age 2 trawl fish (Fig 10.14c). This clearly shows that spawners in Lower Arrow streams were a mix of age 2 and age 3 fish with slightly more age 2s. The otolith interpretations for Hill Creek spawners were less convincing since the large majority were estimated to be age 2 fish while the range in lengths of both age 2 and age 3 fish was extensive and did not fit well with the trawl information or with Lower Arrow age interpretations (Fig.10.15). If otolith interpretations are reliable it suggests that the majority of spawners sampled from Hill Creek were most likely from Lower Arrow. This contradicts the general belief that the majority of Hill Creek fish rear in Upper Arrow Reservoir but is supported by earlier evidence of Upper Arrow fry moving to Lower Arrow between August and October surveys (Pieters et. al., 2003). If age proportions for spawners (used to assess fry survival) will rely primarily on otolith interpretations, it is recommended that otolith samples be sent to more than one lab and results compared to gain more confidence in these results.

Combining the trawl and spawner length frequencies from both Upper and Lower basins (Fig. 10.14a) suggests that spawners were a mix of age 2 and age 3 fish with likely more age 2 fish in 2003 .

Fish Density distributions

Kokanee densities in 2003 ranged from 184-629 fish·ha⁻¹ in Upper Arrow, and from 173-938 fish·ha⁻¹ in Lower Arrow (Appendix 10.11). In Upper Arrow both age 0+ and age 1-3+ fish densities were consistently higher in the lower half of the basin as in 2001. This was in contrast to 2002 when the highest densities of all age groups were found near the fertilization zone. In Lower Arrow age 0+ fish densities, as in previous years, were highest in the narrows and lowest in the center of the basin. The distribution of age 1-3 fish in Lower Arrow has changed the last three years from highest numbers at the upper end in 2001, evenly distributed in 2002 and congregated in lower half of the basin in 2003. Kokanee distributions appear to be highly variable both seasonally and from year to year, presumably in response to food availability.

The vertical distribution was similar to previous fall sampling. The main fish layer was found at 20 - 30m depth in Upper Arrow and at 20 - 35m in Lower Arrow. Kokanee were found closer to the surface in Upper Arrow and extended deeper (i.e. to 50m) in Lower Arrow (Fig. 10.17). These distributions are thought to be largely determined by temperature preferences. Although small numbers of age 0 fish were found above the main night-time layer in Upper Arrow, the large majority of both fry and age 1-3 fish were found at similar depths (Fig. 10.18), indicating that age groups did not appear to be segregated by depth. The vertical distribution in both basins in 2003 provided optimal conditions for conducting a population assessment with a downward looking echosounder.

Abundance estimates

The abundance of kokanee in Arrow Reservoir was estimated at 11.7 million (10.8-12.7) in September 2003 (Table 10.7). Individual basin populations were estimated at 7.6 and 3.8 million in Upper and Lower Arrow, respectively, although the individual basin estimates are not considered as statistically rigorous as the whole basin estimate. There was a significant decline in the numbers of pelagic fish in 2003, which marked the first decrease evident since the fertilization experiment began (Table 10.7; Fig. 10.19). A decrease of 40-50% was observed in both basins.

Table 10.7. Comparison of maximum likelihood abundance estimates (and 95% C. L.) for kokanee by basin and year for Arrow Reservoir during the fertilization period, 1999-2003.

Fertilization year	Month	Upper Arrow (millions)	Lower Arrow (millions)	Arrow Reservoir (millions)
1. 1999	October	4.0 (3.2-4.9)	2.1 (1.8-2.4)	6.1 (5.3-7.1)
2. 2000	October	7.56 (7.1-8.1)	4.1 (3.6-4.6)	11.6 (10.9-12.4)
3. 2001	October	13.4 (12.2-14.6)	6.5 (5.5-7.5)	20.0 (18.3-21.4)
4. 2002	October	12.5 (11.3-13.6)	7.7 (5.9-9.6)	20.1 (18.1-22.3)
5. 2003	September	7.6 (7.0-8.7)	3.8 (3.5-4.3)	11.7 (10.8-12.7)

Acoustic size analyses

It is often possible to separate kokanee into two size groups corresponding to age 0 and age 1-3 fish based on their acoustic size distribution alone. This method relies on a high proportion of age 0 fish resulting in a visible inflection point between the two groups at around -47dB or approximately 75 mm. Unfortunately the low proportions of fry in Arrow during 2003 resulted in no distinct inflection, so it was necessary to apply a theoretical cut-off point based on previous studies on Arrow Reservoir and the measured size of age 0 and 1+ fish captured in the trawl. The fry proportions using a -47dB cut-off were estimated at 44% in Upper Arrow and 38% in Lower Arrow (Table 10.8). The acoustic method suggested slightly higher proportions of fry than the trawl catch estimates of 33% and 31% for Upper and Lower Arrow respectively. Both methods agreed that age 0 kokanee proportions in 2003 were abnormally low in the two basins compared with previous years giving cause for some concern. Due to known difficulties with size biases in trawl catches, the acoustic proportions were preferred for estimating the numbers of age 0 and 1-3 fish from total acoustic populations.

The Arrow Reservoir kokanee population in 2003 was estimated at 11.6 million, comprised of about 4.9 million fry and 6.7 million age 1-3+ fish in 2003 (Table 10.8). The numbers of age 1-3 fish remained high and were similar to 2002 levels which were the highest on record. The short term prediction is for better than average spawner returns in 2004 based on a second consecutive year of high age 1-3 abundance.

Table 10.8. Kokanee proportion, abundance and mean density by age group for Upper and Lower Arrow Reservoir during September 2003.

Location	Age group	Proportion (by age)		Abundance and density	
		Acoustic (%)	Trawl (%)	Number (millions)	Density (Fish/ha) ¹
Upper Arrow	Age 0	44	33	3.38	175
	Age 1-3	56	67	4.28	222
	Total			7.63	397
Lower Arrow	Age 0	38	31	1.46	161
	Age 1-3	62	69	2.36	261
	Total			3.82	422
Total Arrow ²	Age 0	42	32	4.94	175
	Age 1-3	58	68	6.72	237
	Total			11.66	412

1. Mean basin densities were based on reservoir area at the average depth of the fish layer (Fig. 8).

2. Note the total Arrow abundance estimate (for the combined basins) was derived from a separate maximum likelihood estimate so may not be equal to the sum of individual basin estimates (which are less statistically rigorous).

The age 0 fish, however, declined 63% in 2003 from an estimated 13.9 million in 2002 (Fig. 10.20). The decline in fry was **not** due to low spawner numbers since the 2002 return estimated at 650,000 fish was one of the two highest returns in recent record. The other high return was in 2001 estimated at 658,000 fish (see Andrusak in this ALR report).

Discussion

The most significant result from the 2003 survey work was the realization that there were far fewer kokanee fry than the previous two years (Figs. 10.19, 10.20). A decline from approximately 13-15 million to 5 million fry was totally unexpected and given the initial success but high cost of lake fertilization some explanation is required.

At first glance one could speculate that declining fry numbers were due to high mortality at the incubation stage in streams or in the spawning channel or were due to poor survival in the reservoir which could indicate in-lake food supply problems. Fortunately the Hill Creek spawning channel provides good estimates of incubation survival. The 2003 fry data indicated that egg-to-fry survival was 32%, only slightly below the previous 12-year average of 36% and not likely to be the cause of the major decline in fry numbers. Overall fry production from the channel however was down 50% from the two previous years due mainly to the smaller size of spawners, lower average fecundity and reduced egg deposition (Table 10.9). Smaller spawner size would not be limited to the spawning channel but in fact the entire spawning population so this was most likely the cause of about 80% of the observed decline (of 63%) in total fry recruitment in the reservoir in September 2003. A significant part of the overall decline in fry numbers can therefore be

Table 10.9. Kokanee fry production from Hill Creek spawning channel during 1992-2003. Note that non-channel production from Hill Creek has been estimated with other tributary production in Table 10.10.

Spawning year	Spawner counts ¹ (no.)	Mean Fecundity (egg no.)	Egg Retention (egg no.)	Females ² (%)	Egg deposition ³ (millions)	Fry emigration ⁴ (millions)	%Egg/fry survival rate
1991	75,000	219	13	49	7.57	2.87	38
1992	75,000	263	33	50	8.63	3.00	35
1993	75,000	248	31	52	8.54	3.43	40
1994	75,000	302	51	51	9.41	2.22	24
1995	16,328	274	1	51	2.26	0.68	30
1996	25,030	172	8	52	2.15	0.69	32
1997	22,566	182	6	50	1.99	0.93	47
1998	19,087	226	12	44	1.81	0.86	47
1999	78,024	424	36	41	12.37	3.72	30
2000	102,597	469	2	47	22.36	8.46	38
2001	122,400	379	7	41	18.82	8.32	44
2002	151,826	212	5	39	12.26	3.93	32

1. Refers only to fish in the spawning channel; other Hill Creek production is primarily surplus since natural fry capacity is estimated at 100,000 based on pre-channel maximum spawner returns.

2. Derived by sampling at spawning channel; note: 1992-94 used 50% as sampling bias suspected

3. Potential egg deposition based on number of adults in channel x (fecundity – retention) x % females.

4. Fry emigration from spring time sampling does not include non-channel production which is estimated at up to 100,000 fry/yr.

traced to reduced growth rates in kokanee during 2001-02 as a result of their higher numbers following initial fertilization. The reduced growth resulted in lower fecundity in the 2002 spawning population which produced the 2003 fry. The relation between total egg deposition and late summer fry abundance estimates from Tables 5 and 6 is fairly evident (Fig. 10.21).

Despite the above revelation the question of in-lake survival also needs to be addressed since it is possible that 2003 lake fertilization did not increase lake productivity as in the previous four years. To address the question of fry survival in the reservoir an attempt was made to estimate the numbers of fry potentially entering the reservoir from all sources and compare this with late summer abundance estimates from hydroacoustic surveys. The stream spawner counts (expanded by 1.5 times to represent total abundance) were used to crudely estimate potential egg deposition in all tributaries by applying annual estimates of fecundity, a 1:1 sex ratio and 10% egg retention derived from Hill Creek spawning channel data (Tables 10.9 and 10.10). A biostandard of 10% egg-to-fry survival was then applied to estimate theoretical fry production from streams. The annual production of fry from the spawning channel (Table 10.9) was combined with the theoretical estimate of fry production from all tributaries to estimate total theoretical fry recruitment each year to the reservoir (Table 10.10). An additional 0.1 million fry were added to the total fry recruitment as a best guess of fry produced naturally in Hill Creek from spawners that were surplus to the spawning channel. This estimate was based on pre-spawning channel estimates of capacity for Hill Creek based on adult counts by Lindsay.

Table 10.10. Estimated total fry production for kokanee to Arrow Reservoir based on adult returns, fecundity and Hill Creek fry counts for spawning years 1991-2002.

Spawning year	Total tributary spawners ¹ (no)	Potential egg deposition ² (millions)	Tributary fry recruitment ³ (millions)	Hill Creek & channel fry recruitment ⁴ (millions)	Total fry production all sources ⁵ (millions)	Spawning channel contribution (%)
1991	402,300	43.17	4.32	2.97	7.29	39
1992	153,430	27.65	2.77	3.10	5.12	59
1993				3.53		
1994				2.32		
1995	187,800	26.05	2.61	0.78	3.39	20
1996	183,610	16.57	1.66	0.71	2.37	29
1997	37,600	3.42	0.34	1.03	1.37	68
1998	220,670	22.06	2.21	0.96	3.17	27
1999	299,330	51.87	5.19	3.82	9.01	41
2000	312,250	68.34	6.83	8.56	15.39	55
2001	521,870	81.73	8.17	8.42	16.59	50
2002	455,240	37.66	3.77	4.03	7.80	50

1. peak counts expanded by 1.5 times

2. based on Hill Creek fecundities and sex ratio (egg retention assumed low).

3. assumes egg-to-fry survival in wild averages 10%
4. Hill Creek fry production estimates from Table 5 plus 100,000 fry from Hill Creek (est. capacity).
5. Note fry contribution refers to following year.

A regression was used to see if the two independently derived indices of fry abundance (i.e., for spring and fall the same year) correlated (Fig. 10.22). The result was a surprisingly good correlation when combining all years of data (i.e. slope of 0.89 and R^2 of 0.88, $n=11$). The slope provides an index of relative survival with points below the line suggesting poorer than average survival and points above the line representing better than average survival in the reservoir. The point “X” representing the 2003 fry relation was well below the line suggesting that survival in the reservoir was about 20% lower than average in 2003 after reduced fry numbers due to lower fecundity was accounted for.

From this analysis we conclude that the most significant contributor to low fry numbers in 2003 was reduced spawner size and fecundity in 2002 as a result of density growth interactions in the reservoir during 2002 and possibly 2001. Lower than average survival of newly emerged fry entering the reservoir in spring 2003 may also have contributed to lower numbers of fry by fall of 2003. Rae and Ashley and Rae et al. (in Andrusak et al. 2004) point out that poor quality phytoplankton that contain little fatty acids are poor food sources for cladocerans hence kokanee. Kokanee over winter survival is believed to be highly dependent upon a good supply of fatty acids (Post and Parkinson 2001). It is recommended that Arrow Reservoir food quality and abundance be reviewed during the fertilization period to determine if food quality is an issue that may partially explain the results (lower kokanee fry survival in 2003) in this report.

With lower numbers of fry in 2003 it is anticipated that there will be subsequent declines in the age 1-3 population in 2004 and 2005 which will likely lead to lower adult returns by 2006. If lower age 1-3 densities lead to increased growth and earlier maturity (e.g., age 2+ spawners in 2005), the impact of the low 2003 fry year could be less evident.

For continued tracking of the kokanee populations during the Arrow Reservoir fertilization experiment it is essential to continue spawner counts in tributaries as well as annual estimates of spawner numbers, sex ratio, length, fecundity, egg deposition and fry recruitment from Hill Creek spawning channel. Efforts should also be made to improve on estimation of stream egg deposition, especially for the lower basin tributaries. The same kokanee biological parameters measured at the spawning channel need to be recorded from some of the larger spawning streams (e.g. Caribou, Burton and Mosquito creeks).

Recommendations:

1. Continue monitoring of in-lake kokanee distribution and abundance by size (age) groups using annual acoustic surveys during fall.

2. Continue monitoring kokanee growth (i.e., mean length-at-age) and relative age structure by trawl sampling as near to October 1 as sampling schedules permit.
3. Maintain the kokanee spawner count time series by continuing annual spawner enumerations using standardized methods in both Upper and Lower Arrow tributaries.
4. Continue biological sampling at Hill Creek to determine kokanee spawner numbers, size, fecundity, egg deposition and fry recruitment. Some additional monitoring of spawner size distributions (and fecundity if possible) in Lower Arrow streams would verify whether Hill Creek statistics represent to Lower Arrow tributaries.
5. Consider sending otoliths from spawning kokanee to two different scale aging labs and compare results, particularly where ages appear to be at odds with length frequency analyses.
6. Some accurate estimates of adult numbers in and fry numbers out of a key kokanee production tributary (i.e. Caribou, Snow etc) could be used to verify/improve biostandards for stream production to Arrow Reservoir.

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Figure 10.11. Arrow Reservoir showing hydroacoustic transects and trawl station locations for surveys conducted in October of 2003.

Figure 10.12. Length-frequency of trawl caught kokanee by age in a) Upper and b) Lower Arrow Reservoir during October 2003.

Figure 10.13. Trends in kokanee mean length at age for a) Upper Arrow and b) Lower Arrow Reservoir based on trawl caught fish from 1989-2003. Note trawl fish lengths have been corrected to October 1. Upper Arrow spawner lengths were obtained from Hill Creek Spawning Channel.

Figure 10.14. Kokanee length-frequency distributions by age for trawl caught fish and spawner length for a) combined Upper and Lower basins, b) Upper Arrow and Hill Creek, and c) Lower Arrow Reservoir and Lower Arrow tributary spawners in 2003.

Figure 10.15. Kokanee spawner length frequency by age based on otolith interpretations.

Figure 10.16. Density distributions of age 0 and age 1-3 kokanee by transects from the September 2003 acoustic survey. Note: transects are in order from north to south (transect 18 is a new transect at the upper end of Lower Arrow; transects 19 and 20 are located in Reach 2 just below the Narrows).

Figure 10.17. Vertical distribution of kokanee densities by transects from the September 2003 acoustic survey. Transects 1-18 are shown as these are used to develop population estimates. Densities are shown by 5m depth stratum such that a depth of 20 m includes fish density from 20-25m deep.

Figure 10.18. Proportions of age 0 and age 1-3 kokanee by depth from 2003 acoustic surveys.

Figure 10.19. Kokanee abundance estimates (all ages) for Arrow Reservoir (combined upper and lower basins), Upper and Lower Arrow from annual fall acoustic surveys, 1988-2003.

Figure 10.20. Comparison of trends in kokanee abundance by age before and during experimental fertilization of Arrow Reservoir based on acoustic surveys, 1993-2003

Figure 10.21. Trends in potential egg deposition from kokanee spawners and following year fry abundance for Arrow Reservoir, 1991-2002. Note data is presented by spawning year (rather than acoustic survey year).

Figure 10.22. Comparison of theoretical fry recruitment (based on spawner numbers and size) with late summer fry abundance (acoustic estimates) from Arrow tributaries, 1991-2002.

APPENDIX 10.7. Habitat areas for kokanee surveys

a) Water level and limnetic habitat areas in Arrow Reservoir during acoustic surveys.

Survey Dates		Water level	Habitat area >20 m depth (km ²)		
Year	Month / day	(m)	Upper Arrow	Lower Arrow	Total
2003	Sept. 27-29	433.8	197	97	293

b) Reach map and surface area estimates by Reach at full pool from three different sources: Canadian Hydrographic Series, Pieters et al. (1998) and Fisheries GIS map base.

Reach No.	Reservoir description	Hydrographic Charts (digitized) ¹ (ha)	<i>Pieters et al</i> (1998) (ha)	<i>Fisheries</i> Victoria (GIS) ² (ha)
1 and 2	Lower Arrow basin ³	15,493	17,724	17,113
3	Narrows	2,200		3,374
4	Upper Arrow basin ⁴	19,298	30,600	21,327
5	Beaton Arm ⁴	3,284		3,150
6	Revelstoke Reach ("flats")	6,437		6,981
Total		46,712	47,724	51,945

1 These estimates were used for expanding the acoustic/ trawl populations.

2. GIS Applications Unit, Fisheries Victoria used Arcview based on 1:50,000 scale polygons, April, 1999.

3. Includes 3,300 ha of shallow habitat (reach 2) which were not used in acoustic population estimates.

Total Lower Arrow habitat included in acoustic populatin estimates is 12,193 ha

Note: Narrows and Revelstoke reaches also not included in acoustic estimates (too shallow)

4. Total Upper Arrow acoustic habitat areas include reaches 4 & 5

APPENDIX 10.7. continued

c) Habitat area estimates by depth strata used for acoustic population estimates.

Depth (m) from surface	Revelstoke Reach	Upper Arrow	Narrows	Lower Arrow	Depth (m) from surface	Upper Arrow	Lower Arrow
full pool	6437	22,582	5,500	12,193	41	18,729	8,354
1		22,456		12,092	42	18,665	8,268
2		22,330		11,991	43	18,602	8,181
3		22,205		11,890	44	18,539	8,095
4		22,079		11,789	45	18,476	8,008
5		21,953		11,688	46	18,413	7,921
6		21,827		11,587	47	18,350	7,835
7		21,702		11,486	48	18,286	7,748
8		21,576		11,385	49	18,223	7,662
9		21,450		11,284	50	18,160	7,575
10		21,324		11,183	51	18,068	7,511
11		21,198		11,082	52	17,977	7,447
12		21,073		10,981	53	17,885	7,384
13		20,947		10,880	54	17,794	7,320
14		20,821		10,779	55	17,702	7,256
15		20,695		10,678	56	17,611	7,192
16		20,570		10,577	57	17,519	7,129
17		20,444		10,476	58	17,427	7,065
18		20,318		10,375	59	17,336	7,001
19		20,192		10,274	60	17,244	6,937
20		20,055		10,173	61	17,153	6,874
21		19,992		10,086	62	17,061	6,810
22		19,929		10,000	63	16,969	6,746
23		19,866		9,913	64	16,878	6,682
24		19,803		9,827	65	16,786	6,619
25		19,739		9,740	66	16,695	6,555
26		19,676		9,653	67	16,603	6,491
27		19,613		9,567	68	16,512	6,427
28		19,550		9,480	69	16,420	6,364
29		19,487		9,394	70	16,328	6,300
30		19,424		9,307	71	16,237	6,236
31		19,360		9,220	72	16,145	6,172
32		19,297		9,134	73	16,054	6,109
33		19,234		9,047	74	15,962	6,045
34		19,171		8,961	75	15,870	5,981
35		19,108		8,874	76	15,779	5,917
36		19,045		8,787	77	15,687	5,853
37		18,981		8,701	78	15,596	5,790
38		18,918		8,614	79	15,504	5,726
39		18,855		8,528	80	15,413	5,662
40		18,792		8,441			

Data interpolated from Canadian Hydrographic Service charts: # 3056, 3057 and 3058,
Areas are in Hectares (Ha.); Full pool elevation reference 440.24 m

APPENDIX 10.8. Kokanee length correction factors for Arrow Reservoir.

Correction factors for >180 mm fish and for 100-180 mm fish are from Rieman (1992). Correction factors for <100 mm fish were derived from Okanagan Lake trawl samples collected during 1988-93.

Date	> 180 mm	100 - 180 mm	<100 mm	Date	> 180 mm	100 - 180 mm	<100 mm
1-Sep	1.025	1.064	1.090	7-Oct	1.000	1.000	0.982
2-Sep	1.023	1.061	1.087	8-Oct	1.000	1.000	0.979
3-Sep	1.021	1.058	1.084	9-Oct	1.000	1.000	0.976
4-Sep	1.020	1.056	1.081	10-Oct	1.000	1.000	0.973
5-Sep	1.018	1.053	1.078	11-Oct	1.000	1.000	0.970
6-Sep	1.016	1.050	1.075	12-Oct	1.000	1.000	0.967
7-Sep	1.014	1.047	1.072	13-Oct	1.000	1.000	0.964
8-Sep	1.012	1.044	1.069	14-Oct	1.000	1.000	0.961
9-Sep	1.011	1.042	1.066	15-Oct	1.000	1.000	0.958
10-Sep	1.009	1.039	1.063	16-Oct	1.000	1.000	0.955
11-Sep	1.007	1.036	1.060	17-Oct	1.000	1.000	0.952
12-Sep	1.005	1.033	1.057	18-Oct	1.000	1.000	0.949
13-Sep	1.003	1.030	1.054	19-Oct	1.000	1.000	0.946
14-Sep	1.002	1.028	1.051	20-Oct	1.000	1.000	0.943
15-Sep	1.000	1.025	1.048	21-Oct	1.000	1.000	0.940
16-Sep	1.000	1.023	1.045	22-Oct	1.000	1.000	0.936
17-Sep	1.000	1.022	1.042	23-Oct	1.000	1.000	0.933
18-Sep	1.000	1.020	1.039	24-Oct	1.000	1.000	0.930
19-Sep	1.000	1.018	1.036	25-Oct	1.000	1.000	0.927
20-Sep	1.000	1.017	1.033	26-Oct	1.000	1.000	0.924
21-Sep	1.000	1.015	1.030	27-Oct	1.000	1.000	0.921
22-Sep	1.000	1.013	1.027	28-Oct	1.000	1.000	0.918
23-Sep	1.000	1.011	1.024	29-Oct	1.000	1.000	0.915
24-Sep	1.000	1.010	1.021	30-Oct	1.000	1.000	0.912
25-Sep	1.000	1.008	1.018	31-Oct	1.000	1.000	0.909
26-Sep	1.000	1.006	1.015	1-Nov	1.000	1.000	0.906
27-Sep	1.000	1.005	1.012	2-Nov	1.000	1.000	0.903
28-Sep	1.000	1.003	1.009	3-Nov	1.000	1.000	0.900
29-Sep	1.000	1.001	1.006	4-Nov	1.000	1.000	0.897
30-Sep	1.000	1.000	1.003	5-Nov	1.000	1.000	0.894
1-Oct	1.000	1.000	1.000	6-Nov	1.000	1.000	0.891
2-Oct	1.000	1.000	0.997	7-Nov	1.000	1.000	0.888
3-Oct	1.000	1.000	0.994	8-Nov	1.000	1.000	0.885
4-Oct	1.000	1.000	0.991	9-Nov	1.000	1.000	0.882
5-Oct	1.000	1.000	0.988	10-Nov	1.000	1.000	0.879
6-Oct	1.000	1.000	0.985	11-Nov	1.000	1.000	0.876

APPENDIX 10.9. Equipment and Data Processing Specifications

a) Echosounder Specifications and Field Settings:

Description	SIMRAD EY200P-P
transducer type	Single beam 70 kHz
beam angle	11.6 degree
receiver gain	3 (0 dB)
pulse width (msec)	0.3
ping rate (p/sec)	medium (1.5)
time varied gain	40 log r
TVG range (m)	2 to 66
Attenuation	-15 dB
Power	1/1
Calibration	2 min. AC tone
Tape recorder	Sony TCD-D10
Record volume	3.5 fixed

b) Data Processing Specifications

Description	HADAS version 3.98
Interface gain	calibration tone to intersect 2 volts at 50 milliseconds
Threshold	minimum detectable target approximately - 65 dB
Field calibrations	Date, peak sphere voltage, sphere depth and threshold used for survey September 28, 2003 Upper Arrow 3600mV, sphere at 20m., threshold 200mV September 29, 2003 Lower Arrow 3500mV, sphere at 20m., threshold 200mV
Lab calibration	July 8 1998, Applied Physics Laboratory UWA

APPENDIX 10.10A Maximum likelihood estimates and bounds for all fish in September 2003 Arrow Reservoir surveys based on Monte Carlo Simulations. Note: LB=Lower bounds, UB=Upper bounds, MLE=Maximum likelihood estimate.

October 2003 Systat coefficients for fish >-62 dB in 4 zones (zone 1: transects 1-5; zone 2: transects 6-10; zone 3: transects 11-13+18 and zone 4: transects 14-17)									
Zone *	Depth	N	R2	Density	Std Dev	Area	Stratum population	Statistic	Abundance
1	5	4	0.85	15.3	3.69	10012	153,503	LB=	6,990,661
1	10	4	0.95	16.5	2.11	9687	159,683	Upper MLE=	7,633,800
1	15	5	0.86	43.7	8.71	9447	413,196	Basin UB=	8,737,661
1	20	4	0.95	97.9	13.14	9283	908,366	LB=	3,455,440
1	25	4	0.99	77.5	3.50	9119	706,679	Lower MLE=	3,815,100
1	30	4	0.98	35.8	3.23	8955	320,414	Basin UB=	4,322,723
1	35	4	0.81	8.3	2.30	8791	72,846	LB=	10,776,996
1	40	4	0.54	1.3	0.70	8628	11,319	Total MLE=	11,656,000
1	45	5	0.39	3.6	2.21	8501	30,341	UB=	12,732,434
2	5	5	0.23	4.8	4.44	10935	52,914		
2	10	4	0.98	34.1	2.58	10631	362,042		
2	15	4	0.99	32.4	1.59	10419	337,611		
2	20	5	0.77	109.7	30.00	10267	1,126,422		
2	25	4	0.95	181.4	23.54	10115	1,835,199		
2	30	4	0.94	82.2	11.84	9963	818,703		
2	35	4	0.94	35.9	5.16	9811	352,325		
2	40	5	0.78	12.8	3.40	9659	124,087		
2	45	5	0.79	6.1	1.58	9384	57,504		
2	50	5	0.60	2.7	1.10	9027	24,427		
3	5	4	0.13	3.1	4.75	5410	16,836		
3	10	3	0.36	1.1	1.05	5139	5,653		
3	15	3	0.44	4.0	3.22	4858	19,565		
3	20	3	0.92	23.2	4.83	4571	106,033		
3	25	3	1.00	113.7	4.56	4283	486,931		
3	30	3	0.99	121.6	7.05	3996	485,950		
3	35	3	0.91	44.5	9.94	3708	165,169		
3	40	3	0.72	11.9	5.28	3421	40,864		
3	45	3	0.92	9.0	1.88	3228	29,010		
3	50	3	0.79	3.8	1.41	3098	11,816		
4	5	3	1.00	10.8	0.25	5470	59,075		
4	10	3	0.95	10.5	1.67	5236	54,792		
4	15	3	0.83	4.4	1.44	5055	22,377		
4	20	3	0.97	42.8	5.68	4909	210,290		
4	25	3	0.94	148.4	26.77	4764	706,776		
4	30	3	1.00	208.8	6.30	4618	964,465		
4	35	3	0.77	76.3	29.49	4473	341,271		
4	40	3	0.98	26.5	19.47	4327	114,762		
4	45	3	0.39	9.1	8.06	4156	37,638		
4	50	3	0.47	3.5	2.60	3967	13,809		

* Each basin is divided into *zones* for the analysis. Zones are determined using Figure 14.3. Zones typically, though not always, correspond to the Upper and Lower Arrow basins. For example, Beaton Arm, would, in certain years, need to be a separate zone. Reservoir level elevation was 434m in September 2003. Depths indicate upper bounds of 5 meter depth strata.

Areas in October were based on 6m below full pool and 2 m to center of strata (down 8m in total).

APPENDIX 10.10B Maximum likelihood estimates and bounds for big fish (>-45.5dB)
in September 2003 Arrow Reservoir surveys based on Monte Carlo
Simulations.

September 2003 Systat coefficients for fish >-47dB in 4 zones (zone 1: transects 1-5; zone 2: transects 6-10; zone 3: transects 11-13 + 18 and zone 4: transects 14-17)								
Zone*	Depth	N	R2	Density	Std Dev	Area	Stratum population	Statistic ³
1	5	4	0.90	8.0	1.57	10012	79,986	LB= 3,651,637
1	10	5	0.86	3.1	0.63	9687	29,970	Upper MLE= 4,274,900
1	15	4	0.93	16.8	2.58	9447	158,446	Basin UB= 5,040,807
1	20	5	0.86	35.2	6.98	9283	326,563	LB= 1,872,187
1	25	4	1.00	25.9	1.06	9119	236,079	Lower MLE= 2,361,900
1	30	4	0.96	12.4	1.42	8955	111,127	Basin UB= 2,634,233
1	35	4	0.79	1.9	0.57	8791	16,994	LB= 5,813,525
2	10	4	0.88	5.6	1.18	10631	59,206	Total MLE= 6,724,100
2	15	4	0.97	14.4	1.44	10419	150,114	UB= 7,393,362
2	20	5	0.74	69.1	20.43	10267	709,015	
2	25	4	0.90	139.9	26.81	10115	1,415,556	
2	30	4	0.99	71.7	4.75	9963	714,163	
2	35	4	0.98	23.1	2.06	9811	226,718	
2	40	5	0.71	7.8	2.53	9659	75,754	
2	45	5	0.64	2.6	0.97	9384	23,948	
2	50	4	0.91	1.3	0.24	9027	11,654	
3	10	4	0.26	1.5	1.45	5139	7,694	
3	15	4	0.21	0.5	0.60	4858	2,575	
3	20	3	0.94	4.8	0.83	4571	21,941	
3	25	3	0.97	30.5	3.61	4283	130,805	
3	30	3	0.99	55.5	4.74	3996	221,830	
3	35	3	0.95	20.1	3.29	3708	74,500	
3	40	4	0.69	5.9	2.28	3421	20,044	
3	45	3	0.81	1.3	0.44	3228	4,180	
3	50	3	0.73	1.3	0.55	3098	4,018	
4	15	3	0.99	1.7	0.10	5055	8,800	
4	20	3	0.85	20.0	5.99	4909	98,326	
4	25	3	0.85	98.2	29.17	4764	467,748	
4	30	3	0.99	137.6	10.09	4618	635,663	
4	35	3	0.91	94.6	21.52	4473	423,131	
4	40	4	0.43	25.3	16.97	4327	109,508	
4	45	3	0.41	4.1	3.45	4156	17,043	
4	50	3	0.56	1.8	1.12	3967	7,109	

³ Key: LB=Lower bounds, UB=Upper bounds, MLE=Maximum likelihood estimate

APPENDIX 10.11A Summaries of fish density (number/ha) by transect for September 2003 acoustic analysis.

Transect number	All ages	Age 0	Age 1-3
1	300	196	104
2	480	385	95
3	330	191	139
4	184	127	57
5	214	144	70
6	561	248	313
7	574	198	376
8	629	177	452
9	439	198	240
10	284	125	160
11	391	307	84
12	173	128	45
13	302	180	122
14	729	203	526
15	500	218	282
16	844	465	379
17	938	398	540
18 ^a	540	435	105
19 ^b	613	509	104
20 ^b	898	555	343

a. Transect No. 18 is new and is used with #11-17 to estimate Lower Arrow abundance

b. Transects 19 and 20 are in Reach 2 below the Narrows and are used for qualitative information only at this time.

APPENDIX 10.1B Total transect fish density (number/ha) 1992 to 2003

Transect	Year											
	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1		199	343	32	32	63	197	474	420	376	696	300
2		113	288	117	84	134	179	459	441	643	1448	480
3	135	135	260	162	138	277	97	263	733	923	721	330
4	196	90	146	73	22	87	50	231	389	295	1306	184
5	105	56	121	97	29	29	141	160	298	505	873	214
6	76	60	122	80	24	114	93	158	442	605	375	561
7	73	35	144	53	66	39	91	130	320	1073	311	574
8	82	77	171	94	65	49	70	151	434	775	440	629
9	94	70	104	110	77	38	111	167	427	830	372	439
10	90	103	140	139	107	36	97	134	280	773	1245	284
20								1335	807	1109	1606	898
21								1666				
19									2191	647	1507	613
18			266					389	711	1593	3818	540
11	354	365	162	309	99	101	198	204	502	2621	587	391
12	83	178	454	110	75	146	534	313	408	705	731	173
13	100	162	288	253	137	102	218	231	637	1181	1662	302
14	122	224	282	121	318	107	144	178	483	528	473	729
15	67	180	162	162	377	139	135	261	926	1682	1238	500
16	254	333	245	455	154	305	145	203	408	941	734	844
17	216	203	331	199	174	196	301	253	194	781	621	938
Upper Arrow ave.	106	94	184	96	64	87	112	233	418	680	779	399
Lower Arrow ave.	171	235	274	230	191	156	239	254	534	1254	1233	552

Transects 1 and 2 Beaton Arm, Upper Arrow

Transects 3 to 10 main basin, Upper Arrow

Transects 19 to 21 Narrows

Transects 11 to 18 Lower Arrow

APPENDIX 10.12. Love's (1977) empirical relation of fish length to acoustic target strength

$TS = 19.1 \log_{10} (L) - 0.9 \log_{10} (F) - 62$ where TS=target strength in decibels (dB),
L=length in cm and F=frequency in kHz

HADAS size class (db) ¹	Acoustic size range (dB)		Fish length range ² (mm)	
-35	-35	-33.1	317	500+
-38	-38	-35.1	221	317
-41	-41	-38.1	154	221
-44	-44	-41.1	107	154
-47	-47	-44.1	75	107
-50	-50	-47.1	52	75
-53	-53	-50.1	36	52
-56	-56	-53.1	25	36
-59	-59	-56.1	18	25
-62	-62	-59.1	12	18

1 HADAS was set up to view 30 dB range in 10 size classes of 3 dB

2 from Love's (1977) empirical formula (Dorsal aspect).

CHAPTER 11

RESPONSE OF ARROW LAKES RESERVOIR KOKANEE TO EXPERIMENTAL FERTILIZATION, YEARS 4 and 5 (2002 and 2003)

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Introduction

Kokanee (*Oncorhynchus nerka*) are a keystone species in most large lakes in southern British Columbia and their abundance usually dictates the health of many other predator species that are reliant on them as a primary food source. In particular piscivorous rainbow trout (*Oncorhynchus mykiss*) and bull trout (*Salvelinus confluentus*) prey upon kokanee in Arrow Lakes Reservoir (ALR) once they achieve a size > 40 cm (Andrusak and Parkinson 1984; Arndt 2004). Kokanee also provide excellent fishing opportunities during the summer months and this fact combined with the importance of the rainbow trout and bull trout sport fisheries on ALR dictates that fisheries management constantly monitor the status of the ALR kokanee population.

During the last two decades ALR has undergone oligotrophication as a result of nutrient uptake in Mica and Revelstoke reservoirs (Pieters et al. 1999; Pieters et al. 2003 *in* Stockner 2003). Similarly Kootenay Lake underwent severe nutrient impoverishment due to upstream dams (Daley et al. 1981) but the impacts were not totally reflected in the upper trophic levels until two decades later. It wasn't until the late 1980s that Kootenay Lake kokanee began to decline to seriously low levels (Ashley et al. (1997). Similar to the downward trend documented on Kootenay Lake the ALR kokanee population began to decline in numbers and growth by the mid 1990s and the whole lake population was on the verge of collapse by the late 1990s (Sebastian et al. 2000).

In response to the kokanee declines in both Kootenay and ALR the province decided to experimentally fertilize Kootenay Lake starting in 1992 and ALR commencing in 1999. The Kootenay Lake kokanee population responded rapidly to fertilization with total lake abundance increasing threefold (Andrusak et al. 2003). Pieters et al. (1999; 2000) developed the background physical, chemical and biological data of ALR in preparation for initial fertilization of the upper basin in 1999. Preliminary results of fertilization of Upper Arrow have been documented by Pieters et al. (*in* Stockner 2003). ALR kokanee have responded to lake fertilization in a similar manner to Kootenay Lake kokanee.

There are several partnerships involved in the ALR fertilization program led by the Ministry of Environment (MOE). Most of the ALR work is funded by a compensation program jointly established by the provincial government and BC Hydro. This program, the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) administers the fertilization and monitoring aspects of the program with much of the technical support provided by MOE.

A more detailed description of fish losses and the compensation program are described by Pieters et al. (2000) and Pieters et al. 2003 (*in* Stockner 2003). Sebastian et al. (2000) has produced a comprehensive review of ALR kokanee biology. Arndt (2004a) provides an updated summary of the ALR sport fish statistics and recently he demonstrated improved growth and condition of 2003 rainbow trout and bull trout attributable to increased kokanee abundance (Arndt 2004b). This report summarizes 2002 and 2003 results of the routine monitoring work on ALR kokanee, compares this information with previous trend data

summarized by Sebastian et al. (2000) and provides some comparison with similar work on Kootenay and Okanagan lakes. The impact on the kokanee population from five years of experimental fertilization is discussed.

Methods

ALR kokanee are monitored annually through escapement estimates, acoustic surveys, trawl sampling and biological sampling at the Hill Creek and Bridge Creek spawning channels. Periodically angler surveys have been conducted to obtain crude estimates of kokanee harvest levels and most recently a partial census of the sport fishery has been conducted (Arndt 2004b). In 2005 a comprehensive review of all kokanee escapement data and Hill Creek biological data was conducted by the Ministry of MOE to ensure quality control of data entry (C. Spence MOE Fisheries Biologist Nelson BC pers. comm.) Minor discrepancies existed between previously reported data and the revised database but the differences do not make any appreciable change to long-term trends in escapements or fish sizes. The 2005 revised database was used for this report.

Spawner Escapement, Size and Fecundity

Kokanee escapements to most ALR streams have been estimated periodically since 1966 and annually since 1988 (Sebastian et al. 2000). Estimates are made through a combination of aerial surveys and visual ground counts. These escapement estimates serve as indices of abundance since budget limitations do not provide the opportunity to estimate total numbers through the area-under-the-curve (AUC) methodology (see Hill and Irvine 2001; Parken et al. 2003). These index streams represent the vast majority (~ 90%) of the total available stream spawning habitat. Total counts are conducted at fish fences located at Hill and Bridge spawning channels. A complete description of methods used can be found in Sebastian et al. (2000). Run timing generally occurs between late August and late September with the peak of spawning usually occurring in the third week of September. Streams surveyed and used as index sites for estimates of abundance are shown in Table 11.1. These index systems account for approximately 90% of all the kokanee counted in the last two decades. Estimates from a number of smaller systems periodically enumerated can be found in Appendix 1.

Table 11.1. Upper and Lower Arrow Lakes Reservoir tributaries used as index sites for kokanee spawner estimates.

Upper Arrow	Lower Arrow
Hill Creek spawning channel	Burton Creek
Bridge Creek spawning channel	Caribou Creek
Drimmie Creek	Deer Creek
Halfway River	Mosquito Creek
Kuskanax Creek	
McDonald Creek	

As mentioned, kokanee returning to the Hill and Bridge creek spawning channels are enumerated annually using permanent fish fences. Redfish Consulting Ltd. (1999) has described the operation and performance of these channels in detail. At Hill Creek the total number of fish in the system is estimated through a combination of the channel fence count and ground estimates of fish downstream of the channel. Kokanee at both channels are sub-sampled at the lower channel fence site for length, sex ratio, and fecundity. Annual egg deposition is estimated from the mean fecundity, less egg retention, determined from samples taken within the channel over the spawning period. Fry out-migration is determined each spring and the methods are described by Redfish Consulting Ltd. (1999).

Kokanee fry-to-adult survival rates are determined from data generated from the two spawning channels. Several assumptions are made to determine these survival rates, the primary one being that the majority of kokanee spawn at age 3+ (Redfish Consulting Ltd. 1999; Sebastian et al 2000). With the majority of spawners of one age group and long-term escapement estimates available from Bridge and Hill creeks a crude analysis of the spawner-recruit relationships of these two streams has been possible. Since 1999 the proportion of age-at-spawning has changed with age 2+ fish well represented in some years. Therefore, adjustments have been made to the estimated contribution of each age group to the returning numbers based on the proportion of each age group for each year.

Size-at-Age

Except for 1990, night acoustic surveys of the limnetic habitat of ALR have been conducted each fall since 1988. At the same time, standard trawl surveys have also been conducted. Details of the number of stations and locations can be found in Sebastian et al. (*in* Pieters et al. 1999). The standard annual trawl series were again conducted in the fall of 2002 (October 7-12 2002) and 2003 (September 23-29, 2003) to monitor annual variation in kokanee density, and obtain length and weight-at-age data. Scale samples and otoliths were collected from all age groups to confirm age. Trawling was done during the new moon, when the fish are found nearest to the surface and are least able to avoid the sampling gear.

Age

Age determination through scale or otolith analysis has been periodically conducted on Hill Creek spawners. Otoliths were obtained in 2001 from representative samples of Hill Creek spawners and an independent contractor was provided a set of otoliths for age determination. As noted by Sebastian et al. (2000) there have been very few kokanee samples collected from the Lower Arrow Basin. Octopus Creek was chosen as a representative site for Lower Arrow Basin kokanee and in 2001 a sample of kokanee was taken from this stream to obtain otoliths. No ages were determined from kokanee collected from any streams including Hill Creek in 2002 but samples were obtained and aged from 2003 spawners. Uncertainty exists regarding the age of ALR kokanee spawners aside from small sample size(s) therefore length frequency analysis and ageing of trawl captured fish (see Sebastian et al. in this ALR report – Chapter 10) has been relied upon for age analysis of 2002 and 2003 fish.

Results

Spawner Escapement Estimates

2002

Escapement numbers in 2002 continued to show considerable improvement over the levels recorded in the mid 1990s. The 2002 kokanee escapement index estimate for Upper ALR streams was approximately 273,000 while the Lower Arrow tributary estimate was about 340,000 (Figs. 11.1, 11.2). The Upper Arrow streams supported between 300,000-400,000 spawners during the 1980s through to the early 1990s (Fig.11.1; Appendix 1) but decreased to < 100,000 during the mid 1990s. The Upper Arrow escapements trended downward through the 1990s to a record low of ~47,000 in 1996. A similar pattern persisted for the Lower Arrow streams (Fig.11.2) with a record low escapement of ~25,000 in 1997. Since then however, there have been increased numbers for five consecutive years.

Hill Creek total escapement was estimated at 195,000 the highest number since 1993. (Fig.11.1). Hill Creek continue to account for a disproportionate number of spawners compared to other streams on the Upper Arrow. The highly productive state of this channel produces very large numbers of fry due to high egg-to-fry survival rates (Appendix 2) compared to natural stream egg-to-fry levels (see Redfish Consulting Ltd. 1999). Numbers returning to Bridge Creek spawning channel in 2002 were higher (~17,000) than estimates made during the previous ten years and represents the fourth year of increases since fertilization began in 1999.

2003

Record hot summer temperatures were experienced throughout the Columbia Basin in 2003 resulting in extreme fire conditions. As a consequence all available helicopters were commandeered for forest fire fighting and therefore most of the index streams could not be enumerated by air for kokanee numbers. A few streams were enumerated by means of ground counts and the two spawning channels were enumerated as in previous years. Only three of the eight index streams (excluding the channels) listed in Table 11.1 were enumerated and these were the smaller ones that were feasible to enumerate by walking. All three stream counts were lower than 2002 numbers and two (Drimmie and McDonald creeks) were lower than their long term average (1988-2002) and lower than their parental year(s) regardless if they were age 2 or 3+ at maturity. The 2003 expanded estimate for Deer Creek (19,170) was higher than the long term average (11,433) and higher than the parental year (s) regardless of age at maturity.

In an effort to understand what the 2003 index stream escapement numbers most likely were the average of the previous four years for these streams was determined and applied to Figures 11.1 and 11.2. The logic for applying this four year average is supported by actual counts made at Hill Creek in 2003.

The most useful information from the partial 2003 escapement estimates was obtained from the two spawning channels. Hill Creek escapement was 155,279, higher than the parental years (1999, 2000) and similar to the previous four years, i.e. > 100,000 (Fig. 11.1). Bridge

Creek numbers (4,237) were far lower than 2002 and less than half of the parental years (Appendix 11.1).

In overview, the ALR kokanee population is rebuilding from the low numbers recorded in the mid 1990s and is now close to the numbers estimated in the late 1980s and early 1990s.

Spawner Size and Fecundity

Length measurements of Hill Creek spawners have been recorded since 1977 and larger sample sizes (> 100) have been available since the inception of the spawning channel in 1984. Hill Creek length frequency histograms representative of the last three decades are illustrated in Figure 3. The mean size and length frequency of Hill Creek kokanee in the 1980s (e.g. 1984) were somewhat larger than the 1970s most likely because overall numbers in the reservoir were low (er) due to the Revelstoke Dam that eliminated all kokanee spawning in the Upper Columbia River in the early 1980s. Kokanee mean size was very small during the 1990s (e.g. 1997, Fig. 11.3) probably due to a combination of increased fry production from Hill Creek spawning channel and reduced lake productivity due to nutrient retention in the upstream reservoirs (Pieters et al. 1999).

Size frequency distributions of Bridge Creek kokanee over time show a similar trend to that displayed by Hill Creek kokanee. Kokanee spawner size in the late 1980s and early 1990s was small with a single mode at approximately 210-230 mm (Fig. 4). (Note other year's data on file). By the late 1990s spawner size had increased to over 300 mm, two overlapping modes were present and some individual fish were measured > 350 mm. Similar to Hill Creek spawners (Fig. 3) the size of Bridge Creek kokanee began to decrease in 2000 and by 2002 they were of similar size to those observed in the late 1980s except that a few large individual fish > 300 mm were present.

Overall, the size of upper ALR kokanee increased from 1999-2001 compared to sizes typically recorded from 1990-1998; of considerable significance was a change in the single mode typically observed in the frequency distribution. While not as evident from the Bridge Creek data a bimodal distribution became evident in the Hill Creek size frequency by 2000 that was even more pronounced in 2001. Age data (see below) indicated that two age groups ages 2+ and 3+ made up the spawner population from 2000-2003. Prior to 2000 the Hill Creek spawners were almost invariably age 3+ (Sebastian et al. 2000). Based on size frequency alone, the 2002 and 2003 data (Fig. 11.3) suggests a possible shift back to predominately age 3+ as mean size decreased from 258 mm in 2001 to only 213 mm in 2002 and 214 mm in 2003. It appears that numbers of kokanee in the reservoir have increased to the point that the 2002 and 2003 spawners exhibited density dependent growth. i.e. increased total numbers in the reservoir resulted in decreased growth.

Fecundity of Hill and Bridge creek spawners has undergone rather dramatic changes within the last five years. Fecundity rose significantly from lows recorded in 1996 and 1997 to peak levels in 2000 and 2001 that were > 400 eggs /female (Figs. 11.5, 11.6). However female spawners in 2002 and 2003 were much smaller in size at both channels and their fecundity declined by over 200 eggs/female to means of 212 (2002) and 233 (2003) for Hill Creek and

243 (2002) and 238 (2003) at Bridge Creek (Figs. 11.5, 11.6). These noteworthy declines in fecundity played a major role in spawning channel operations (see below).

Kokanee abundance, age and size-at-age

Hydroacoustic and trawl results from 1988 up to and including 2003 are reported by Sebastian et al. (in this ALR report). For over a decade abundance of kokanee in the reservoir remained static at < 5 million. However, coincidental with the inception of lake fertilization in 1999 kokanee numbers began to increase and since then the numbers have expanded four fold and in 2002 the total was > 20 million. The 2003 data indicates a decline to just under 12 million. Estimates of total numbers closely track what has been observed in the spawner escapement estimates (Figs. 11.1, 11.2). Trawl catches in 2002 and 2003 also suggests four age groups. i.e. three ages 0-2+ caught in the trawl while the fourth group were mature fish and were spawning at the time of the trawl surveys.

Age of ALR kokanee spawners in recent years has been considerably different between years and between basins. Age data prior to lake fertilization was obtained primarily by ageing scale samples from trawl captured fish and comparing these with size of spawners from Hill Creek. Between size frequency analysis, scale reading and limited otolith ageing there was good evidence that these fish spawned predominately as age 3+. In 1997-98 marked fed fry were recovered from the spawning channel as age 2+ fish but the unmarked (wild) fish were age 3+, again supporting the notion that most spawners were age 3+ (Sebastian et al. 2000).

Since lake fertilization began the age structure of Hill Creek spawners has changed with far more age 2+ being represented in the spawning population. It was noted in 2000 that a significant shift in age-at-maturity of Hill Creek spawners had occurred and the 2000 and 2001 length frequency data showed bimodal length frequencies (Figs. 11.3, 11.4). The 2001 age data determined from the Hill Creek kokanee otoliths confirm what the length frequency distribution suggested. Of 253 otoliths interpreted from the 2001 sample 49% were age 2+, 51% were age 3+ with one fish age 4+. The 2003 ageing data from otoliths were read as 94% age 2+ and only 6% age 3+ (Fig. 11.7). This data is suspect since the length frequency data from trawl captured fish (see Sebastian et al. in this ALR report) clearly indicates that the size range and mode of age 2+ fish does overlap with the size of the spawners. The trawl age and length frequency data shows three age groups (ages 0+, 1+,-2+) therefore it is concluded that age at maturity of 2003 fish was almost entirely age 3+. The 2003 Lower Arrow age data was obtained from a small sample of Octopus and Deer creek spawners (total n= 39) and suggests a mix of ages 2+ and 3+ (Table 11.2).

Pieters et al. (2000) had noted from the 1999 size-at-age data of trawl caught fish that the 1998 (1+) and 1999 (2+) age classes had experienced high growth rates, the initial year of fertilization. Evidently, these high growth rates continued through 2000 and 2001 resulting in a large component of the age 2+ fish of these two cycles maturing a year earlier than usual. The 1999 cohort (1999 fry) experienced enriched lake conditions for three or four years depending on when they matured (as ages 2+ or 3+). It appears some of these fish grew fast enough to mature as 2+ as indicated by the age data. However, this same group of fish lived in the lake when the total population was rapidly expanding and

therefore growth of those that matured as age 3+ must have been slower in the final year as evidenced by much smaller overall size-at-maturity (mean length 213 mm; Fig. 11.5) and lower fecundity (Fig. 11.6). It is believed that this cohort is reflecting a classic density growth response and this notion is supported by the decline in growth rates of the other age groups based on the 2002 and 2003 trawl data (Fig. 11.8; data from Sebastian et al. in this ALR report). Accelerated growth rates of the 1997-2001 year classes evidently resulted in a shift in the dominant age at maturity of 3+ to a mix of ages 3+ to 2+. The 2002 trawl length frequency and age data suggests a shift back towards age 3+ although a good proportion of the spawners were represented by age 2+ fish. As mentioned above, analysis of the 2003 Hill Creek spawner size compared to the size frequency and age of trawl captured fish strongly suggests most of the spawners were age 3+.

The age data for Lower Arrow basin fish is sparse but a somewhat different pattern seems to be emerging. Sebastian et al. (in this ALR report) illustrate different size-at-age data for trawl capture fish between the two basins. In recent years age-at-maturity for Upper Arrow kokanee seems to have changed from age 3+ to age 2+ then back to predominately age 3+(Table 11.2). In contrast the Lower ALR fish appear to be more of a mix of 2+ and 3+ supporting Sebastian et al.'s (in this ALR report) observation that there is more overlap in size of trawl caught 2+ and 3+ fish.

Table 11.2. Age composition (%) of Upper and Lower Arrow basin kokanee spawners 1999-2003.

	Year	% Age 2+	% Age 3+	% Age 4+	Sample size
Upper Arrow					
Hill Creek	1999	20	73	7	182
	2000	52	46	2	194
	2001	49	51	<1	253
	2002	50	50		N/A
	2003		95	5	N/A
Lower Arrow					
Octopus Creek	1999	22	66	11	53
	2000	7	90	3	29
	2001	9.5	86	4.5	21
	2002	41	59	0	22
	2003	95		5	20
Deer Creek	2003	16	84		19

*N/A = not available

Fry-to-Adult Survival Rates

Performance of the lake fertilization experiment and benefits to kokanee can be crudely measured through analysis of fry survival (in-lake) through to maturity. Long term kokanee escapement estimates and fry production data from the Hill and Bridge creek spawning channels provide very good insights into possible trends of in-lake kokanee survival. (Note: fry estimates for Bridge Creek ceased after 2002). To generate fry-to-adult survival rates prior to 2000, the assumptions made for this analysis included a minimal harvest, natural stream egg-to-fry survival of 5%, and a single dominant age of spawning (3+). These assumptions are still considered reasonable but the shift in age at maturity from 2000-2003 from age 3+ dominance to variable proportions of ages 2+ and 3+ required an adjustment to the respective fry production estimates that contributed to the 2000-2003 escapements.

The derived fry-to-adult fry survival rates for 2000 and 2001 assumes all fry produced in 1997 and 1998 returned to spawn as age 3+ but about 50% of the 1998, 1999 fry returned as age 2+ ($\approx 50\%$ of 2000 and 2001 Hill Creek fish were age 2+). The 2000 and 2001 ages (i.e. mixed ages 2+ and 3+) are supported by the length frequency data that shows bimodality indicative of two age groups. No age data was obtained in 2002 but based on the length frequency histogram (Fig. 11.3) and the trawl size and age data from Sebastian et al. (in this ALR report) it was concluded that the spawners were comprised of an equal mix of ages 2+ and 3+. The 2003 age data based on otolith reading provided by a contractor was believed to be incorrect. This conclusion was reached after conducting the same analysis of length frequency data of the spawners, comparing their size to known ages 0+-2+ from the trawl and size frequency of the trawl caught fish. The size frequency histogram from the trawl caught fish show three distinct modes representing ages 0+-2+ with the spawner size representing a fourth mode. The 2002 and 2003 age data shown in Table 11.2 has been

determined from this analysis. With these assumptions and age proportions in mind it is quite clear that in-kokanee lake survival has been elevated considerably since 1999, the first year of fertilization (Fig. 9). Under a single age or multi-age proportioning of fry production (see discussion below) fry-to-adult survival rates increased for four consecutive years (1999-2002) only to decrease in 2003. This decline is not surprising and in fact predictable (density growth response) since total lake abundance was at record highs by 2001-2002 (Sebastian et al. in this ALR report). The Bridge Creek data also shows similar increases in survival rates from 1999-2002 (Fig. 11.9).

The high survival rates during the 1980s shown in Figure 11.9 at first glance seem contradictory to what occurred during the 1999-2002 period. (i.e. comparatively high survival rates nearly twenty years ago without fertilization). The difference between then and the early 2000s is that lake abundance was very low in the latter part of the 1980s and reduced lake productivity had only begun following completion of the Revelstoke Dam. It also should be noted that the same trend in fry-to-adult survival rates has been observed in pre and post fertilization of Kootenay Lake. Survival rates increased for four consecutive years following fertilization that started in 1992. Total lake abundance increased dramatically and survival rates then decreased and now range from ~ 3-5% (Andrusak 2005).

Spawner–Recruit Relationship

The number of recruits that are produced by a group of spawners varies and is usually dependent on several density dependent factors from eggs through to adults. Since kokanee grow primarily based on the production of the secondary trophic level (zooplankton) it can be argued that the spawner-recruit relationship is an indicator of the lakes' trophic status provided that exploitation is not a major factor. A generalized spawner-recruit relationship can be generated for both ALR spawning channels since there is a sufficient amount of escapement data from a number of cycles that can be assembled for analysis. Also, egg-to-fry survival rates have been reasonably constant over the last decade and harvest has been negligible thus minimizing potentially major sources of error. Escapement levels for ALR (Figs. 11.1, 11.2) and sport catch of < 20,000 (Sebastian et al. 2000; Arndt 2002) suggests fishing mortality is not an important factor.

The kokanee spawner-recruit relationship (S/R) for the ALR can be characterized as having two peaks and one trough (Fig. 10). There were several cycles in the 1980s that had S/R ratios > 1 but these ratios were decreasing and by the early 1990s cycles were unable to replace themselves (i.e. < 1). Hill and Bridge creek escapements fell to very low levels in the mid 1990s with S/R ratios low, some calculated between 0.2-0.4. These estimates were made on the assumption that the vast majority (> 90%) of spawners were age 3+. A change in the downward trend of the S/R was initially observed in 1999 when both Hill and Bridge creek spawning runs reached replacement level and since then have replaced themselves for four more cycles. Regardless of the age of spawners that provided the recruits it is quite evident that for the last five years kokanee spawners at both spawning channel sites have replaced themselves and in some years as much as 3-4 fold.

The high(er) spawner–recruit ratios ($S/R > 1$) calculated in the late 1980s were most likely because the Upper Arrow kokanee population at that time was very low due to significant habitat loss and subsequent reduced fish production from construction of the Revelstoke dam. For example, fewer kokanee in the upper basin due to loss of production from the Upper Columbia River above Revelstoke Dam meant good growing conditions for those kokanee produced below Revelstoke. However, declining lake productivity began to be reflected in the kokanee population by the early 1990s and S/R ratios fell to < 1 . The positive spawner-recruitment ratios for both spawning channel populations from 1999-2003 signals a reversal of the downward trend that began in 1992-93 (Figs. 11.9, 11.10).

Discussion

Profound changes are taking place with Upper ALR kokanee directly related to the fertilization experiment that began in 1999. Kokanee data collected through 2003 strongly indicates that a major change in the kokanee population has occurred. Much higher escapements, increased growth, higher fecundity, higher fry-to-adult survival rates, and spawner-recruit ratios > 1 all support the notion that much improved growing conditions now exist within the reservoir.

The 2002 Upper and Lower Arrow escapements were again higher than the 2000 and 2001 levels, much higher than most of those recorded in the 1990s but still below the levels recorded in the late 1980s. The 2003 escapement estimates were incomplete due to the serious fire hazard that prevented aerial estimates to be conducted. The derived spawner-recruit ratio for the two spawning channels exceeded replacement level for the fifth consecutive year in 2003 after nearly a decade where replacement levels were not achieved. From 1992-1998 escapements to both Hill and Bridge creeks had fallen below replacement levels despite good egg-to-fry survival rates.

Size-at-maturity of Hill Creek spawners decreased slightly in 2001 and more so in 2002, most likely reflecting a density growth response since numbers in the lake have been increasing dramatically. Size of 2003 spawners was smaller yet and comparable to the sizes observed in the 1980s and early 1990s. The 2001 data was the first indication of a density dependent growth response and the 2002 data tends to confirm what was expected i.e. size of fish should decrease as numbers increase as the capacity of the lake to produce more kokanee is approached. The decrease in size was expected as whole lake kokanee numbers increase similar to what happened with Kootenay Lake North Arm kokanee. The growth curves for Hill Creek spawners (Fig. 11.8) illustrate changes from rapid growth during initial years of fertilization followed by a decline as time advances. Kokanee numbers in Kootenay Lake are rebuilding after experimental reduction in the fertilizer loading from 1997-2000 and resumption of full loading again in 2001 (Andrusak et al. 2004). With the decline in size, fecundity also has decreased in 2002 and 2003. Such a decline has serious implications for future production, especially from the spawning channels. Adjustment in total numbers permitted into the channel should be made to ensure target numbers of eggs are deposited.

Age determination of ALR kokanee has been fraught with problems for a number of years, especially since lake fertilization began. Conventional ageing using scales or otoliths of

mature fish has been problematic not only on ALR fish but also for Okanagan Lake kokanee. Despite use of a number of people with considerable experience in ageing of salmonids considerable uncertainty persists regarding age-at-maturity of Okanagan Lake stream and shore spawners (Andrusak et al. 2004). The most reliable method of ageing these fish has been to analyse the trawl captured fish that can be readily aged by scale reading and compared with the length frequency histograms. This technique was used for the 2002 and 2003 Upper Arrow kokanee samples (Hill and Bridge Creek) when analysis of the 2003 assigned ages from otoliths did not correspond with the length frequency data from the trawl captured fish.

A major shift in age at maturity of Hill Creek spawners was initially detected in 2000 and length frequency analysis and age data indicated that ages 2+ and 3+ were present in the 2001 spawning population. Prior to 2000, age-at-maturity had been confirmed as predominately age 3+ (Sebastian et al. 2000). It is not unusual to see kokanee mature early if growing conditions are good and this appears to have happened to Hill Creek kokanee from 2000-2002. Age data for 2000 and 2001 Hill Creek kokanee were in fact made up of equal numbers of age 2+ and 3+ (Fig. 11.7). No age data was available for 2002 but the size and age frequency analysis of trawl caught fish suggested a mix of ages 2+ and 3+. The 2003 data was determined as age 3+ to be the primary age at spawning based on analysis of size and age of the trawl caught fish.

Early maturation accounted for some of the unexpected high escapements observed at Hill Creek and Bridge Creek from 2000-2002. Thompson (1999) also observed a shift towards age 2+ spawners at Meadow Creek immediately following fertilization of the North Arm of Kootenay Lake. With the decrease in fry numbers observed by Sebastian (in this ALR report) in 2003 it is likely that future spawners may be a mix of ages 2 and 3+ during the next 2-3 years but it is expected that ALR kokanee will soon become predominately age 3+ spawners once the population fully rebuilds and becomes limited in growth, i.e., density dependent growth response. The Lower Arrow age data, as sparse as it is, suggests more of mix of ages 2 and 3+ spawners.

The crude data generated for fry-to-adult survival rates and the spawner recruit relationship provides further evidence that a major change has taken place with ALR kokanee. The Hill Creek fry-to-adult survival rates appear to have peaked in 2000 at slightly > 12% and have since declined but remaining above the estimates of the early 1990s (Fig. 11.9). The fry-to-adult survival rates should fall as the population rebuilds similar to what has been observed in Kootenay Lake (see discussion below). The rates for Hill Creek fish have indeed fallen since the high estimated in 2000 and were just above 3% in 2003. The spawner-recruit ratios for both Hill and Bridge Creek kokanee were well above 2 in 2002. The 2003 Hill Creek ratio declined but remained above replacement whereas Bridge Creek kokanee did not for the first time since 1998. This is the fifth year that replacement has been achieved at Hill Creek after two cycles had failed to replace themselves (Fig. 11.10). It should be emphasized that the fry-to-adult estimates and replacement ratios are very rudimentary intended only to indicate trends over time. Assignment of ages for each spawning year is imprecise with numerous assumptions made. Nonetheless, even if all years were assigned as

either age 2+ or age 3+ the results are the same. i.e. increased survival rates and spawner replacement since the inception of lake fertilization.

Kokanee data for Arrow Lakes Reservoir from 1999-2003 indicate a change in abundance, growth and survival that can only be accounted for with the inception of lake fertilization in 1999. It should be mentioned that most of the data is from the Upper Arrow where the impact of fertilization should be greatest. The Lower Arrow kokanee have responded as evidenced by increased escapements but limited biological data is available to understand the extent of the response. While the Upper Arrow kokanee response seems rather immediate and sharp it should be noted that their densities in the reservoir prior to fertilization had been trending downward (Sebastian et al. 2000). Low densities in the reservoir, small size and low fecundities (Figs. 11.6, 11.7) in the latter part of the 1990s probably reflected the new (lower) carrying capacity of the reservoir. This is most likely why some year classes of kokanee growth actually improved prior to fertilization (Pieters et al. 1999) and further accelerated with the advent of fertilization commencing in 1999.

Fertilization of a portion of Kootenay Lake has resulted in some dramatic changes to the kokanee population over the last decade. The experiment has been underway on Kootenay Lake much longer than on ALR but the results have been very similar. The whole lake kokanee population in Kootenay rose almost immediately upon commencement of fertilization in 1992 (Andrusak et al. 2004). Escapements began to increase similar to what has been observed on ALR. Initially Meadow Creek age at maturity shifted from predominately ages 3+ to age 2+ as noted for Hill and Bridge creeks. When the fertilizer loadings were deliberately reduced in Kootenay Lake in 1997 the escapements decreased for three consecutive years and are only now (2003) expected to recover because full fertilizer loadings were re-established in 2000 (Fig. 11.11). The 2002 escapement (~354,000) to Meadow Creek was the second lowest recorded since 1992 after near record escapements were recorded in 1998 and 1999 (Fig. 11.12). However, the 2003 escapement was the largest (~0.86 million) since 1999 (Andrusak et al. 2004).

Of interest is the difference in estimates and trend in fry-to-adult survival rates between ALR (Bridge and Hill creeks) and Kootenay Lake (Meadow Creek). On Kootenay Lake the survival rates have been in decline since a high of nearly 16% was recorded in 1994 (Fig. 11.13). Evidently such high rates were not that uncommon in the late 1970s when the lake was highly productive (Ashley et al. 1997; 1999). On ALR the survival rates have been increasing since fertilization began in 1999 and have ranged from about 3- 9% after falling to < 1-2% in the mid 1990s. It is believed that the difference between the survival rates of the two lakes is carrying capacity. In the case of Kootenay Lake the data indicates the lake in the 2000s is again close to carrying capacity as evidenced by increased escapements and whole lake numbers but decreasing size at maturity, decreasing fecundity and growth rates. ALR kokanee have experienced increased escapements and whole lake numbers but not until 2001 and 2002 had there been any evidence of decreased fecundity (Fig. 11.6), growth (Fig. 11.8) or major changes in age at maturity (Fig. 11.7). The fry-to-adult survival rates in Upper ALR increased from 1999-2002 but fell considerably in 2003. The decrease in fry

production from Hill Creek spawning channel in 2003 may delay the reduction of survival rates as has occurred to Kootenay Lake kokanee.

Recommendations

1. The Hill Creek spawning channel should be evaluated for fry production, spawner numbers and associated biological data collected as in previous years.
2. Ageing of Hill Creek spawners should be repeated annually with a minimum of 100 fish aged. Samples should also be obtained from the sport fishery.
3. Lower Arrow kokanee spawners need to be sampled more frequently (e.g. Octopus and Deer creeks) to determine age-at-maturity. A minimum of 100 samples per stream should be collected.
4. The most valuable kokanee data collected on ALR is the trawl and hydro-acoustics data and this needs to be conducted each year.
5. Fecundity needs to be monitored weekly at Hill Creek to ensure egg deposition targets are met.

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Figure 11.1. Kokanee spawner estimates for Hill Creek vs. estimates for five index streams of the Upper Arrow basin, 1966 – 2003. Note: estimate for 2003 index streams was based on average escapement of the previous four years. All index stream estimates expanded by 1.5.

Figure 11.2. Kokanee spawner estimates for four index streams of the Lower Arrow basin, 1966 – 2003. Note: estimate for 2003 index streams was based on average escapement of the previous four years. All index stream estimates expanded by 1.5.

Figure 11.3. Length frequency histograms of Hill Creek for select years. Sample size >100 per year.

Figure 11.4. Length frequency histograms of Bridge Creek kokanee for select years. Sample size >100 per year.

Figure 11.5. Mean length (cm) of male and female Hill Creek kokanee spawners and mean fecundity.

Figure 11.6. Mean fecundity of Hill Creek (1977-2003) and Bridge Creek spawners (1990-2003) (sample size usually >100).

Figure 11.7. Size-at-age of Hill Creek kokanee spawners; 2001 and 2003 determined by otolith 4+ aging. Note: one age fish age 4+ in 2001.

Figure 11.8. Growth curves of successive brood years 1989-2003. Growth was slow under low abundance conditions from approximately 1989-1997; growth increased prior to fertilization due to very low abundance conditions from 1995-1998. Growth was rapid and abundance increased from 1999-2002 and decreased slightly in 2002-2003 for younger fish. All data from Upper Arrow basin. Age-at-maturity is shown as age 3+ for illustrative purposes only for the years 1999-2002 (i.e. some fish matured as age 2+).

Figure 11.9. Calculated fry-to-adult survival for Hill and Bridge Creek. Spawner ages prior to 1999 assumed to be age 3+ but since then ages and fry production have been determined based on proportions of ages determined by otolith aging (2000-2001) and size and length frequency analysis of trawl captured fish (2002-2003).

Figure 11.10. Spawner/recruit relationship for Hill and Bridge Creeks for those years data was available. Age at spawning assumed to be age 3+ prior to 1999; commencing 1999, recruits have been assigned based on otolith determinations (2000 & 2001) and size and age of trawl captured fish (2002 & 2003). Bridge Creek ages assumed to be the same as Hill Creek. See text for explanation on age determinations.

Figure 11.11. Total kokanee abundance estimates vs tonnes of combined N & P added to the North Arm of Kootenay Lake. Note: Error bars denote 95% confidence limits on abundance estimates.

Figure 11.12. North Arm of Kootenay Lake kokanee escapements to Meadow Creek, 1967-2003. Note: Fertilization commenced in 1992.

Arrow Reservoir estimated total kokanee spawner numbers (peak counts expanded)									Index systems highlighted in green											
										Expansion factor =										
Upper Arrow	1966	1969	1974	1978	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Hill channel ¹					150,000	150,000	180,000	75,000	75,000	75,000	75,000	16,328	25,030	22,566	19,087	78,024	102,597	122,400	151,826	133,951
Hill Creek other ²	6,750		12,250		148,112	173,437	97,239	160,443	166,871	198,679	99,224	57,126	4,042	36,411	23,453	22,915	39,506	14,696	43,236	21,328
Bridge channel ¹					7,000	14,000	18,000	18,000	28,000	7,981	13,875	12,696	5,758	4,836	3,600	13,000	10,643	14,263	17,262	4,237
Alkokolex	12,000																			
Bannock					150									0	0	0	128	53	0	
Blanket					150	3,000	1,200	300	750				555	1,395	750	30	2,255	530	4,818	227
Cranberry		6,000				11,250	6,150	11,700	2,025	2,400	98	630	750	4,524	1,826	6,750	6,300	9,975	4,715	1,046
Crawford					3,750				825				270	45	900	90	2,130	1,500	3,246	
Drimmie		1,800			12,000	10,500	3,150	7,500	1,650	6,300		1,710	3,450	3,932	1,732	3,300	8,775	7,425	7,646	953
Halfway	900	12,000	23,310		28,500	30,000	21,150	6,000	2,700			1,680	900	525	1,175	7,050	7,058	12,638	8,850	
Jordan	0	30,000	25,500		9,375	12,000	3,150	4,800	3,150			1,080	150	165	75	375	683	5,850	3,488	
Kuskanax	1,500	37,500	37,500		71,250	65,250	24,150	37,050	15,750	5,003		7,995	750	525	2,715	9,675	8,700	26,775	33,450	
McDonald	5,250	15,000	5,250		15,000			6,300	4,590			9,968	7,244	2,277	8,963	17,076	5,997	23,790	10,260	7,151
McKay					1,875		1,650	1,200	2,025			75		75	615	375	1,406	11,130	281	
MacKenzie	3,750		1,090		4,500	2,625						75								
Mulvehill														18		0	0	0	39	
St. Leon	900	1,800	3,390		4,500	9,750	2,700	750	300	1,761		150		75	360	2,067	2,364	5,396	6,300	3,618
Thompson							3,000	3,150	600			2,147	1,800	1,185	153	1,530	3,518	2,966	2,651	
Tonkawatla	6,000	37,500	12,450		6,750	8,250	1,200	6,750	2,550			1,695	525	99	840	975	3,773	10,950	4,203	
Upper Arrow Index Total	9,150	51,300	73,060	0	416,862	443,187	343,689	303,993	289,971	292,963	188,099	97,535	39,930	68,795	51,762	133,964	177,279	198,197	262,270	160,469
Upper Arrow Total	37,050	141,600	120,740		462,912	490,062	362,739	338,943	306,786	297,124	188,197	113,354	51,224	78,653	66,244	163,232	205,830	270,335	302,269	
Lower Arrow	1966	1969	1974	1978	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Burton	150,000	120,000		136,500	103,500	99,750	114,000	118,500	35,250			78,390	99,600	10,575	56,070	105,450	114,750	181,500	190,950	
Caribou	150,000	78,000		36,000	47,250	25,500	85,500	72,000	15,750			21,263	55,500	10,125	43,350	50,100	63,600	105,150	61,800	
Deer	1,125	2,250		16,500	8,250	6,000	9,750	9,000	2,250					1,659	17,250	16,875	11,838	16,977	25,916	19,170
Dog				9,750			150		75					500		396				
Eagle				24,750		750		750	300					2,175	915	6,029	5,624	0	345	0
Fauquier																	872	62	273	0
Heart				750	450	375	450	750	300				75	30	555	803	1,038	285	767	92
Mosquito	67,500	120,000		117,750	112,500	50,250	51,000	92,250	33,000			48,300	6,075	2,277	68,250	61,500	58,350	101,400	61,800	
Little Cayuse														500	333	1,305			2	
Octopus				3,000	3,750	1,500	2,250	1,500					75	750	1,095	5,955	3,249	1,065	4,814	4,271
Taite	7,200	6,300		6,675	3,750	563	1,500	4,050	1,500				4,335	930	16,715	23,220	11,792	12,012	21,741	510
Lower Arrow Index Total	368,625	320,250		306,750	271,500	181,500	260,250	291,750	86,250			147,953	161,175	24,636	184,920	233,925	248,538	405,027	340,466	
Lower Arrow Total	375,825	326,550		351,675	279,450	184,688	264,600	298,800	88,425			147,953	165,660	29,520	204,533	271,632	271,112	418,451	368,406	
Columbia tribs u/s REV	500,000	500,000	500,000																	
Overall Arrow Index Total	377,775	371,550			688,362	624,687	603,939	595,743	376,221			245,488	201,105	93,431	236,682	367,889	425,817	603,224	602,735	
Total Arrow	912,875	968,150	620,740	351,675	742,362	674,750	627,339	637,743	395,211	297,124	188,197	261,307	216,884	108,173	270,776	434,864	476,941	688,785	670,675	
1. Hill Creek and Bridge Creek represent total counts so were not subject to expansion factors. Additional data for Hill for the years 1979-87 available in Hill Creek electronic data records.																				
NOTE: Italicized (blue) numbers indicate ground count, all others except Hill and Bridge were counted from the air.																				
All peak counts (except complete counts at Hill and Bridge) have been expanded by 1.5x to represent total spawning escapement.																				
2. Hill Creek "other" is based on a combination of fence counts, electronic counters and ground counts for the spawning channel AND the creek downstream (see Hill Creek reports). Expansion factor, where applicable, is built into the estimate.																				

Appendix 11.1. Kokanee escapement data – Arrow Lakes Reservoir.