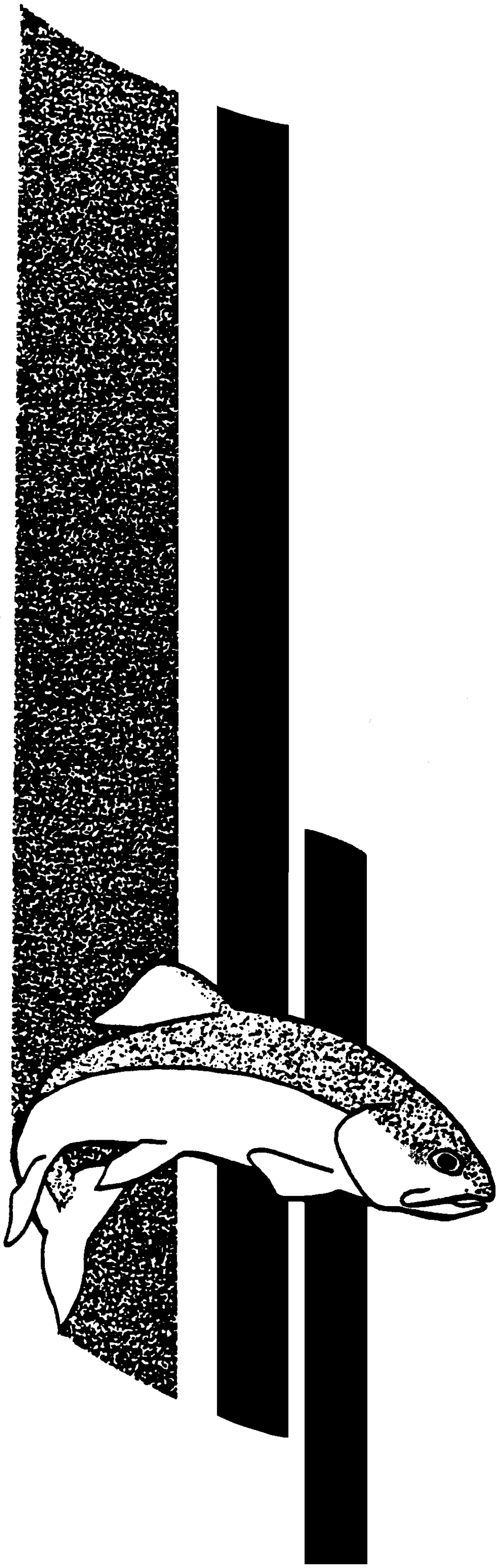

ARROW LAKES RESERVOIR
NUTRIENT RESTORATION PROGRAM, YEAR 9 (2007) REPORT

by

E. U. Schindler, D. Sebastian,

L. Vidmanic, H. Andrusak,

J. Stockner, M. Bassett and K. I. Ashley

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ARROW LAKES RESERVOIR NUTRIENT RESTORATION PROGRAM
YEAR 9 (2007) REPORT

by

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The Fish and Wildlife Compensation Program – Columbia Basin is a joint initiative between BC Hydro, BC Ministry of Environment and Fisheries and Oceans Canada. The program was established to conserve and enhance fish and wildlife compensation populations affected by BC Hydro dams in the Canadian portion of the Columbia River Basin.

The ministry's vision is a clean, healthy and naturally diverse environment.

Funding is provided by Arrow Lakes Power Corporation (ALPC) which owns the Arrow Lakes Generating Station. ALPC is jointly owned by Columbia Power Corporation and Columbia Basin Trust. Columbia Power Corporation manages the operations of the ALPC on behalf of the joint venture. The funding is being provided as a compensatory benefit for the operations of the Arrow Lakes Generating Station on the Lower Arrow Lake.

EXECUTIVE SUMMARY

This report summarizes results from the ninth year (2007) of nutrient additions to Arrow Lakes Reservoir. These additions were conducted using an adaptive management approach in an effort to restore lake productivity lost as a result of nutrient uptake in upstream reservoirs. The objectives of this program were to (1) replace lost nutrients as a result of upstream impoundments and (2) to restore productivity in the Upper Arrow basin that would in turn rebuild kokanee (*Oncorhynchus nerka*) and other sport fish populations -rainbow trout (*Oncorhynchus mykiss*) and bull trout (*Salvelinus confluentus*) throughout the entire reservoir.

Nutrients added were in the form of agricultural grade liquid fertilizer (10-34-0, ammonium polyphosphate (phosphorus, P) and 28-0-0, urea ammonium nitrate (nitrogen, N). During 1999 to 2003, the seasonally adjusted blend of fertilizer was modeled on the successful Kootenay Lake fertilization experiment. Results from 2003 onward suggested that a closer examination of monthly phytoplankton biomass, species composition and water chemistry parameters was required to adaptively manage the weekly nutrient loading schedule to optimize food web transfer of ‘new’ carbon. From 2004 to 2007 less phosphorus and more nitrogen was added than the 1999 to 2003 period to ensure an adequate nitrogen to phosphorus (N:P) ratio for optimal phytoplankton growth. In 2007, 46.8 tonnes of phosphorus and 267.5 tonnes of nitrogen were added to the reservoir.

Adaptively managing the 2007 weekly nutrient loading rates resulted in sufficient nitrogen to phosphorus ratios suitable for phytoplankton growth. Monthly monitoring indicated Arrow Lakes Reservoir remained oligotrophic according to nutrient and chlorophyll *a* concentrations taken from 0-20 m integrated epilimnetic samples. Additional discrete-depth photic zone sampling at two stations in 2007 indicated that the reservoir was not nitrogen limited, an occurrence observed during 2001 to 2003.

Overall phytoplankton abundance and biomass was slightly higher in 2007 compared to 2006 results. The temporal trend of phytoplankton was bacillariophytes and chryso/cryptophytes co-dominating in April to June with a shift to bacillariophytes being dominant in July and August with dinophytes, chlorophytes and cyanophytes contributing higher abundances in October and November.

Zooplankton density and biomass, especially *Daphnia* was the lowest on record in the nine years of study. Lower Arrow had higher zooplankton biomass than Upper Arrow, a trend that followed previous years. In Upper Arrow only a few individuals of *Daphnia* were found during the entire sampling season. The decrease in *Daphnia* is potentially explained by a faster flushing rate of the reservoir than previous years and grazing by kokanee.

The overall trend of mysid density and biomass in 2007 decreased compared to the 2006 results. Mysid density and biomass was higher in the fertilization period relative to the two year period prior to nutrient additions.

The number of kokanee spawners in tributaries to Arrow Lakes Reservoir declined again in 2007 for the third consecutive year since their peak in 2004. Low returns in 2007 can be attributed to a combination of small spawner size, low fecundity and poor egg-to-fry surivival during the fall and winter of 2003. This emphasizes the importance of continuing to operate Hill Creek spawning channel to ensure that fry recruitment is not limiting to kokanee production in Arrow Reservoir.

Mean size-at-maturity and fecundity of Hill Creek kokanee spawners decreased in 2007 compared to 2006 mainly due to the return of some 2+ spawners. The age and size of the kokanee have been variable during the nutrient addition period (1999 to 2007) with a temporary shift in age of maturity to age 2+ during 2000 to 2002 following exceptional growth in 1999. Since 2002, the majority of kokanee have been maturing at age 3+. Good growth starting in 2006 has again led to a shift to a mix of 2+ and 3+ spawners in 2007.

A kokanee hydroacoustic survey estimate in the fall of 2007 indicated a lower pelagic kokanee density relative to 2006. The total of all age classes in the reservoir was only 5.5 million kokanee, compared to 9 million in 2006. Transect densities in 2007 ranged from 75-498 fish·ha^{-1} compared to 218-638 fish·ha^{-1} in 2006.

The mean kokanee biomass in 2007 was 4.6·kg ha^{-1}. During the pre- nutrient addition (‘control’) period (1993-1998), biomass was estimated at ~2.8 kg ha^{-1}. The average kokanee biomass throughout the nutrient addition period (1999 to 2007) was 10.0 kg ha^{-1}.

An overall assessment of the nine years of nutrient additions to Arrow Lakes Reservoir indicates that the approach to restoring kokanee was successful. Kokanee biomass increased on average by three times indicating restoration was successful. The 2007 data indicated the transfer of nutrients from one trophic level to the next was not as effective as previous years of the program. Physical changes from increased discharge in 2007 could be attributable to this. The adaptive management approach of applying nutrients to Arrow Lakes Reservoir needs to be continuously applied to ensure favourable water quality and pelagic food resources for kokanee and higher trophic level insectivorous and piscivorous fish.

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CHAPTER 1

INTRODUCTION – ARROW LAKES RESERVOIR NUTRIENT RESTORATION PROGRAM, YEAR 9 (2007)

by

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Introduction

Nutrient additions (or fertilization) have been widely used in lakes and reservoirs throughout British Columbia and Alaska as a technique for improving sockeye and kokanee stocks (Stockner and MacIsaac 1996; Perrin et al. 2006; Ashley et al. 1999, Mazumder and Edmundson 2002). Nutrient additions have also been used in Scandinavia as a technique for improving Arctic char and brown trout (Rydin et al. 2008 and Milbrink et al. 2008). Prior to nutrient additions, systems such as Arrow Lakes Reservoir, Kootenay Lake, Packers Lake, and Wahleach Reservoir were ultra-oligotrophic (Pieters et al. 1999; Ashley et al. 1999; Mazumder and Edmundson 2002 and Perrin et al. 2006). An ultra-oligotrophic reservoir or lake has extremely low levels of nutrients, which results in low productivity and biomass at all subsequent trophic levels in the aquatic food web. To address the ultra-oligotrophic status of these systems, a bottom-up approach was taken with the addition of nutrients (nitrogen and phosphorus in the form of liquid fertilizer) to increase the production of Daphnia, a main food source for kokanee. Lake fertilization has been a successful technique used for both the enhancement and conservation of sockeye salmon populations (Hyatt et al. 2004). Fertilization has also been successful in restoring kokanee populations in lakes and reservoirs altered by hydroelectric construction (Ashley et al. 1999; Perrin et al. 2006).

This report describes the results from the ninth year (2007) of a multi-year (1999-2007) fertilization experiment (presently referred to as the nutrient restoration program) on Arrow Lakes Reservoir, with the results and analysis of monitoring of physical limnology, water chemistry, phytoplankton, zooplankton, Mysid shrimp and kokanee. Concern over the declining kokanee, a landlocked sockeye salmon (*Oncorhynchus nerka*) and keystone of the local ecosystem, resulted in a two year comprehensive study of the Upper and Lower Arrow Lakes Reservoir commencing in 1997 (Pieters et al. 1998 and 1999). A fertilization program was then initiated in 1999 to try and restore kokanee populations by replacing nutrients lost from upstream impoundments. The project was modelled on the existing, successful Kootenay Lake fertilization project (Ashley et al. 1999; Schindler et al. 2007a).

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). The fourth and fifth years of the fertilization program results from 2002 and 2003 are described in Schindler et al. 2006b and a summary report of results from 1999 to 2004 are described in Schindler et al. 2006c. The sixth and seventh years (2004 and 2005) of the fertilization program are described in Schindler et al. 2007b. The eight year results are described in Schindler et al. 2009.

Study Area

Arrow Lakes Reservoir originally consisted of two lakes, Upper Arrow Lake and Lower Arrow Lake, which lie between the Selkirk and Monashee mountain ranges in southeastern British Columbia (50 ºN and 118 ºW). These lakes were changed into a reservoir when the Hugh Keenleyside Dam was constructed in 1969, flooding the narrow strip of land separating them. There are two additional dams on the main tributary, the Columbia River, which flows into the north end of Upper Arrow. The Mica Dam was constructed in 1973 and the Revelstoke Dam in 1983. Both the Mica and Hugh Keenleyside dams were constructed under the terms of the Columbia River Treaty and are operated for hydroelectric generation and flood control. These operations altered the hydrology of the lakes: the mean water level of the Arrow lakes rose by 12.6 m and mean water level variation doubled from 8 m to 15.5 m with peak variations of 20 m. Prior to impoundment, water levels remained near the low water level throughout the year with a brief peak in the spring. Reservoir operations also altered the hydrology of the Columbia River and changed the timing of its inflow to the reservoir. The spring peak flows were reduced and there is more variable flow throughout the year (Fig. 1.2). Phosphorus inputs to Arrow Lakes Reservoir have also been reduced as a result from reservoir operations (Fig. 1.3). Nutrients were added to Upper Arrow to compensate for losses pre-impoundment (see Chapter 2 for details).

At full pool, Arrow Lakes Reservoir has a surface area of 464.5 km^2 at mean water level and a mean elevation of 342.4 m. Upper Arrow has six major tributaries and 25 minor tributaries, and Lower Arrow has four major tributaries and 26 minor tributaries. The Arrow Lakes Reservoir is 240 km in length, has a mean depth of 83 m, a maximum depth of 287 m and a mean width of 1.8 km (Pieters et al. 2003a, c).

Causes of Kokanee Decline

The construction of upstream impoundments affected the fish stocks in Upper and Lower Arrow lakes in several ways. The construction of Hugh Keenleyside Dam resulted in flooding that eliminated an estimated 30% of the available kokanee spawning habitat in Lower Arrow tributaries and at least 20% of spawning habitat in Upper Arrow tributaries (Andrusak, 1969; Sebastian et al 2000). The Mica Dam contributed to the water level fluctuations and blocked upstream migration of all fish species including kokanee. The Revelstoke Dam flooded 150 km of the mainstem Columbia River and 80 km of tributary streams which were used by kokanee, bull trout, rainbow trout and other species. The dam also blocked upstream passage to an estimated 500,000 kokanee spawners (Martin 1976). As compensation for some of the lost kokanee habitat resulting from dam construction, the Hill Creek spawning channel was completed in 1980.

The construction of upstream dams results in a boom-and-bust nutrient response (Horne and Goldman 1994; Ney 1996; Stockner et al. 2000). In other words, nutrient retention by upstream impoundments ultimately reduced reservoir productivity. In Arrow Lakes Reservoir, nutrients settled out in the Revelstoke and Mica reservoirs, resulting in decreased productivity, a process known as oligotrophication. Kokanee are typically the first species to respond to oligotrophication resulting from impoundments (Ney 1996). The pre-impoundment annual escapement in the Upper and Lower Arrow lakes was estimated at 0.8 to 1.6 million kokanee by Sebastian et al (2000) using three different methods. The post-impoundment escapement declined as low as 108,000 kokanee in 1997.

In addition to the lost habitat and oligotrophication caused by impoundments, kokanee populations have been negatively affected by an exotic species. *Mysis relicta*, a small exotic crustacean, was introduced into ALR in mid-1968 and again in 1974 (Northcote, 1991; Sebastian et al. 2000). *M. relicta*, also referred to as mysid shrimp, was discovered to be a major competitor for the zooplankton species (*Daphnia*) preferred as a food source by kokanee.

Additional Fish Stocks

In addition to kokanee, Arrow Lakes Reservoir supports a variety of other fish species, including rainbow trout and bull trout. Based on work of Martin (1976) Lindsay (1977a and b) and Paish (1974) an estimated 1000 rainbow spawners and 4000 bull trout spawners were blocked by the Revelstoke Dam (Sebastian et al 2000). A stock of smaller-sized native rainbow trout also contributed to the Arrow Lakes Reservoir sport fishery. Lindsay (1976) and Lindsay and Seaton (1978) estimated losses of these smaller rainbow at 1250 spawners per year based on an estimated 30% loss of spawning and rearing habitat through flooding of Arrow Lakes tributaries. Production of small rainbow trout occurred at the Hill Creek Hatchery from 1983 to 2000. A bull trout stocking program began in 1981 at Wardner Hatchery and then Hill Creek Hatchery starting in 1983, but was discontinued in 1999 following an evaluation by Winsby and Stone (1996). Gerrard rainbow trout were stocked into ALR from 1984 to 1997. The stock originated from Kootenay Lake and was introduced into ALR in an attempt to provide a sport fishery for the public. The stocking was discontinued in 1998 as a result of the decline in kokanee. With an increase in kokanee abundance in the reservoir since nutrient additions commencing in 1999, Gerrard rainbow trout yearling have been stocked into Arrow Lakes Reservoir, beginning in 2005. In May 2005, 2000 triploid Gerrard rainbow trout yearlings weighing an average of 14.5g and 10,500 yearlings weighing an average 12.2 g were stocked into Lower Arrow Reservoir. In April 2006, 83380 triploid yearlings weighing an average of 7.4 g were stocked into Upper Arrow Reservoir. In 2007 and 2008, 3000 triploid yearlings were stocked into Lower Arrow and 7000 triploid yearlings were stocked in Upper Arrow.

A more detailed description of ALR fish losses and the compensation program are described in Sebastian et al. (2000), Pieters et al. (2000) and Pieters et al. 2003c *in* Stockner 2003). A summary of the Arrow Lakes Reservoir sport fish statistics are described in Arndt 2004a. Growth and condition of 2003 rainbow trout and bull trout attributable to increased kokanee abundance is described in Arndt 2004b.

The overall expenditure of the Arrow Lakes Reservoir nutrient restoration program in 2007 was $820,406 - $470,289 of this was the cost of fertilizer. The Columbia Power Corporation contributed $206,013 to the project.

Personnel, Affiliation and Responsibilities

Table 1.1. Listing of 2007 Arrow Lakes Reservoir project focus, personnel and affiliation.

Project Focus	**Personnel**	**Affiliation**
Fertilization Limnologist	Eva Schindler	Fish and Wildlife, MoE, Nelson
Fertilizer schedule	Eva Schindler Dr. Ken Ashley	Fish and Wildlife, MoE, Nelson BC Institute of Technology
Fertilizer application	Crescent Bay Construction Galena Bay ferry Shelter Bay ferry	Crescent Bay Construction, Nakusp Western Pacific Marine, Revelstoke Western Pacific Marine, Revelstoke
Reservoir limnology sampling	Don Miller Mike Lindsay Marley Bassett Eva Schindler	Kootenay Wildlife Services Ltd. Kootenay Wildlife Services Ltd. Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson
Limnology analysis and reporting	Eva Schindler Marley Bassett	Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson
Phytoplankton analysis and reporting	Dr. John Stockner	Eco-Logic Ltd.
Zooplankton analysis and reporting	Dr. Lidija Vidmanic	Limno-Lab Ltd., Vancouver
Mysid analysis and reporting	Dr. Lidija Vidmanic	LimnoLab Ltd., Vancouver
Kokanee acoustic surveys	Dale Sebastian Don Miller	Biodiversity Branch, MoE, Victoria Kootenay Wildlife Services Ltd.
Kokanee analysis	Dale Sebastian George Scholten	Fisheries Science Section, MoE, Victoria Fisheries Science Section, MoE, Victoria
Kokanee reporting	Dale Sebastian Harvey Andrusak	Fisheries Science Section, MoE, Victoria Redfish Consulting Ltd.
Kokanee aerial spawner surveys	Grant Thorp Eva Schindler Albert Chirico Marley Bassett Mark Homis	Columbia Aquatic and Technical Services Ltd. Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson Highland Helicopters, Nakusp
Kokanee ground spawner surveys	Karen Bray Shawn Ord Michael Zimmer Les Brazier	BC Hydro BC Hydro Zimmer Environmental Zimmer Environmental
Hill Creek Spawning Channel Operations	Steve Arndt Brian Barney Jeff Burrows Colin Spence	Fish and Wildlife Compensation Program – Columbia Basin (FWCP), Nelson Kingfisher Silviculture Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson
Creel survey report	Steve Arndt	FWCP, Nelson (separate report)
Creel survey	Glen Olson Allsion Alder Deb Imeson	Nakusp Hailstorm Ridge Environmental Services, Galena Bay Scottie's Marina, Robson
Regional support and logistics	Jeff Burrows Colin Spence	Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson

Table 1.1. continued

FWCP Technical Committee	Jeff Burrows Dale Sebastian Trevor Oussoren Dave Wilson Louise Porto	Fish and Wildlife, MoE, Nelson Biodiversity Branch, MoE, UBC BC Hydro, Castlegar BC Hydro, Vancouver Fisheries and Oceans, Nelson
Steering Committee	Wayne Stetski Ted Down Kevin Conlin Maureen DeHaan Bruce MacDonald Richard Spilker Greg Mustard Joe Nicholas Byron Louis	MoE, Cranbrook Biodiversity Branch, MoE, Victoria BC Hydro, Vancouver BC Hydro, Castlegar Fisheries and Oceans Canada, Nelson Public Representative Public Representative First Nations Representative First Nations Representative
Project co-ordination and scientific liaison	Eva Schindler	Fish and Wildlife, MoE, Nelson
Annual report preparation	Eva Schindler Marley Bassett	Fish and Wildlife, MoE, Nelson Fish and Wildlife, MoE, Nelson
Editorial comments	Eva Schindler Steve Arndt	Fish and Wildlife, MoE, Nelson FWCP, Nelson
Contract administration	Edward Hill John Krebs James Baxter Beth Woodbridge	FWCP, Nelson FWCP, Nelson FWCP, Nelson FWCP, Nelson
Administrative support	Louise Bowolin Theresa Hall Elaine Perepolkin Linda Reid Anne Reichert	Corporate Services Division, Nelson Corporate Services Division, Nelson Corporate Services Division, Nelson Corporate Services Division, Nelson Environmental Stewardship, MoE, Nelson

Table 1.2. Arrow Lakes Reservoir physical, chemical, plankton and kokanee sampling program for 2007.

Parameter sampled	**Sampling frequency**	**Sampling technique**
Temperature, dissolved oxygen, pH, ORP, specific conductance, turbidity	Apr - Nov	(a) SeaBird profiles at 8 AR sampling stations from surface to 5 m off the bottom
Transparency	Apr - Nov	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);	Apr - Nov	(a) Integrated sampling tube at 0 - 20 m at 8 AR sampling stations.
	May - Oct	Discrete sample 5 m off the bottom at stations AR 1-3, 6-8
Nutrients (TP, TDP, LL SRP, NO_3+NO_2, NH_3);	Jun - Sep	Discrete depth profiles, 2, 5, 10, 15 and 20 m at stations AR 2 and AR 7.
Total and dissolved metals	Jun and Sept	(b) Integrated 0-20 m at 8 AR sampling stations plus a sample 5 m off the bottom at stations AR 1-3 and 6-8.
Chlorophyll *a* (not corrected for phaeophytin)	Apr - Nov	Integrated sampling tube at 0 - 20 m at AR 1-8 sampling stations
	Jun – Sep	Discrete samples - 2, 5, 10, 15 and 20 m, stations AR 2 and AR 7
Phytoplankton	Apr – Nov (twice in June)	Integrated sampling tube at 0 - 20 m at AR 1-8 sampling stations
Macrozooplankton	Apr - Nov	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	Apr - Dec	3 replicate hauls with mysid net, two deep and one shallow at AR 1-3, 6-8
Kokanee acoustic sampling	Fall survey	Standard MoE Simrad and Biosonics hydroacoustic procedure at 20 transects in Upper and Lower Arrow
Piscivore Monitoring	Creel survey Jan - Dec	Data collected from 3 locations – Castlegar, Nakusp and Shelter Bay (catch, effort and biological information)

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Funding was provided by the Fish and Wildlife Compensation Program – Columbia Basin (FWCP) and the Arrow Lakes Power Corporation (ALPC) which owns the Arrow Lakes Generating Station. ALPC is jointly owned by Columbia Power Corporation (CPC) and Columbia Basin Trust (CBT). The FWCP is a joint initiative between BC Hydro, the BC Ministry of Environment and Fisheries and Oceans Canada. The program was established to conserve and enhance fish and wildlife compensation populations affected by BC Hydro dams in the Canadian portion of the Columbia River Basin. Thanks to Karen Bray, BC Hydro, Revelstoke who provided discharge data.

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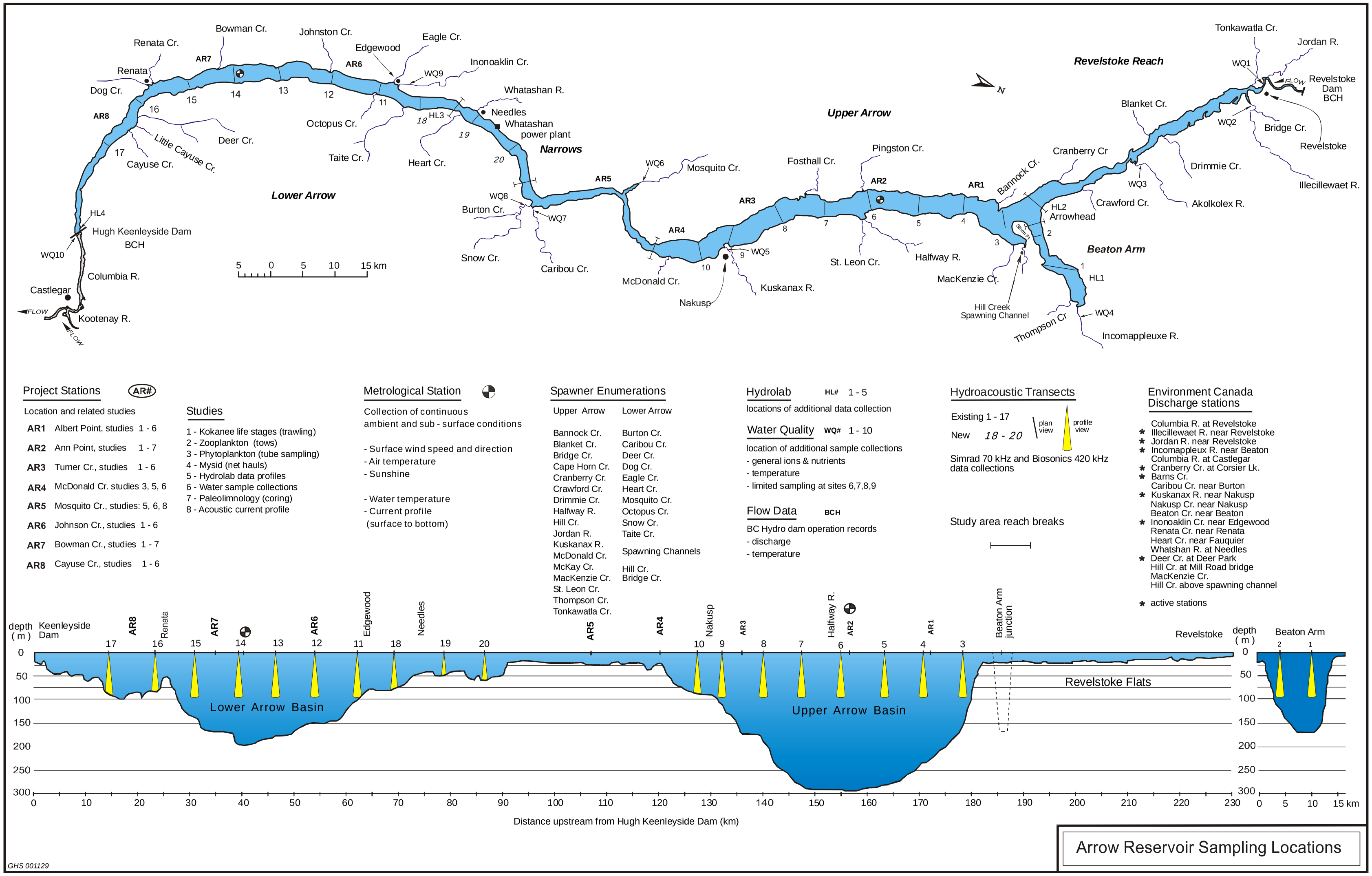

Figure 1.1 Arrow Lakes Reservoir sampling stations and locations.

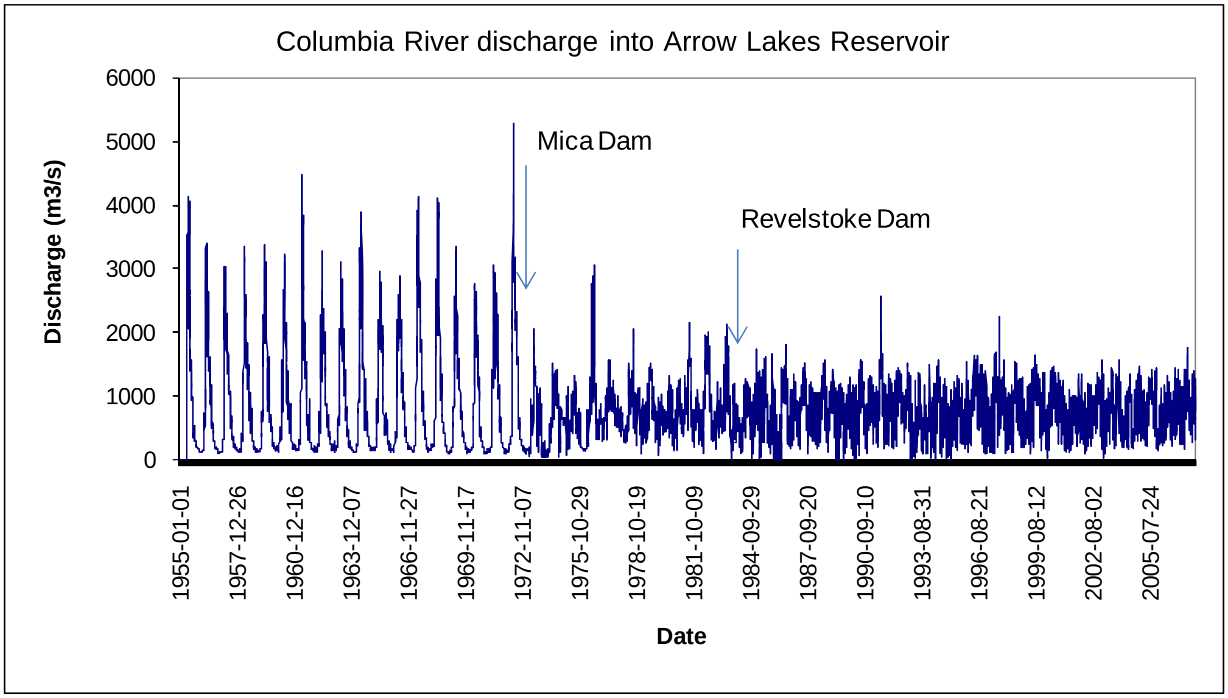

Figure 1.2. Discharge from the Columbia River into Arrow Lakes Reservoir, 1955 to 2007.

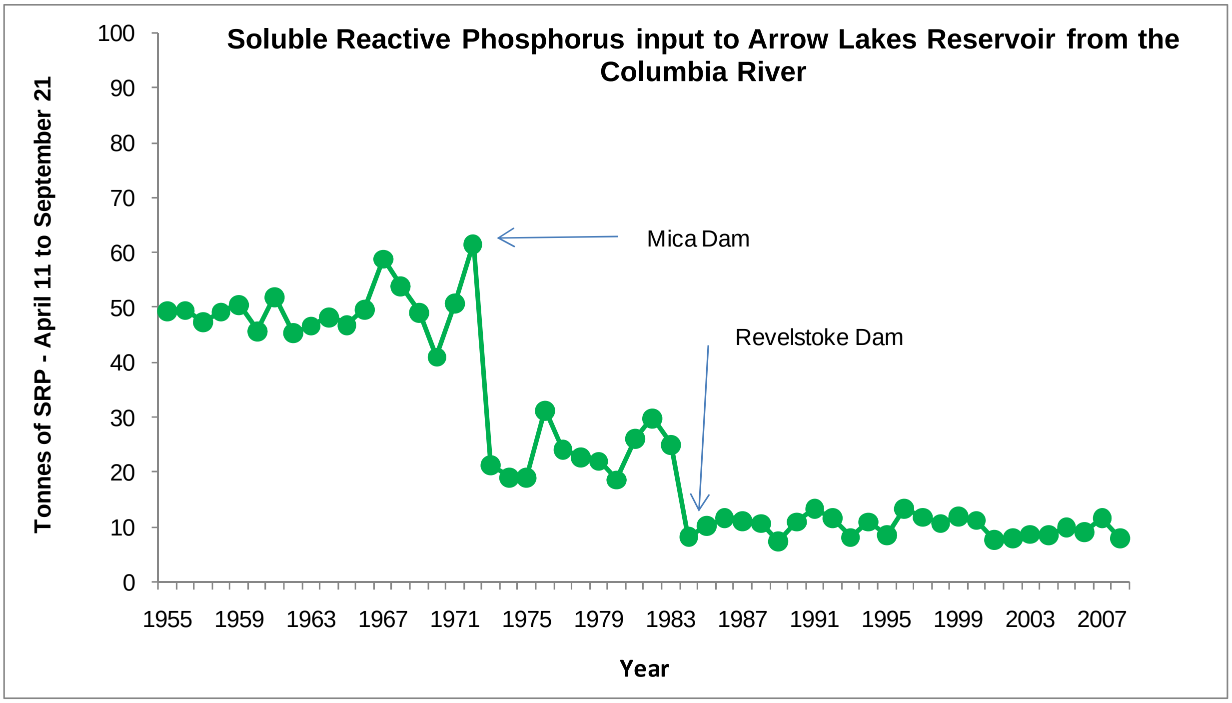

Figure 1.3. Soluble reactive phosphorus input to Arrow Lakes Reservoir from the Columbia River, 1955 to 2007.

CHAPTER 2

FERTILIZER LOADING IN ARROW LAKES RESERVOIR, YEAR 9 (2007)

by

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Fertilization Experiment

The Arrow Lakes Reservoir fertilization experiment (presently described as the nutrient restoration program) was 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, Schindler et al. 2009 and Wright et al. 2002). An adaptive management strategy was also adopted for the Arrow Lakes Reservoir experiment, which began in 1999, after two years of an intensive study of the reservoir's pelagic ecosystem (Pieters et al. 2000). The fertilization of Arrow is undertaken as a large-scale experiment, and as such, is potentially subject to the risk of failure due to the size and complexity of the experiment. Adaptive management requires that adequate information be collected to assess the progress of the experiment so that necessary changes (i.e., adaptive responses) can be made in a timely fashion.

Fertilizer type

A seasonally adjusted blend of agricultural grade liquid ammonium polyphosphate (10-34-0: N-P_2O_5-K_2O; % by weight) and liquid urea-ammonium nitrate (28-0-0: N-P_2O_5-K_2O; % by weight) was added to Arrow Lakes Reservoir in 2007. The fertilizer was purchased from a Canadian supplier, Agrium Ltd., and delivered from their Kamloops distribution center.

Seasonal loading and timing

During 1999 to 2003, the seasonally adjusted blend of fertilizer was modeled on the Kootenay Lake fertilization experiment (Ashley et al. 1997, 1999a, b, Schindler et al. 2009). The results from 2003 onwards indicated a closer examination of monthly phytoplankton biomass, species composition and water chemistry parameters was required to adaptively manage the weekly nutrient loading schedule in future years of the experiment. In 2007, adaptive management was continued to be implemented to ensure an adequate nitrogen to phosphorus (N:P) ratio was present for optimal phytoplankton growth (Table 2.1).

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 (Table 2.2, Figs. 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).

In 2007, fertilizer treatment started the week of April 22nd and ended the week of September 16th. The fertilizer N:P ratio (weight to weight basis) was modified throughout the season and increased from 0.67:1 (i.e., 10-34-0 only) in the initial spring applications to 9:1 in the late summer applications. Based on an in-lake area of 193 km^2, this corresponds to a loading of phosphorus that ranged from 7.6 to 20 mg/m^2/week. The total seasonal phosphorus loading from liquid fertilizer in Upper Arrow was 246.5 mg/m^2 –

this differs from the 1999 to 2003 application rate which was 274 mg/m^2 (Schindler et al. 2006). A total of 46.8 tonnes of phosphorus and 267.5 tonnes of nitrogen were added to Upper Arrow in 2007 (Table 2.2, Fig 2.1).

Fertilizer application

In 2007, the fertilizer was dispensed from the Galena ferry as was conducted in 2006 for the first 8 weeks of the season. During the next 13 weeks fertilizer was dispensed from the Shelter Bay ferry and the last week of the season, fertilizer was dispensed from the Galena Bay ferry. When using the Shelter Bay ferry, dispensing occurred over approximately a 15 km distance beginning mid-way between hydroacoustic transects 3 and 4, travelling to the mid-way point between hydroacoustic transects 5 and 6, at which point the ferry traveled north-northwest 15 km to the ferry slip (Fig 1.1, Chapter 1). One half of the fertilizer was dispensed as the ferry traveled south and the other half was dispensed on the return trip.

Fertilizer trips

Galena Bay ferry

A 7,700 litre capacity tank and truck capable of hauling this amount was used to dispense the fertilizer. The number of trips varied depending on the weekly loading schedule (Table 2.1). The fertilizer was stored at a tank farm located at the Hill Creek Spawning Channel where the contractor would fill their truck with the appropriate amount and blend of fertilizer, drive on to the ferry and dispense during the passenger run.

Two diffuser pipes were installed in opposing corners on the rails of the ferry so that the dispensed fertilizer could directly be mixed into the propeller wash of the ferry. The diffuser units were 3.6 m in length, 7.5 cm in diameter and had 0.6 cm orifices at 30 cm spacing along the length of the pipe (Pieters et al. 2003a). The ferry crossing time was approximately 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 was applied on the trip from Galena Bay to Shelter Bay and the remaining fertilizer was dispensed on the return trip.

Shelter Bay ferry

The Shelter Bay ferry was used for a portion of the season and the fertilizer was dispensed over a course of 15 km and a total of 2.5 hours of dispensing time. Two dispenser pipes were placed on the stern of the ferry (size of pipes was similar to those used on the Galena Bay ferry), and hoses were connected from the delivery trucks to the pipes where the fertilizer blend could mix into the propeller wash of the ferry. The fertilizer delivery trucks drove on to the ferry and the product would be directly dispensed from the delivery trucks to the reservoir. Table 2.2 identifies the ferry used in specific weeks.

Table 2.1. Total tonnes of phosphorus and nitrogen and total mg/m^2 of phosphorus and nitrogen dispensed into Upper Arrow from 1999 to 2007, April to September. The area of Upper Arrow is 193 km^2.

Year	Phosphorus Tonnes	Nitrogen Tonnes	Phosphorus mg/m2	Nitrogen mg/m2
1999	52.8	232.3	274	1203
2000	52.8	232.3	274	1203
2001	52.8	232.3	274	1203
2002	52.8	232.3	274	1203
2003	52.8	267.8	272	1389
2004	39.1	276.9	180	1436
2005	45.0	278.8	245	1479
2006	41.6	244.9	219	1289
2007	46.8	267.5	246	1362

Table 2.2. Arrow Lakes Reservoir nutrient loading from fertilizer during 2007 – liquid ammonium polyphosphate (phosphorus: 10-34-0)(P) and liquid urea-ammonium nitrate (nitrogen: 28-0-0)(N).

Week	Date	Load mg/m^2	P kgs	10-34-0 Tonnes	Load mg/m^2	N Kgs	28-0-0 Tonnes	N:P wt:wt	Ferry
1	Apr 22	7.6	1,440	9.7	5.11	970	0.0	0.67	Galena
2	Apr 29	7.6	1,440	9.7	5.11	970	0.0	0.67	Galena
3	May 06	11.4	2,168	14.6	7.68	1,460	0.0	0.67	Galena
4	May 13	15.2	2,895	19.5	10.26	1,950	0.0	0.67	Galena
5	May 20	19.5	3,712	25.0	13.16	11,180	31.0	3.0	Galena
6	May 27	20.2	3,845	25.9	60.97	11,584	32.1	3.0	Galena
7	Jun 03	14.9	2,836	19.1	57.21	10,870	32.0	3.8	Galena
8	Jun 10	11.7	2,227	15.0	59.47	11,300	35.0	5.1	Galena
9	Jun 17	11.7	2,227	15.0	80.10	15,220	49.0	6.8	Shelter
10	Jun 24	10.5	2,004	13.5	88.16	16,750	55.0	8.4	Shelter
11	Jul 01	5.2	995	6.7	44.07	8,373	27.5	8.4	Shelter
12	Jul 08	5.3	1,010	6.8	49.54	9,413	31.2	9.3	Shelter
13	Jul 15	9.4	1,782	12.0	87.37	16,660	55.0	9.3	Shelter
14	Jul 22	9.4	1,782	12.0	87.37	16,660	55.0	9.3	Shelter
15	Jul 29	9.4	1,782	12.0	87.37	16,660	55.0	9.3	Shelter
16	Aug 05	9.4	1,782	12.0	87.37	16,660	55.0	9.3	Shelter
17	Aug 12	9.4	1,782	12.0	87.37	16,660	55.0	9.3	Shelter
18	Aug 19	11.7	2,227	15.0	88.95	16,900	55.0	7.6	Shelter
19	Aug 26	11.7	2,227	15.0	88.95	16,900	55.0	7.6	Shelter
20	Sep 02	11.7	2,227	15.0	88.95	16,900	55.0	7.6	Shelter
21	Sep 09	11.7	2,227	15.0	88.95	16,900	55.0	7.6	Shelter
22	Sep 16	11.7	2,227	15.0	88.95	16,900	55.0	7.6	Galena
Total		**246.5**	**46,843**	**316**	**1362**	**267,540**	**843**		

Acknowledgements

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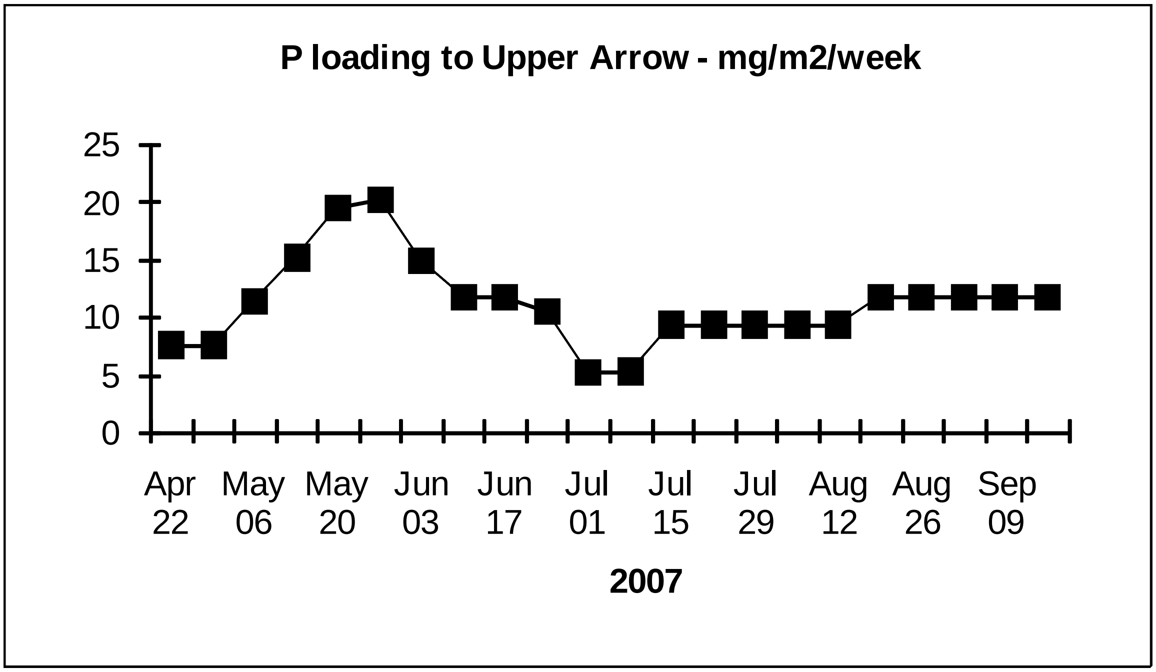
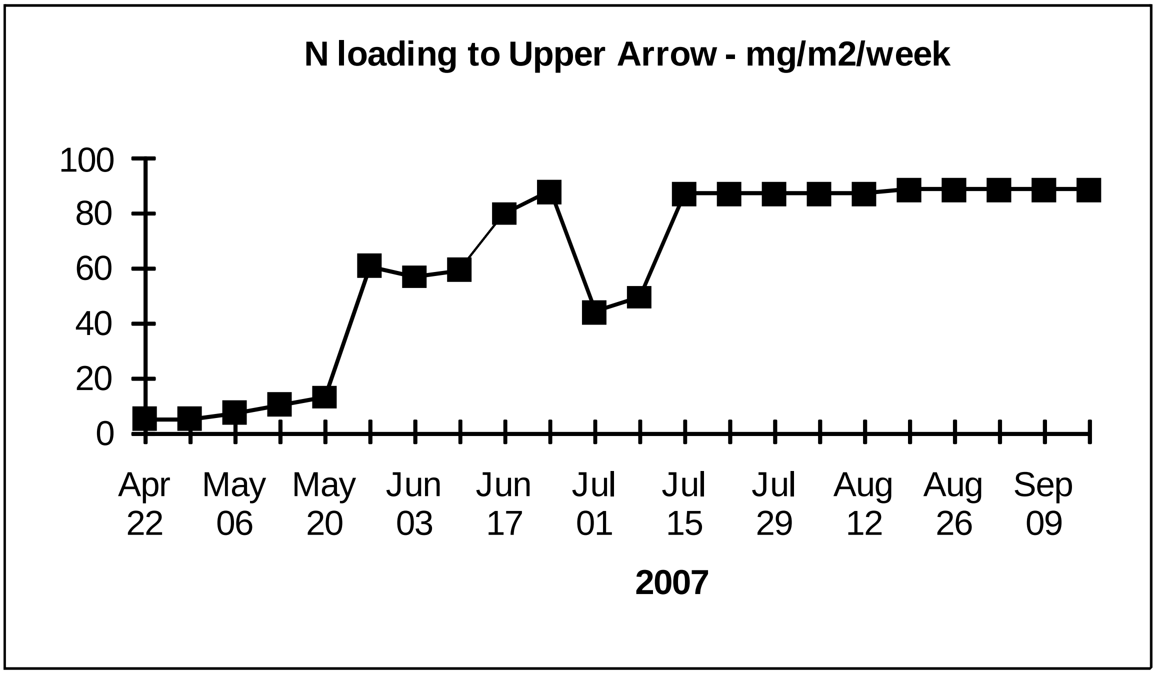
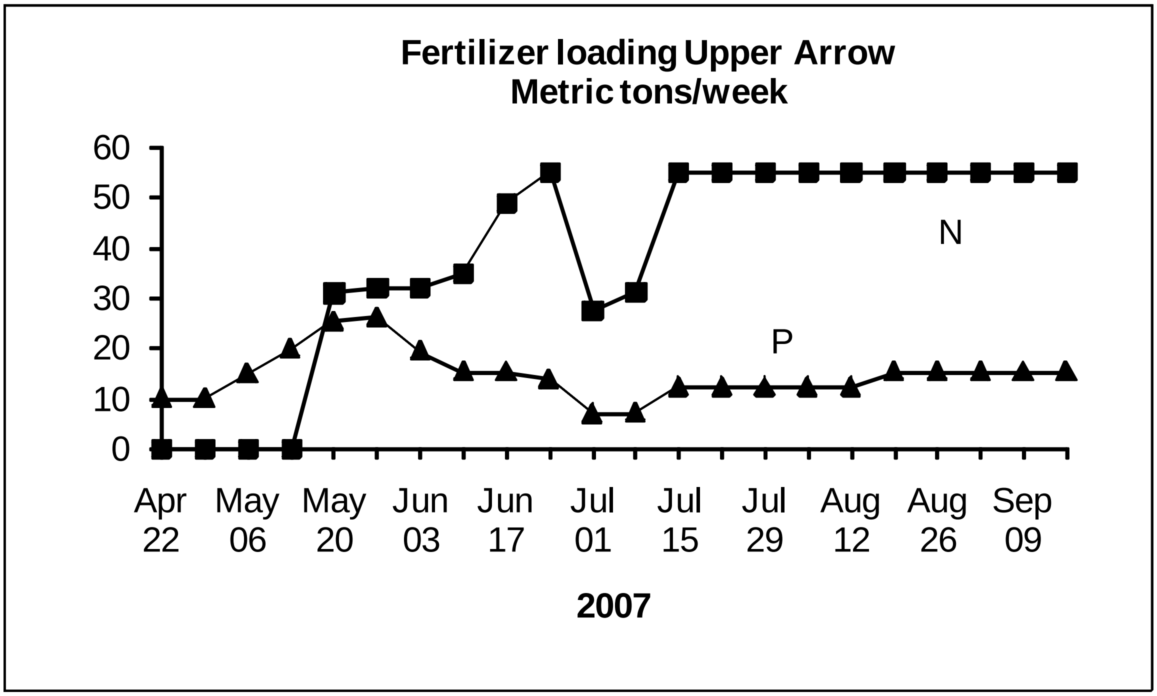


a)



b)

Figure 2.1. Arrow Lakes Reservoir nutrient loading in 2007 with weekly distributions of: a) phosphorus loading to Upper Arrow, b) nitrogen loading to Upper Arrow.



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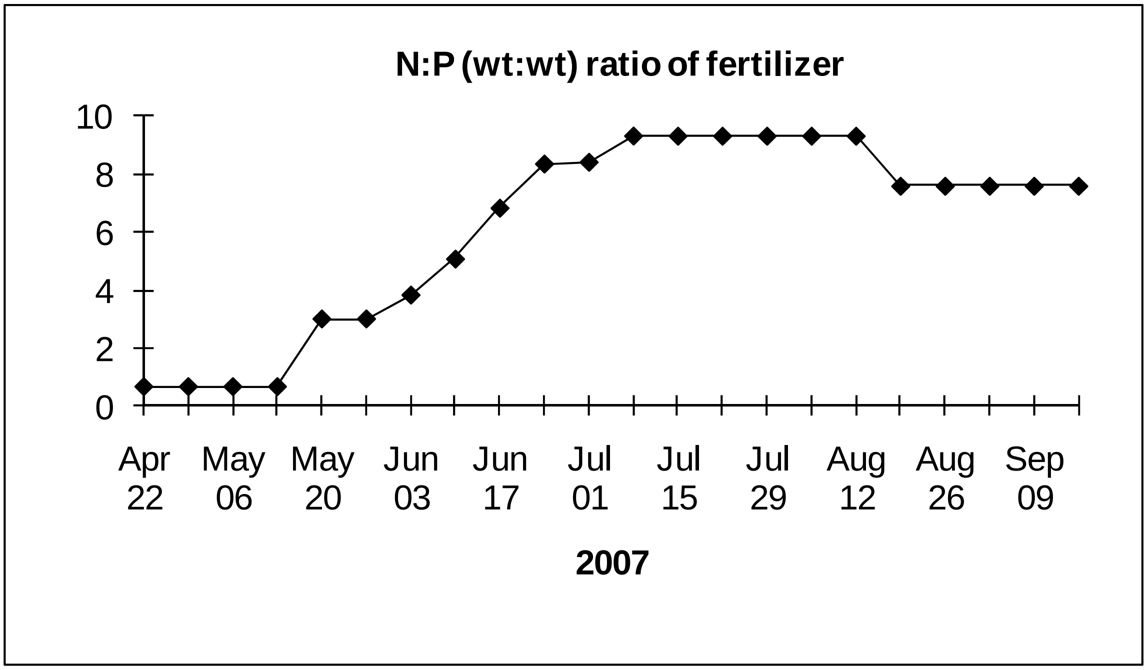

d)

Figure 2.2 Arrow Lakes Reservoir nutrient loading in 2007 with weekly distributions of: c) the N:P ratio (weight:weight) of fertilizer dispensed and d) the combined nutrient loading of metric tons of fertilizer per week.

CHAPTER 3

RESPONSE OF PHYSICAL AND CHEMICAL LIMNOLOGY OF ARROW LAKES RESERVOIR TO NUTRIENT ADDITION, YEAR 9 (2007)

by

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Introduction

Experimental nutrient additions (fertilization) to Arrow Lakes Reservoir began in 1999 to restore lost nutrients from upstream hydroelectric impacts and reverse the oligotrophication of the reservoir. The objective of the nutrient additions is restore the abundance of kokanee and other sport fish by replacing lost nutrients through the continued application of appropriate quantities of fertilizer (Schindler et al. 2006b). Nutrient additions have been used in British Columbia, Alaska, Idaho and Sweden as a technique for rebuilding depressed sockeye, kokanee and arctic char (Sweden) stocks in lakes and reservoirs (Stockner and MacIssac 1996, Ashley et al. 1999, Mazumder and Edmundson 2002, Pieters et al. 2003, Perrin et al. 2006, Rydin et al. 2008).

Nutrients have been added to the reservoir in the form of liquid ammonium polyphosphate (phosphorus, P; as 10-34-0, N-P_2O_5-K) and urea ammonium nitrate (nitrogen, N; as 28-0-0), from the end of April through September during each year of the experiment (1999 to 2007). During 2007, 46.8 tonnes of phosphorus (P) and 267.5 tonnes of nitrogen (N) were added to the reservoir (see Chapter 2).

This report summarizes the physical, chemical, and chlorophyll a data collected on Arrow Lakes Reservoir in 2007. Seasonal averages from previous years are shown in the tables and discussed in relation to previous years but are not included in graphs.
Details of previous years data can be found in Pieters et al. 1998, 1999, 2000, 2001a, 2003 a, 2003 b, Schindler et al. 2006 a and b, 2007 and 2009.

Materials and Methods

Water samples for physical and chemical analyses were collected at eight established sampling stations (see Fig 1.1 Chapter 1) in conjunction with phytoplankton samples (Table 3.1). Stations AR 1 through AR 4 are located in Upper Arrow, AR 5 is located in the old river channel that connected the original Upper and Lower Arrow lakes pre-dam impoundment, and AR 6 through AR 8 are located in Lower Arrow.

Table 3.1. Limnological sampling stations for the Arrow Lakes Reservoir Nutrient Restoration Program.

Site ID	EMS Site No.	Site name	Depth (m)
AR 1	E225768	Arrow Lake @ Albert Point	220
AR 2	E225769	Arrow Lake @ Ann Point	285
AR 3	E225770	Arrow Lake @ Turner Creek	155
AR 4	E225771	Arrow Lake @ Slewiskin Creek	75
AR 5	E225779	Arrow Lake, downstream Mosquito Creek	50
AR 6	E225781	Arrow Lake @ Johnson Creek	145
AR 7	E225782	Arrow Lake @ Bowman Creek	155
AR 8	E225783	Arrow Lake @ Cayuse Creek	85

In 2007, temperature and oxygen profiles were taken from April through November at stations AR 1-8 using a SeaBird (SBE 19-plus, SeaBird Electronics, Bellevue, Washington) profiler. The SeaBird profiler was used to collect data from the reservoir's surface to approximately 5 m off the bottom. Water transparency was measured at each sampling station using a standard 20-cm Secchi disk.

During 2007 water samples were collected at AR 1-8 from April through November using a 2.54-cm (inside diameter) tube sampler to collect an integrated water sample from 0-20 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 from May to October (Table 3.1). 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, 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 formula using the absorbance of the supernatant at specific wavelengths.

Additional water samples were taken at stations AR 2 and AR 7 at discrete depths from June to September, using a Van Dorn sampling bottle, in the epilimnion of Arrow Lakes Reservoir. These 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, and Chl *a*.

In this report, average measurements from the spring, summer, and fall of 1997-2007 are given for Upper Arrow (AR 1-4) and Lower Arrow (AR 6-8). Seasonal variations of the 2007 data are illustrated in the figures of this report. Detailed data and analysis of the 1997-2006 data are available in previous annual reports (Pieters et al. 1998, 1999, 2000, 2003a and 2003b and Schindler et al. 2006a, 2007, 2009). 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 warm monomictic lake, with isothermal temperatures from late fall to early spring and stratification during the summer months. The reservoir began to stratify in June with August being the warmest month at stations AR 1, AR 2 and AR 5 – AR 8. July was the warmest month at stations AR 3 and AR 4 (Figs. 3.1- 3.8). The warmest surface temperature was at station AR 5 in August with 23.4 ^{o}C. The maximum surface temperature in Upper Arrow and Lower Arrow was 20.1 ^{o}C.

Dissolved Oxygen

Dissolved oxygen profiles in Arrow Lakes Reservoir showed oxygen throughout the water column at all stations for the entire sampling season as in previous years. 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). Nutrient enrichment has had no detectable effect on hypolimnetic oxygen concentrations.

Secchi depth

The Secchi depth in Upper Arrow ranged from 2.13 m to 13.41 m and from 2.74m to 11.89 m in Lower Arrow in 2007 (Fig. 3.9). Secchi depths were highest in April and then declined with the onset of the spring freshet and increasing phytoplankton biomass. Secchi depths increased again in September in Upper and Lower Arrow. Averages of spring, summer and fall Secchi depths trends were similar to previous years except in the summer in Upper Arrow where the average depth was lower (Table 3.2**)**. This coincides with the turbidity and chlorophyll results which were higher during the summer of 2007 in both Upper and Lower Arrow.

Turbidity

Turbidity is caused by suspended particles (e.g., fine particulate matter), plankton and other small organisms (Wetzel and Likens, 2000). In 2007, turbidity increased as the season progressed from spring to summer and then decreased again during the fall months (Fig. 3.10). Peak turbidity occurred in July in Upper Arrow. Spring, summer and fall averages from 1997 through 2007 ranged from 0.1 to 0.92 NTU in Upper Arrow and from 0.22 to 0.78 NTU in Lower Arrow (Table 3.3). Average turbidity was higher during the summer of 2007 compared to all other years in Upper Arrow and was the second highest in Lower Arrow. This coincides with lower Secchi depth and higher chlorophyll concentrations during the summer months.

Conductivity

Conductivity or specific conductance is a measure of resistance of a solution to electrical flow (Wetzel 2001). Conductivity or specific conductance ranged from 91 to 137 µs/cm in Upper Arrow and from 101 to 133 µs/cm in Lower Arrow in 2007 (Fig 3.11). Values were highest in the spring, decreased slightly as the summer progressed and increased during the fall months. Conductivity averages showed little variability in spring, summer and fall from 1997 to 2007 **(**Table 3.4).

Table 3.2. Average Secchi depth (m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct – Nov) in Upper Arrow and Lower Arrow from 1997 to 2007.

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
2004	8.20	6.40	7.62	8.16	6.71	9.09
2005	8.38	5.01	6.82	6.71	6.98	7.27
2006	8.56	7.34	9.57	7.44	11.14	9.96
2007	7.65	3.61	8.00	6.40	5.15	7.67

Table 3.3. 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. Samples were collected from 0- 20 m in 2004 to 2007.

Year	Upper Arrow AR 1-4			Lower Arrow AR 6-8		
	Spring	Summer	Fall	Spring	Summer	Fall
1997	0.55	0.52	0.27	0.53	0.37	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	0.29	0.70	0.32	0.44	0.52	0.39
2003	0.44	0.65	0.51	0.58	0.63	0.37
2004	0.32	0.82	0.47	0.37	0.78	0.34
2005	0.40	0.61	0.51	0.48	0.49	0.62
2006	0.47	0.75	0.30	0.78	0.68	0.37
2007	0.48	0.92	0.46	0.56	0.74	0.45

Table 3.4. Average conductivity (µs/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. Samples were collected from 0- 20 m in 2004 to 2007.

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
2004	134	109	117	125	111	108
2005	123	114	127	121	108	115
2006	127	108	123	124	108	112
2007	128	106	124	127	105	111

Chemical Limnology – Integrated samples

Phosphorus

Total phosphorus (TP) ranged from 2 to 7 µg/L in Upper Arrow and from 2 to 6 µg/L in Lower Arrow in 2007 (Fig 3.12**)**. The highest concentrations occurred in April and July in Upper Arrow and in August, September and October in Lower Arrow. Seasonal averages of TP ranged from 2 to 4 µg/L from 1997 to 2007 in the entire reservoir (Table 3.5**)**. These results are indicative of an oligotrophic lake (Wetzel 2001).

Total dissolved phosphorus (TDP) ranged from 2 to 7 ug/L in Upper Arrow and from 2 to 5 µg/L in Lower Arrow in 2007 (Fig 3.13). Seasonal averages of TDP ranged from 2 to 4.25 µg/L from 1997 through 2007 (Table 3.6). Summer averages in Upper and Lower Arrow in 2007 were similar to previous years.

Orthophosphate ranged from 1 to 4 µg/L in Upper Arrow and 1 to 5 µg/L in Lower Arrow in 2007 (Fig 3.14). Concentrations decreased from April to the end of June, increased in July, remained fairly constant to October and increased slightly in November. Most results were above the detection limit of 1 µg/L. A portion of the orthophosphate results in 2007 were higher than total phosphorus and total dissolved phosphorus - this is indicative of results being close to the minimum detection limits.

Table 3.5. 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. Samples were collected from 0- 20 m in 2004 to 2007.

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
2004	3.75	2.42	2.88	2.22	4.11	2.83
2005	3.47	2.33	2.00	4.17	2.11	2.00
2006	2.63	3.67	2.88	2.50	3.11	2.33
2007	3.50	3.25	2.25	2.92	3.33	3.50

Table 3.6. Average total dissolved 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. Samples were collected from 0- 20 m in 2004 to 2007.

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	3.57	3.08	2.63	2.67	3.89	3.67
2003	2.58	3.25	2.00	2.89	2.44	3.00
2004	2.75	2.08	2.25	2.67	2.78	2.33
2005	2.69	2.00	2.00	2.33	2.11	2.00
2006	2.75	3.25	2.13	2.67	3.44	2.33
2007	2.81	3.08	3.00	3.17	2.75	2.80

Nitrogen

The nitrogen cycle within freshwaters is highly complex and occurs through various forms of fixation, assimilation, and reduction (Wetzel 2001). In fresh water, complex biochemical processes utilize nitrogen in many forms consisting of dissolved molecular $N_{2,}$ ammonia nitrogen, nitrite, nitrate, and organic nitrogen. A major source of nitrogen in lakes is the nitrate in precipitation in their watersheds (Horne and Goldman, 1994).

Nitrate is the most abundant form of inorganic nitrogen in lakes (Horne and Goldman, 1994). Total nitrogen is comprised of dissolved inorganic forms (i.e., nitrate, nitrite and ammonia) and particulate nitrogen.

Total Nitrogen (TN) concentrations ranged from 120 to 230 µg/L in Upper Arrow and from 120 to 190 µg/L in Lower Arrow in 2007 (Fig. 3.15). The average seasonal concentration was 30 ug/L higher in Upper Arrow than in Lower Arrow; a trend similar to 2006.

In 2007, ammonia concentrations were at or near the detection limit of 5 µg/L except for the following: at station AR 1 the concentration was 25 µg/L in late June. At station AR 2, the concentration was 32 µg/L in late June. At station AR 3, the concentrations were 11 µg/L in mid-June and 20 µg/L in late June. At station AR 4, the concentrations were 19 µg/L in mid-June, 18 µg/L in late June, and 26 µg/L in July. At stations AR 6, AR 7 and AR 8, the ammonia concentrations in late June were 12 µg/L, 11 µg/L and 10 µg/L, respectively.

Dissolved inorganic nitrogen (DIN), consists of nitrite, nitrate and ammonia. Nitrate and ammonia are the forms of nitrogen most readily available to phytoplankton (Wetzel 2001). Dissolved inorganic nitrogen (DIN = NH3 + NO3 + NO2) concentrations ranged from 59 to 181 µg/L in Upper Arrow and from 56 to 154 µg/L in Lower Arrow during 2007 (Fig. 3.16). Concentrations in Upper Arrow did not decrease as rapidly over the sampling season compared to previous years. The concentrations decreased over the sampling season in Lower Arrow – this is due to phytoplankton utilizing nitrate (the dominant component of DIN) during summer stratification. The seasonal averages of DIN were similar in the spring of 2007 compared to 2006 in Upper Arrow. The summer seasonal average was slightly higher than the previous four years (Table 3.7). The fall averages were lower than 2006 but higher than the 2004 and 200r results. The results in Lower Arrow were similar to previous years.

Table 3.7. Average dissolved inorganic nitrogen (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. Samples were collected from 0- 20 m in 2004 to 2007.

Year	Upper Arrow AR 1-4 Spring	Upper Arrow AR 1-4 Summer	Upper Arrow AR 1-4 Fall	Lower Arrow AR 6-8 Spring	Lower Arrow AR 6-8 Summer	Lower Arrow AR 6-8 Fall
1997	162	147	130	120	131	111
1998	155	121	114	117	115	99
1999	142	152	137	123	118	144
2000	153	159	no data	129	116	no data
2001	201	147	140	192	116	117
2002	158	134	153	133	89	120
2003	138	112	136	141	55	90
2004	159	103	105	131	74	92
2005	134	117	116	113	77	92
2006	136	107	155	107	80	96
2007	137	122	125	106	79	104

Silica

Silica is an integral structural component in diatomaceous algae and is considered a major factor influencing algal production in many lakes (Wetzel 2001). Silica can have an influence on the succession and productivity of algal communities in lakes and streams. As a result, silica can be considered a limiting factor in diatom production when its availability is low. Silica occurs primarily in two major forms: dissolved silicic acid and particulate silica. Silica concentrations ranged from 2 to 4.2 mg/L in Upper Arrow and from 2.4 to 4.6 mg/L in Lower Arrow in 2007 (Fig. 3.17). Silica was always well above 0.5 mg/L, which is considered the limiting concentration for diatoms (Wetzel, 2001). Silica decreased from spring to summer and then increased from summer to fall; the decrease was more pronounced in Lower Arrow compared to Upper Arrow. The trend of seasonal averages from 1997 to 2007 indicated a decrease from spring to summer with similar results from summer to fall. Average silica for the summer months in Upper Arrow in 2001 was lower than the average values from all other years (Table 3.8).

Table 3.8. Average silica (mg/L) (0-30m) in spring (Apr – Jun), summer (Jul – Sep) and fall (Oct-Nov) in Upper Arrow and Lower Arrow from 1997 to 2003. Samples were collected form 0-20 m in 2004 to 2007.

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	3.56	3.03	3.21	4.08	3.18	3.28
2003	3.99	3.15	3.40	4.09	2.49	3.13
2004	4.13	3.27	3.09	4.72	3.52	4.25
2005	5.28	5.48	4.89	5.64	4.59	5.03
2006	4.86	3.70	4.60	5.79	3.90	5.47
2007	3.84	3.32	3.43	4.29	3.09	3.73

Alkalinity

Alkalinity is the buffering capacity of lake water (i.e, the sum of the titratable bases) to resist pH changes and involves the inorganic carbon components in most fresh waters (Wetzel 2001). Alkalinity in Upper and Lower Arrow decreased through the summer during 2007 and then increased during the fall, a pattern observed in other years (Figs. 3.18). In 2007, alkalinity ranged from 41 to 58 mg CaCO3/L in Upper Arrow and from 43 to 56 mg CaCO3/L in Lower Arrow. Seasonal averages remained uniform from year to year between 1998 and 2007, except during the summer of 2001 where alkalinity was lower than other years by 10 to 20 mg CaCO3/L in Upper Arrow (Table 3.9).

Total organic carbon

Total organic carbon (TOC) includes both dissolved and particulate organic carbon (Wetzel 2001). Total organic carbon ranged between 0.5 to 1.9 mg/L in Upper Arrow and from 0.7 to 4 mg/L in Lower Arrow (Fig. 3.19). Peak results occurred in October in both Upper and Lower Arrow.

Although these values are at the low end of the range (TOC of 1 - 30 mg/L) in natural waters, they are consistent with oligotrophic systems (Wetzel 2001). The values suggest that the lake does not receive large allochthonous organic inputs or produce large amounts of autochthonous organic carbon.

Table 3.9. 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. Samples were collected from 0- 20 m in 2004 to 2006.

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
2004	57	46	49	54	47	47
2005	53	50	53	52	47	49
2006	55	45	52	54	45	47
2007	54	44	52	54	45	46

pH

pH is the negative log of the hydrogen-ion concentration (Horne and Goldman, 1994). During 2007, the pH ranged from 7.7 to 8.1 in Upper Arrow and from 7.9 to 8.0 in Lower Arrow. Seasonal averages are listed in Table 3.10, indicating the spring 2007 pH level in Upper Arrow was higher in 2007 than in 2006 or 2005. The summer fall results were similar to 2006. The spring pH was higher in Lower Arrow than in 2006 – fall and summer results were similar.

Table 3.10. 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. Samples were collected from 0- 20 m in 2004 to 2007.

Year	Upper Arrow AR 1-4 Spring	Summer	Fall	Lower Arrow AR 6-8 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
2004	7.58	7.93	7.56	7.59	8.03	7.30
2005	7.35	7.06	7.56	7.20	7.02	7.15
2006	7.38	7.93	7.88	7.40	7.94	7.85
2007	7.88	7.93	8.00	7.90	8.00	7.95

Chlorophyll a

Chlorophyll *a* (Chl *a*) is the primary photosynthetic pigment in algae (Wetzel, 2001). It also indicates a lake's phytoplankton standing crop. Chl *a* (µg/L) ranged from 0.5 to 5.4 µg/L in Upper Arrow and from 0.5 to 4.1 µg/L in Lower Arrow in 2007 (Fig 3.20**)**. The maximum concentration was slightly higher than the 2006 maximum. Peak chlorophyll results occurred in late June in Upper Arrow and in April in Lower Arrow. A sharp increase seasonally was pronounced in Upper Arrow and concentrations remained fairly uniform in Lower Arrow. The results from Upper Arrow coincide with the phytoplankton results (Fig 4.2b, Chapter 4). Results increased from the spring through the summer and declined into the fall months.

Spring chlorophyll results in 2007 were similar to results in the spring of 2006 (Table 3.11). In Upper and Lower Arrow, summer chlorophyll results in 2007 were higher than in 2006. Fall results in 2007 were lower than 2006 in Upper Arrow.

Table 3.11. 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. Samples were collected from 0- 20 m in 2004 to 2007.

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
2004	2.41	3.83	2.15	1.58	3.87	2.48
2005	2.76	2.33	2.31	2.42	2.50	2.58
2006	1.50	1.85	2.26	1.11	1.43	2.37
2007	1.69	2.93	1.19	1.84	2.53	2.32

Discrete depth sampling

Nitrate concentrations were higher than 25 µg/L (which is the concentration where nitrate is considered limiting to phytoplankton) in Upper and Lower Arrow (Wetzel, 2001) (Fig. 3.21).

Nitrogen to phosphorus ratios is used as a measure to determine nutrient limitation in lakes. Ratios less than 10 (by weight) (dissolved fractions) indicate nitrogen limitation and ratios greater than 10 to 15 indicate phosphorus limitation (Downing and McCauley, 1992; Horne and Goldman, 1994). The ratios (weight:weight) ranged from 17 to 82 in Upper Arrow and 10 to 46 in Lower Arrow depending on the depth of the profile (Fig. 3.22). The low N:P ratio was at station AR 7 in June at a depth of 2m.

Chl *a* results ranged between 0.5 and 4.0 µg/L in Upper Arrow and 0.8 and 3.9 µg/L in Lower Arrow. Peak biomass occurred at 2 and 5 m in June and at 10 m in July in Upper Arrow (Fig. 3.23). In Lower Arrow, peak biomass occurred at 2 m in June and at 2, 5 and 10 m in July. Results for August and September are not illustrated as there was an issue with analysis. Discrete phytoplankton taxonomy samples were not collected in 2007, therefore comparisons cannot be made between Chl *a* and phytoplankton.

Hypolimnion samples

Turbidity

Turbidity ranged from 0.2 to 1.2 NTU in Upper Arrow and 0.2 to 0.5 NTU in Lower Arrow in 2007 (Fig. 3.24). Turbidity was higher in Lower Arrow than Upper Arrow except at station AR 2 in May where the result was 1.2 NTU.

Conductivity

Conductivity ranged from 133 to 145 µs/cm in Upper Arrow and 126 to 137 µs/cm in Lower Arrow in 2007 (Fig. 3.25). Conductivity was slightly lower at Lower Arrow stations; these results are similar to previous years (Schindler et al. 2009).

Phosphorus

Total phosphorus ranged from 2 to 4 µg/L in Upper and Lower Arrow in 2007 (Fig 3.26). In Upper Arrow, the concentrations were higher in July and August at station AR 3. In Lower Arrow, concentrations were higher at station AR 7.

Total dissolved phosphorus ranged from 2 to 8 µg/L in Upper Arrow and from 2 to 4 µg/L in Lower Arrow in 2007 (Fig 3.27). The result of 8 µg/L is potentially an outlier especially since total phosphorus for the same station and date is 4 µg/L. Total phosphorus is usually higher than dissolved since it comprises of both the particulate and dissolved fractions.

Orthophosphate concentrations ranged from 2 to 4 µg/L in Upper Arrow and from 2 to 5 µg/L in Lower Arrow in 2007 (Fig 3.28). The peak in concentrations occurred in July and October in Upper Arrow and in July in Lower Arrow.

Nitrogen

Total nitrogen concentrations ranged from 160 to 210 µg/L in Upper Arrow and from 180 to 250 µg/L in Lower Arrow in 2007 (Fig. 3.29).

Ammonia concentrations were at or near the detection limit of 5 µg/L during 2007.

Dissolved inorganic nitrogen (ammonia plus nitrate plus nitrite) concentrations ranged from 133 to 173 µg/L in Upper Arrow and from 180 to 250 µg/L in Lower Arrow in 2007 (Fig. 3.30). All results were indicative of typical oligotrophic systems.

Silica

Silica concentrations ranged from 3.2 to 4.1 mg/L and from 3.9 to 4.9 mg/L in Lower Arrow in 2007 (Fig. 3.31). Results remained uniformly distributed amongst stations and depths except in August at station AR 1 where silica was slightly less than the results from stations AR 2 and AR 3. Concentrations in Lower Arrow slightly increased from spring through the fall months.

Alkalinity

Alkalinity concentrations ranged from 58.4 to 61.6 mg CaCO3/L in Upper Arrow and from 53.7 to 58.6 mg CaCO3/L in Lower Arrow in 2007 (Fig 3.32).

pH

pH ranged from 7.9 to 8.0 pH units in Upper and Lower Arrow. The results are similar to the epilimnion values.

Conclusions

Arrow Lakes Reservoir is oligotrophic according to nutrient and chlorophyll *a* concentrations from the 0-20 m integrated measurements (Wetzel, 2001). The additional discrete-depth sampling in 2007 indicates that the reservoir was not nitrogen limited except at two metres in one Lower Arrow station in June.

Adaptively managing the weekly nutrient loading rates in 2007 resulted in N:P ratios favourable for phytoplankton growing conditions. Phytoplankton species composition is key for zooplankton growth, especially *Daphnia*, the preferred food for kokanee.

Recommendations

Vertical profiles of nutrients, as conducted with the discrete-depth sampling in 2007, 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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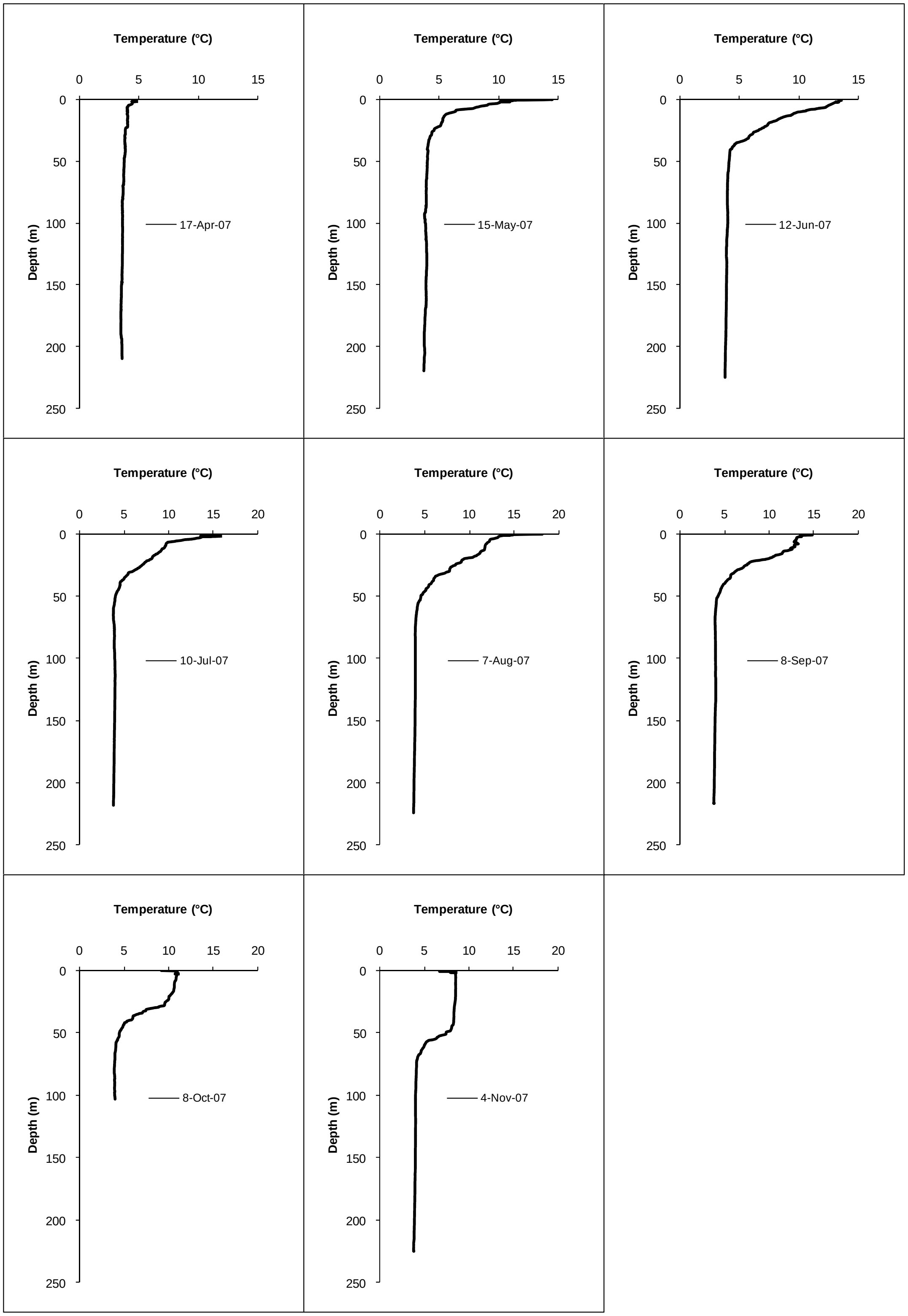


Figure 3.1. Temperature profiles, station AR 1, April to November, 2007.

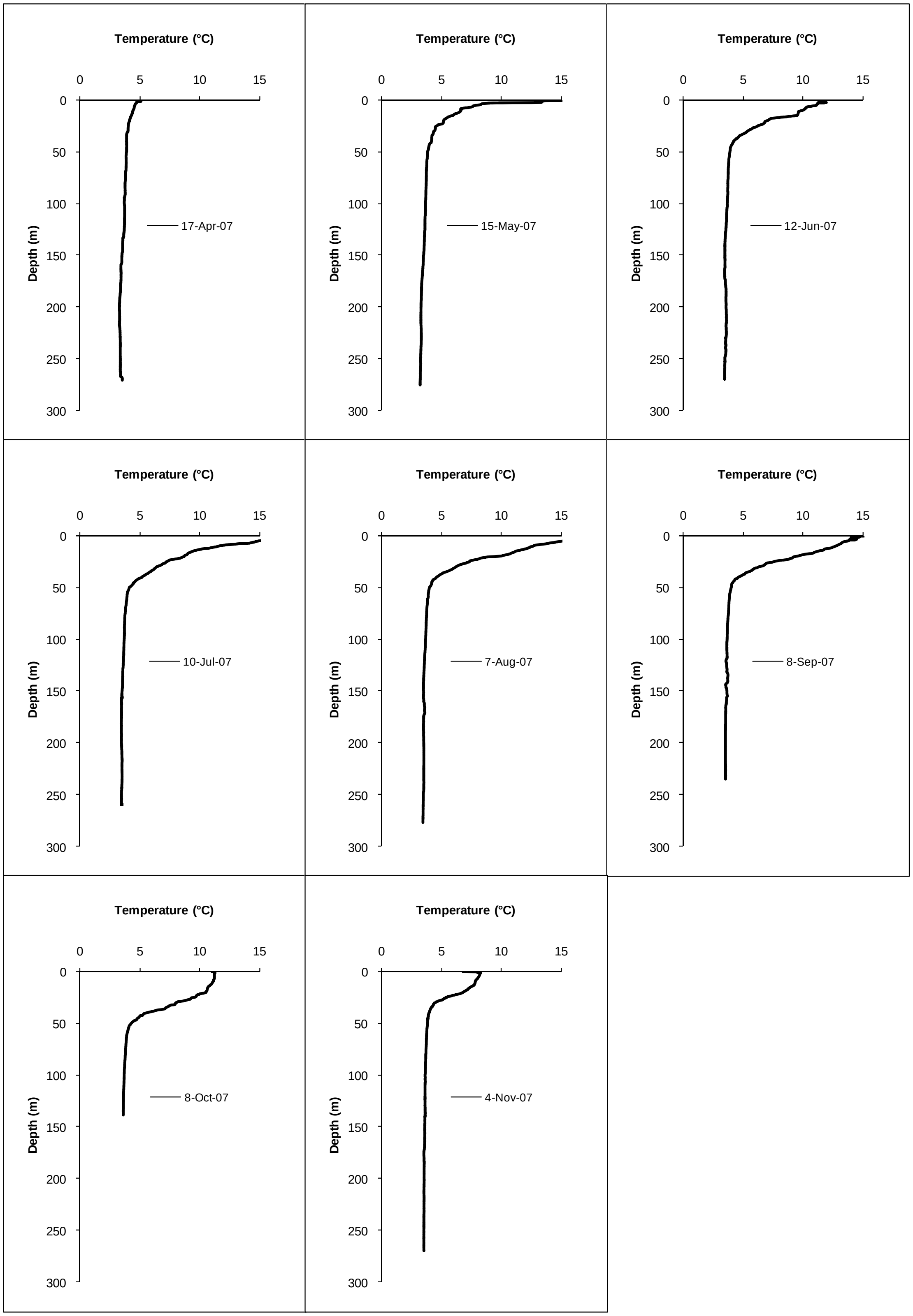


Figure 3.2. Temperature profiles, station AR 2, April to November, 2007.

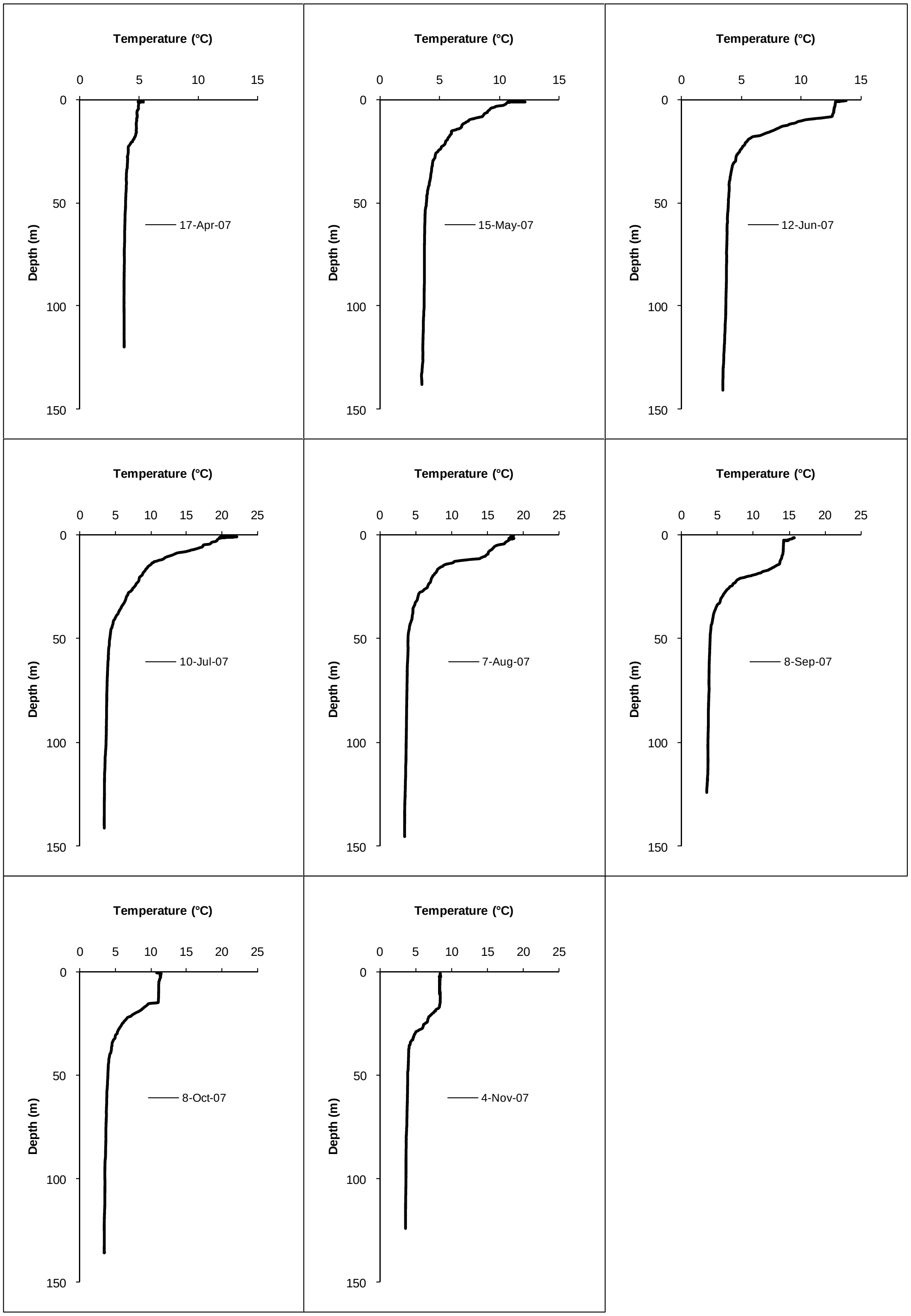


Figure 3.3. Temperature profiles, station AR 3, April to November, 2007.

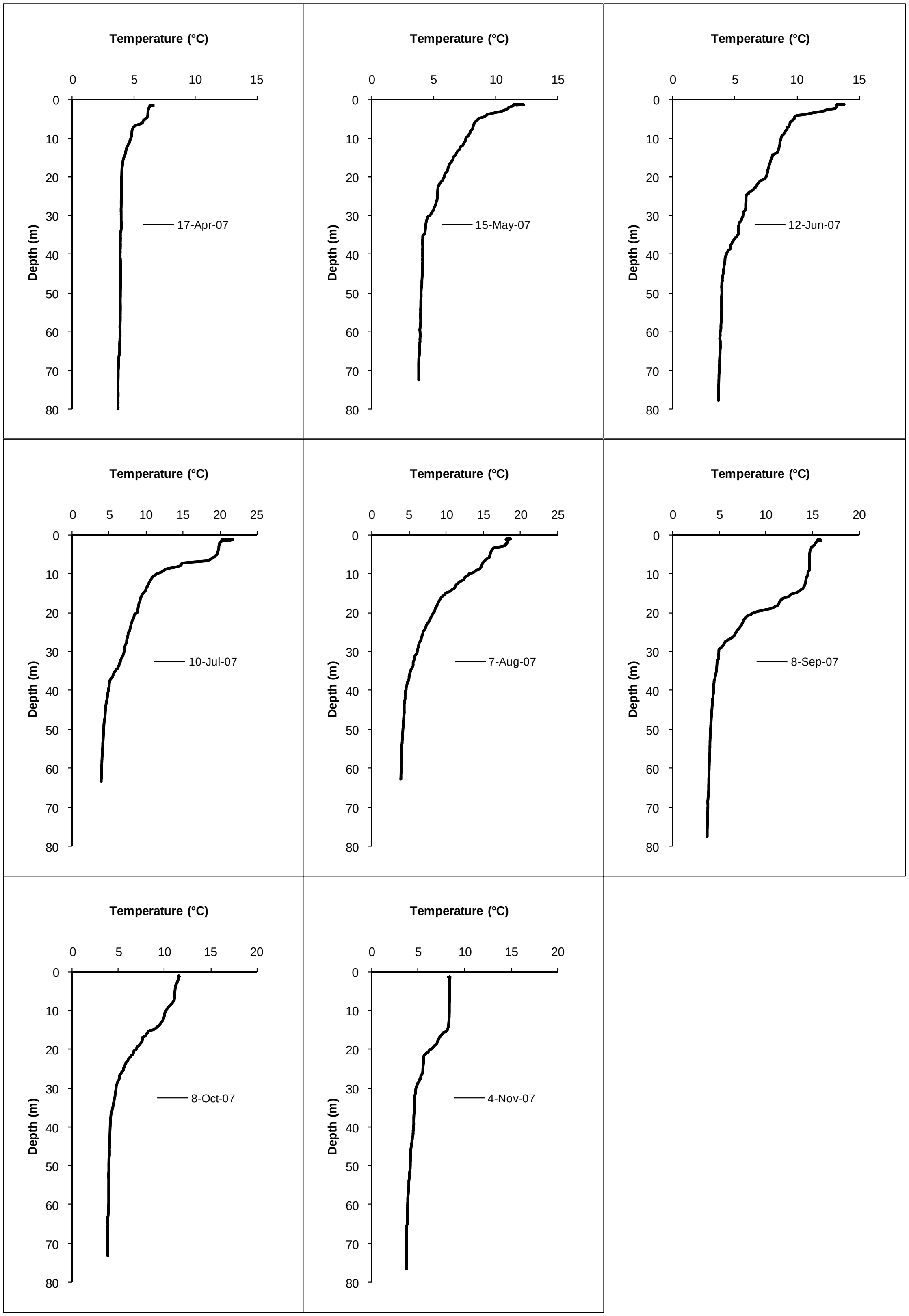


Figure 3.4. Temperature profiles, station AR 4, April to November 2007.

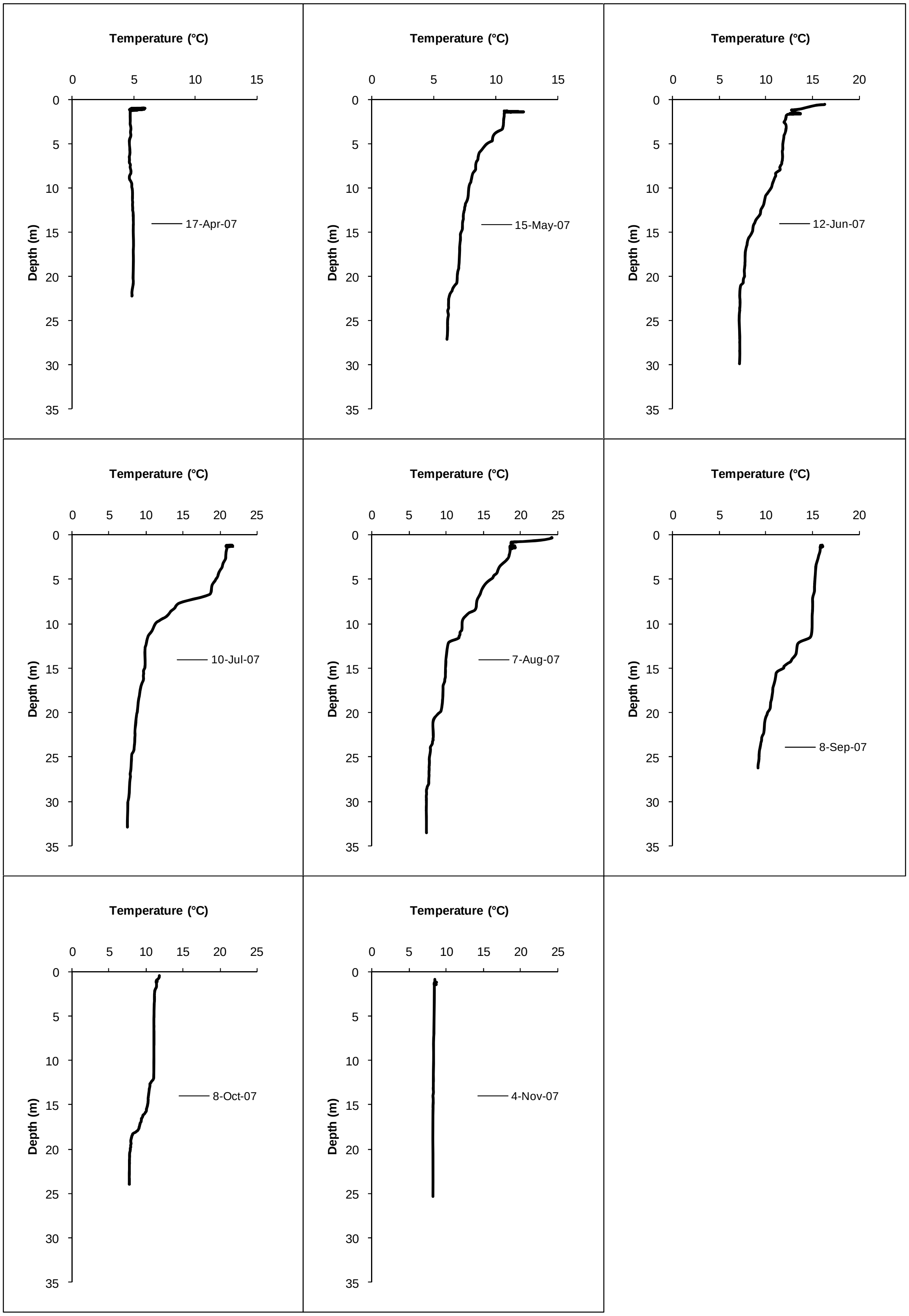


Figure 3.5. Temperature profiles, station AR 5, April to November 2007.

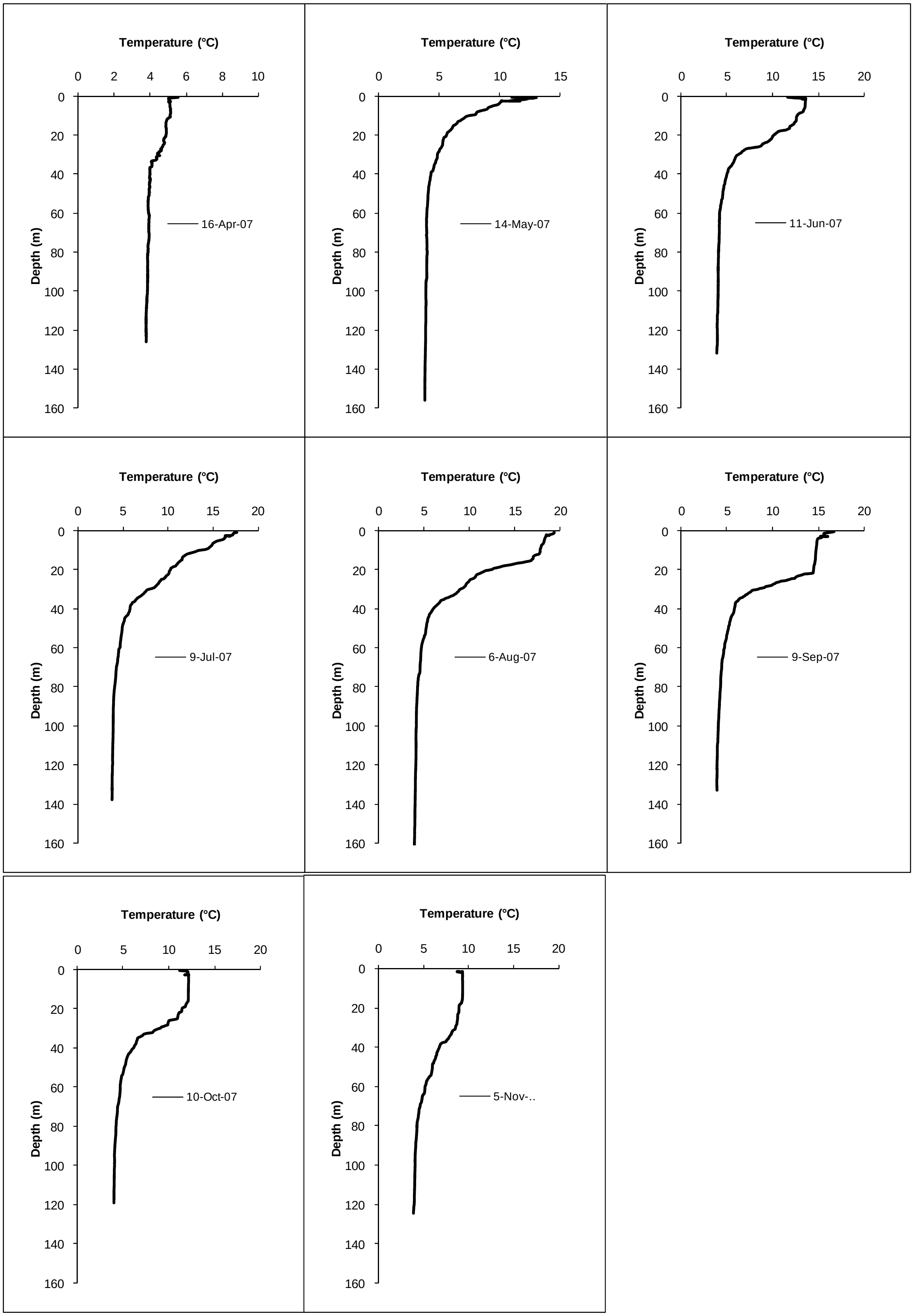


Figure 3.6. Temperature profiles, stations AR 6, April to November 2007.

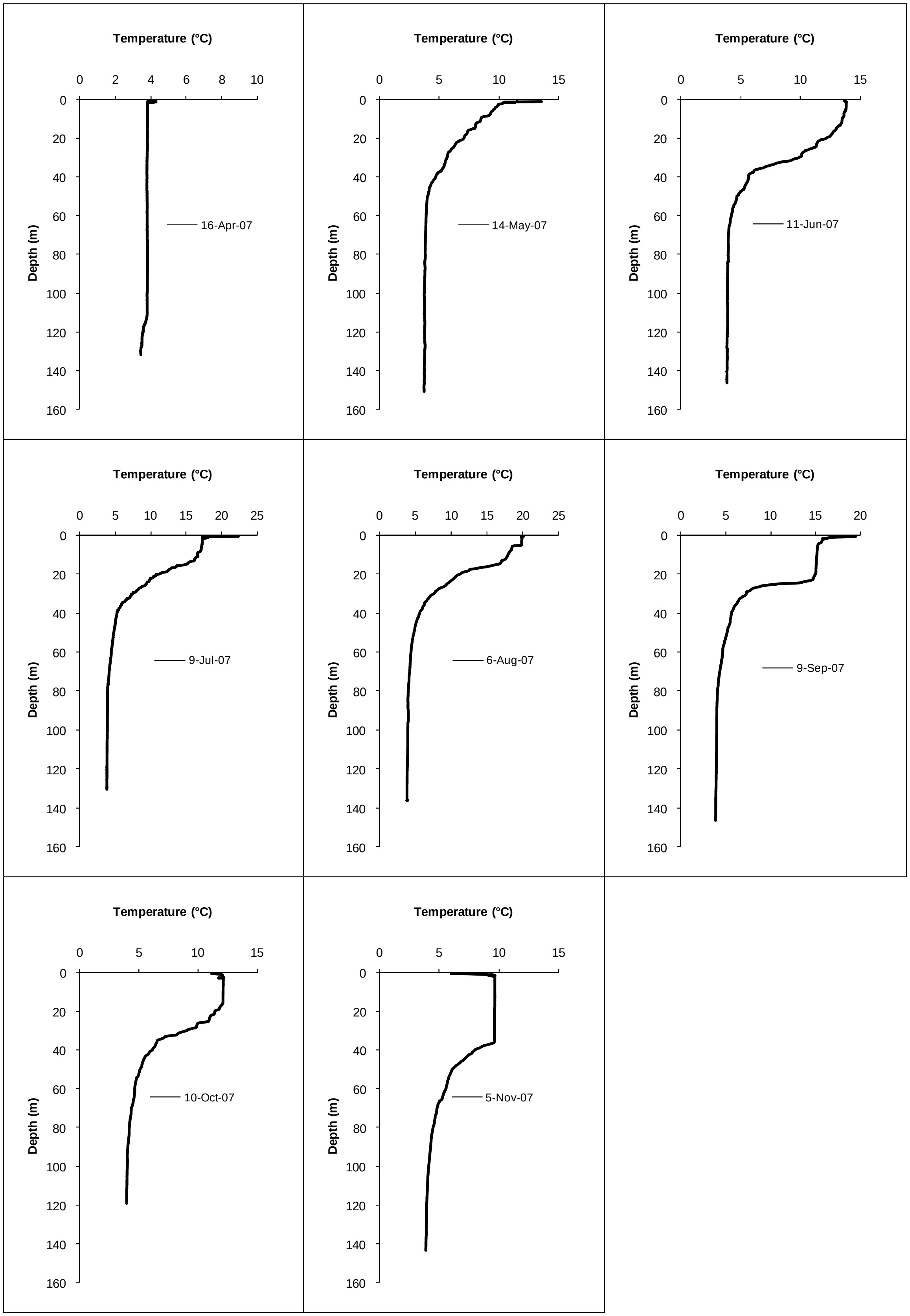


Figure 3.7. Temperature profiles, station AR 7, April to November 2007.

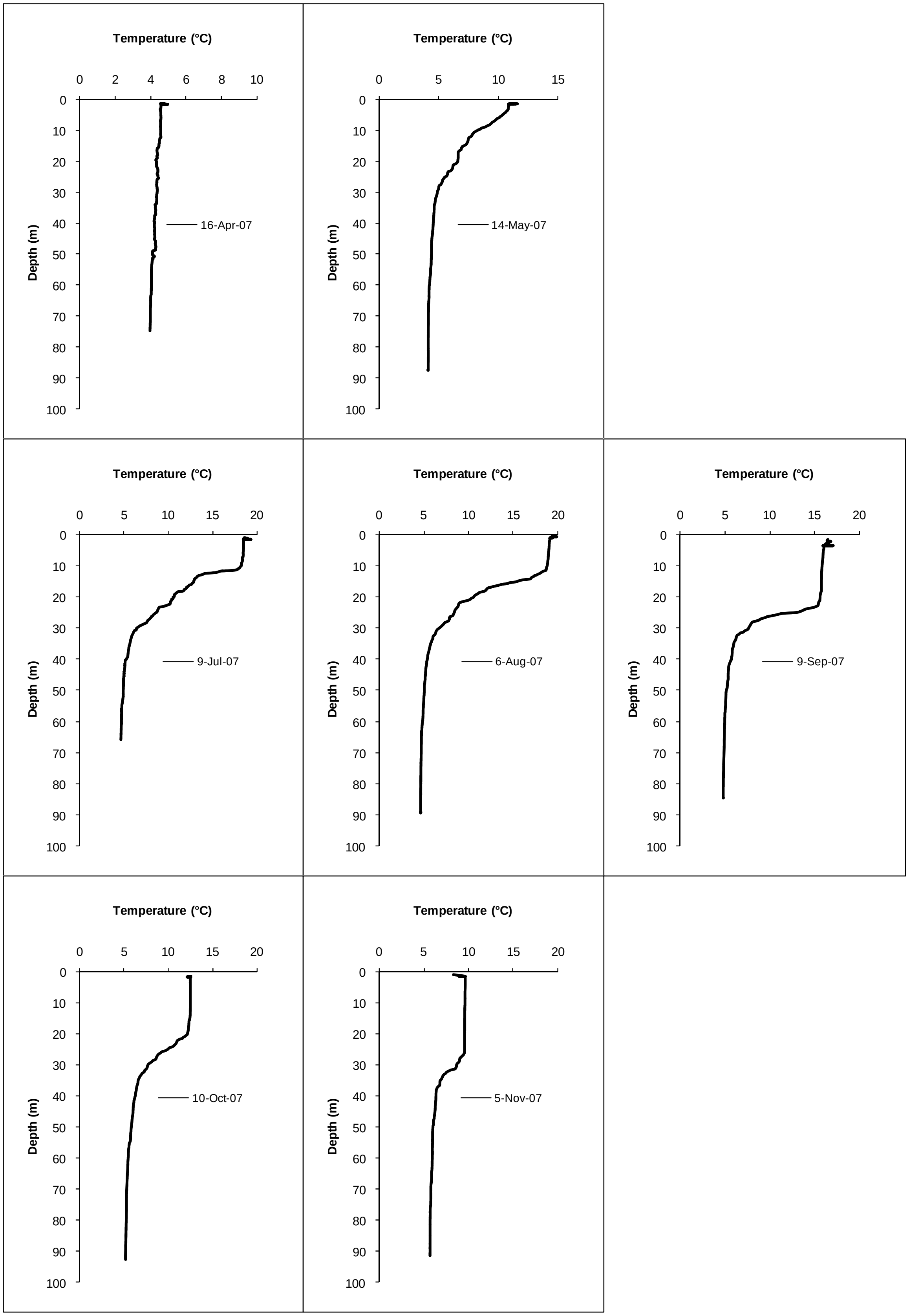


Figure 3.8. Temperature profiles, stations AR 8, April to November 2007.

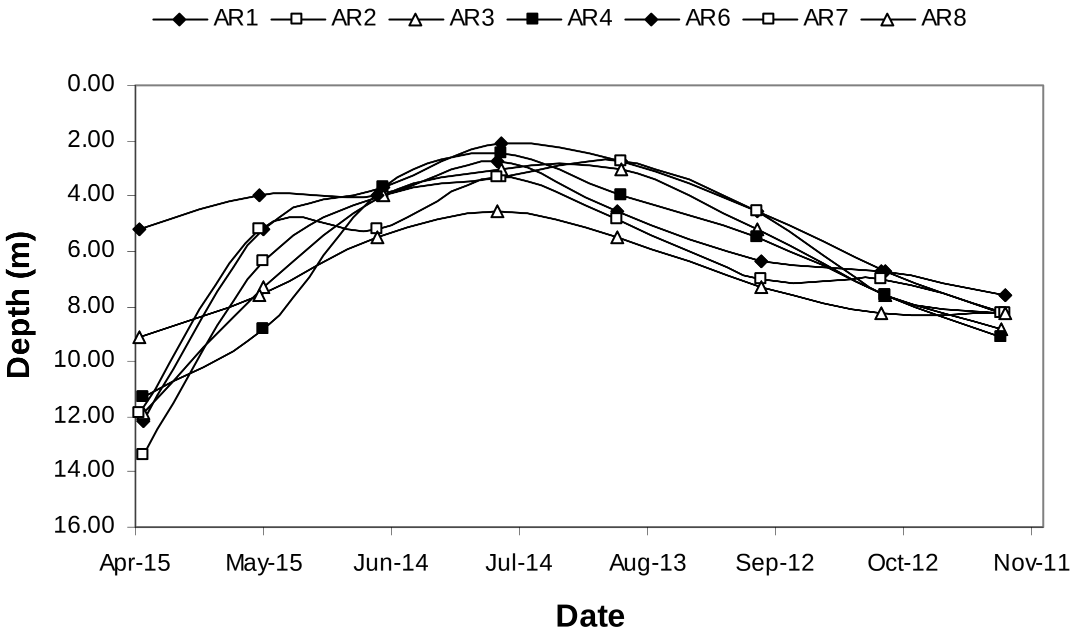
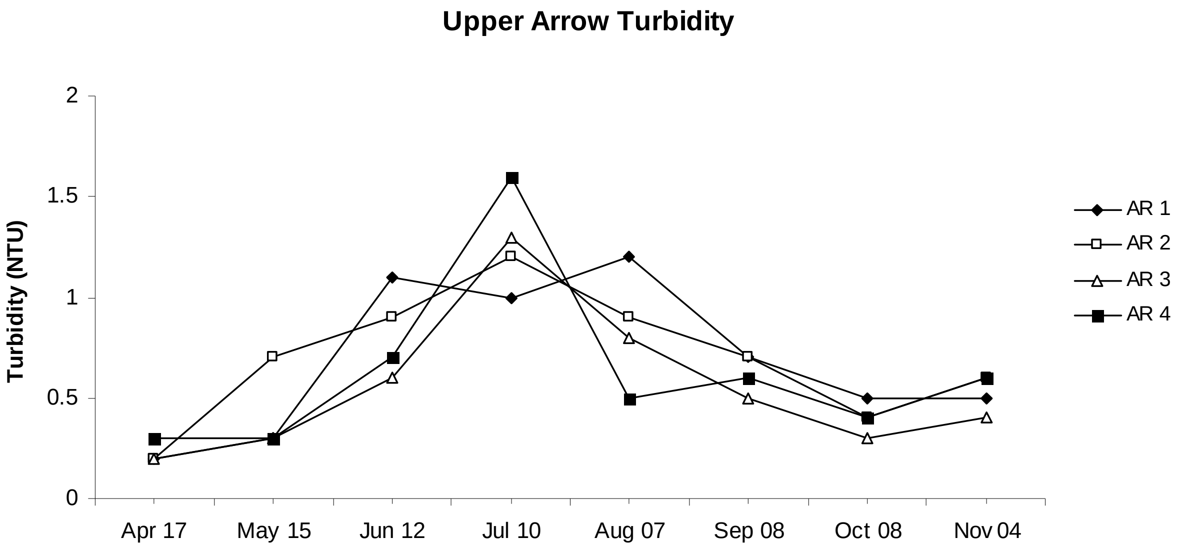


Figure 3.9. Monthly Secchi disk depths, April to November, 2007.



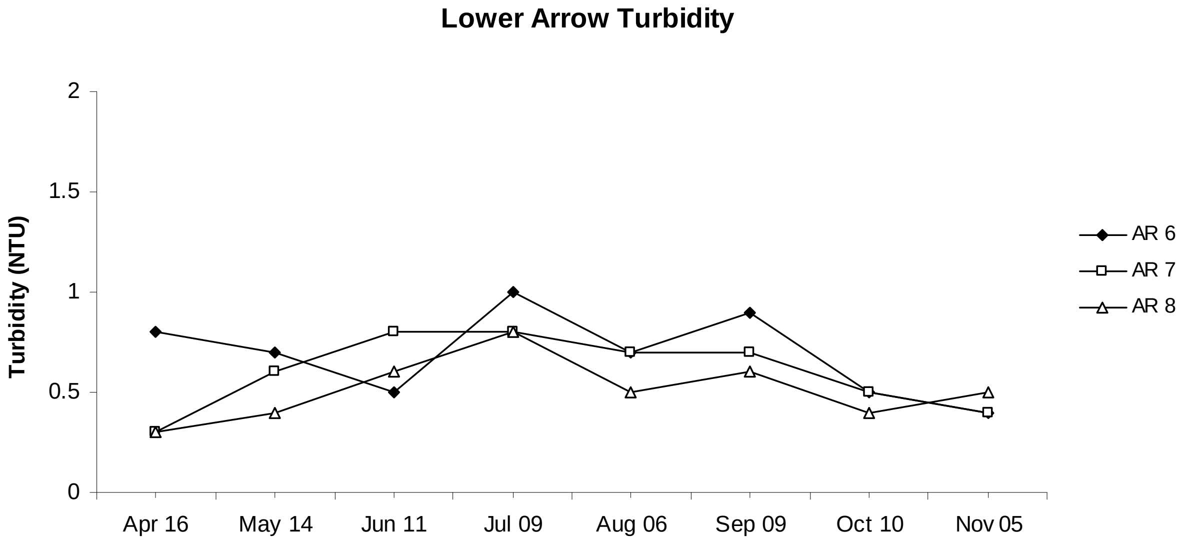
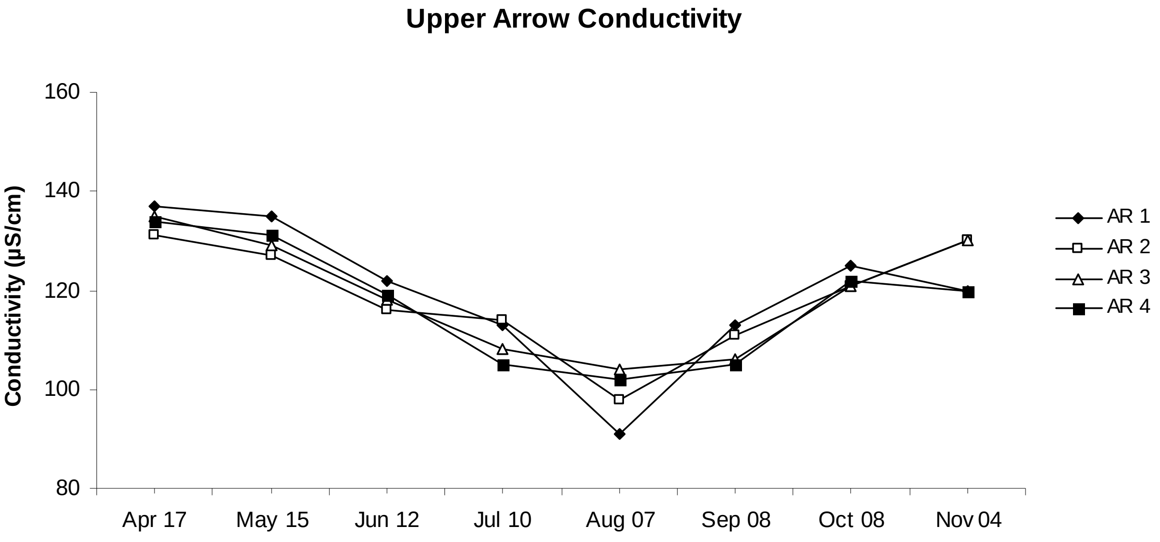


Figure 3.10. Seasonal turbidity, 0-20 m integrated samples, 2007.



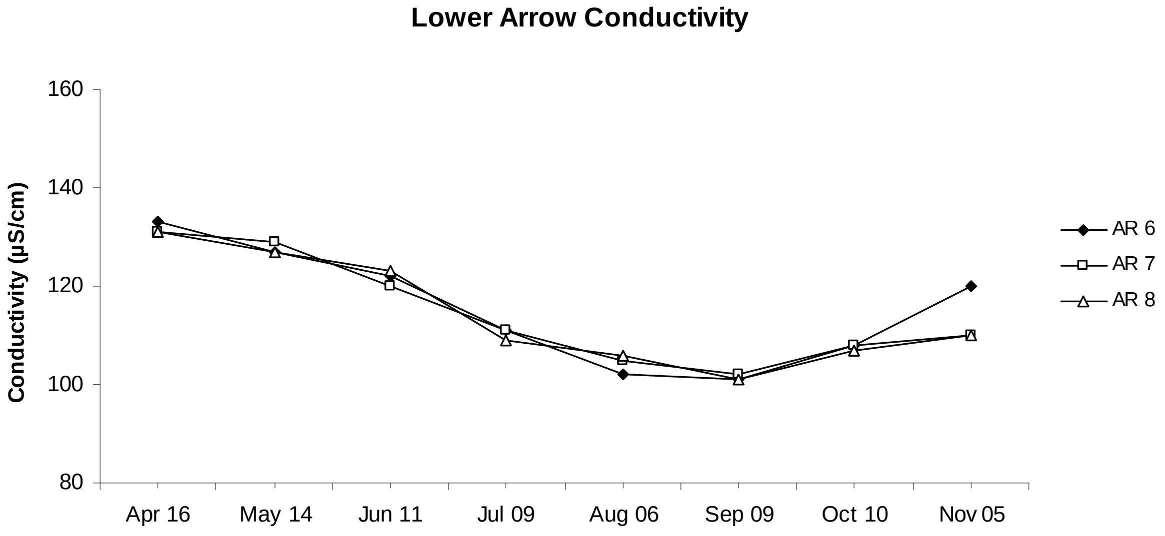
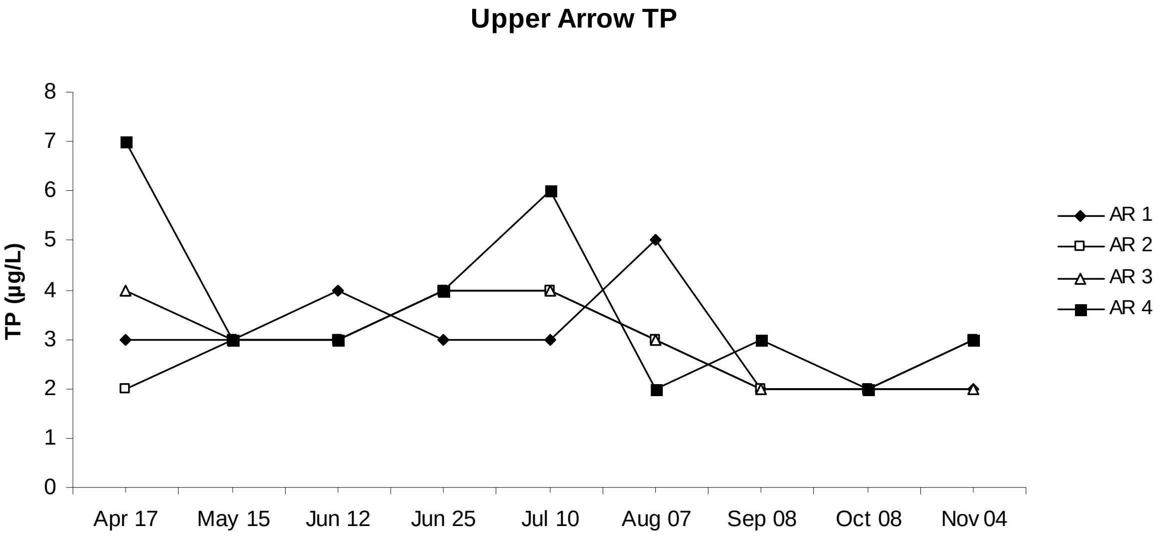


Figure 3.11. Seasonal conductivity, 0-20 m integrated samples, 2007.



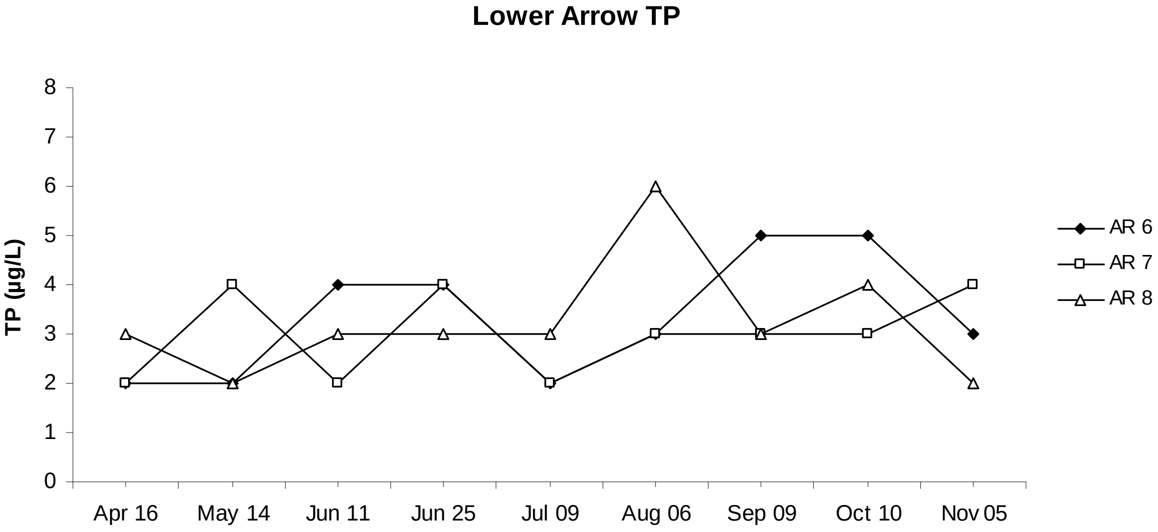
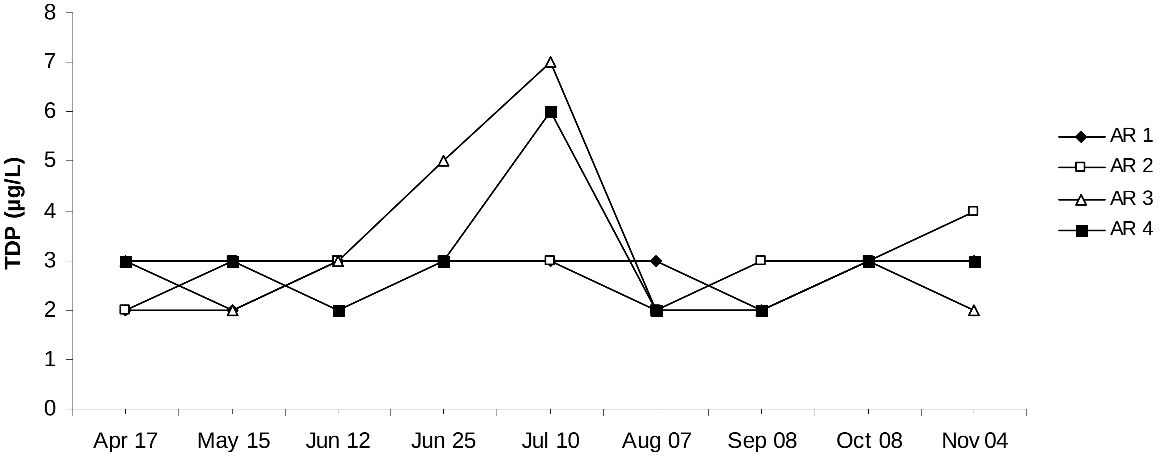


Figure 3.12. Seasonal total phosphorus, 0-20 m integrated samples, 2007.

Upper Arrow TDP



Lower Arrow TDP

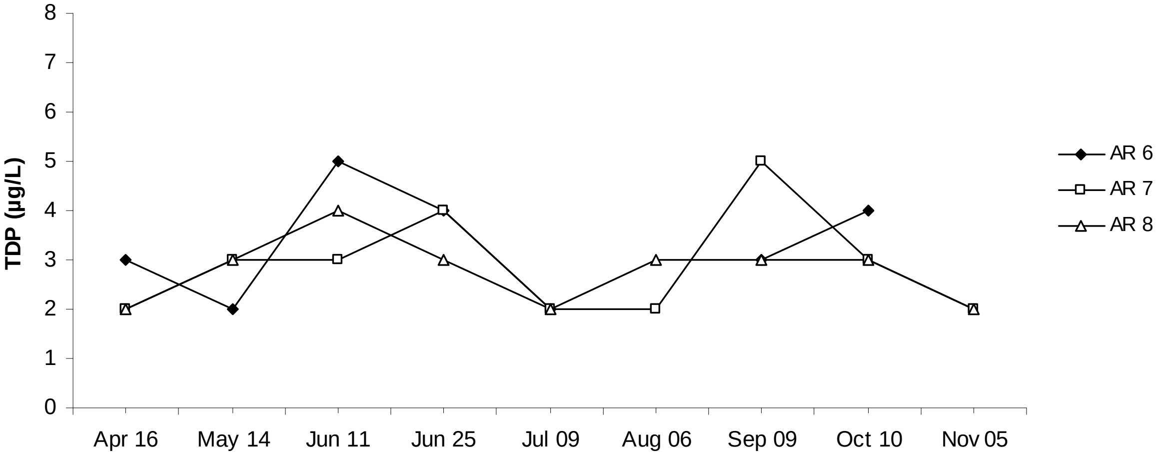
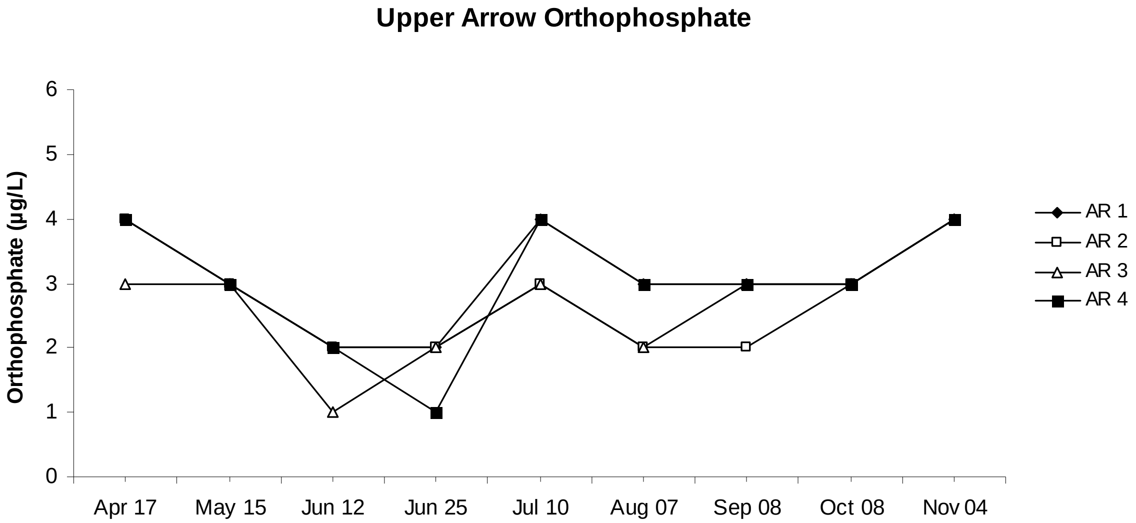


Figure 3.13. Seasonal total dissolved phosphorus, 0-20 m integrated samples, 2007.



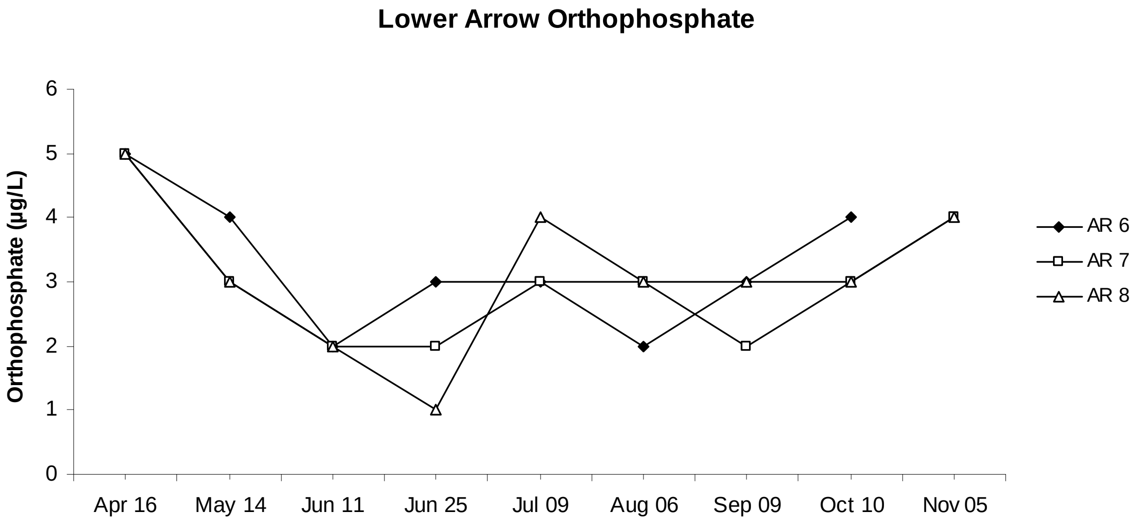
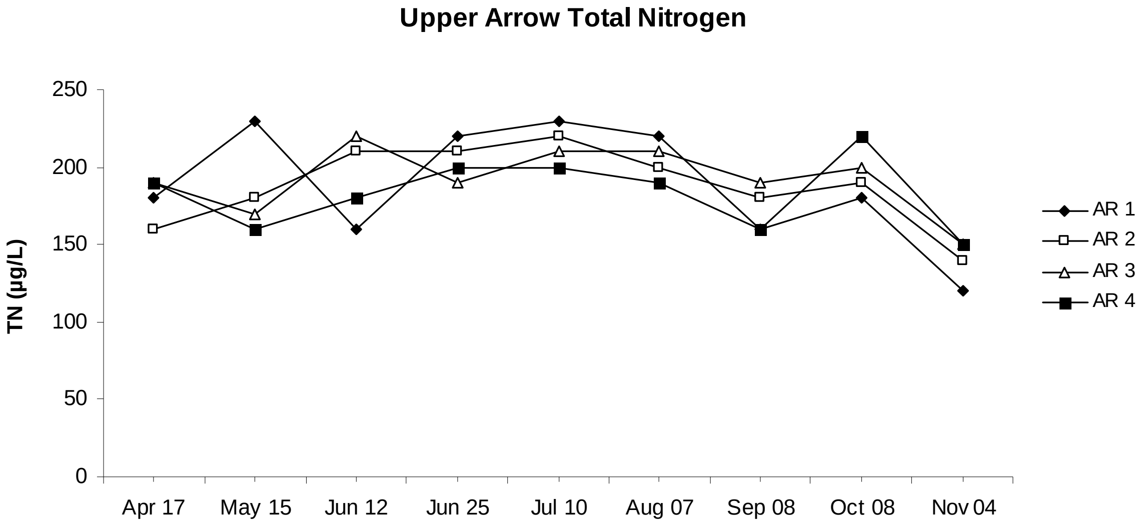


Figure 3.14. Seasonal orthophosphate, 0-20 m integrated samples, 2007.



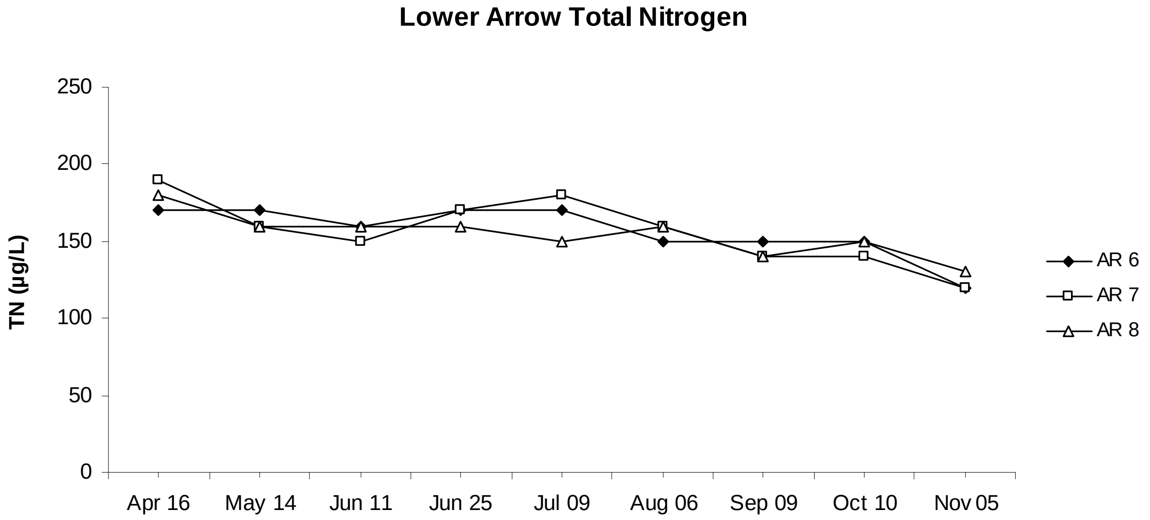
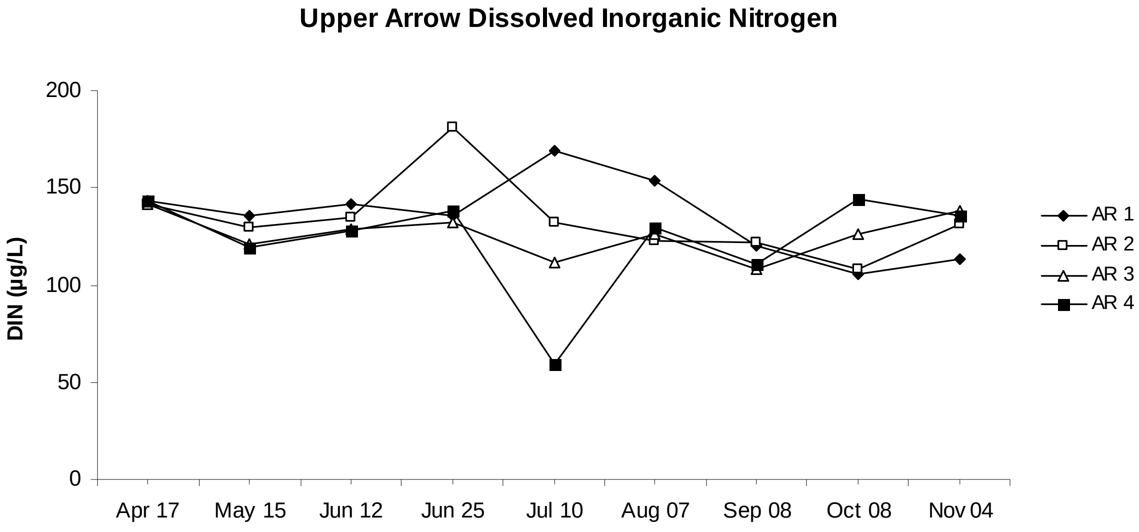


Figure 3.15. Seasonal total nitrogen, 0-20 m integrated samples, 2007.



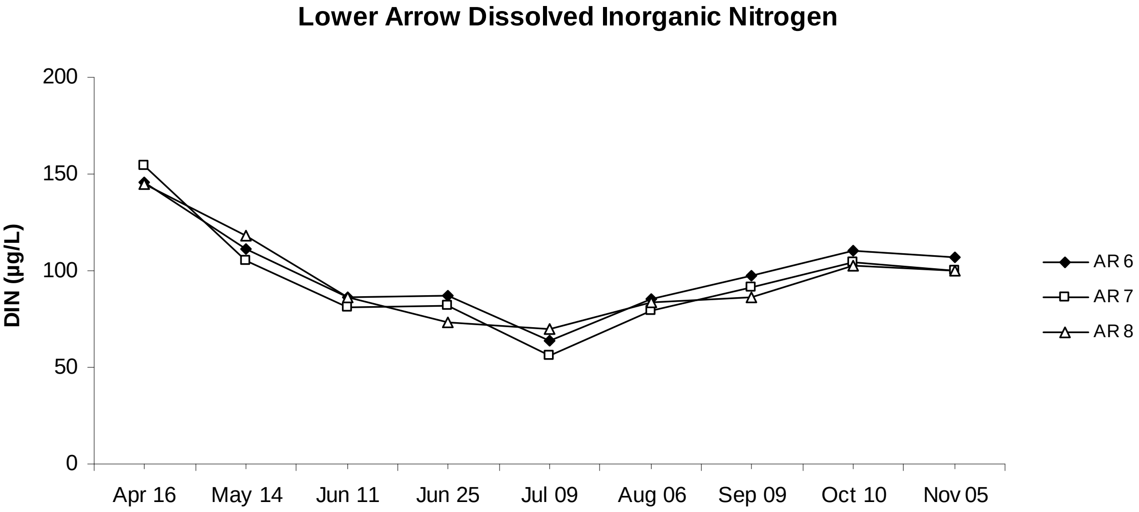


Figure 3.16. Seasonal dissolved inorganic nitrogen, 0-20 m integrated samples, 2007.

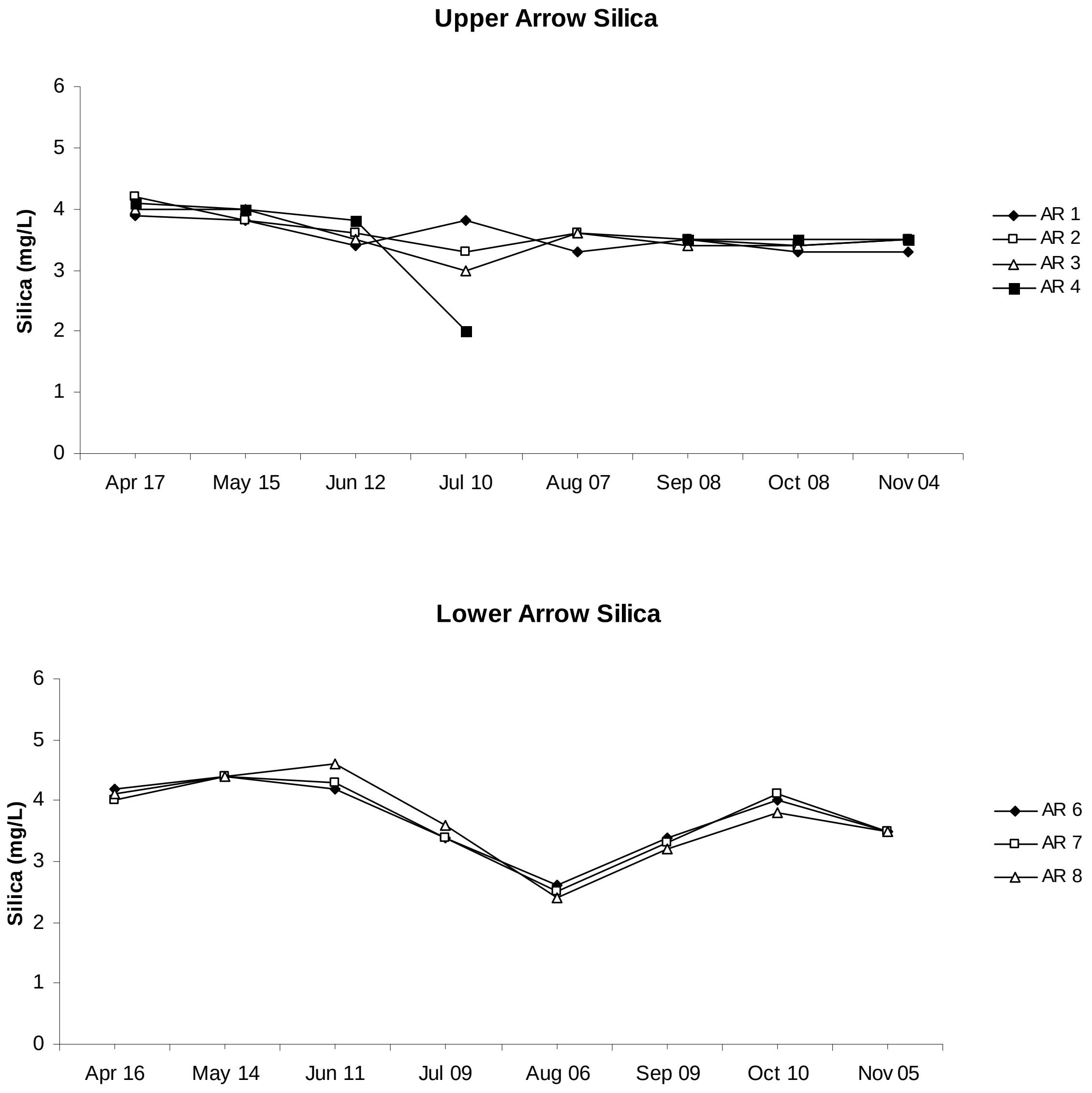


Figure 3.17. Seasonal dissolved reactive silica, 0-20 m integrated samples, 2007.

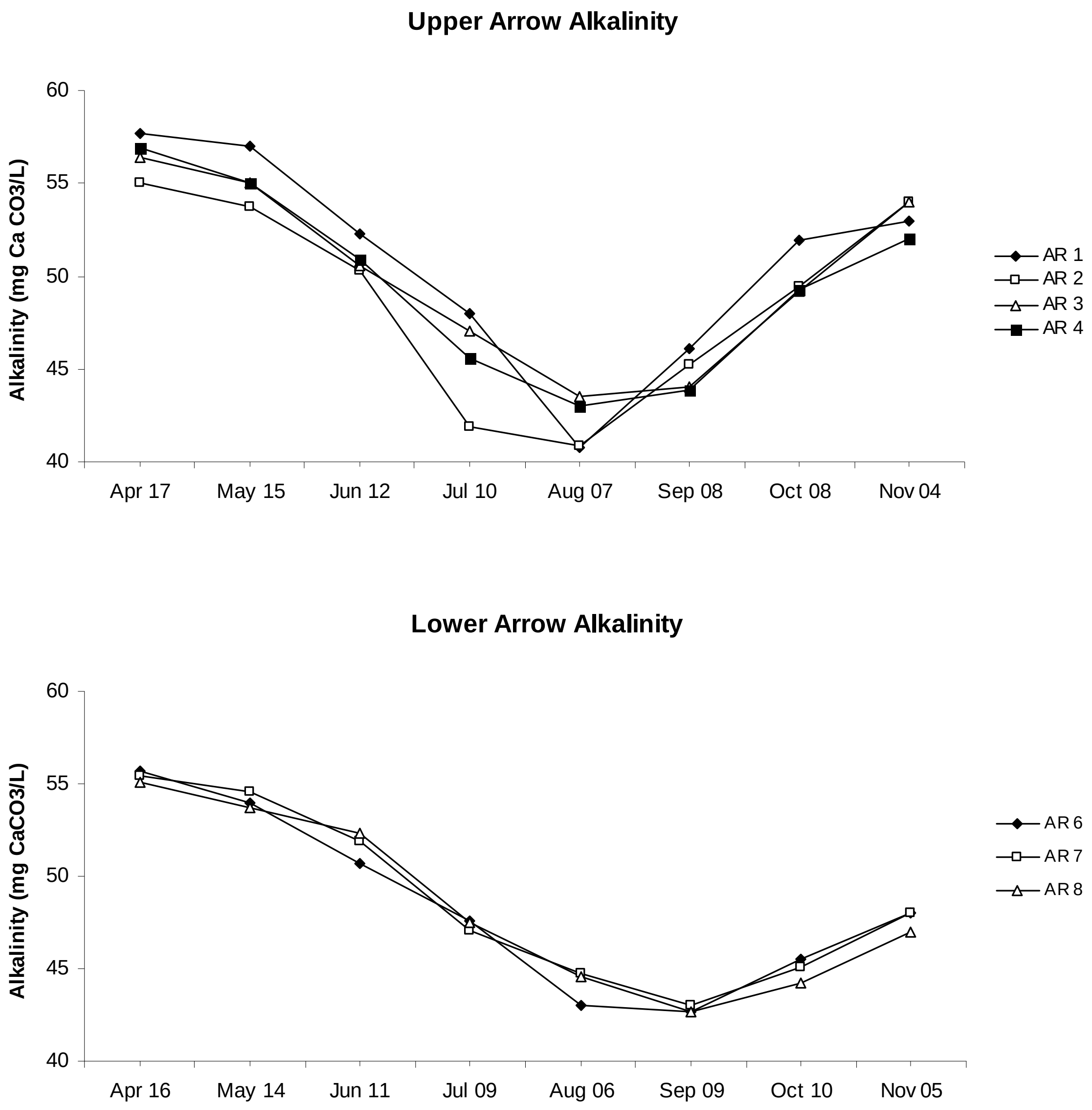
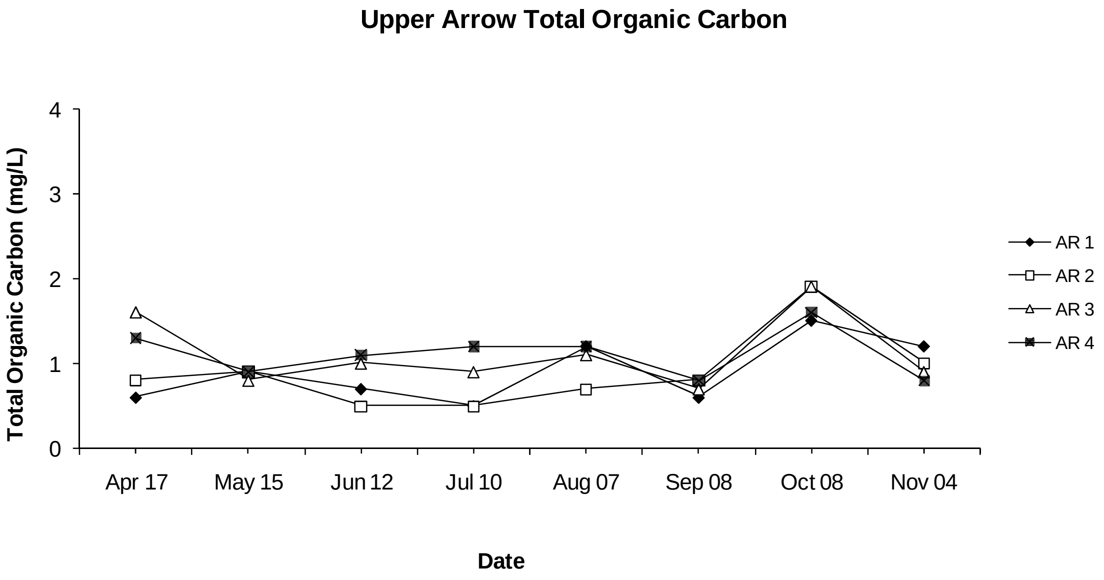
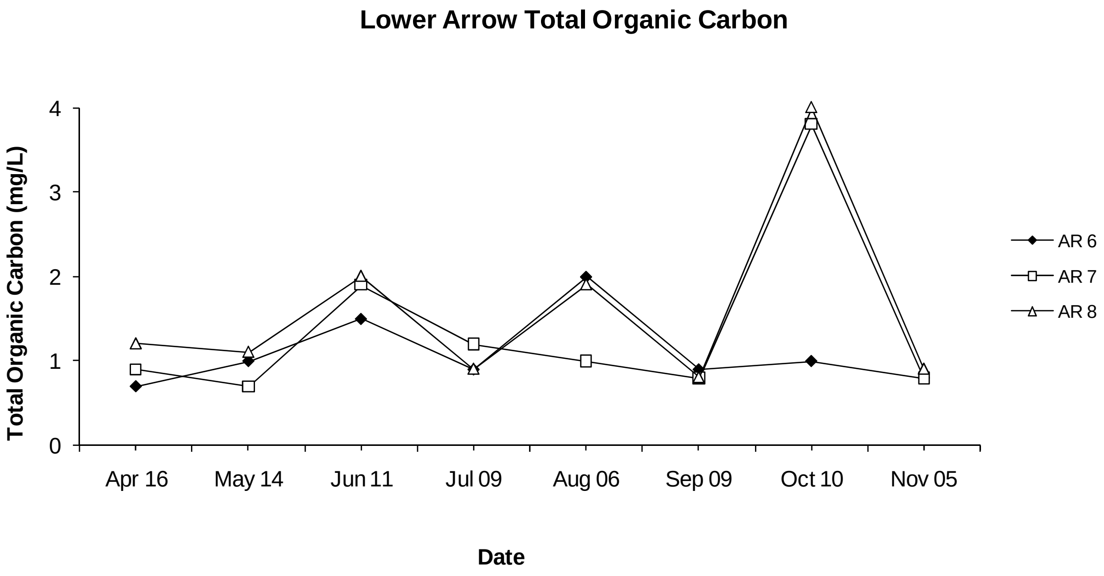


Figure 3.18. Seasonal alkalinity, 0-20 m integrated samples, 2007.



Upper Arrow Total Organic Carbon



Lower Arrow Total Organic Carbon

Figure 3.19. Total organic carbon in 0-20 m samples, April to November, 2007.

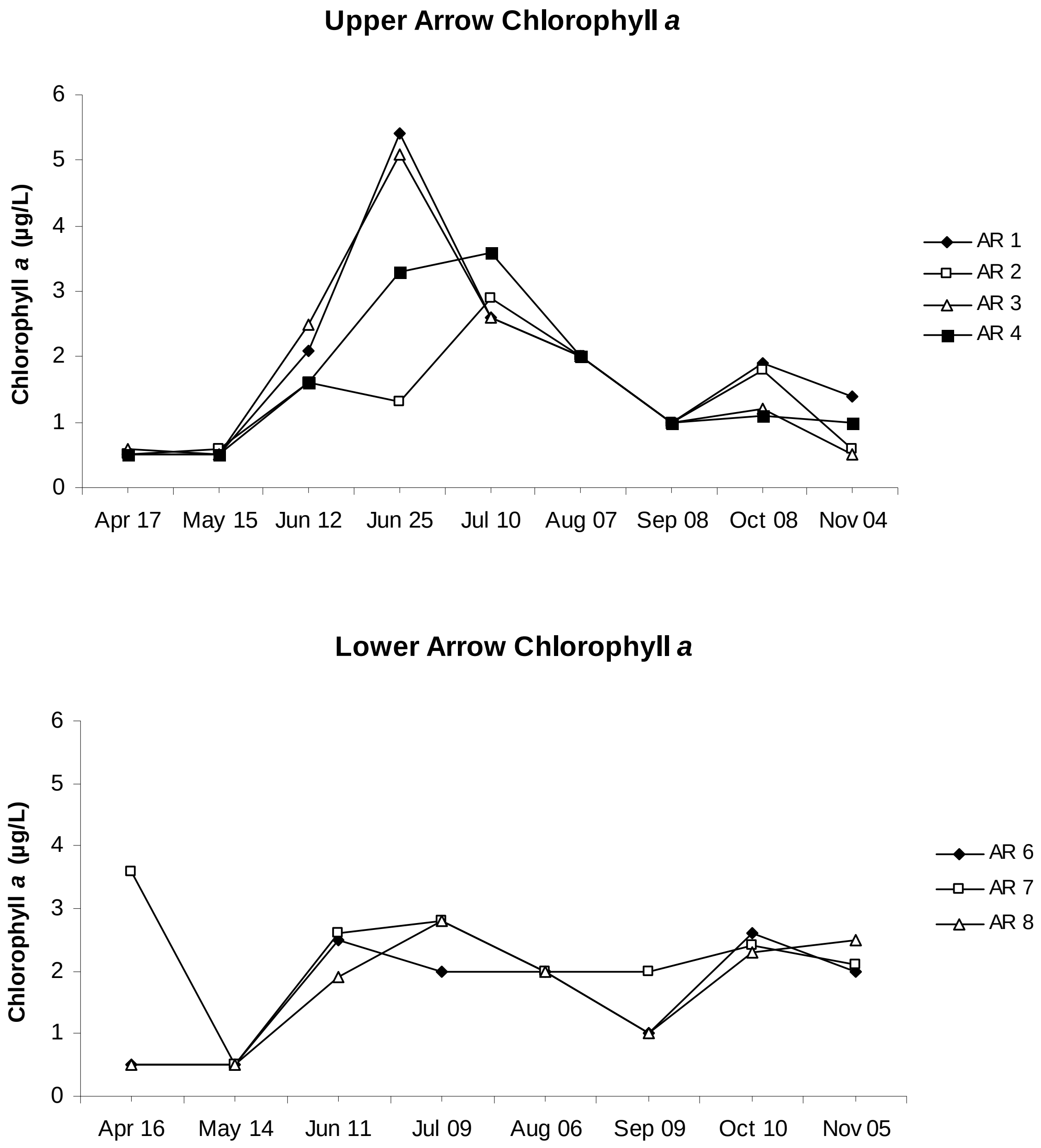


Figure 3.20. Seasonal chlorophyll *a*, 0-20 m integrated samples, 2007.

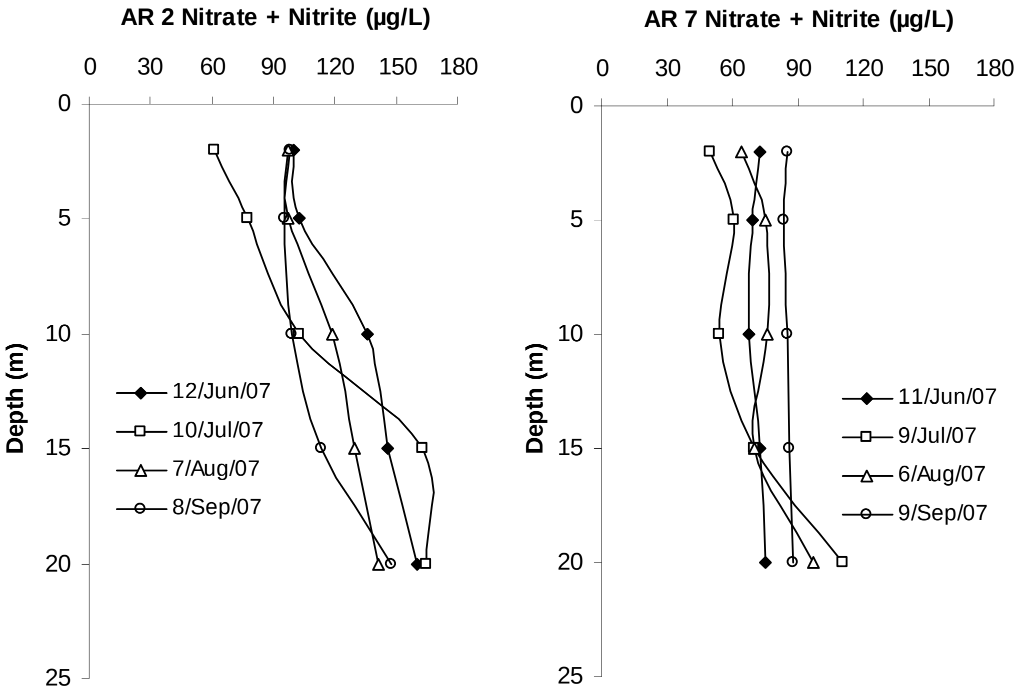


Figure 3.21. Discrete depth nitrate-nitrogen profiles, stations AR 2 and AR 7, 2007.

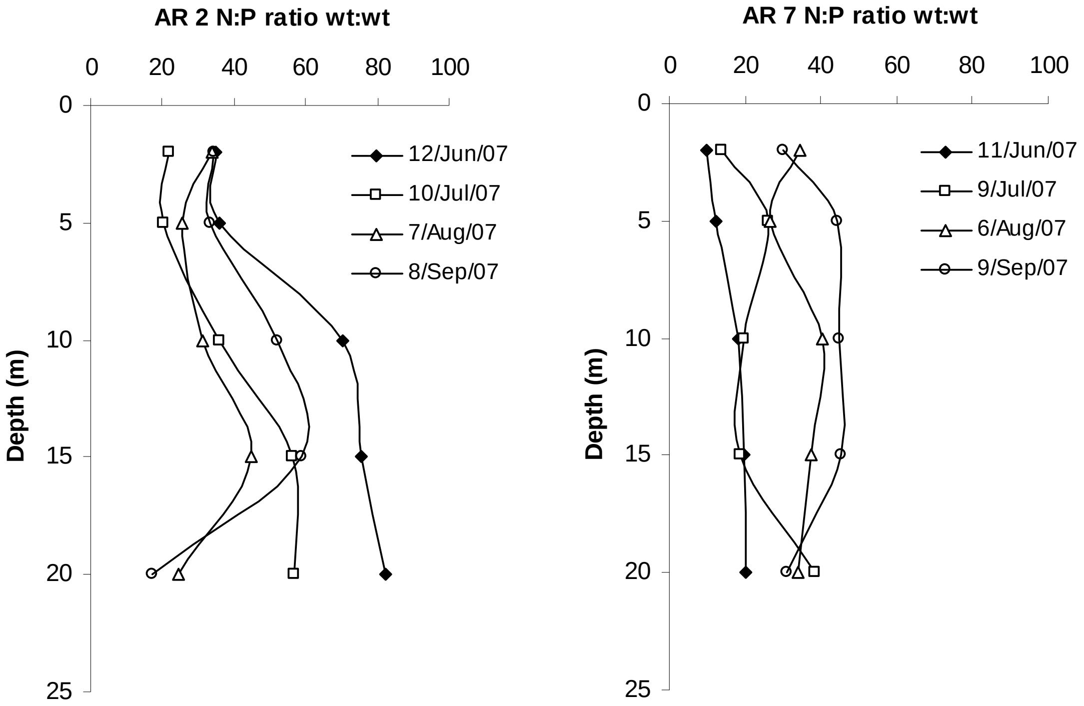


Figure 3.22. Discrete depth nitrogen to phosphorus ratios (weight:weight), stations AR 2 and AR 7, 2007.

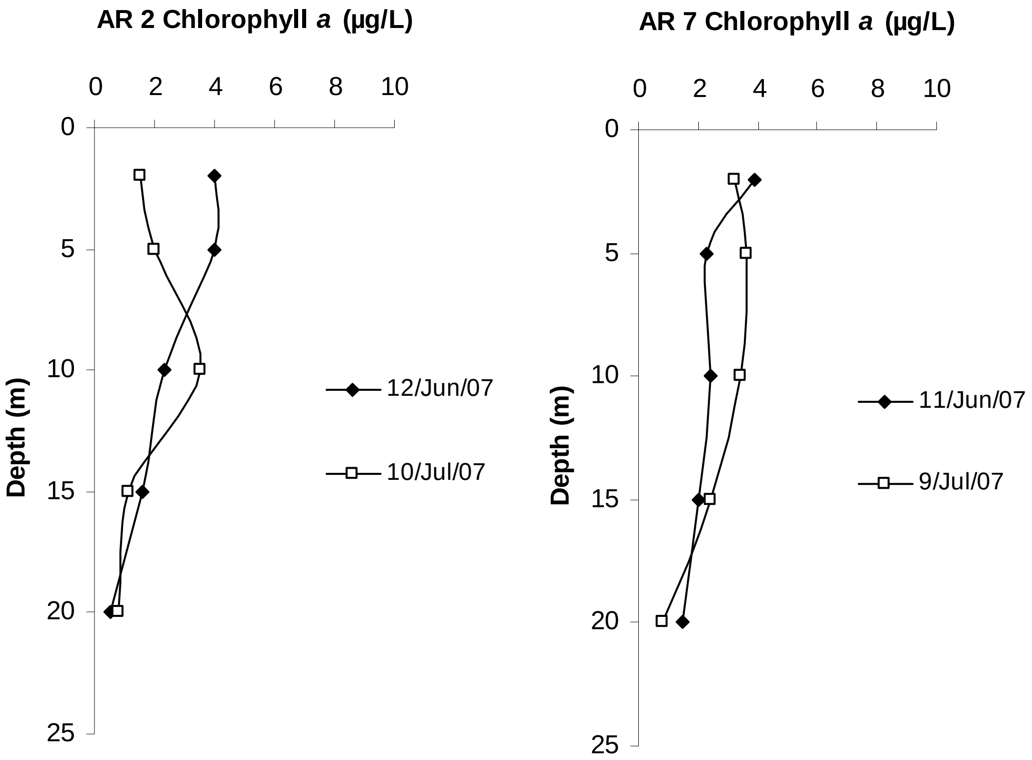
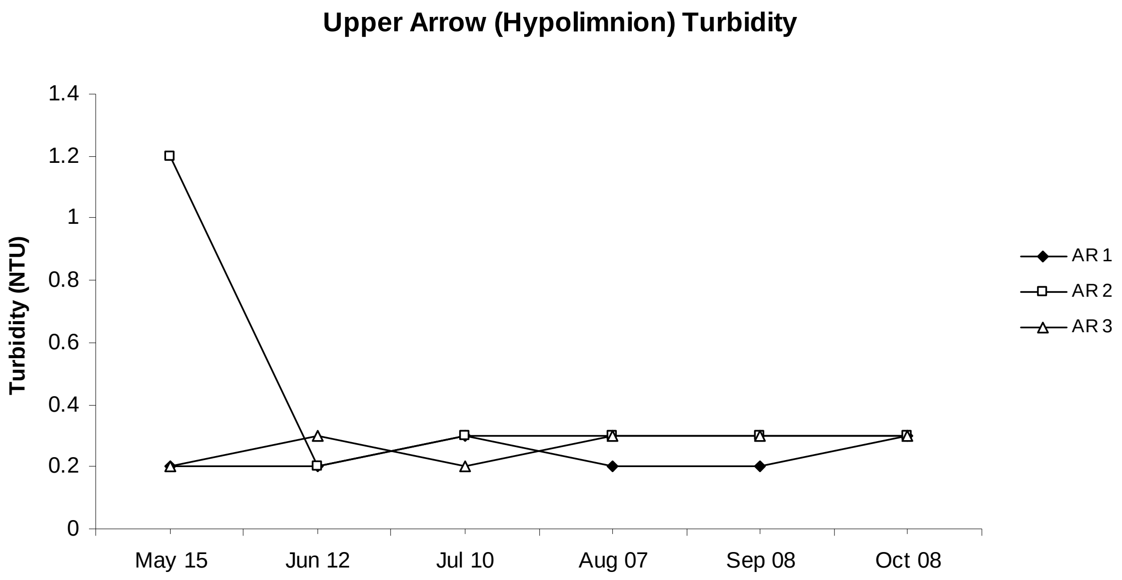


Figure 3.23. Discrete depth chlorophyll *a*, stations AR 2 and AR 7, 2007.



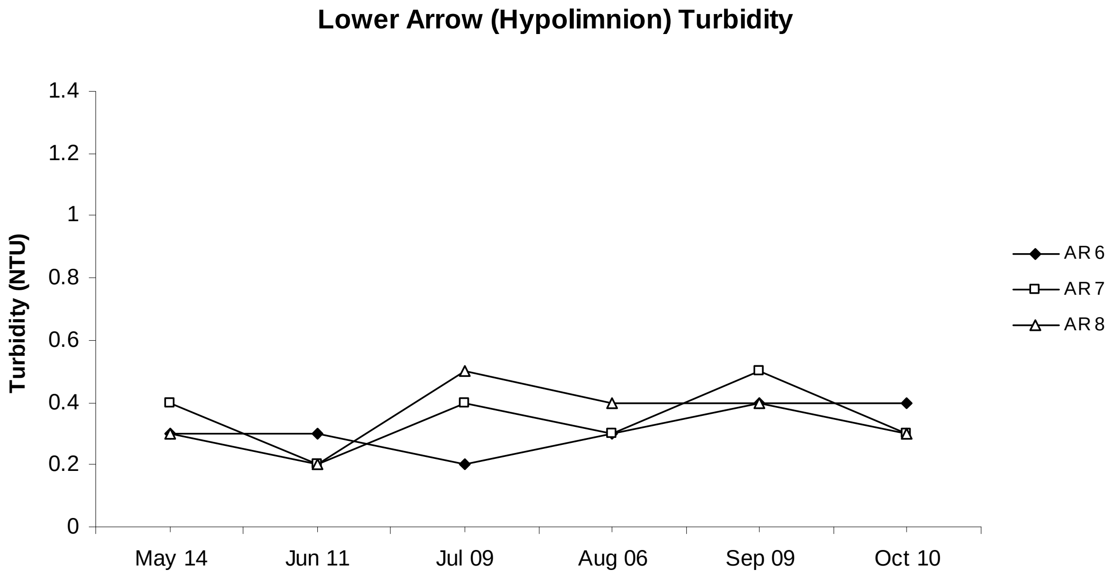
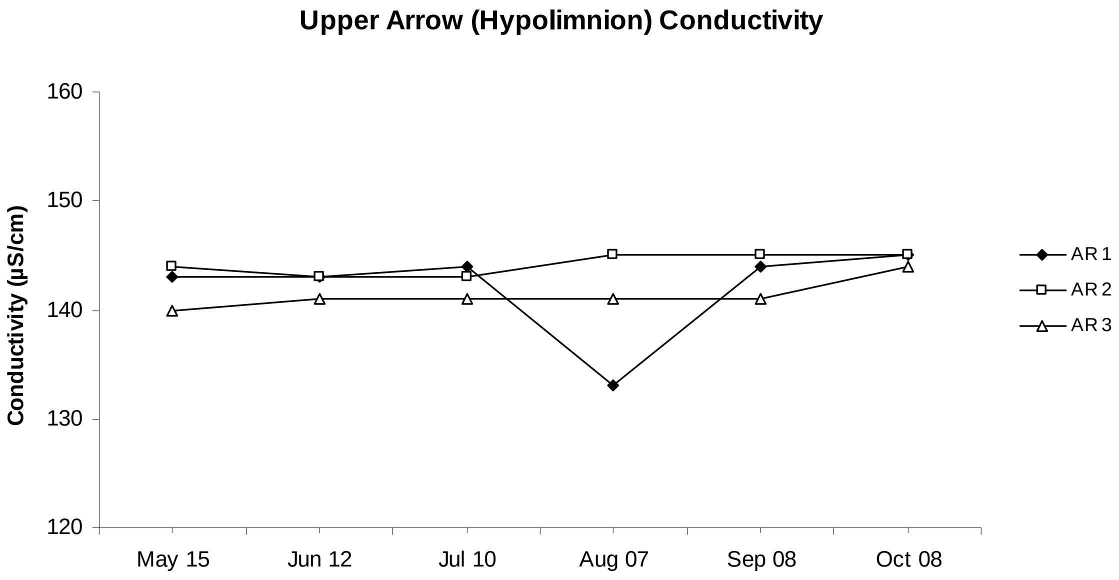


Figure 3.24. Seasonal discrete turbidity, hypolimnion samples, 2007.



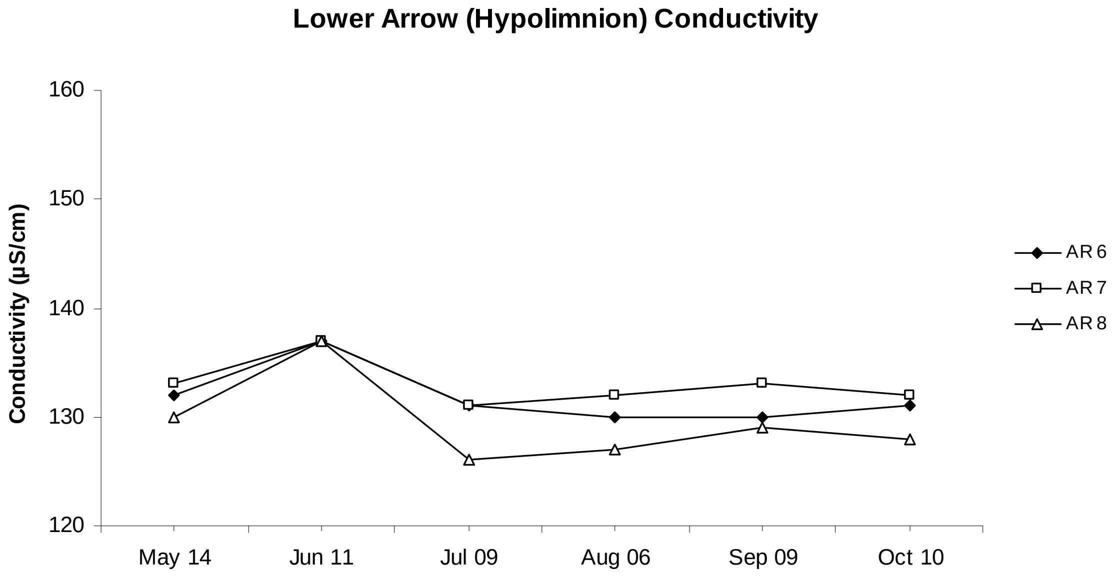
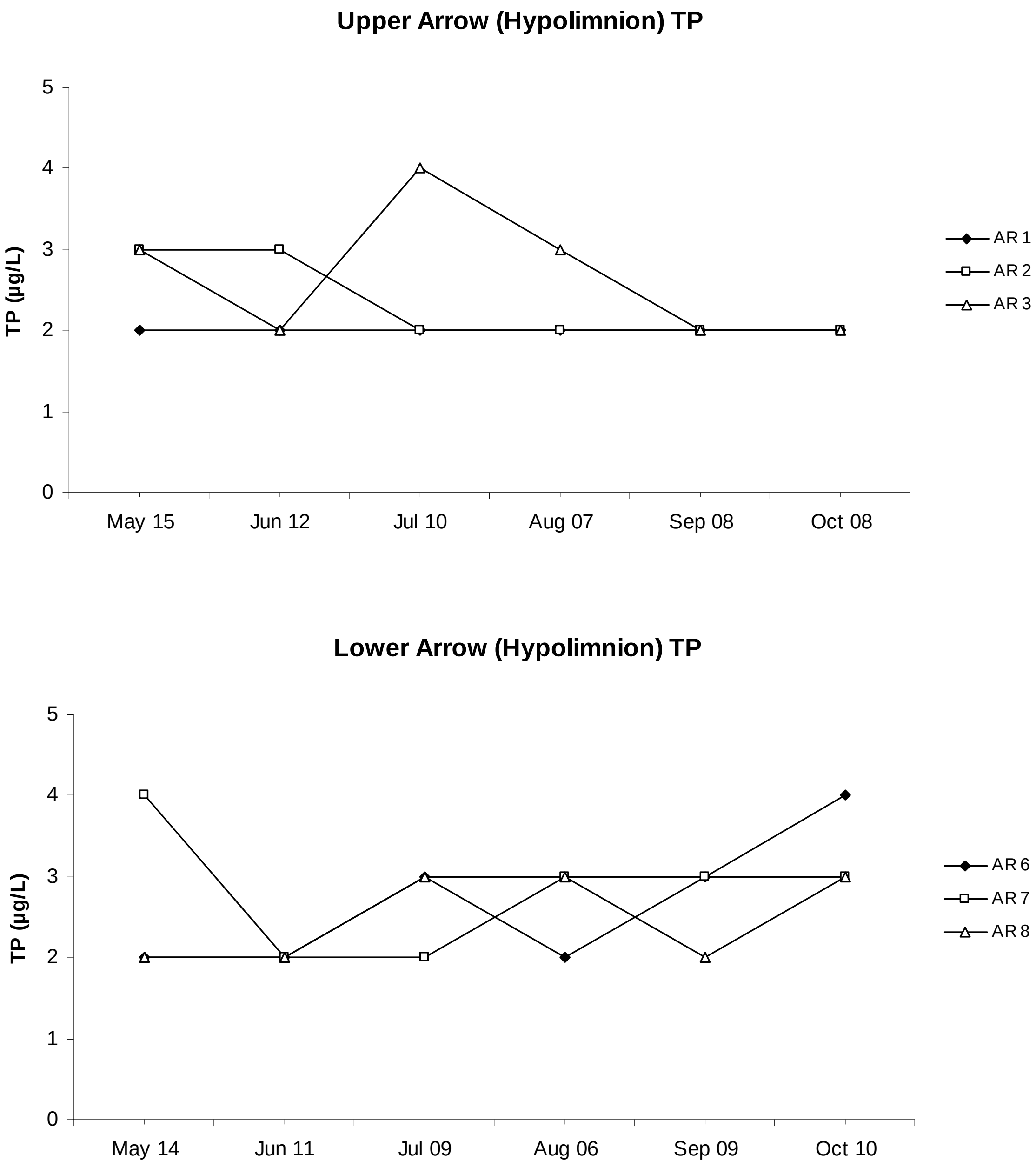
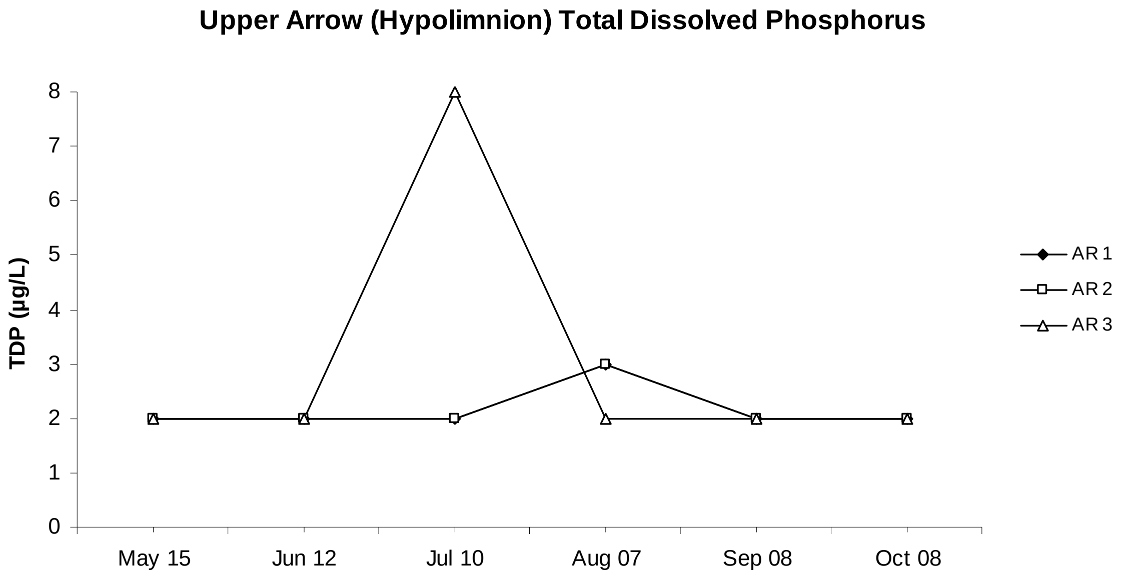


Figure 3.25. Seasonal discrete specific conductivity, hypolimnion samples, 2007.


Upper Arrow (Hypolimnion) TP

Lower Arrow (Hypolimnion) TP

Figure 3.26. Seasonal discrete total phosphorus, hypolimnion samples, 2007.



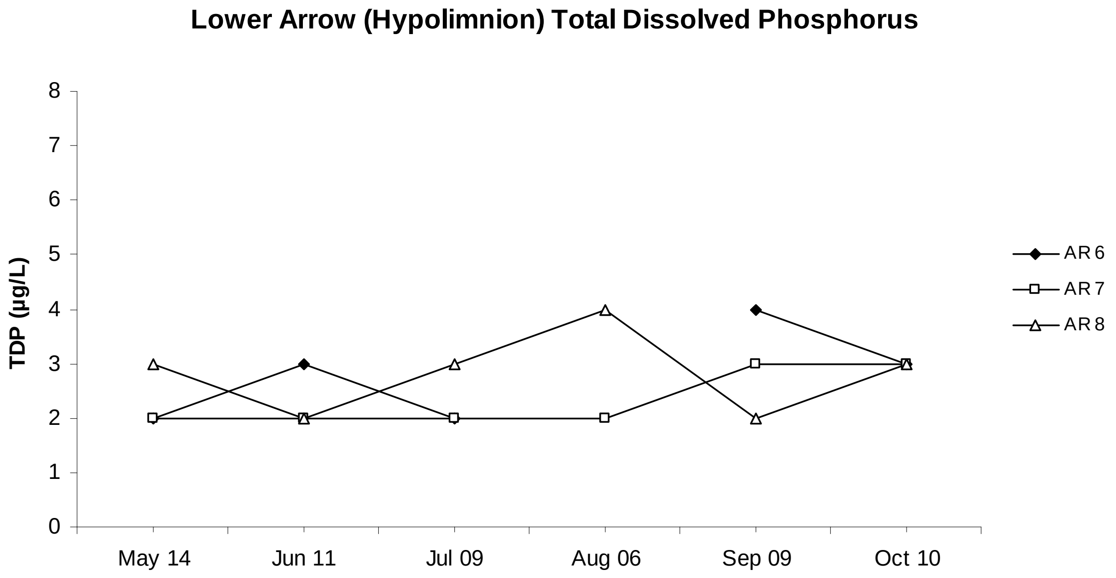
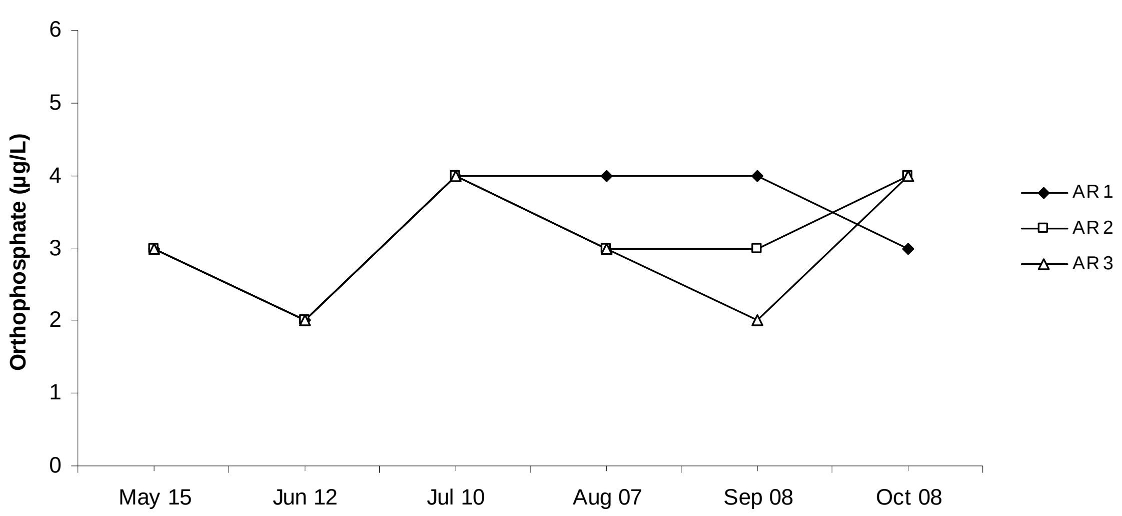


Figure 3.27. Seasonal discrete total dissolved phosphorus, hypolimnion samples, 2007.

Upper Arrow (Hypolimnion) Orthophosphate



Lower Arrow (Hypolimnion) Orthophosphate

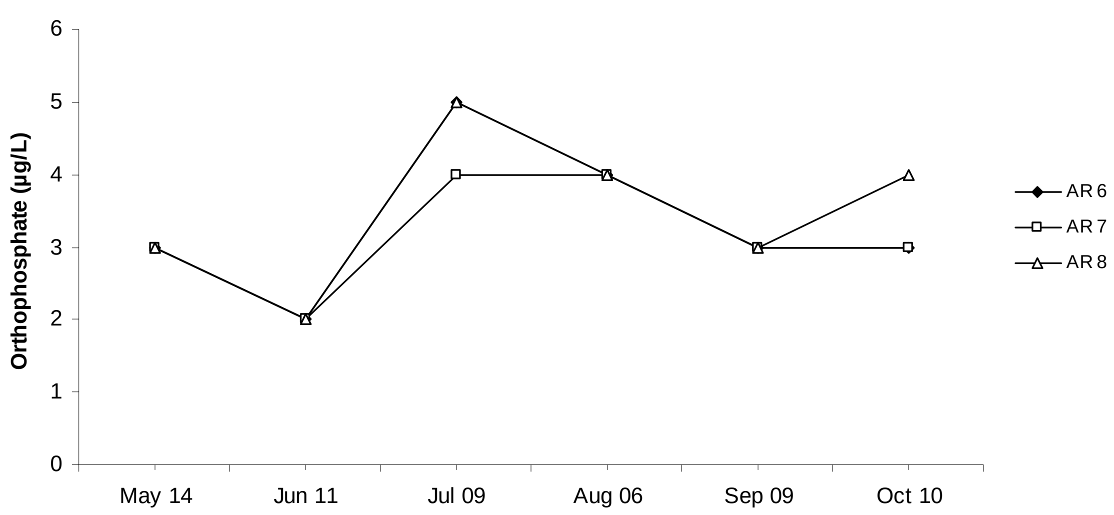
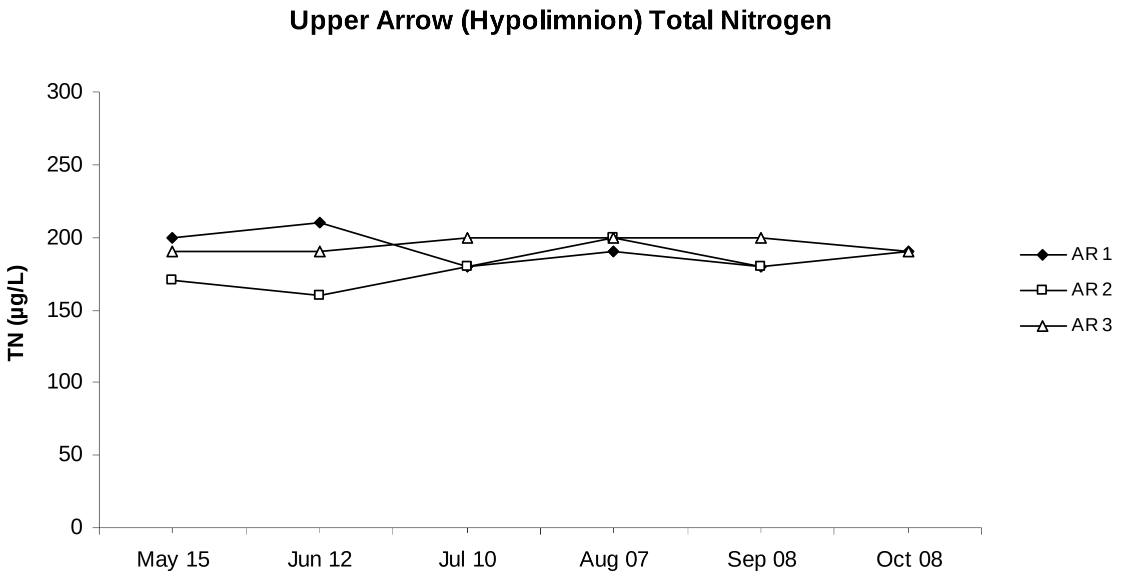


Figure 3.28. Seasonal discrete orthophosphate, hypolimnion samples, 2007.



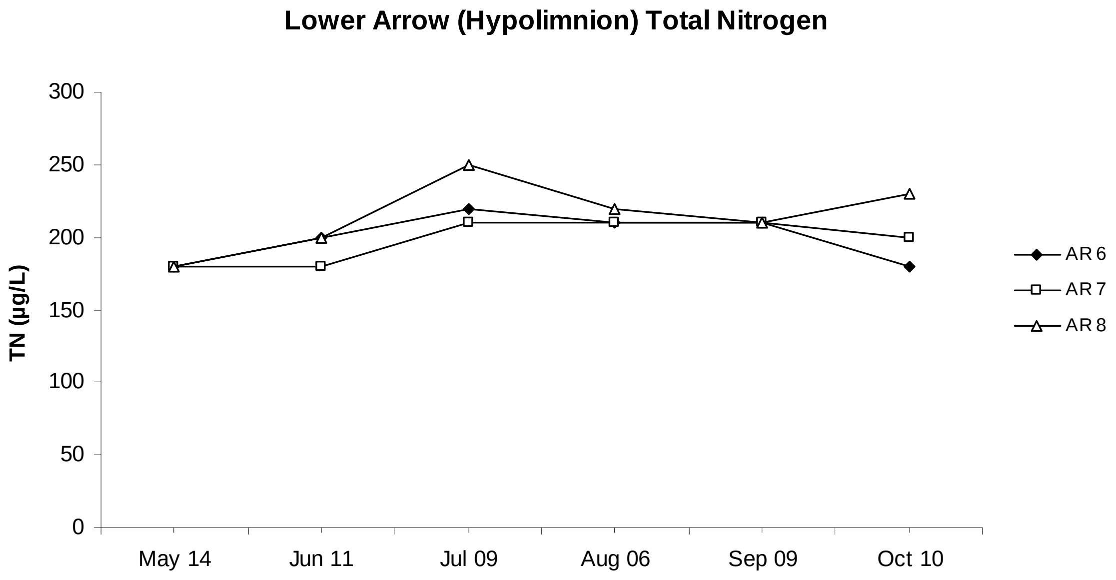
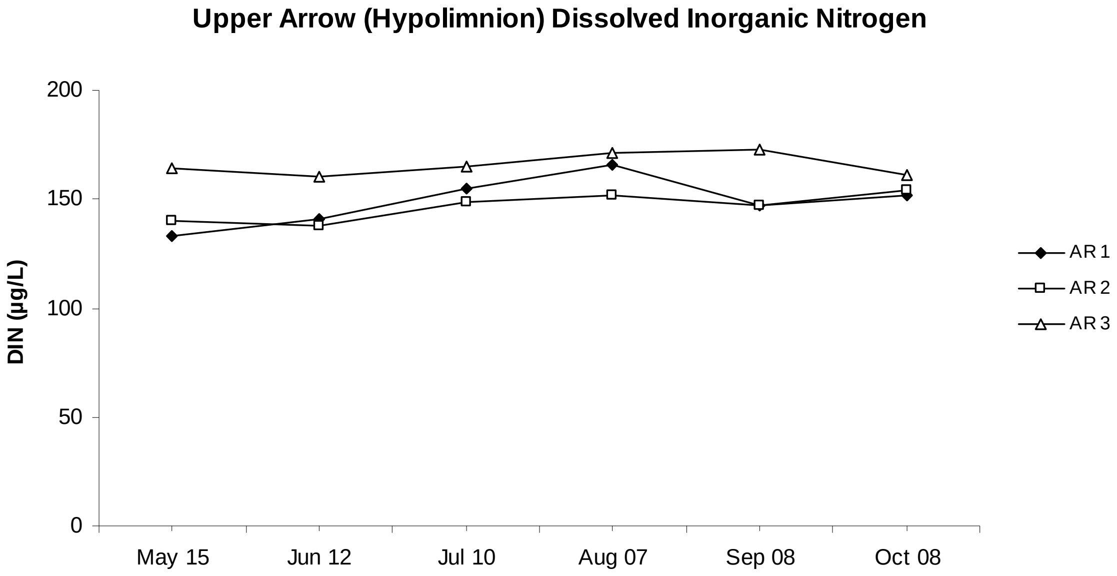


Figure 3.29. Seasonal discrete total nitrogen, hypolimnion samples, 2007.



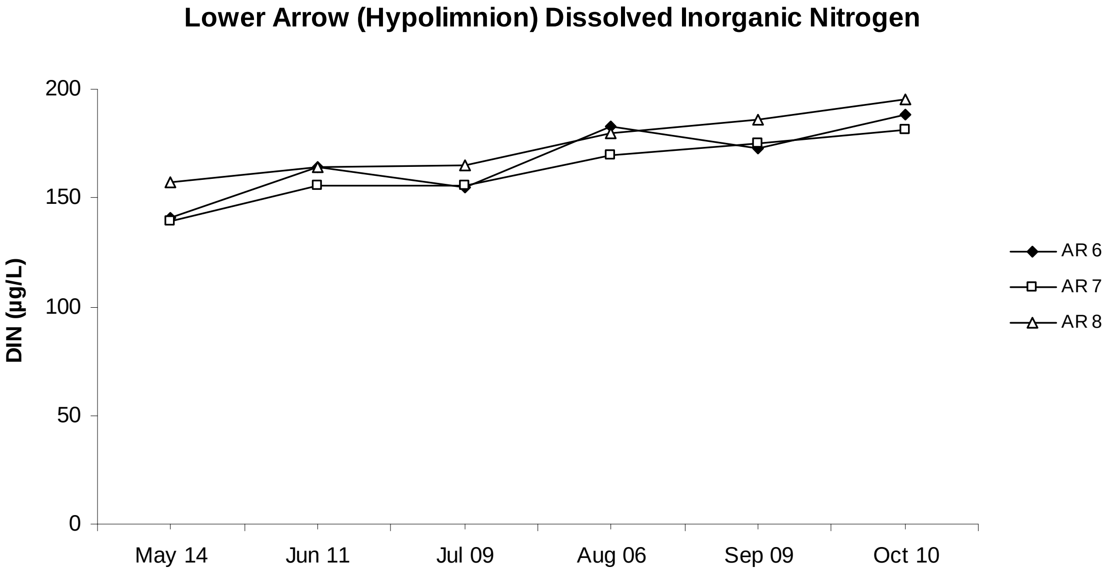


Figure 3.30. Seasonal discrete dissolved inorganic nitrogen, hypolimnion samples, 2007.

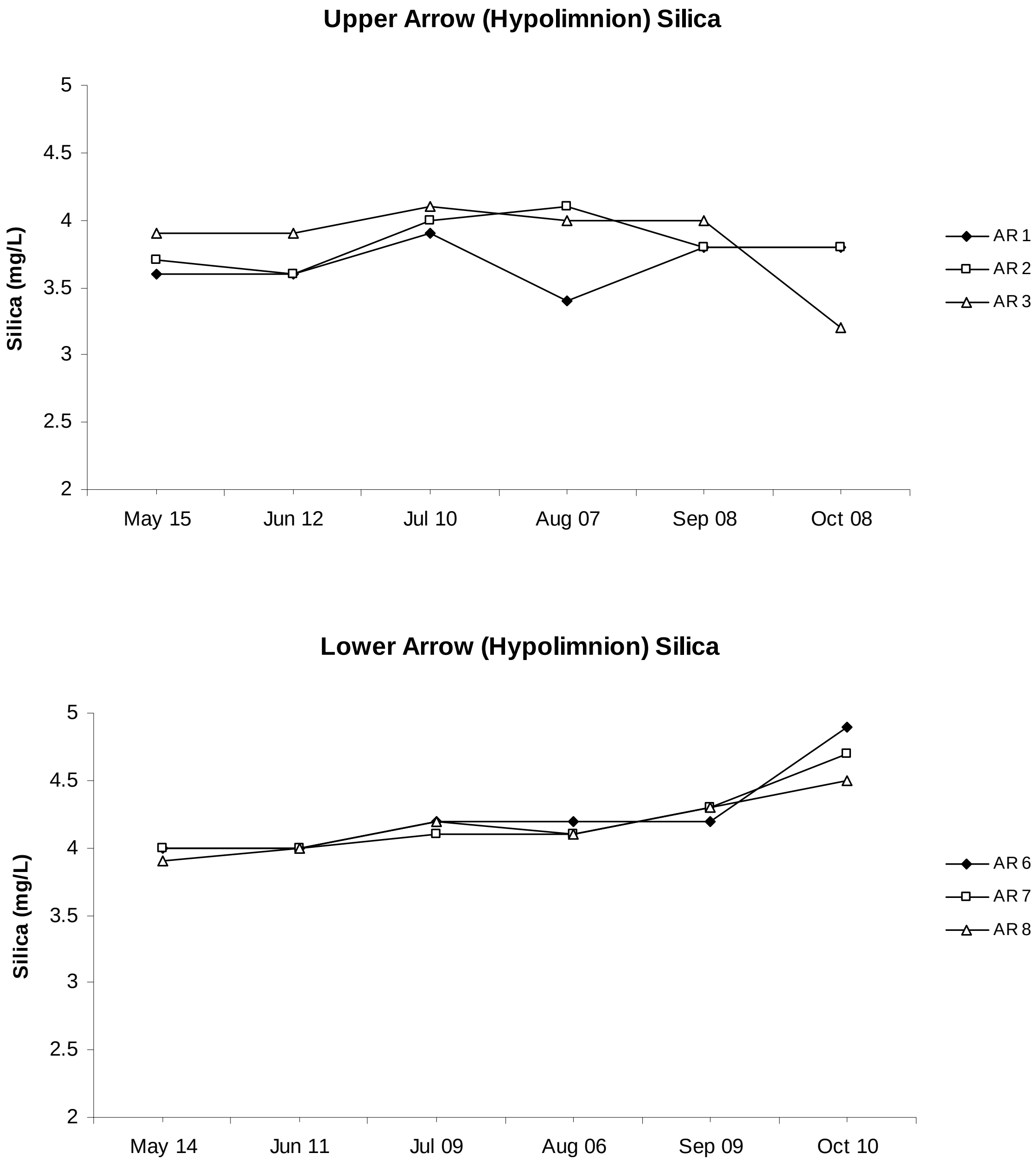


Figure 3.31. Seasonal discrete dissolved reactive silica, hypolimnion samples, 2007.

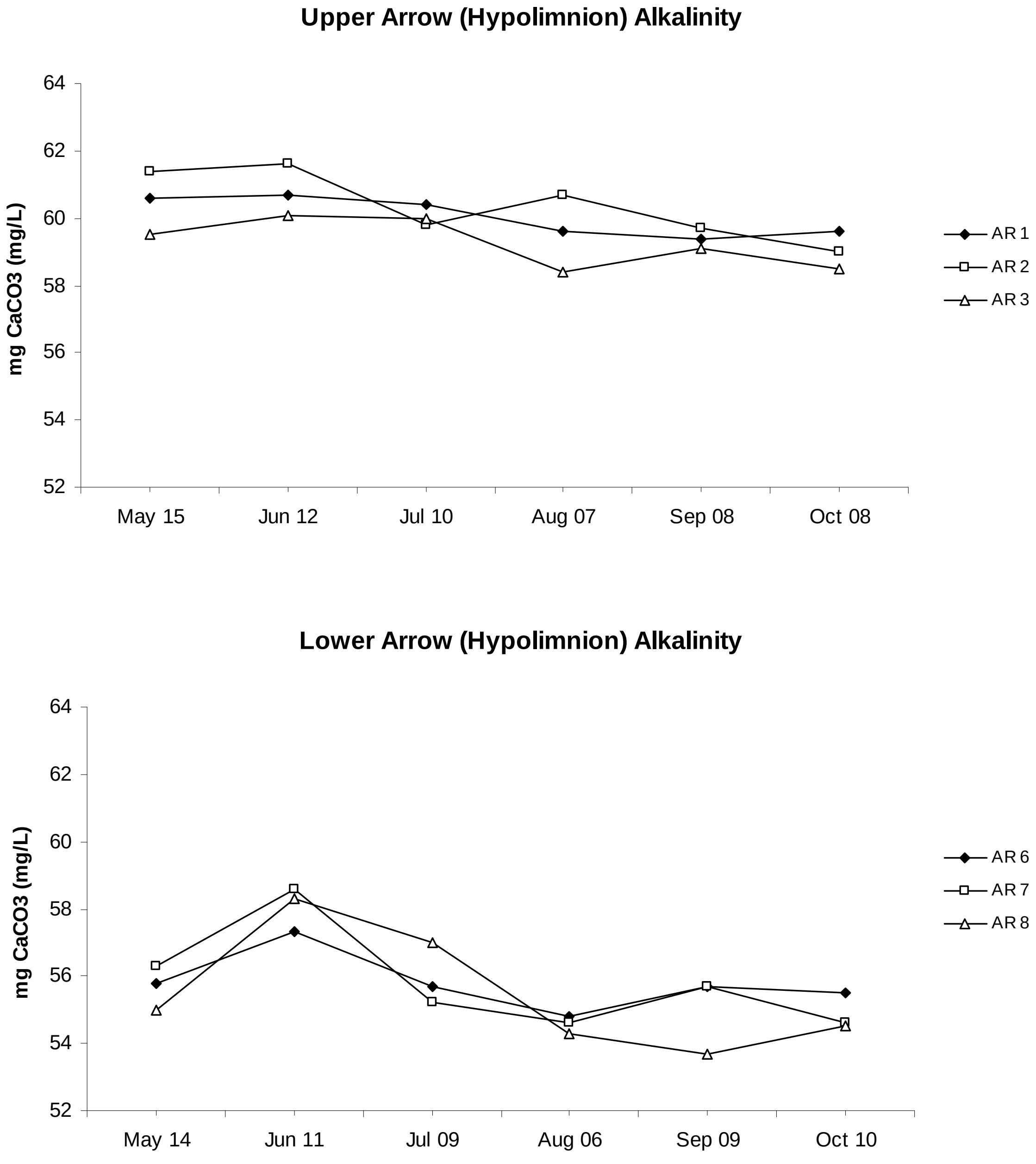


Figure 3.32. Seasonal discrete alkalinity, hypolimnion samples, 2007.

CHAPTER 4

PHYTOPLANKTON POPULATIONS IN ARROW LAKES RESERVOIR - 2007

by

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Introduction

Background and objectives

Arrow Lakes Reservoir in the upper Columbia River basin is a large, narrow, fjord-like hydroelectric system in BC's interior. It was created over 40 years ago by impounding the Columbia River behind Keenleyside Dam at the outlet of Lower Arrow Lake. Prior to the start of fertilization (1999), the reservoir was considered ultra-oligotrophic, with low concentrations of total dissolved phosphorus (TDP), low phyto- and zooplankton biomass, and declining fish production (Pieters et al. 1998, 1999). Fisheries studies have documented the decline in pelagic kokanee populations (*Oncorhynchus nerka*) since impoundment and it is hypothesized that competition with *Mysis relicta* coupled with oligotrophication were major contributing factors in the decline. Recent studies propose that oligotrophication caused by reservoir aging through nutrient trapping and sedimentation in upstream impoundments (Revelstoke Dam/Reservoir and Mica Dam/Kinbasket Reservoir) may be a more important component than *Mysis* competition in triggering the kokanee decline (Stockner et al. 2000; Pieters et al. 2000, 2003).

As part of a continuing study to document the productive status of Arrow Lakes Reservoir, an eleventh year of monitoring was funded in 2007 together with a ninth year of fertilizer application to the northern part of Upper Arrow basin. An important change in the method of fertilizer application from single-point dosing by short ferry crossings to longer north–south–north transects by ferry within the upper basin began in 2005 and continued for 10 weeks in 2006 and 13 weeks in 2007. A key component of the monitoring continues to be the assessment of phytoplankton populations at eight stations along the north–south axis to track their population responses to nutrient supplementation.

Study limitations

Phytoplankton monitoring is limited to a single depth-integrated (0-20 m) sample taken monthly (bimonthly in June) at each of eight stations. These 9 samples provided a 'snapshot' of phytoplankton population abundance, biovolume or biomass[1], community diversity, and spatial-temporal variability in this very large reservoir. Thus, interpretations of phytoplankton population trends reported here are based on two key variables: abundance or density (cells/mL) and biomass (mm^3/L) of species and genera and their respective taxonomic classes.

[1] Instead of using biovolume/biomass interchangeably, in remaining text 'biomass' will be used.

Methods

Sampling

Sampling consisted of a single, depth-integrated (0-20 m) tube sample from each of eight monitoring stations (AR 1-8) along the north–south axis of Arrow Lakes Reservoir (see Fig. 1.1 in Chapter 1 of this report). Samples were obtained monthly from April to November 2007 and couriered to West Vancouver for processing by Eco-Logic Ltd. Each phytoplankton sample was preserved in acid Lugol's iodine shortly after collection. Stations AR 1-3 represent pelagic conditions in the larger, deeper upper basin (i.e., 'historic' Upper Arrow Lake), while stations AR 6-8 represent the smaller lower basin (i.e., 'historic' Lower Arrow Lake). Stations AR 4 and 5 are located in the Narrows sector of the reservoir, a shallow part of the old Columbia River bed channel that connected historic, pre-dam Upper and Lower Arrow lakes. These Narrow's stations represent conditions in what can best be described as a 'transition' region and 'zone of mixing' between the two historic upper and lower Arrow 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 6-8 hours. Counts were done using 25 mL settling chambers on a Carl Zeiss inverted phase-contrast plankton microscope (Utermohl 1958). Counting followed a two-step process: 1. micro-phytoplankton (20-200 μm) within 5 to 10 random fields were enumerated at 250X magnification, and 2. pico-phytoplankton (0.2-2.0 μm) and nano-phytoplankton (2.0-20.0 μm) within or touching a 10 to 15 mm transect line were counted at 1560X magnification. The micro-phytoplankton includes diatoms, dinoflagellates, and filamentous blue-greens. The pico-phytoplankton includes minute (< 2.0 μm) autotrophic cells in Class Cyanophyceae, and the nano-phytoplankton includes auto-, mixo-, and heterotrophic flagellates in Classes Chrysophyceae and Cryptophyceae. In total, about 250 to 300 cells were consistently enumerated in each sample to ensure statistical accuracy (Lund et al. 1958). The compendia of Prescott (1978) and Canter-Lund and Lund (1995) were used as taxonomic references. The phytoplankton species list and estimates of each species' biomass (cell biovolume) used for the computation of population and class biomass estimates for Arrow Lakes Reservoir in 2007 are given in Appendix 4.1.

Results

Basin summaries for seasonal trends in abundance and biomass

Upper Arrow (AR 1-3)

In 2007, average phytoplankton densities at stations within Upper Arrow were slightly higher than in 2006 (the year of lowest recorded abundance for the 11-year time series) but still the third lowest in the time series for this sector and for the first time in the time series -lower than the average in the lower basin (Fig. 4.1, Table 4.1). Peak values at all three stations in 2007 occurred in mid-July, with densities approaching 9,000 cells/mL at all stations. Diatoms (Bacillariophytes) and flagellates (Chryso-Cryptophyceae) were major co-dominant groups up to May and early June, but by July diatoms were predominant, notably *Asterionella formosa*, and they remained so until September when remaining groups made significant contributions to total abundance, i.e., cyanobacteria (Cyanophyceae), dinoflagellates (Dinophyceae), and green algae (Chlorophyceae) (Figs. 4.2a).

Average biomass in 2007 in Upper Arrow basin stations was slightly higher than noted in 2006, with peak values exceeding 1.1 mm^3/L occurring in July concurrent with the diatom abundance peaks (Table 4.1, Fig. 4.2b). In June, both diatoms and flagellates were major contributors to biomass, but in July diatoms were clearly dominant and the principal contributor to biomass. Biomass among Upper Arrow stations was similar with the lowest average biomass at station AR 2 and the highest at station AR 3. Major contributors were diatoms, flagellates and dinoflagellates; of lesser significance were contributions from chlorophytes (green algae) and small coccoid blue-greens (pico-cyanobacteria) (Figs. 4.2b).

Narrows (AR 4-5)

The Narrows had the highest average values of all Arrow stations in 2007 with similar values to those of early treatment years; 2000-2001 (Table 4.1). Large July peaks (>10,000 cells /mL), composed predominantly of *Asterionella, Fragilaria* and flagellates occurred at AR 4 and AR 5 (Figs. 4.2a, b). Throughout the season diatoms, flagellates and to a lesser extent cyanobacteria, were the dominant groups in this shallow sector of the reservoir. Dinoflagellates and greens contributed mostly in September and October but at other times showed low and invariable populations. In October, greens contributed 0.01% and 5% at stations AR 4 and AR 5, respectively. In September greens contributed 3% at both stations. Flagellates were the main contributors in September and October.

Average biomass at Narrows's stations in 2007 was moderately high, owing largely to the greater abundance of large colonial diatoms concentrated here. Peak biomass values were in July and ranged from 1.3-1.6 mm^3/L, highest in Arrow in 2007 (Figs.4.2a, b). Values of average biomass over the season (0.57mm^3/L) in 2007 were the fifth highest in the time series (Table 4.1). Diatoms were the dominant contributor to biomass at both stations, followed by flagellates and some dinoflagellates in late summer and fall. Green algae and pico-cyanobacteria contributed little to biomass (Figs. 4.2a, b).

Lower Arrow (AR 6-8)

Since 1998 the station average phytoplankton abundance within Arrow's lower basin has consistently been the lowest recorded in the 11-year time series, but in 2007 the average was slightly higher than the upper basin (Table 4.1, Figs. 4.2b). The 2007 pattern is no exception with an average value of 3,655 cells /mL. Major peaks reaching >8,000 cells /mL occurred in July at AR 6 and later in August at AR 7. There is a slight peak in August in abundance but overall densities at station AR 8 were more evenly distributed through-out the season. Inedible diatoms decline progressively from peak values at station AR 5 in the Narrows to the lowest values in the reservoir at stations AR6, 7 and 8 in the lower basin. At all south basin stations diatoms and flagellates were the most important contributors to abundance with other groups of lesser significance throughout the growing season (Fig. 4.2b).

The average phytoplankton biomass in 2007 at lower basin stations was 0.56mm^3/L, slightly higher than the upper basin average and lower than the Narrow's average. The peak values (<1.10 mm^3/L) were in July at AR 6 but in August at AR 7 and 8, with much less pronounced and multiple peaks at AR 8 (Fig. 4.2b). The lower biomass was caused by a lower abundance of colonial diatoms, particularly at AR 7 and 8. Flagellates and dinoflagellates were common here and together with diatoms were the most significant contributors to biomass (Figs. 4.2b).

Table 4.1. Phytoplankton abundance and biomass by sector of Arrow Lakes Reservoir, averaged over the growing season (April/May - November) from 1997 to 2007.

	Year	Upper Basin (Sta. 1-3)	'Narrows' (Sta. 4,5)	Lower Basin (Sta. 6-8)	Whole Reservoir (Sta. 1-8)
Abundance (cells·mL^{-1})	1997	4,440	6,945	6,200	5,725
	1998	4,265	3,798	3,879	4,004
	1999	5,235	3,815	4,956	4,775
	2000	4,896	4,966	4,751	4,859
	2001	5,407	7,094	5,385	5,820
	2002	4,771	4,958	3,780	4,446
	2003	5,791	6,227	4,663	5,477
	2004	4,718	4,264	3,595	4,183
	2005	4,307	5,161	3,695	4,291
	2006	3,233	3,298	2,749	3,068
	2007	3,569	4,046	3,655	3,720
Biomass (mm3·L^{-1})	1997	0.30	0.58	0.54	0.46
	1998	0.25	0.42	0.30	0.31
	1999	0.23	0.26	0.36	0.29
	2000	0.43	0.43	0.45	0.44
	2001	0.54	0.77	0.57	0.61
	2002	0.50	0.55	0.37	0.47
	2003	0.54	0.67	0.52	0.57
	2004	0.73	0.67	0.51	0.63
	2005	0.61	0.81	0.54	0.64
	2006	0.45	0.47	0.39	0.43
	2007	0.47	0.57	0.56	0.53

Comparison among years, 1997-2007

2005-2007 Overview

In 2007, for the third consecutive year, the fertilizer application strategy included a mid-June to early September application by ferry on a north - south transects in the upper basin of Arrow Lakes Reservoir (see Chapter 2 for details). The application period by transect in 2006 was 10 weeks but in 2007 it was extended by 3 weeks to 13 trips. The phytoplankton response noted in 2007 was very similar to 2006. Results continued to show declining populations of the colonial diatoms *Fragilaria* spp. but an increase of the 'star' diatom – *Asterionella formosa* (see Plate 1), that peaked in July in the upper basin and Narrows and in August at lower basin stations. The overall reservoir-wide phytoplankton population response in 2007 was slightly higher than 2006, a record low year, but was only moderately larger, ranking as the 4th lowest year of the of 11 yr time-series. There was a clear and more striking diatom peak at all stations (except AR 8) that occurred in July in the upper basin and Narrows sectors but a month later in August in the lower basin. The largest populations in 2007, as in previous years, were again found in the Narrows sector. It is likely that the 'transect' application of fertilizer has led to a better dispersion and created more uniform populations between upper and lower basins with the Narrows sectors or shallower 'mixing' sector the optimal region for phytoplankton growth.

The 2006 phytoplankton response was the smallest yet noted in Arrow Lakes Reservoir, and was in some respects similar to the 2005 response which was considered a sign of impending changes in phytoplankton seasonal distribution, owing in part to the change in application strategy. There were only small, barely perceptible diatom peaks that occurred in July 2006 instead of in June as in previous years, when a single, large diatom peak (spike) occurred. Results from 2006 showed a moderate to large reduction of all species populations, seemingly related to the larger fertilizer application area within the upper basin. The largest populations in 2005, 2006 and 2007 were found in the Narrows sector, but the total population response in 2006 was smaller. In 2006 and 2007 phytoplankton populations at stations AR 7 and 8, the southern most stations in the reservoir, seemed unaffected by the fertilizer application change and exhibited the lowest densities in the reservoir.

Comparison among years, 1999-2007

Since the start of nutrient supplementation in 1999, several notable changes have occurred in the phytoplankton community dynamic of Arrow Lakes Reservoir. To summarize by year (see time-series 1998-2007; Figs. 4.3a, b; 4.4a, b):

- In 1999 (1st year of fertilization), pico-cyanobacteria were the first component of the community to respond to nutrient supplementation, developing large populations but low biomass owing to their small size.
- In 2000 (2nd year of fertilization), the year of 'diatom return' to Arrow, moderately large autumn populations of diatoms were noted at most stations for the first time since monitoring began (1997).

- In 2001 (3rd year of fertilization), the year of 'diatom ascendancy,' diatoms became the predominant phytoplankton group throughout the growing season, with large populations at all stations from July to October.
- In 2002 (4th year of fertilization), the year of 'Chlorophyte ascendancy,' large populations of *Ulothrix elongatum* occurred in late summer along with a concurrent decline of colonial diatom populations.
- In 2003 (5th year of fertilization), the year of 'diatom recurrence,' there were again striking increases in large populations of colonial diatoms, most notably *Fragilaria* spp. that dominated *both* basins of Arrow. The abrupt decline of *Ulothrix* coincident with the re-ascendancy of diatoms in 2003 was one of the more striking shifts among phytoplankton populations yet seen over the past five treatment years.
- In 2004 (6th year of fertilization), the year of 'diatom supremacy,' a 'wall' of *Fragilaria* spp., *Diatoma elongatum*, and *Asterionella formosa* dominated both in terms of numbers and biomass from July to November, and there was a concurrent decline in flagellates, dinoflagellates, greens, and cyanobacteria.
- In 2005 (7th year of fertilization), the year of 'supposition,' implementation of a 'new' application strategy led to many shifts in composition and distribution occurring in all sectors of the reservoir during the growing season. Diatoms were again predominant but more widely dispersed. Compared with 2004, they did not form such large populations or 'walls' in the euphotic zone of either Upper or Lower Arrow. Their ubiquity at most stations led to the highest average phytoplankton biomass seen in the reservoir over the span of the nine-year monitoring period, but the third lowest average abundance.
- In 2006 (8th year of fertilization), owing to the noticeable decline of diatom and flagellate populations, the change would aptly be named the year of 'subsidence.' Reasons for the reservoir-wide declines in abundance may be related either to modification of application strategy resulting in greater population dispersion or to increased phytoplankton population mortality, i.e., losses from grazing, sinking (sedimentation rates), and/or export. My supposition is that grazing losses were the most significant factor responsible for the marked reduction of phytoplankton populations in 2006.
- In 2007 (9th year of fertilization), is highlighted by the resurgence in populations of *Asterionella formosa*, most notably in the upper basin and narrows sectors. This colonial diatom can uptake P at very low concentrations and internally store large quantities for future growth requirements provided there is sufficient silica and turbulence to overcome a high sinking rate. The larger populations in 2007 may be related to in-lake flows and currents imparted by a high water year (discussed in subsequent sections of this report).

The first two-years of nutrient addition (1999, 2000) resulted in large increases in two species: *Synechococcus and Synechocystis* (pico-cyanobacteria) and the instigation of perceptible increases of colonial diatoms. By the third year of treatment (2001) the pico-cyanobacteria declined and the major diatom species responding to Upper Arrow basin fertilization were all colonial: *Fragilaria crotonensis, F. acus* cf. *actinastroides, F. ulna*, and *Diatoma elongatum*. These diatoms formed large populations that were present throughout the summer months and well into the autumn deep-mixing period. These species, plus the 'little star' diatom *Asterionella formosa,* were the major 'inedible' diatoms in the epilimnion of Arrow Lakes Reservoir from 2001 until 2005 when there was a noticeable shift away from predominance by *Fragilaria* to a mid-summer to fall predominance of *D. elongatum, A. formosa*, and two small species of *Cyclotella*. In 2006, there were further reductions in density of all diatom populations and no major, sharp abundance peaks in either upper or lower basins of the reservoir. Nano-flagellates were less common and their populations were smaller than seen in 2005 (Figs. 4.3a, b; 4.4a, b). The dominant flagellate genera were *Dinobryon*, *Cryptomonas, Chromulina, Chrysochromulina*, and *Rhodomonas*. Other phytoplankton groups (Chlorophytes, Dinophytes) were present but never abundant and seem to always shown invariable seasonal patterns. As such, they continue to be minor players within the phytoplankton community's fertilization response.

Colonial diatom population abundance, 2000 - 2007

As mentioned in previous sections of this report, several species of the diatom genus *Fragilaria* have been major contributors to the total phytoplankton community abundance and biomass response to treatment of Arrow Lakes Reservoir since 2001, the third year of fertilization of the upper basin (Fig. 4.5a, b). A protracted summer and autumnal bloom in 2001 was the first clear signal that increased nutrient concentrations in the euphotic zone were sufficient to support larger and heavier siliceous diatoms in Upper Arrow basin. By mid-summer of 2001, *Fragilaria* spp. populations increased abruptly. By September, they had attained very high densities at all stations in the reservoir, but most notably at station AR 5 in the Narrows where the highest numbers of diatoms yet to be recorded (>18,000 cells/mL) were observed (Fig. 4.5b). In 2002 and 2003, the total numbers of *Fragilaria* remained high and steady through the growing season, ranging from 2,000-6,000 cells/mL at Upper Arrow and Narrows stations and from 2,000-4,000 cells/mL or fewer at Lower Arrow stations. *F. crotonensis* was the major species responsible for the huge 'bloom' throughout the reservoir in 2001, but *F. acus* cf. *actinastroides* was increasing and became the major *Fragilaria* species from 2002 to 2003. The gradual decline of *F. crotonensis* and *F. acus* in 2004 and 2005 was followed by moderate increases in other 'inedible' colonial species, such as *Diatoma elongatum, Asterionella formosa*, and the large, solitary *F. ulna*, together with an increase in smaller, 'edible' *Cyclotella* species. In 2006, the density of *Fragilaria* had further declined at all stations but especially in the lower basin, and the most common species were *D. elongatum, A. formosa*, and *F. crotonensis*. These species in 2006 ranged in density from 500-2,500 cells/mL with much smaller populations than heretofore seen in either basin of the reservoir. In 2006, they contributed even less to both basins, notably at the lower basin stations. In 2006, *Cyclotella* species were present in much reduced densities as compared to their 2005 population levels. In 2007 *F. crotonensis* and *F. acus* remained low while *A. formosa* populations were considerably larger than noted in 2006 with *Cyclotella* spp. populations only slightly higher.

Flagellate population abundance, 1999 – 2007

With few exceptions, the average densities of Chryso-Cryptophycean flagellates have declined over the past nine years of fertilization of Arrow Lakes Reservoir (Fig. 4.6). In 1999, densities ranged from 1,700-2,300 cells/mL across all stations, with slightly higher densities occurring in the Narrows and lower basin stations, particularly at station AR 5 & 6. Over the next three years up to 2002, flagellate abundance gradually declined to a station average of 1,600 cells/mL. However, in 2003, concomitant with a huge increase in colonial diatoms, flagellate populations increased again to levels seen in 1999 and attained peak densities at AR 1 and AR 4 of >2,400 cells/mL (Fig. 4.6). With successive years of colonial diatom dominance, flagellate populations waned at all stations and showed progressive declines to 2006 when populations at all stations attained their *lowest* recorded densities averaging 1,000 cells/mL. This density represents a two-fold decline in abundance since 2003. The most common pattern of this decline in flagellate populations is best illustrated by values from stations AR 1 and AR 6, but the declines in 2006 were prevalent across *all* stations and hence were a whole-reservoir occurrence. In 2007 populations were marginally higher at all stations but on a whole-reservoir basis were still the second or third lower among years of comparison.

Responses to nutrient application 2005-2007: Absence of a 'gradient' (Fig. 4.7a, b)

The year 2005 was the first year a distinct change in fertilizer application by ferry on a north–south–north 'transect' was initiated. This change was made to avoid the upsurge of large diatom populations in Upper Arrow created by point-source application, i.e., the 'chemostat' effect. In 2006, the transect method of application was used more extensively, beginning in mid-June and lasting until the end of August and in 2007 from mid-June to early September. The major phytoplankton response in 2005 was the elimination of a clear north-south gradient by July, concurrent with start-up of the new application procedure. Within a month, peak diatom populations were in the Narrows at stations AR 4 and AR 5 (>7,000 cells/mL) with much smaller populations of diatoms at AR 1 and AR 2 and also at lower basin stations (AR 6-8). A similar pattern with a lack of any distinct gradient was noted in 2006 as well, with peak phytoplankton densities in the Narrows' sector. In 2007 sampling there was no indication of a 'gradient' until late June when, with the exception of AR 2, there was a clear gradient from north to south (Fig. 4.7a). By July this pattern had changed to a 'normal' bell-shaped distribution with highs at the two Narrow's stations gradually declining to lows at the most northern and southern stations - AR 1 and 8. From August to October showed little or no gradient but by November there was clearly higher densities in the south basin stations and lowest densities in the upper basin (Fig. 4.7b).

Comparison with Okanagan Lake

Arrow Lakes Reservoir has *on average* shown moderate *densities* of phytoplankton that have, since treatment began, equaled or exceeded phytoplankton densities in Okanagan Lake (Table 4.2). However, Arrow's phytoplankton *biomass* values have always been less than in Okanagan Lake owing to the prevalence of colonial blue-green algal populations with a larger cell-size in Okanagan Lake in late summer and fall. But in 2005, average biomass values in both Okanagan and Arrow Lakes Reservoir were similar; in 2006 Arrow's biomass was nearly two-fold higher than in Okanagan; and in 2007 in was > 2-fold higher (Table 4.2). These reductions in Okanagan Lake are largely due to diminished populations of blue-greens, even at the most productive north end of the lake—the Vernon/Armstrong basin, regions that have historically been the most productive sectors of the lake (Stockner and Northcote 1974). Both 2006 and 2007 were unusual years in both ecosystems with *either* lower nutrient/primary production control (bottom-up) *or* higher phytoplankton mortalities (grazing, sinking) or top-down controls accounting for very low phytoplankton populations.

Table 4.2. Comparison of average phytoplankton abundance and biomass in Okanagan Lake and Arrow Lakes Reservoir from May to October from 1999 to 2007.

	Year	**Okanagan**	**Arrow**
Abundance (Cells/mL)	1999	5,354	5,274
	2000	5,100	5,086
	2001	3,978	6,173
	2002	5,345	4,713
	2003	4,658	6,239
	2004	2,651	4,183
	2005	3,249	4,806
	2006	1,267	3,393
	2007	1,425	4,190
	N=8	**3,669**	**4,912**
Biomass (mm^3/L)	1999	0.77	0.29
	2000	0.69	0.46
	2001	0.75	0.67
	2002	0.80	0.51
	2003	0.85	0.67
	2004	0.50	0.63
	2005	0.74	0.72
	2006	0.26	0.49
	2007	0.27	0.60
	N=8	**0.63**	**0.53**

Discussion

Year 2007 was the eleventh year of phytoplankton enumeration from Arrow Lakes Reservoir and the ninth year of fertilization of the Upper Arrow basin. The 11-year phytoplankton time-series provides abundant evidence of substantial changes in the phytoplankton community dynamic and notable shifts in the relative abundance of species populations since the start of nutrient supplementation in 1999. During the early untreated or ‘control’ years (1997, 1998), the composition of the phytoplankton community was very similar to communities in Kinbasket and Revelstoke reservoirs and also to communities observed in other British Columbia ultra-oligotrophic lakes (Stockner 1981, 1987, 1991; Shortreed and Stockner 1990, Stockner 2005). The community composition and size structure of populations in ultra-oligotrophic systems are largely composed of small, mobile flagellates and ciliates that are primary grazers of minute picoplankton (bacteria and cyanobacteria). These species are the major components of microbial food webs, are well adapted to low nutrient conditions, and are reliant on 'recycled' nutrients from the euphotic zone to sustain their populations (Stockner 1987, 1991; Weisse and Stockner 1993). Microbial food webs are dominated by small, single-celled autotrophic picoplankters (*Synechococcus* spp.), free-living heterotrophic bacteria, phototropic and heterotrophic nano-flagellates, and micro-zooplankton grazers, e.g., ciliates and rotifers (Stockner and Porter 1988). Large-celled micro-phytoplankton species, such as dinoflagellates, desmids, colonial diatoms, and large, filamentous blue-greens, were seldom seen in Arrow Lakes Reservoir *prior* to fertilization. These large-celled species are much more abundant in lakes with higher levels of C productivity, e.g., Okanagan, Shuswap, Babine, and Kootenay lakes (Stockner 1987, Northcote et al. 2005).

The chronology of phytoplankton change in Arrow Lakes Reservoir since 1997, pre-fertilization period, to changes with the commencement of fertilization in 1999 is very informative, and such changes have seldom been tracked in detail in previous studies (Stockner and MacIsaac 1996). The first year of Arrow Lakes Reservoir fertilization in 1999 elicited a large growth response from components of microbial communities—pico-cyanobacteria, flagellates and ciliates. This initial response was basically limited to the northern portion of the upper basin at stations AR 1, 2, and 3, within the 'zone of influence' of point-source fertilizer applications by the Galena ferry. The second year of treatment, in 2000, resulted in a small but noticeable increase of diatoms that heralded the 'return' of large, colonial diatoms, that had heretofore only been present in *very* low numbers in Arrow Lakes Reservoir. Even today in 'untreated' Revelstoke and Kinbasket reservoirs they remain in *very* low numbers with low species diversity (Stockner 2005). Another feature of the second year of treatment (2000) was the slight increase in populations in the lower basin, indicating some moderate advection of phytoplankton from the upper basin. This wider distribution pattern suggested that the reservoir was beginning to show signs of a more nutrient-enriched ecosystem. This response was quite similar to those seen in the first years of fertilization of Kootenay Lake in the early 1990's and was also seen in the 1990's in Okanagan Lake (Rae et al. 1997, Stockner, J.G. in Andrusak et al. 2000). Thus, conjecture based on this early monitor data suggested that nutrient enrichment was indeed working in Arrow and that the zone of influence was no longer restricted to the upper basin but was having an effect on communities of the lower basin (Pieters et al. 2000).

In the third year of treatment (2001), large diatom populations were *very* conspicuous and occurred throughout most of the growing season, a pattern seldom seen in untreated oligo-mesotrophic lakes (Stockner and Northcote 1974; Stockner and Shortreed 1975, 1985, 1994; Stockner and MacIsaac 1996). It was then suggested that the dominant diatom species were 'inedible' and could potentially form carbon sinks if they persisted in future years. In 2002, a filamentous green alga (*Ulothrix* sp.) became dominant in the upper basin along with diatoms, and concerns were again expressed that now *Ulothrix*, like colonial diatoms, could form another carbon sink that could further exacerbate trophic transfers within the food web and inefficient carbon (C) flow to zooplankton and planktivous kokanee. By 2003, Upper Arrow again contained a great density of

Fragilaria spp. but *Ulothrix* did not recur. In 2004, diatoms were still dominant, although their densities were less than in 2003, the 'peak' diatom year. In 2005, with a change in the application procedure, populations of 'inedible' diatoms were further reduced and were more dispersed, and there seemed to be a moderate resurgence of 'edible' diatoms, e.g. *Cyclotella* spp. Year 2006, the eighth year of treatment and second year of change in application protocol, brought record low densities of phytoplankton and an absence of clearly perceptible north-south biomass or density gradients among stations. Flagellate densities were the lowest yet seen since fertilization began, and at some stations they were nearly two-fold lower than in 1999, the first year of treatment. Finally, in 2007 there was a rebound with moderate increases in both density and biomass and a large population of the 'star' diatom - *Asterionella formosa* that showed large abundance peaks in July in the upper basin and narrows that extended as far as AR 7, well into the lower basin (Fig. 4.8). As well at most all stations there were slightly higher densities of flagellates, and there were lower populations of *Fragilaria* spp.

Diatoms and Flagellates – key changes in seasonal patterns.

Through-out the period of nutrient enrichment of the upper basin, there has been many changes in seasonal patterns and often subtle shifts of major species assemblages as highlighted in previous sections. Some of these are well illustrated in Fig. 4.7, where I have selected total abundance of diatoms and Chryso-Cryptophycean flagellates from what I consider to be four *key* periods of phytoplankton change in the 11 yr Arrow Lakes Reservoir time series, namely: 1999 – response to first year of treatment; 2001 – the second largest phytoplankton abundance yet observed; 2003 – the largest phytoplankton abundance noted with species shifts; 2006 – the lowest recorded phytoplankton abundance, and 2007 – the rebound year. The gradual decline of total diatoms from 2001 to 2006 and the striking reduction in flagellates at all stations since 1999 as well as the rebound in 2007 were prominent features (Fig. 4.9). This depiction shows that the reservoir's pelagic food web has been changed from what was largely 'microbial,' driven by a predominance of flagellates, to a more 'classic' diatom food web that regrettably is being short-circuited by a great abundance of inedible species, i.e., C sinks. If the decline of flagellates since 2003 can be linked to significant increases of zooplankton biomass, then concerns for kokanee production, the major planktivore in the ecosystem, can be reduced. Conversely, if the flagellate decline correlates with declining zooplankton and increasing *Mysis*, then two sinks are operative and the efficacy of fertilization or its N:P nutrient balance must be questioned. As discussed above, the negative aspect of colonial diatom dominance is their 'inedibility,' which creates pelagic C 'sinks' that further diminish the phytoplankton forage base available for herbivorous zooplankton. Most of the dominant 'inedible' diatom species in Arrow form either cell clusters or colonies (e.g., long chains, stars, ladders, etc.) that are morphological adaptations have the potential to slow their sinking rate from the euphotic zone, and/or by virtue of their size/shape to avoid zooplankton grazing (Jackson et al. 1989). The only positive C gain for such an ecosystem is an increase in pelagic/benthic coupling that will eventually augment benthic invertebrate populations and enhance demersal fish production.

The 'drivers' of C production and succession in Arrow Lakes Reservoir

Since 1967/68 and the impoundment of historic Arrow Lakes the annual hydrologic nutrient loads from major inflows coupled with a deeper 'narrows' riverine sector and deep water releases from Keenleyside Dam have contributed to the development of a 'nutrient bypass' system that has the potential to short-circuit nutrient re-entrainment at the narrows and has further reduced ecosystem productive capacity (Matzinger et al. 2007). Nutrient supplementation (fertilization) of surface waters since 1999 has served to alleviate some of the symptoms of 'oligotrophication' imparted by the bypass system and together P-sedimentation are currently the principal 'metrics' responsible for the observed changes in the phytoplankton community dynamic of Arrow Lakes Reservoir. Other features of the hydrologic or hydraulic 'metric' include turbidity (sediment load), dilution, sedimentation and transport (advection/export), factors that are determined by interannual climatic variability. For example, 2003 and 2004 (*Fragilaria* years) were moderately low-water years, but 2002 (*Ulothrix* year) was a high-water year, while 2001 (*Fragilaria* year) was another moderately low-water year. Year 2005 had moderate to low water levels and 2006 and 2007 (*Fragilaria* and *Asterionella* years) were moderately high-water years with substantial mid-summer fall discharges.

Arrow Lakes Reservoir has a highly variable and to some extent unpredictable annual hydrograph that is highly dependent on reservoir 'operational' requirements and the reservoir also receives an annual load of N and P from fertilizer application to the upper basin. It makes sense to pay attention to the influence of these 'metrics' on annual phytoplankton responses, i.e., succession, distribution, and production (Pieters et al. 2000, Binsted and Ashley 2006, Matzinger et al. 2007, Schindler et al. 2007, 2009). For example, with a partial change in application protocol in 2005, 2006 and 2007 (i.e., point-source vs. transects), we have seen the effects on phytoplankton spatial and temporal distribution throughout the reservoir, notably in the upper basin and within the Narrows sector.

Of further significance in the multi-factorial equation that controls the primary production response is the balance/imbalance of the N to P ratio at critical periods during the growth cycle. It is this ratio that ultimately determines population dominance and seasonal succession patterns (Stockner and Shortreed 1988, 1994). Epilimnetic residence time is an important variable as well, but has more to do with distribution, i.e., transport or export, than growth. Reservoirs like Arrow, Revelstoke, and Kinbasket have a short (monthly) residence time, which is of greater significance than in natural lakes. In shallow regions where entrainment of hypolimnetic and 'interflow' water is forced upward to the euphotic zone by shallow sills and mixing occurs, e.g., Narrows' stations AR 4 and 5, high densities of phytoplankton most often occur. This is certainly the case in Arrow Lakes Reservoir where stations AR 4 and 5 consistently show some of the highest densities of phytoplankton, notably in 2005, 2006 and 2007 owing in part to the change in fertilizer application method (Table 4.1). The high densities in the Narrows is not surprising because of both wind-induced and convective currents and a moderately strong southward flow of the surface layer of the Arrow Upper basin. Commencement of the first colonial diatom blooms usually starts at AR 1 in early June and spreads to AR 2 and 3 by late June and to Narrows by July where entrained nutrients often return to the euphotic layer to further stimulate growth (Matzinger et al. 2007).

Interannual carry-over

After observing the increasing diatom 'blooms' of 2001-2004 in the upper basin, it was assumed that in future years with successive nutrient applications there would continue to be an increasing 'carry-over' effect from over-wintering pelagic biomass in the upper basin. It was further conjectured that without a marked change in nutrient application, both diatom biomass and ambient nutrient concentrations would gradually rise. The observed declines of both diatom and flagellate populations that started in 2005 and were so striking in 2006 and remained low in 2007 (Figs. 4.6, 4.9) bring into question the validity of these assumptions and suggest that the application method coupled with an 'optimal' hydrologic/hydraulic metric can easily override any carry-over effects and may prevent the consequences of *over*-enrichment and C sinks. Arrow Lakes Reservoir's upper basin is to some extent protected by the major Columbia River inflow from Revelstoke Reservoir, an inflow that has remained 'nutrient-poor' owing to nutrient losses by sedimentation/retention in Kinbasket and Revelstoke reservoirs Furthermore, the large export of C from the system in fall and winter with strong hydroelectric demand coupled with high phosphorus sediment retention in both basins may enable the reservoir to annually re-calibrate to a lower ambient nutrient status and potentially negate any carry-over effects in most years with moderate to high inflows (Pieters et al. 1999, 2000; Stockner and Korman 2002; Matzinger et al. 2007).

Conclusions

The picture emerging from 2006 and 2007, the eighth and ninth years of fertilization of Arrow Lakes Reservoir's upper basin is one of smaller phytoplankton populations than heretofore noted during treated years, with a concurrent reduction in both diatom and flagellate abundance. The highest average densities/biomass in both years occurred at upper basin stations and the highest values occurred at stations within the Narrows sector of the reservoir and lowest in the lower basin. The dominance of inedible colonial diatoms was considerably reduced in 2006, but in 2007 they rebounded with increases in *Asterionella*, with peak abundance in July instead of June. There was also an increase of edible flagellates in small *Cyclotella* spp. populations. Thus, there was no major change in the ratio of edible to inedible species within the phytoplankton community in 2007.

There were no 'distinct' north-south phytoplankton abundance gradients in the spatial distribution among stations in 2007. However, by late June highest densities/biomass was clearly in the Upper Arrow basin, but by July population peaks occurred in the Narrows' sector at AR 4 & 5. By August density/biomass peaks were highest in the Lower Arrow basin stations AR 6 & 7. The absence of a strong, easily detectable gradient is likely related to the third year of a change in procedure for fertilizer application from 'point' source to 'transect' from mid-June to early September. Since 2005 this change in application has led to a more even phytoplankton distribution within the epilimnion of both upper and lower basins and a mid-summers increase in the narrows sector. It is recommended that use of the transect application method for the entire growing season would lead to a more uniform distribution of phytoplankton throughout the reservoir by providing better fertilizer dispersal over a greater surface area. It should also eventually reduce the numbers of inedible diatoms that have short-circuited the pelagic food web within Upper Arrow basin since 2001.

The present levels of carbon production under treated conditions in Arrow Lakes Reservoir should be sufficient to sustain efficient pelagic food webs in support of planktivores, e.g., kokanee. However, this is predicated on a continuing shift in species composition away from the predominance of large inedible colonial diatoms to smaller edible species such as flagellates, greens, dinoflagellates and small diatoms e.g. *Cyclotella*. Unfortunately this shift is not evident in the 2007 dataset, only a change from *Fragilaria* spp. to A*sterionella* dominance from July onward. The still low but increased abundance of flagellates in 2007 is hopefully a sign that high zooplankton grazing rates prevail in the euphotic zone. *Daphnia* spp. biomass significantly decreased in Arrow in 2007 compared to 2006. Residence time (flushing rate) of the Arrow narrows in 2007 was the highest since 1999, the year when nutrient additions commenced (R. Pieters, pers comm.).The high flushing rate is a possible explanation for decreased *Daphnia* spp. biomass. Mysid biomass in 2007 slightly decreased compared to 2006 (see Chapter 5). Kokanee abundance also slightly decreased in 2007 (see Chapter 6 in this report), therefore grazing pressure on zooplankton was not likely an issue. If the continued low abundance is related to reduced growth rates caused by competition with inedible diatoms, then further changes in the N:P ratio of fertilizer additions must be considered. In 2007, nitrogen limitation did not occur in Arrow as it has in previous years (2001, 2003 and 2004). The range of N:P ratios (weight:weight, dissolved fractions) from integrated epilimnetic samples (0 – 20 m) in 2007 were 10:1 to 77:1 with an average of 44:1 (from April to November) (E. Schindler, pers comm.).

Recommendations

1. Use of the transect method needs to be expanded to the entire fertilization period and length of transects extended to close to the Narrows region. This change will broaden the dispersal of nutrients in the euphotic zone of Upper Arrow basin and Narrows region and increase fertilizer dispersal and reduce large concentrations of ‘inedible’ phytoplankton.

2. Samples from the eight Arrow Lakes Reservoir monitoring stations should continue to be taken on successive days as has been done since 2004, and phytoplankton sampling in the reservoir should begin in April and terminate the middle of November.

3. Assessments of phytoplankton response to fertilizer addition should continue so as to monitor further effects of changes in application protocol. Tracking the species responses, their relative abundance and the ratio of edible to inedible phytoplankton throughout the season can yield important ecological information required for an assessment of the efficacy of the supplementation technique.

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Appendix 4.1. Arrow Lakes Reservoir phytoplankton species, codes and biovolume (biomass), 2007. (E=edible, I=inedible)

Code	Class	Bvol.	Genus & Species	
Bacillariophytes - diatoms				
AM	Bacillariophyte	80	Achnanthes sp.	E
AY	Bacillariophyte	100	Asterionella formosa var1	I
AZ	Bacillariophyte	120	Asterionella formosa var2	I
CP	Bacillariophyte	200	Cocconeis sp.	E
CU	Bacillariophyte	500	Cyclotella bodanica	I
CZ	Bacillariophyte	350	Cyclotella comta	I
CJ	Bacillariophyte	350	Ceratoneis sp.	I
CS	Bacillariophyte	150	Cyclotella stelligera	E
CW	Bacillariophyte	50	Cyclotella glomerata	E
CT	Bacillariophyte	150	Cyclotella sp.	E
CM	Bacillariophyte	500	Cymbella sp. (large)	I
CO	Bacillariophyte	250	Cymbella sp.	E
DF	Bacillariophyte	150	Diatoma elongatun.	I
EV	Bacillariophyte	250	Eunotia sp.	I
FF	Bacillariophyte	80	Fragilaria construens	I
FC	Bacillariophyte	120	Fragilaria crotonensis	I
FG	Bacillariophyte	100	Fragilaria capucina	I
GG	Bacillariophyte	750	Gomphonema sp.	I
MD	Bacillariophyte	350	Aulicoseira distans	I
MI	Bacillariophyte	200	Aulicoseira italica	I
MJ	Bacillariophyte	250	Aulicoseira granulata	I
MZ	Bacillariophyte	350	Aulicoseira sp.	I
NV	Bacillariophyte	500	Navicula sp.	I
NZ	Bacillariophyte	200	Nitzschia sp.	I
RC	Bacillariophyte	50	Rhizosolenia sp.	I
SH	Bacillariophyte	500	Stephanodiscus hantschii.	I
SE	Bacillariophyte	1500	Stephanodiscus sp.	I
SN	Bacillariophyte	100	Fragilaria acus	I
SO	Bacillariophyte	150	Fragilaria angustissima	I
SU	Bacillariophyte	1000	Fragilaria ulna	I
SS	Bacillariophyte	500	Suriella	I
SR	Bacillariophyte	250	Fragilaria sp.	I
PI	Bacillariophyte	2000	Pinnularia sp.	I
TF	Bacillariophyte	500	Tabellaria fenestrata	I
TB	Bacillariophyte	500	Tabellaria flocculosa	I
DL	Bacillariophyte	250	Diploneis sp.	I

Chryso-Cryptophyte flagellates

BS	Chryso-cryptophyte	200	Bitrichia sp.	E
CH	Chryso-cryptophyte	250	Chilomonas sp.	E
XX	Chryso-cryptophyte	20	Chromulina sp1	E
CA	Chryso-cryptophyte	150	Chroomonas acuta	E
YO	Chryso-cryptophyte	500	Chryptomonas sp.	E
CC	Chryso-cryptophyte	75	Chrysochromulina sp.	E
DN	Chryso-cryptophyte	150	Dinobryon sp1	E
DO	Chryso-cryptophyte	200	Dinobryon sp2	E
KA	Chryso-cryptophyte	50	Kephyrion sp.	E
IS	Chryso-cryptophyte	200	Isthmochloron	E
MH	Chryso-cryptophyte	500	Mallomonas sp1	E
MG	Chryso-cryptophyte	700	Mallomonas sp2	E
SX	Chryso-cryptophyte	75	Stenokalyx	E
YZ	Chryso-cryptophyte	15	Small microflagellates	E
OC	Chryso-cryptophyte	250	Ochromonas sp.	E
PT	Chryso-cryptophyte	100	Pseudokephrion sp.	E
PP	Chryso-cryptophyte	150	Pseudopedinella sp.	E
CI	Chryso-cryptophyte	75	Chrysoikos sp.	E
SY	Chryso-cryptophyte	700	Synura	I
RO	Chryso-cryptophyte	100	Rhodomonas sp.	E
CF	Chryso-cryptophyte	250	Chrysidiastrum	E

Dinophytes

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

Chlorophytes

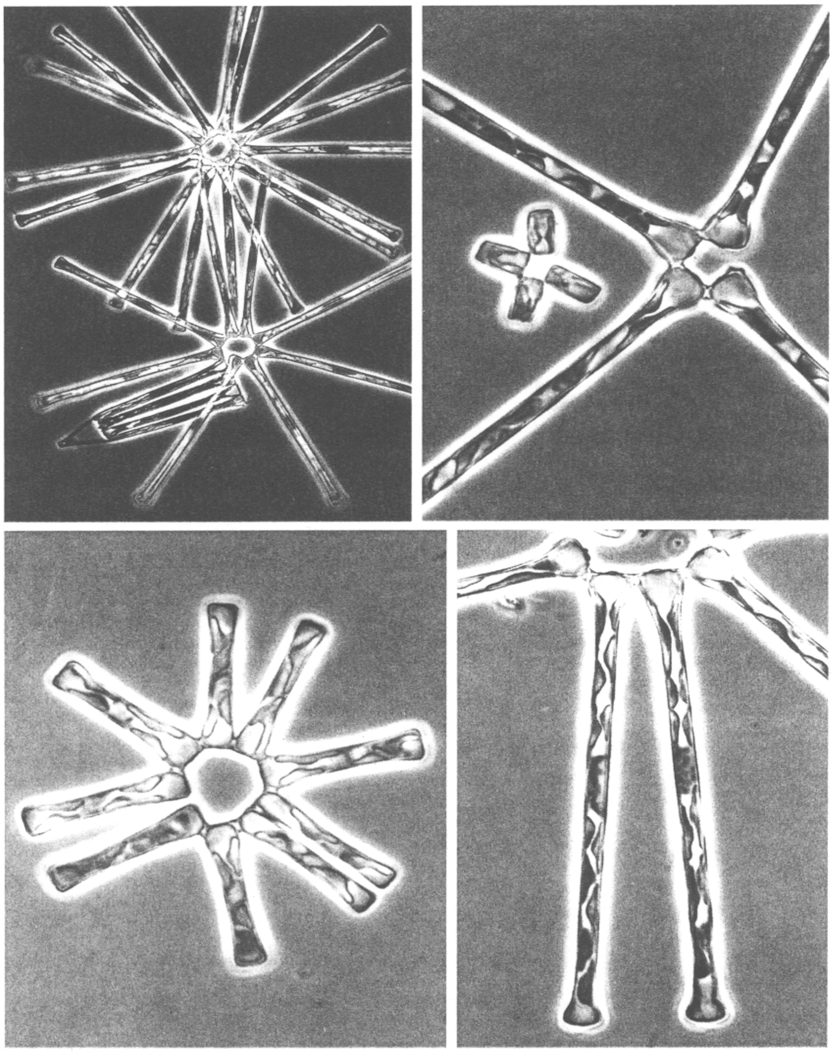
XC	Chlorophyte	80	Ankistrodesmus sp.	E
CX	Chlorophyte	150	Coccomyxa sp.	E
CL	Chlorophyte	500	Coelastrum sp.	I/E
CN	Chlorophyte	500	Cosmarium sp.	E
CK	Chlorophyte	200	Crucigenia sp.	E
XU	Chlorophyte	700	Crucigeniella apiculata	E
DI	Chlorophyte	900	Dichtyosphaerium	I/E
LA	Chlorophyte	30	Langerheimia	E
EL	Chlorophyte	250	Elakatothrix sp3	E
EU	Chlorophyte	2500	Euglena	I/E
GO	Chlorophyte	500	Gonium	E
OO	Chlorophyte	500	Oocystis sp.	E
SI	Chlorophyte	60	Scenedesmus sp.	E
SD	Chlorophyte	1500	Staurodesmus sp.	I/E
QD	Chlorophyte	250	Quadrigula	E

UL	Chlorophyte	700	Ulothrix	I
CD	Chlorophyte	150	Closteriopsis	E
MO	Chlorophyte	200	Monoraphidium	E
NE	Chlorophyte	350	Nephrocytium	E
ST	Chlorophyte	1000	Staurastrum sp.	I
PL	Chlorophyte	350	Planctonema sp.	E
PA	Chlorophyte	1000	Planctosphaeria	I/E
PS	Chlorophyte	100	Paulschultzia sp.	E
CB	Chlorophyte	20	Chlorella	E
KI	Chlorophyte	50	Kirchneriella sp.	E
PE	Chlorophyte	1000	Pediastrum sp.	I/E
PA	Chlorophyte	1500	Pandorina sp.	I
TE	Chlorophyte	50	Tetraedron	E
VO	Chlorophyte	4000	Volvox	I
XI	Chlorophyte	700	Xanthidium	E

Cyanophytes

AC	Cyanophyte	900	Anabaena circinalis	I
AH	Cyanophyte	100	Aphanothecae sp.	I/E
MS	Cyanophyte	20	Merismopedia sp.	E
ZN	Cyanophyte	20	Oscillatoria sp2	E
ZO	Cyanophyte	350	Oscillatoria limnetica	I
LB	Cyanophyte	250	Lyngbya sp.	I
MX	Cyanophyte	500	Microcystis sp.	I
SC	Cyanophyte	5	Synechococcus sp.	E
SY	Cyanophyte	10	Synechocystis sp.	E

Plate 1. Photomicrograph of the 'little-star' diatom *Asterionella formosa*, a pelagic araphinate, colonial diatom common in Arrow Lakes Reservoir, BC, Canada (photo Canter-Lund & Lund 1995)



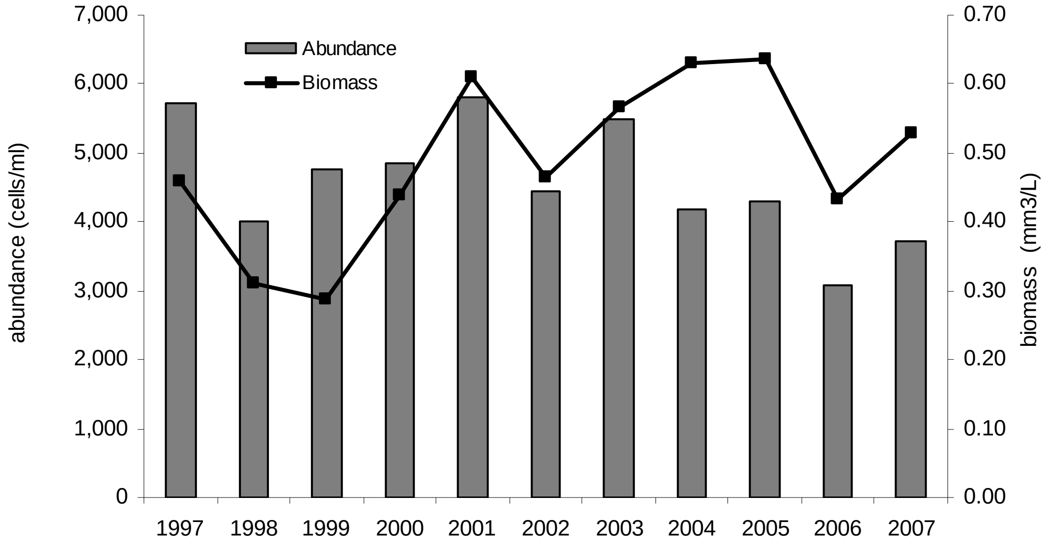


Figure 4.1. Arrow Lakes Reservoir average phytoplankton abundance and biomass, May to November, 1997 – 2007.

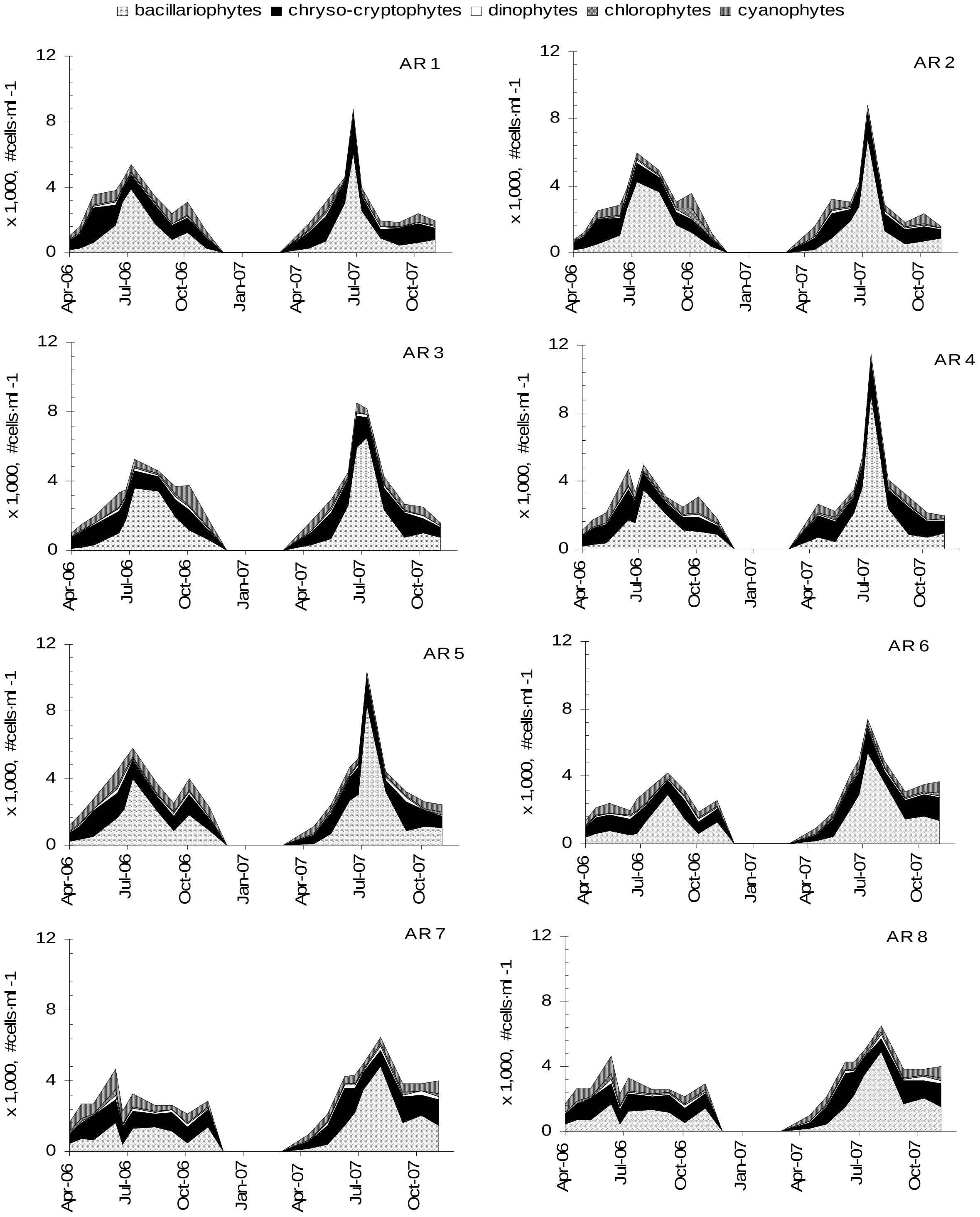


Figure 4.2a. Seasonal (April – November) epilimnetic abundance of major phytoplankton classes in Arrow Lakes Reservoir, stations AR 1-8 in 2006 and 2007.

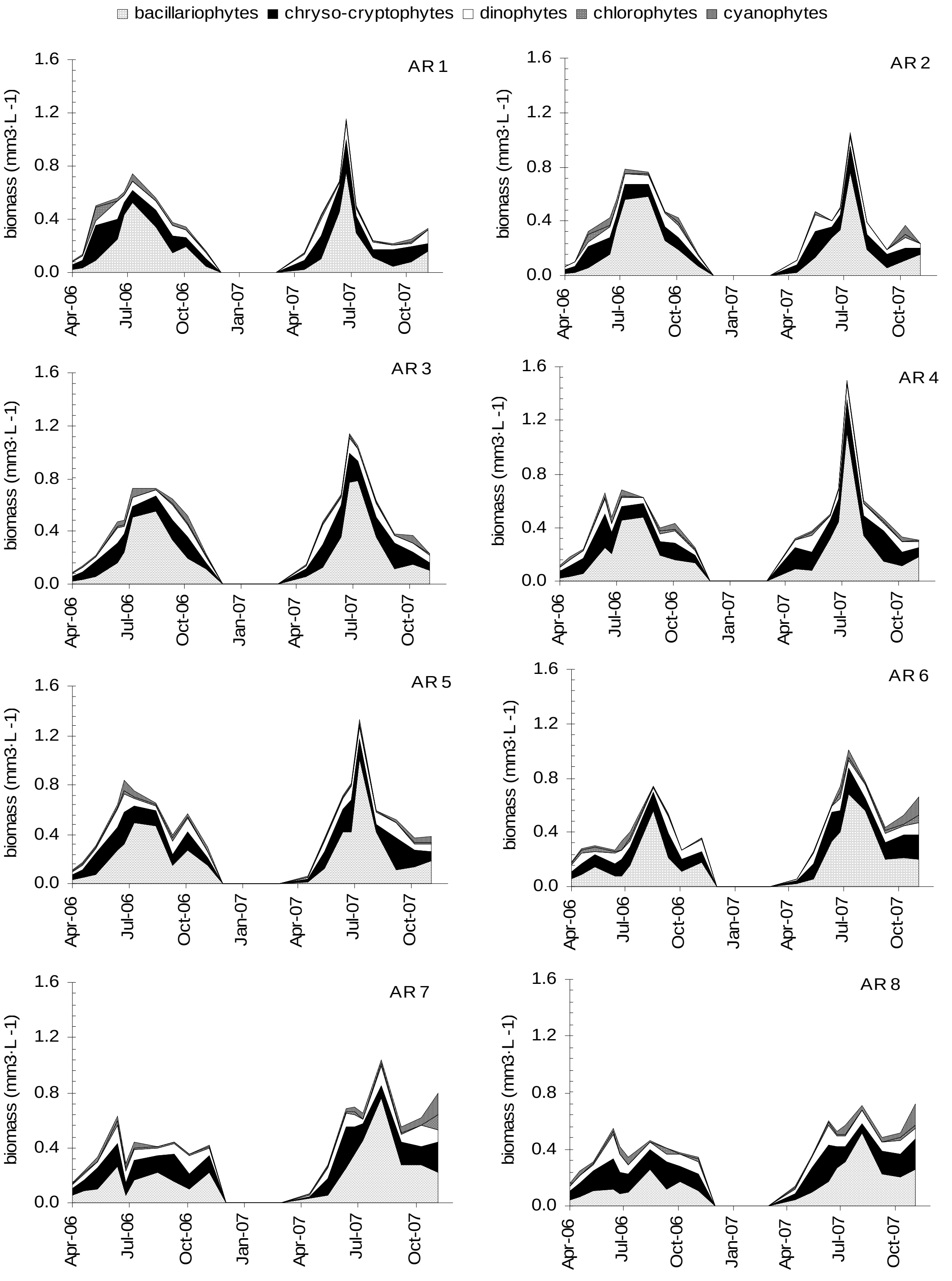


Figure 4.2b. Seasonal (April – November) epilimnetic biomass of major phytoplankton classes in Arrow Lakes Reservoir, stations AR 1-8 in 2006 and 2007.

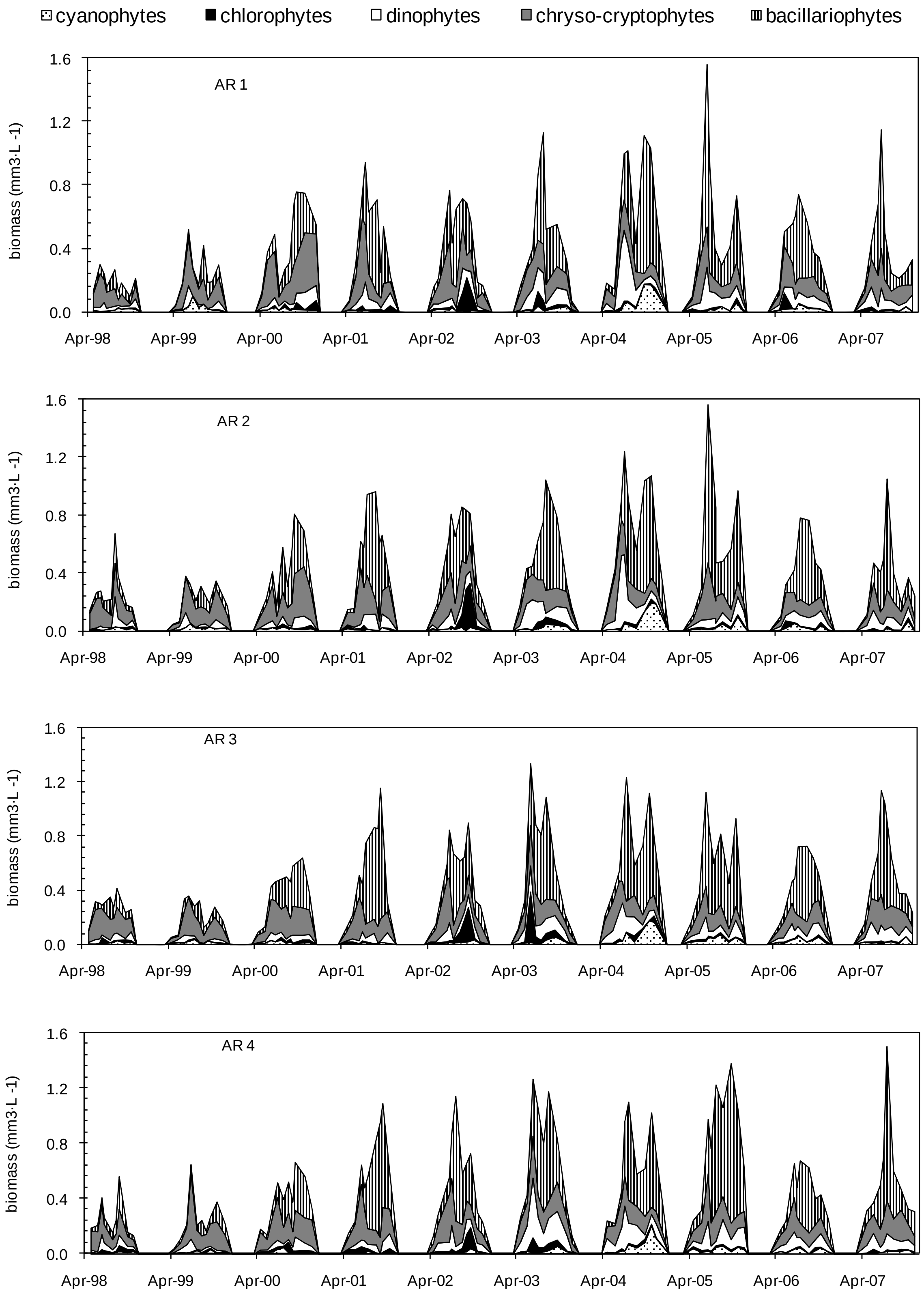


Figure 4.3a. Time series of Arrow Lakes Reservoir phytoplankton biomass by major classes in stations AR 1 - 4, 1998 – 2007.

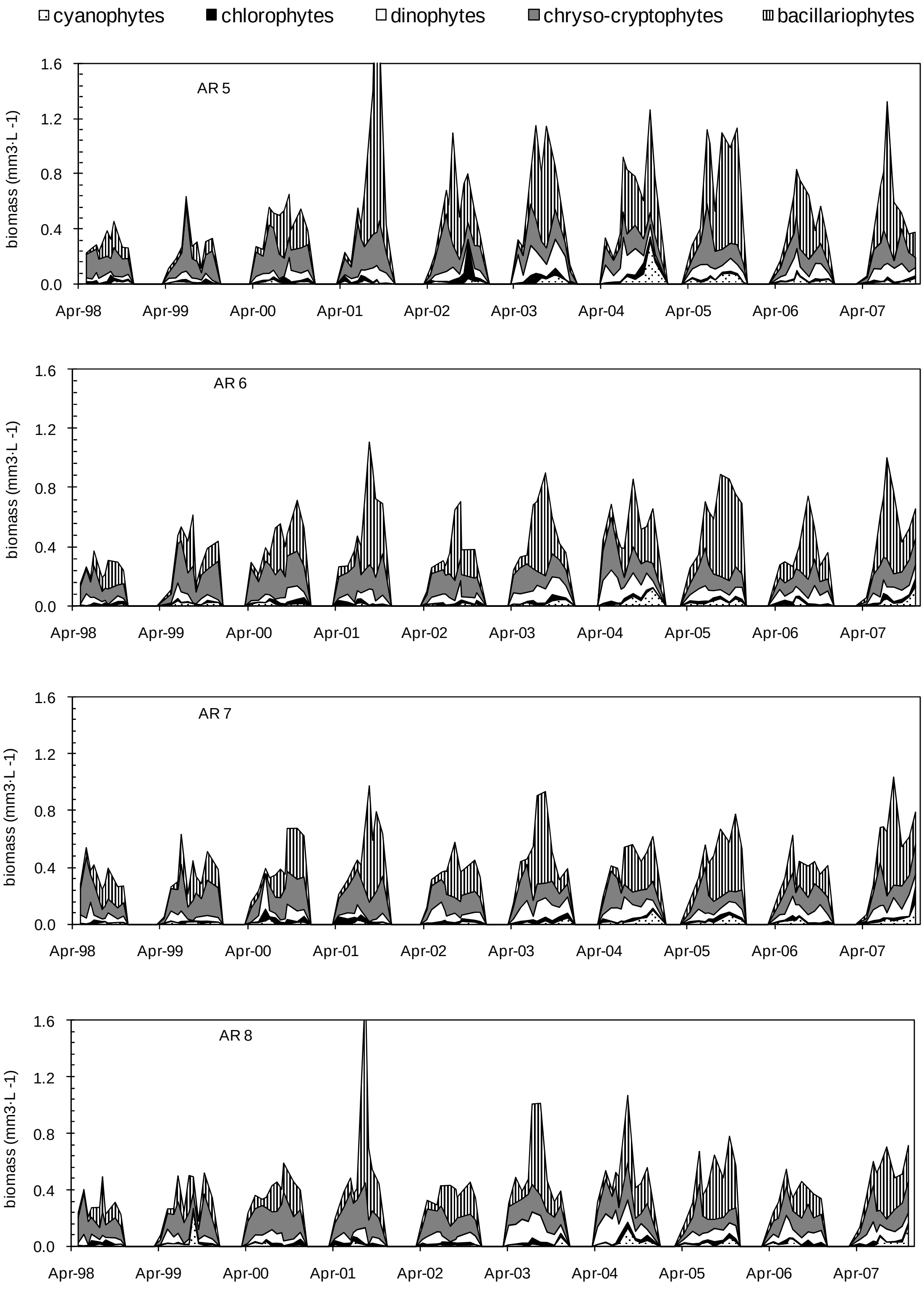


Figure 4.3b. Time series of Arrow Lakes Reservoir phytoplankton biomass by major classes in stations AR 5 - 8, 1998 – 2007.

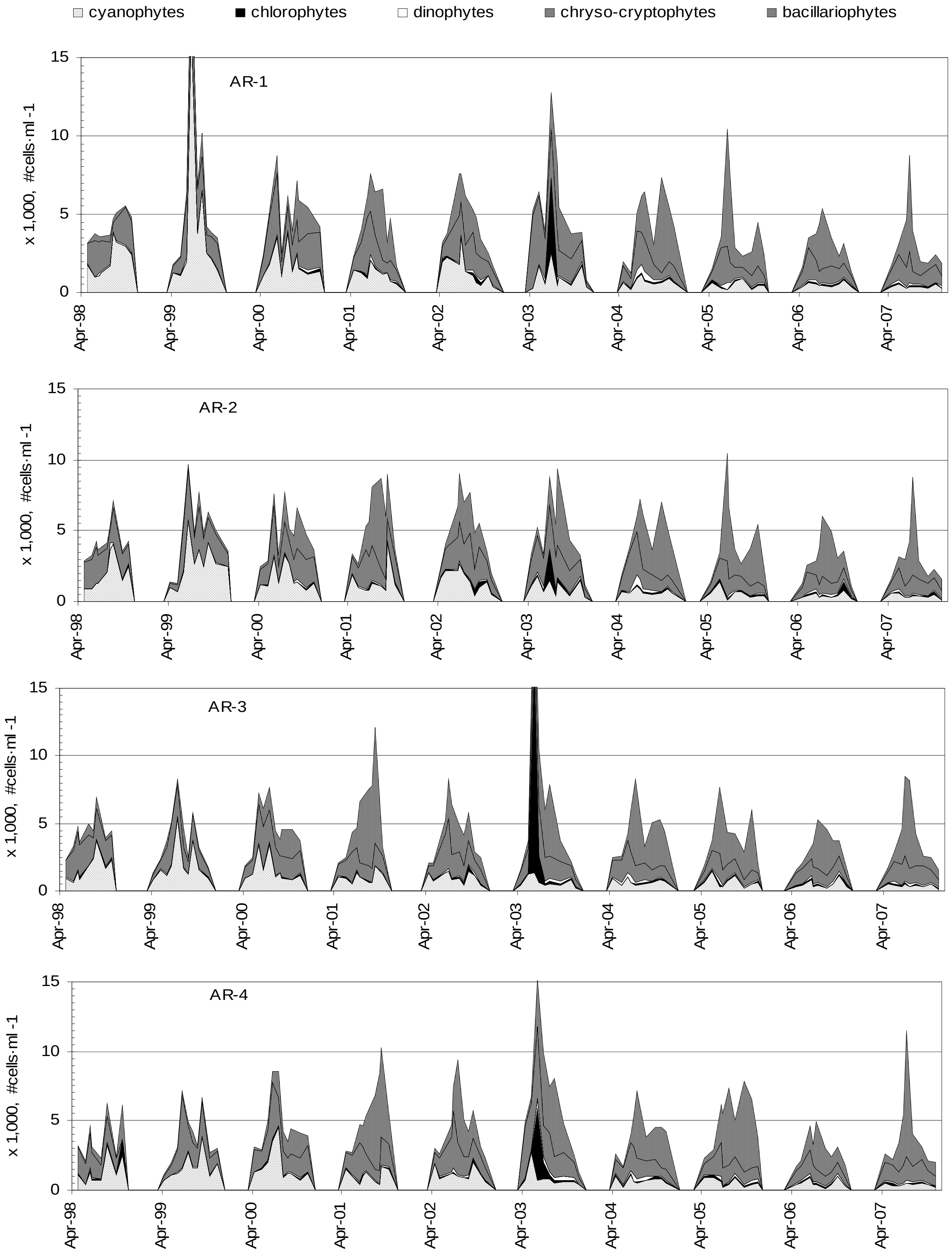


Figure 4.4a. Time series of Arrow Lakes Reservoir phytoplankton abundance by major classes in stations AR 1 - 4, 1998 – 2007.

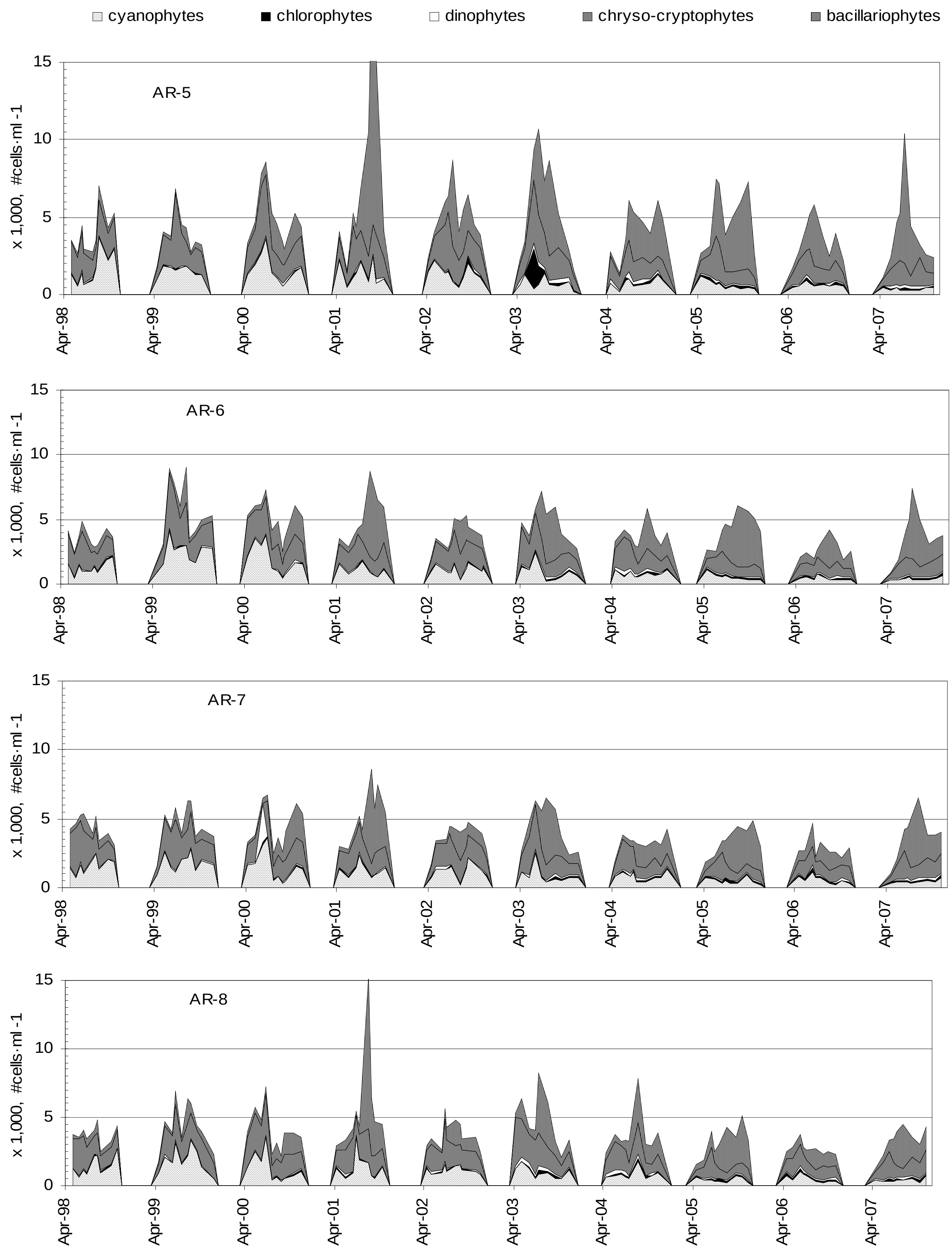


Figure 4.4b. Time series of Arrow Lakes Reservoir phytoplankton abundance by major classes in stations AR 5 - 8, 1998 – 2007.

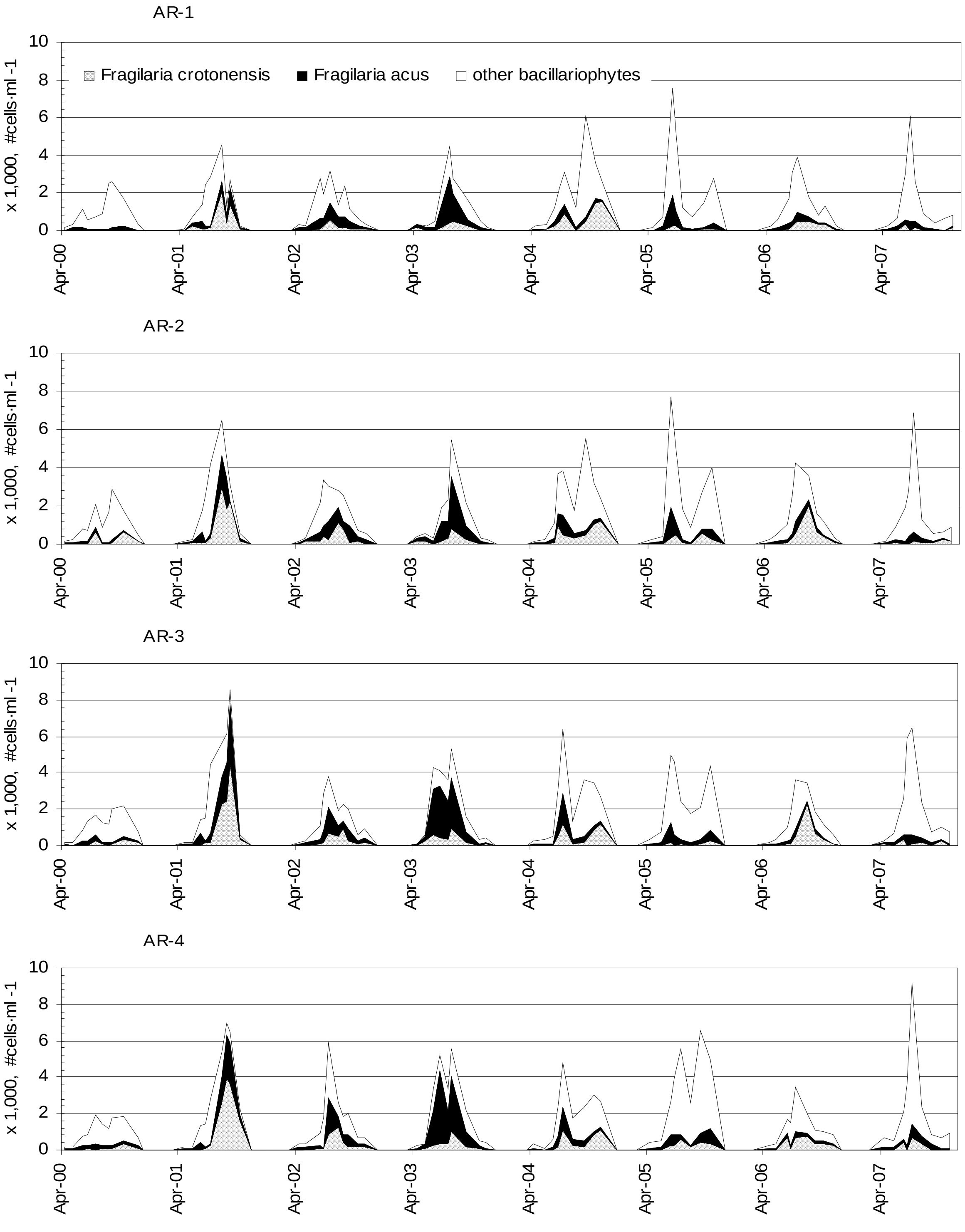


Figure 4.5a. Abundance of *Fragilaria crotonensis, F. acus* and other pelagic diatoms in Arrow Lakes Reservoir, stations AR 1-4, 2000 – 2007.

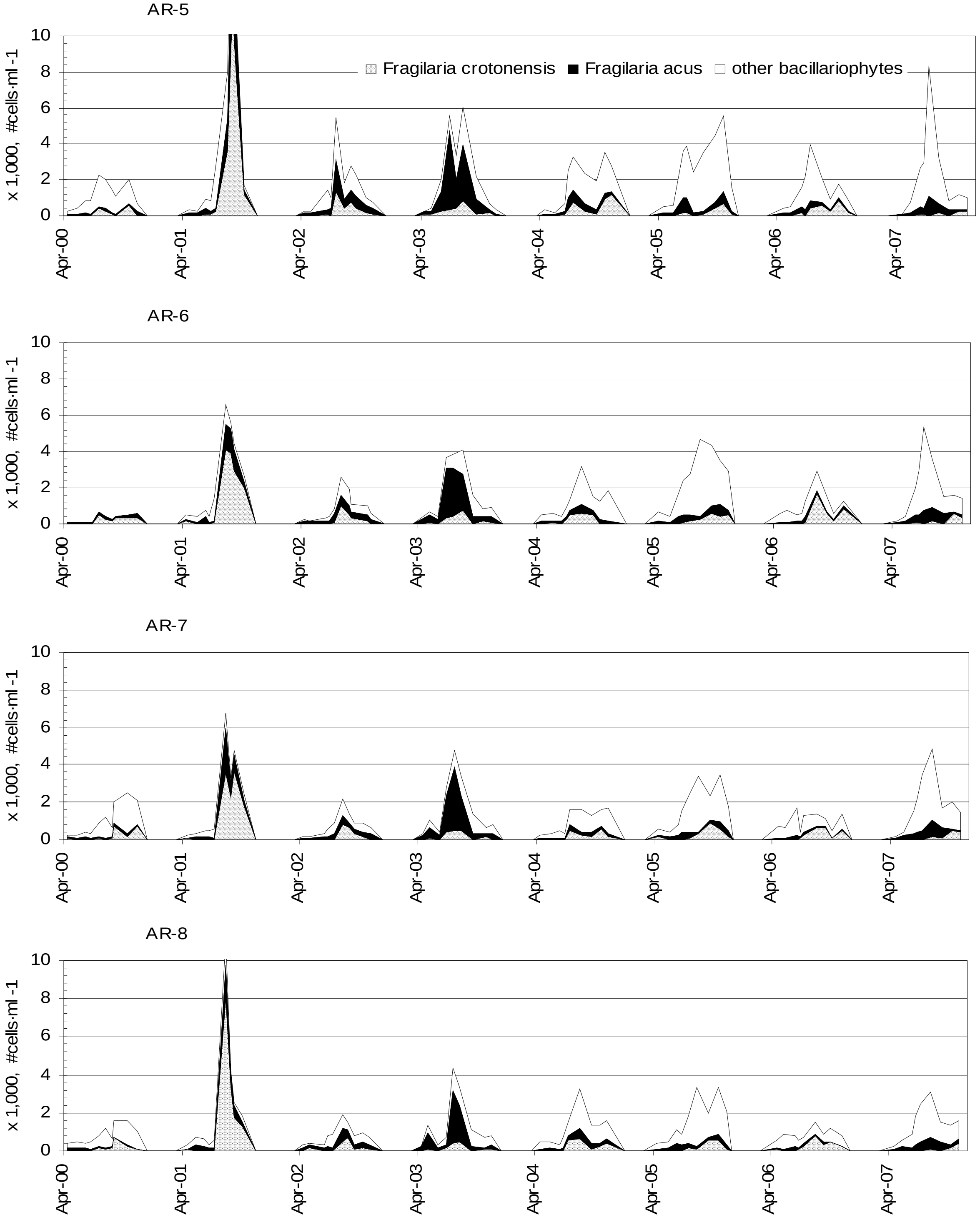


Figure 4.5b. Abundance of *Fragilaria crotonensis, F. acus* and other pelagic diatoms in Arrow Lakes Reservoir, stations AR 5-8, 2000 – 2007.

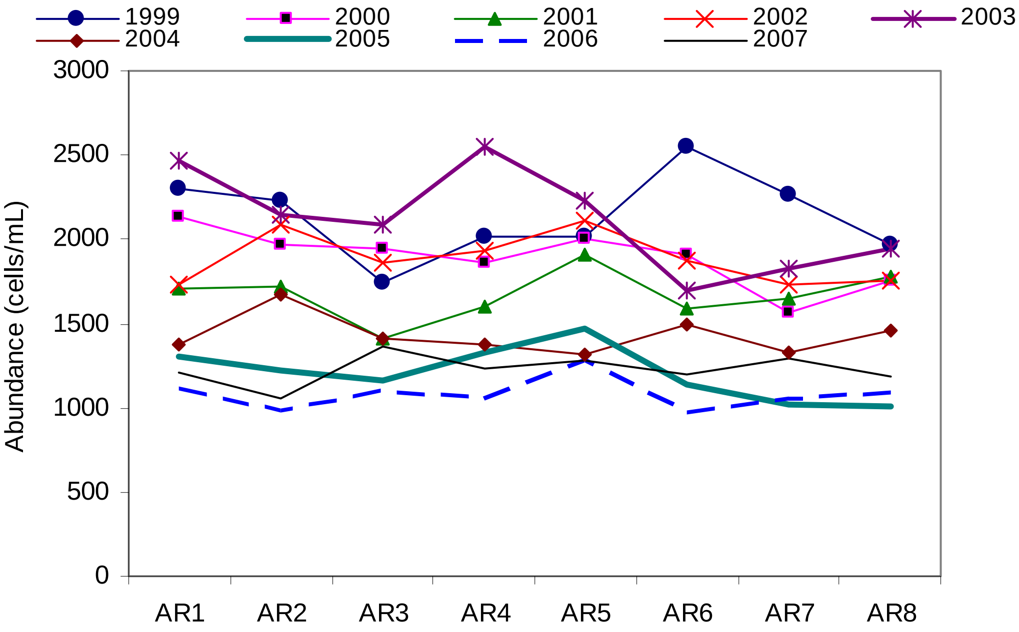


Figure 4.6. Abundance of Chryso- and Cryptophycean flagellates by station in Arrow Lakes Reservoir, 1999-2007.

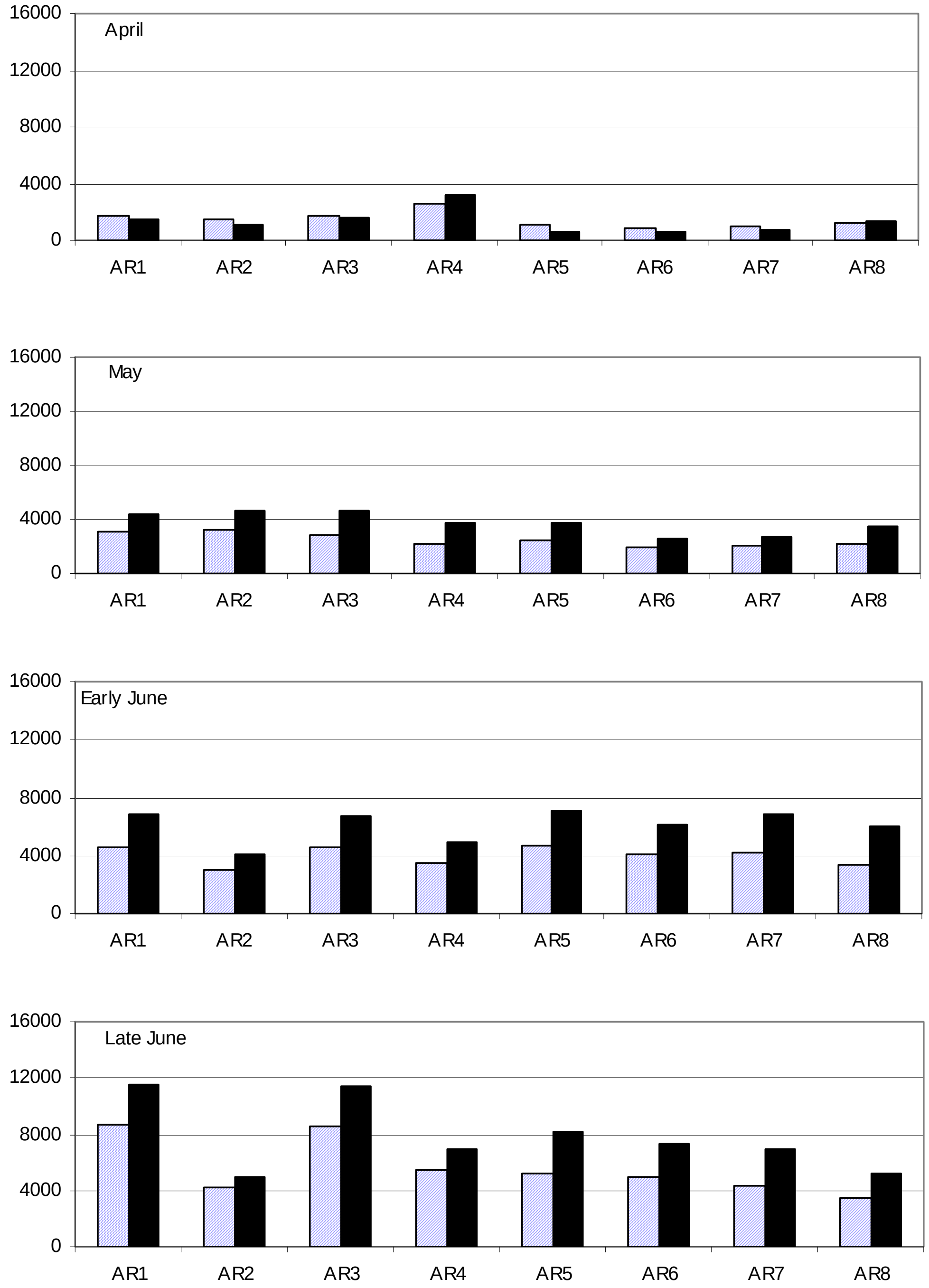


Figure 4.7a. Monthly north-south transects of average abundance (cross-hatching – number of cells/ml) and biomass (solid - mm3/L x 104) by station in Arrow Lakes Reservoir from April to late June.

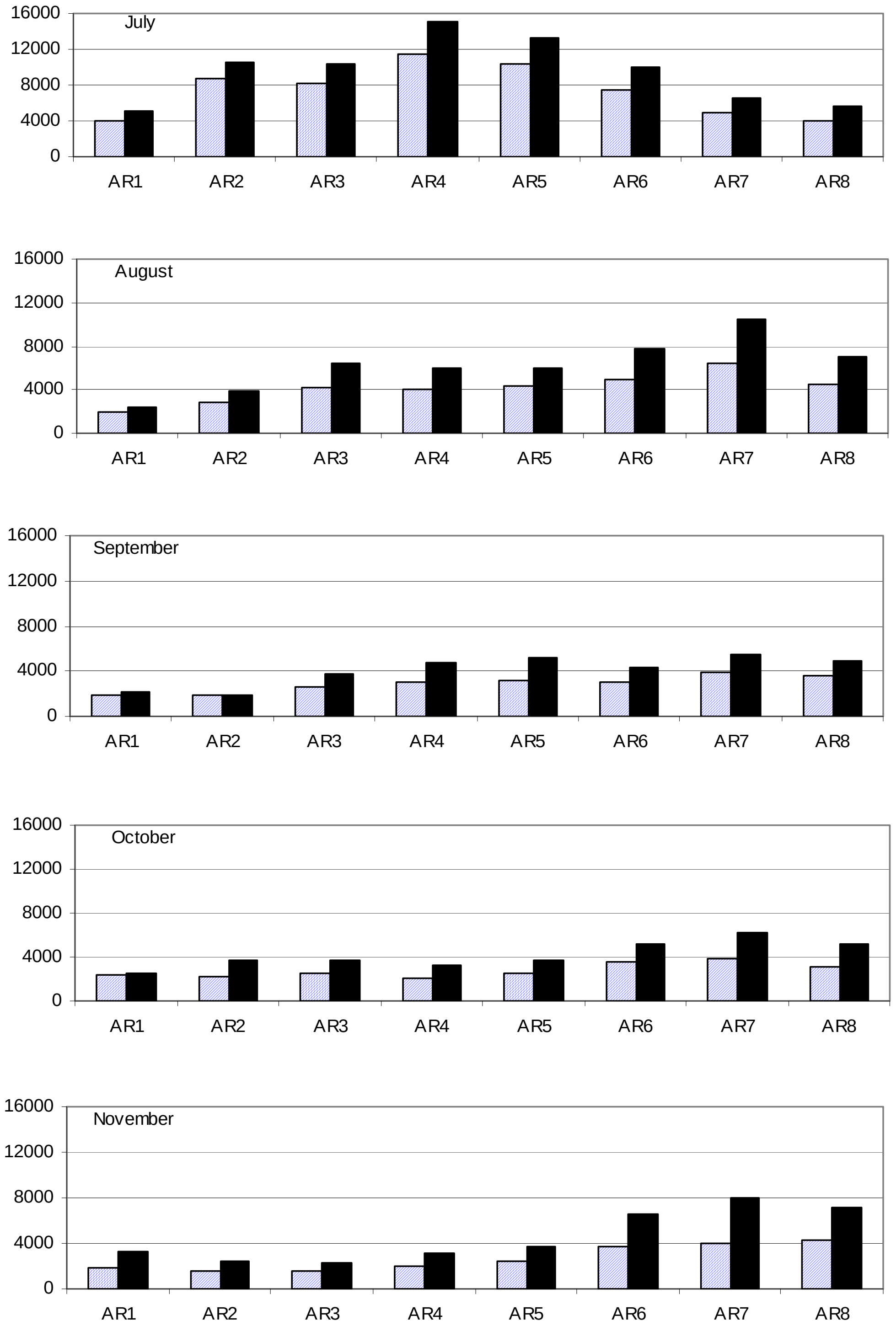


Figure 4.7b. Monthly north-south transects of average abundance (cross-hatching – number of cells/ml) and biomass (solid - mm3/L x 104) by station in Arrow Lakes Reservoir from July to November.

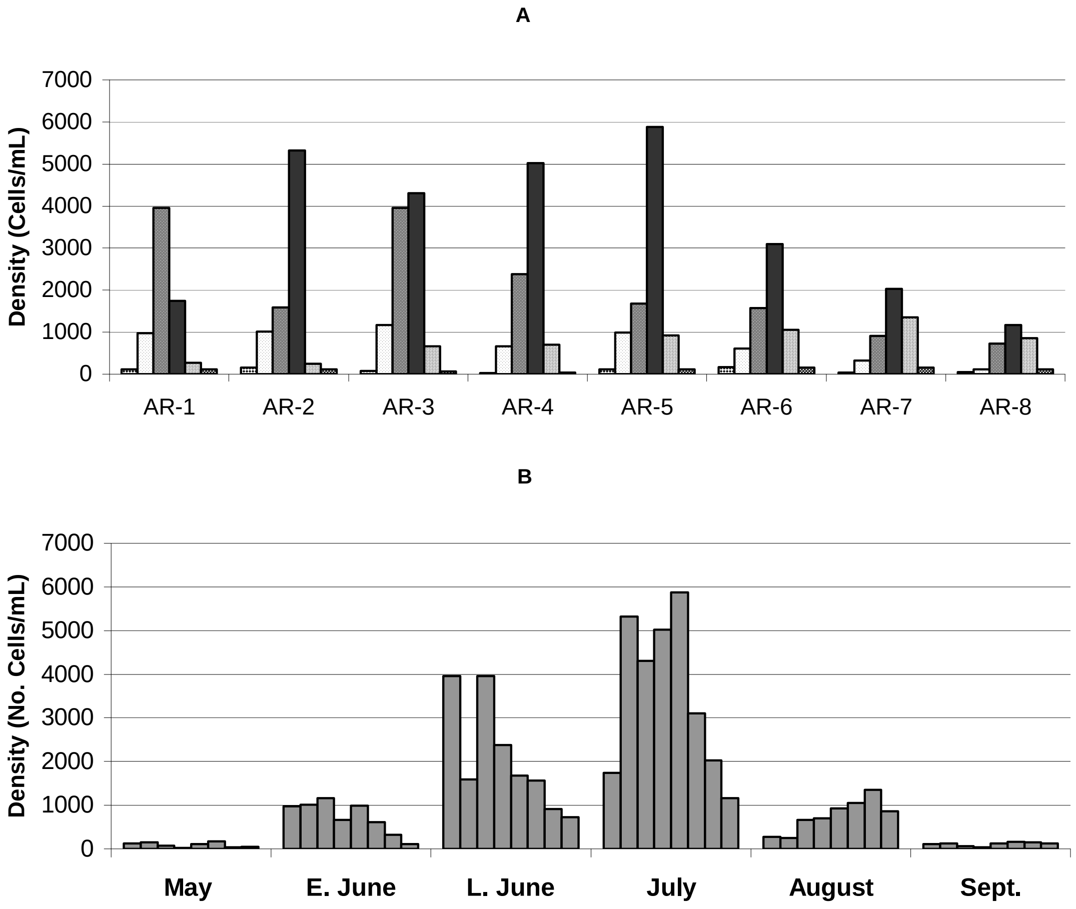
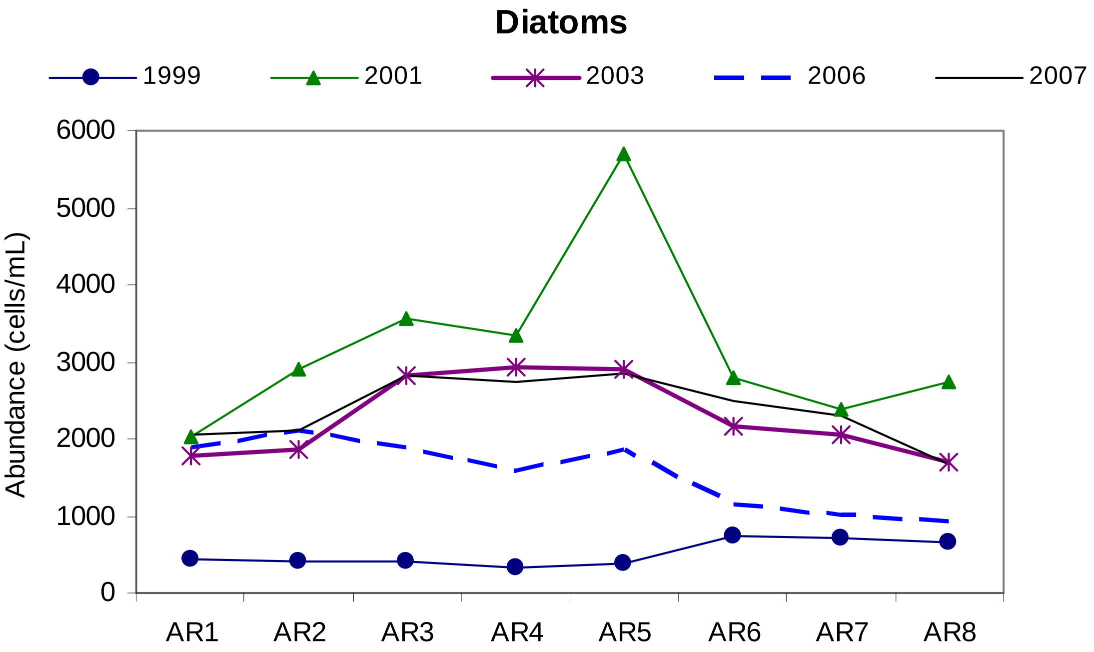


Figure 4.8. Pattern and timing of *Asterionella formosa* maxima in Arrow Lakes Reservoir in 2007: **A**. by station from May to September (solid bar is July sample); **B**. monthly succession at each station (N=8).



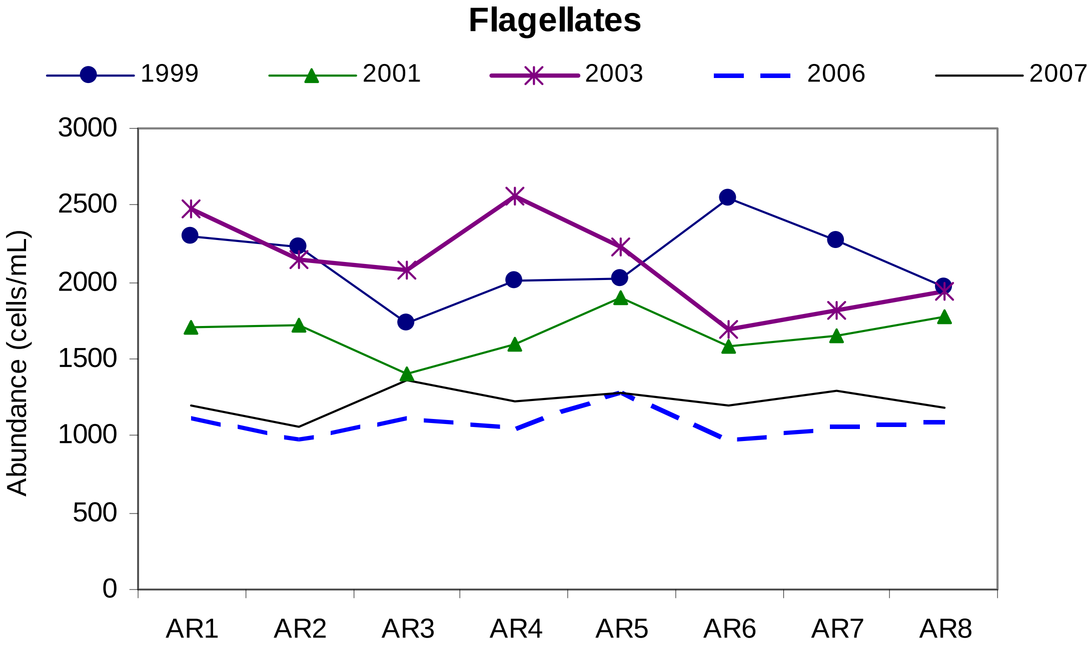


Figure 4.9. Abundance of total diatoms (Bacillariophytes) and flagellates (Chryso-Cryptophyceae) in Arrow Lakes Reservoir in selected years of treatment: 1999 Year 1, 2001 Year 3, 2003 Year 5, 2006 Year 8, and 2007 Year 9.

CHAPTER 5

ZOOPLANKTON AND MYSID RESPONSE TO NUTRIENT ADDITIONS, ARROW LAKES RESERVOIR YEAR 9 (2007)

by

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Introduction

The study of zooplankton (length >150 μm) and mysids (*Mysis relicta)* in Arrow Lakes Reservoir started in 1997 as part of a multidisciplinary project to restore the reservoir's 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, including declining fish stocks. The introduction of *M. relicta* in 1968 has also had a significant effect on the reservoir. The 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 their preferred zooplankton prey.

After positive results of a fertilization project on Kootenay Lake, an initial two-year study of the limnology and trophic status of Arrow Lakes Reservoir started in 1997 (Pieters et al. 1998, 1999). This study was followed by a nine-year fertilization experiment initiated in 1999 (Pieters et al. 2000, 2003a, 2003b, Schindler et al. 2006, 2007a). Changes in mysid and zooplankton composition, density, and biomass during the initial study and subsequent fertilization show positive trends toward more productive conditions. Comparative results from eleven years of the study are presented in this report.

Methods

Zooplankton

Samples have been collected monthly at six stations (AR 1-3, AR 6-8) from May to October in 1997, April to October in 1998 through 2001. In 2002 the sampling season was lengthened, so between 2002 and 2007 samples were collected from April to November. In 2007, samples were collected from April 17 to November 5 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 m to 0 m at a boat speed of 1 m/s. 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 each sampling season. All calibrations were done in a flume at the Civil Engineering Department at the University of British Columbia.

Zooplankton samples were rinsed from the dolphin bucket through a 100-μm filter to remove excess lake water and were 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 that had been filtered through a 74-μm mesh and were 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. Using a mouse cursor on a live television image, the lengths of 30 organisms of each species were measured for use in biomass calculations. Lengths were converted to biomass (μg dry weight) using an 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 estimates.

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 taxonomic keys (Pennak 1989, Brooks 1959, Wilson 1959, Sandercock and Scudder 1996).

Mysis relicta

Samples of mysids from Arrow Lakes Reservoir were collected at six stations (AR 1-3, AR 6-8) monthly from May to December in 1997, January to December in 1998 through 2004, February to December in 2005, February to November in 2006 and April to November in 2007. Sampling was done at night, around the time of the new moon, to decrease the chance of mysids seeing and avoiding the net. With the boat stationary, three vertical hauls were done at each station using a 1-m^2 square-mouthed net with 1,000-µm primary mesh, 210-µm terminal mesh, and 100-µm bucket mesh. Two hauls were made in deep water (0.5 nautical miles from both west and east of lake centre), and one haul was made in shallow water near either the west or east shore. The net was raised from the lake bottom with a hydraulic winch at 0.3 m/s. The contents of the bucket were rinsed through a filter to remove excess lake water and were 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 and DeGraeve 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 that had been 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. Using a mouse cursor on a live television image, the body length (tip of rostrum to base of telson) of up to 30 individuals of each stage and maturity was measured for use in biomass calculations. Lengths were converted to biomass (mg dry weight) using an empirical length-weight regression (Smokorowski 1998).

Results

Zooplankton

Species Present

During the eleven years of the study, five calanoid copepod species have been identified in the samples from Arrow Lakes Reservoir (Table 5.1). *Epischura nevadensis* (Lillj.) and *Leptodiaptomus ashlandi* (Marsh) were observed in all eleven years. *Onychodiaptomus hesperus* (Wilson and Light) was observed in 1997 and 1998, but was rare. From 1998 to 2004 and in 2007, *Leptodiaptomus sicilis* (Forbes) was present in some samples, although rarely, while *Aglaodiaptomus leptopus* (Forbes) was seen in samples for the first time in the ten years during the 2006 season. One cyclopoid copepod species, *Diacyclops bicuspidatus thomasi* (Forbes), was seen in all eleven years.

Table 5.1. List of zooplankton species identified in Arrow Lakes Reservoir, 1997-2007. "+" indicates a consistently present species and "r" indicates a rarely present species.

Species	97	98	99	00	01	02	03	04	05	06	07
Cladocera											
Alona sp.		r									
Ceriodaphnia reticulata	r	r	r	r	r	r	r			r	
Chydorus sphaericus		r	r	r	r	r	r	r		r	r
Daphnia galeata mendotae	+	+	+	+	+	+	+	+	+	+	+
Daphnia pulex	+	+	+	+	+	+	+	+	+	+	+
Daphnia longispina	+	+	+	+	+	+	+	+	+	+	+
Daphnia schoedleri											r
Diaphanosoma brachiurum	r				r	r	r	r	r	r	r
Bosmina longirostris	+	+	+	+	+	+	+	+	+	+	+
Holopedium gibberum		r				r		r		r	
Leptodora kindti	+	+	+	+	+	+	+	+	+	+	+
Polyphemus pediculus	r	r								r	
Scapholeberis mucronata	r	r	r	r	r	r	r	r	r	r	r
Sida crystallina							r			r	r
Copepoda											
Aglaodiaptomus leptopus										r	
Diacyclops bicuspidatus thomasi	+	+	+	+	+	+	+	+	+	+	+
Epischura nevadensis	+	+	+	+	+	+	+	+	+	+	+
Leptodiaptomus ashlandi	+	+	+	+	+	+	+	+	+	+	+
Leptodiaptomus sicilis		r	r	r	r	r	r	r			+
Onychodiaptomus hesperus	r	r									

Fourteen species of Cladocera were present in Arrow Lakes Reservoir during the study period (Table 5.1). Six species were present in the samples in all eleven years: *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.). Species such as *Ceriodaphnia reticulata* (Jurine), *Diaphanosoma brachiurum* (Liéven), and *Chydorus sphaericus*

(O.F.M.) were seen almost every year but only sporadically. Other rare species, such as *Polyphemus pediculus* (L.), *Holopedium gibberum* (Zaddach), *Sida crystallina* (O.F.M.), and *Alona sp*., were observed occasionally. *Daphnia* spp. were not identified to the species level for density counts in any of the ten years.

The zooplankton population composition has remained similar in both Arrow basins during the whole study period. The predominant copepods in Arrow Lakes Reservoir have been *L. ashlandi* and *D. bicuspidatus thomasi*. The cladocerans *Daphnia* spp. and *B. longirostris* have been common in all ten years.

Density and Biomass

The zooplankton density in 2007 was dominated by copepods, which averaged 97% and 94% of the zooplankton community in Upper and Lower Arrow, respectively. *Daphnia* spp. did not develop numerous populations in 2007 season. It made up only 0.5% and 3% of the total zooplankton density, while other cladocerans were 2% and 3% in Upper and Lower Arrow (Fig. 5.1). Copepods were the most abundant zooplankton at each station in all eleven years studied. They dominated during the entire sampling season in 2007, with populations peaking in July in Upper Arrow and August in Lower Arrow. Copepods were composed of cyclopoids and calanoids. Cyclopoids dominated in both Upper and Lower Arrow, in all eleven years studied, although the population had a higher density in the lower basin. Calanoids were more abundant in Upper Arrow than in Lower Arrow (Figs. 5.2 and 5.3)

Total zooplankton density in Upper Arrow increased gradually from 1998 through 2003. From 2004 to 2007 a decreasing trend of zooplankton density was recorded (Fig. 5.4a). The seasonal average zooplankton density in 2007 (April to November) was 6.57 individuals/L in Upper Arrow. *Daphnia* spp. density increased from 1997 to 1999, then declined in 2000, and remained at less than 1 individual/L up to 2007 when it declined to the lowest density over eleven study years with 0.03 individuals/L. Other cladocerans fluctuated in density from 1997 to 2007, reaching a peak in 2003 with 3.80 individuals/L (Fig 5.5). The proportion of cladocerans (including *Daphnia* spp.) in Upper Arrow fluctuated during the study years between 3% and 30%. In 2007, they made up only 3% of the total zooplankton density. The proportion of *Daphnia* spp. in Upper Arrow increased to 17% in 1999, the highest proportion observed, and then decreased over the next years to a record low of 0.5% in Upper Arrow in 2007 (Fig. 5.1).

Zooplankton density in Lower Arrow was greater than in Upper Arrow during the entire study period (Fig. 5.4 a-c). In Lower Arrow, the total zooplankton density had an increasing trend from 1997 to 2004 and decreased during 2005 through 2007. Copepods showed a similar pattern, while the density of *Daphnia* spp. and other Cladocera fluctuated over the years with the lowest abundance in 2007(Fig. 5.4c). The average abundance of *Daphnia* in Lower Arrow during 2007 was 0.45 individuals/L (Fig. 5.5).

The seasonal average zooplankton density in 2007 (April to November) in Lower Arrow was 15.84 individuals/L. The proportion of cladocerans (including *Daphnia* spp.) in Lower Arrow fluctuated between 6% and 31% during the study years with the lowest of 6% in 2007. The proportion of *Daphnia* spp. in the total zooplankton density increased until 1999, making up 22% of total zooplankton density. From 2000 onward, *Daphnia* density has fluctuated with a generally decreasing trend. In 2007, *Daphnia* abundance decreased to comprise only 3% of the total zooplankton density.

From 1997 to 2000 in Lower Arrow, total zooplankton biomass and *Daphnia* spp. biomass increased, reaching 107.41 µg/L and 78.59 µg/L, respectively (Figs. 5.6a and 5.8). In the following years, total zooplankton and *Daphnia* spp. biomass fluctuated from year to year decreasing to 31.07 µg/L and 7.91 µg/L in 2007. From 1997 to 2007, the percentage of *Daphnia* spp. biomass in Upper Arrow fluctuated between 3% and 70% of the total zooplankton biomass, while in Lower Arrow, *Daphnia* spp. was between 11% and 74% of the total biomass (Fig. 5.7). In 2007, *Daphnia* spp. made up 4% and 25% of the total zooplankton biomass in Upper and Lower Arrow, respectively.

The biomass in all zooplankton categories (total, copepod, cladoceran, *Daphnia* spp.) was lower in Upper Arrow than in Lower Arrow (Fig. 5.8). The decrease of total zooplankton biomass in Upper Arrow was due to significant decreases in the biomass of *Daphnia* spp. and other cladocerans, which are larger than copepods.

The zooplankton population in Arrow Lakes Reservoir differed in comparison to other BC lakes. Zooplankton density and biomass in Kootenay Lake fluctuated and did not show a steady increase across years (Fig. 5.9). Total density in Kootenay Lake was higher than in either of the Arrow basins in each year of the Arrow study, except in 2004 when total zooplankton density was slightly higher in Lower Arrow. *Daphnia* density was higher in Lower Arrow than in Kootenay during the first five study years, 1997 to 2001 (Fig. 5.9). In 2002, *Daphnia* density substantially decreased in Arrow Lakes to a level similar to Kootenay Lake. This could be due to increased grazing pressure from kokanee as the abundance increased dramatically during this year (see Chapter 6). From 2003 to 2006, *Daphnia* density in Kootenay Lake and Lower Arrow were at a similar level, while *Daphnia* density in Upper Arrow was much lower. Despite a slight decrease of total zooplankton density and *Daphnia* density in Kootenay Lake from 2006, the density was higher than in either of the Arrow basins.

In contrast to density, total zooplankton biomass in Kootenay Lake was half that of biomass in Lower Arrow in 1999 and 2000 and was also lower than in Upper Arrow in 1999 (Fig. 5.10). From 2001 to 2005, total zooplankton biomass in Kootenay Lake was higher than in either of the Arrow basins (Schindler et al. 2007b). In 2006, seasonal average zooplankton biomass was similar to Kootenay and Lower Arrow, while in Upper Arrow zooplankton biomass was three times lower (Fig. 5.10). In 2007, *Daphnia* biomass in Kootenay lake was approximately 3 times higher than in Lower Arrow and approximately 45 times higher than in Upper Arrow.

From 1997 to 2001, seasonal average *Daphnia* biomass in Lower Arrow greatly exceeded *Daphnia* biomass in Upper Arrow and in Kootenay Lake in 1999 and 2000. In 2000, *Daphnia* biomass in Lower Arrow was more than six times higher than in either Kootenay Lake or Upper Arrow. During 2002 to 2004, *Daphnia* biomass was similar in Kootenay Lake and Lower Arrow. The seasonal average *Daphnia* biomass increased slightly in 2005, significantly in 2006 and decreased in 2007, in Arrow Lakes Reservoir and in Kootenay Lake (Fig. 5.10). The difference between the density and biomass comparisons is due to the greater proportion of *Daphnia* spp. in the Arrow Lakes Reservoir zooplankton. Individual *Daphnia* have greater biomass than individuals of most other zooplankton species in these lakes. From 1997 through 2001, *Daphnia* density and biomass as percentages of total zooplankton in both Upper Arrow and Lower Arrow were higher than in Kootenay Lake while from 2003 to 2007, Upper Arrow had a lower percentage of *Daphnia* density and biomass in comparison to Kootenay (Fig. 5.11).

The seasonal average zooplankton density in Alouette Lake from 2003 to 2007 (data for Alouette Lake was available from 2003 to 2007 only) was lower than in Lower Arrow and similar to Upper Arrow in 2005 to 2007. Total zooplankton biomass and *Daphnia* density and biomass were higher in Alouette than in Upper Arrow in 2005 and higher than in both Upper or Lower Arrow in 2006 (Figs. 5.9 and 5.10). In 2004 and 2007, biomass of both total zooplankton and *Daphnia* in Alouette Lake was the lowest on record (Harris et al. 2007). In 2005 and 2006, Upper Arrow had a lower percentage of *Daphnia* density and biomass in comparison to Alouette Lake.

Seasonal and Along-Lake Patterns

The seasonal development of zooplankton density and biomass was slightly different in Upper and Lower Arrow during 2007. In both basins, copepods dominated numerically during the entire season and peaked in July in Upper Arrow and in August in Lower Arrow. *Daphnia* spp. began to appear in both basins in June, however did not develop into numerous populations in Upper Arrow as in previous years (Figs. 5.12 and 5.13). Other Cladocerans were present in both basins during the entire sampling season. *Daphnia* spp. density and biomass reached their peak in September in Lower Arrow and Upper Arrow. In previous years, *Daphnia* spp. made up the majority of the biomass from July to October in both Upper and Lower Arrow. The trend in Lower Arrow in 2007 was, similar to 2006 where *Daphnia* had the highest density and biomass from August to October (5.14 and 5.15)

In 2001, 2002, and 2003 cladocerans and *Daphnia* spp. first became numerous in August and were considered to be late-season years. Conversely, 2004 and 2006 were early-season years, with *Daphnia* starting to appear in Upper Arrow as early as April. In 1998, 1999, 2000, and 2005 the bloom of cladocerans in both basins started in June - July, and *Daphnia* spp. were present until October. In 2007 *Daphnia* started to appear in June, and were present through the end of the sampling season.

During 2007, peak total zooplankton density occurred in July in Upper Arrow with 15.38 individuals/L and in August in Lower Arrow with 35.52 individuals/L (Table 5.2). The peak total zooplankton biomass also occurred in July with 22.57 μg/L in Upper Arrow and in September with 54.46 μg/L in Lower Arrow. *Daphnia* spp. biomass reached its peak in October with 1.29 μg/L in Upper Arrow and in September with 33.72 μg/L in Lower Arrow (Table 5.3). Peaks in density occurred at the same time in both basins, and biomass peaks either coincided in the upper and lower basins or were only a month apart. At times, there was a one-month delay between the density and biomass peaks, due both to the increase in *Daphnia* spp. density following the copepod density peak and to the large body size of individual daphnids.

Table 5.2. Monthly average density of zooplankton in Upper and Lower Arrow in 2007. Density is in units of individuals/L.

Density 2007		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	4.31	4.95	4.84	14.50	8.20	3.92	5.39	5.08
	Daphnia	0.00	0.00	0.01	0.04	0.07	0.04	0.08	0.00
	Other Cladocera*	<0.01	0.02	0.09	0.84	0.04	0.05	0.11	0.02
	Total Zooplankton	4.31	4.97	4.94	15.38	8.31	4.01	5.58	5.10
Lower Arrow	Copepoda	5.76	5.34	18.43	23.05	33.53	9.57	11.49	11.85
	Daphnia	0.00	0.00	0.03	0.23	0.78	1.68	0.84	0.01
	Other Cladocera*	0.04	0.06	0.60	1.58	1.20	0.34	0.25	0.06
	Total Zooplankton	5.80	5.40	19.06	24.86	35.51	11.59	12.58	11.92

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

Along the length of Upper Arrow (stations AR 1-3) and Lower Arrow (stations AR 6-8), zooplankton densities and biomass tended to be higher in the lower basin throughout 2007 (Table 5.3). This pattern was particularly pronounced in July - September when the biomass of *Daphnia* spp. was significantly higher at the Lower Arrow stations. From July onward, biomass trends along the two basins were largely driven by the development of *Daphnia* spp., since *Daphnia* made up the majority of zooplankton biomass during this time. Upper Arrow, in 2001, 2005, 2006 and 2007, the highest biomass was at station AR 3. In 2000 and 2003 the highest biomass was measured at AR 2, while in 1998, 1999, and 2004 the highest biomass was at AR 1. In Lower Arrow, stations AR 6 and AR 7 had higher biomass than station AR 8.

Table 5.3. Monthly biomass of zooplankton in Upper and Lower Arrow in 2007. Biomass is in units of μg/L.

Biomass 2007		April	May	June	July	Aug.	Sept.	Oct.	Nov.
Upper Arrow	Copepoda	6.43	10.21	7.80	21.07	12.96	7.24	10.96	9.02
	Daphnia	0.00	0.09	0.10	0.37	1.06	0.59	1.29	0.00
	Other Cladocera**	0.00	0.03	0.15	1.13	0.07	0.08	0.16	0.03
	Total Zooplankton	6.43	10.33	8.05	22.57	14.09	7.91	12.41	9.05
Lower Arrow	Copepoda	10.96	8.77	30.82	35.17	41.32	20.18	15.82	16.06
	Daphnia	0.00	0.00	0.18	3.12	10.24	33.72	15.73	0.28
	Other Cladocera**	0.09	0.12	0.91	2.26	1.85	0.56	0.33	0.08
	Total Zooplankton	11.05	8.89	31.91	40.55	53.41	54.46	31.88	16.42

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

Zooplankton Fecundity

Fecundity data and its variability over the time and analysis of ecological factors and food availability are essential elements of any quantitative description of population growth. Data given in this section illustrate the sensitivity of different zooplankton populations, and interactions with other elements of the ecosystems in which they live. Fecundity of the four most common zooplankton species (*L. ashlandi*, *D. bicuspidatus thomasi*, *Daphnia spp*., and *B. longirostris*) was studied during the ten-year period.

L. ashlandi females in both Upper and Lower Arrow were gravid from April to November 2007 (Fig. 5.16). Over the eleven years, females in the upper basin tended to carry slightly more eggs than females in the lower basin, except in 2001, 2003, and 2006 where they carried fewer eggs. During the 2007 sampling season (April-November), *L. ashlandi* females carried an average of 8.65 and 8.26 eggs per gravid female in Upper and Lower Arrow, respectively (App. 5.1, Fig. 5.17). The number of eggs per water volume averaged 0.28 eggs/L in Upper Arrow and 0.21 eggs/L in Lower Arrow. The number of eggs per capita (number of eggs per total number of individuals of a species) was 0.11 eggs/individual and 0.07 eggs/individual in Upper and Lower Arrow. There were no consistent differences in fecundity for the two basins across years.

D. bicuspidatus thomasi females were gravid throughout the sampling period in 2007 (Fig. 5.16). From April to November, the percentage of gravid females averaged 14% in both basins. As in previous years, there was no consistent trend in the number of eggs per female along the reservoir. The seasonal averages in 2007 were 21.92 and 17.22 eggs per gravid female in Upper and Lower Arrow, respectively (App. 5.1, Fig. 5.17). During the sampling season, the number of eggs per water volume averaged 1.82 and 3.53 eggs/L, and the number of eggs per capita averaged 0.65 and 0.42 eggs/individual in Upper and Lower Arrow.

There was no consistent trend in the number of eggs per gravid female of *D. bicuspidatus thomasi* in the two basins. The number of eggs per gravid female was higher in Upper than in Lower Arrow in most years from 1998 - 2007, except in 2001, 2002, and 2004 when females from Lower Arrow carried more eggs than those from Upper Arrow.

In 2007, gravid females of *Daphnia* spp. were observed from July to October in Lower Arrow, while in Upper Arrow they were present from August to October. *Daphnia* spp. gravid females were seen as early as April in 1998 and 1999, but they did not appear until May in 2000, June in 2002 and 2006, July in 2001, 2003, and 2005, and August in 2004. In 2007, the percentage of gravid females averaged 5% and 16% in Upper and Lower Arrow (App. 5.1, Fig. 5.18).

The number of eggs per gravid female of *Daphnia* spp. and the number of eggs per capita were consistently higher in Upper Arrow than in Lower Arrow during all years, but for the other fecundity measures there were no consistent differences (App. 5.1). The seasonal average number of eggs per gravid female in 2007 was 3.22 and 2.41 eggs per gravid female in Upper and Lower Arrow, respectively. During the sampling season, the number of eggs per water volume averaged 0.01 and 0.21 eggs/L in the two basins, and the number of eggs per capita averaged 0.14 and 0.35 eggs/individual (App. 5.1, Fig. 5.19).

During the 2007 season, *B. longirostris* gravid females were observed from April to November in Upper Arrow and May to October in Lower Arrow (Fig. 5.18). In 2007 as well as in 1998, 2002, 2003, 2005 and 2006, gravid females were observed as early as April, although in other study years they did not appear until May. In 2007, the percentage of gravid females averaged 27% in both Arrow Lakes. The proportion of gravid females reached peaks in May (Fig. 5.18). The number of eggs per gravid female of *B. longirostris* tended to be higher in Upper Arrow from 1997 to 2003. From 2004 to 2007, the number of eggs per gravid female was higher in the lower basin. The seasonal average number of eggs per gravid female in 2007 was 2.0 and 2.68 eggs/gravid female in Upper and Lower Arrow (App. 5.1, Fig. 5.19). Across the sampling season, the number of eggs per water volume averaged 0.09 and 0.36 eggs/L in the two basins, and the number of eggs per capita averaged 0.55 and 0.69 eggs/individual. 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 except 2004, 2005 and 2007. The proportion of gravid females and number of eggs per water volume did not show consistent differences between the two basins across years.

Proportion of gravid females of *D. bicuspidatus thomasi* and *B. longirostris* in Arrow Lakes (average for Upper and Lower Arrow) did not differ much in comparison to Kootenay Lake (average for whole lake). It was at the similar level and had similar pattern of fluctuation during the study period from 1998 to 2007 (Fig. 5.20). Opposite to that, percentage of gravid females of *L. ashlandi* and *Daphnia spp.* in Arrow Lakes was lower than in Kootenay Lake during the ten years period, except in 1999 and 2007 when *L. ashlandi* was higher and in 2000 and 2001 when *Daphnia* in Arrow Lakes exceeded those numbers in Kootanay Lake. Gravid females of *D. bicuspidatus thomasi*, *Daphnia spp*., and *B. longirostris* in Arrow Lakes carried more eggs than gravid females in Kootenay Lake during ten study years, while gravid females of *L. ashlandi* in Arrow Lakes carried less eggs than those in Kootenay Lake (Fig. 5.21).

Mysis relicta

Abundance and Biomass

Sampling of *Mysis* began in January and continued until December in each year from 1998 to 2004, so all annual average values for these years represent a twelve-month period. In comparison, eight months were sampled in 1997 (May-December), eleven months in 2005 (February-December), ten months in 2006 (February-November) and eight months in 2007 (April-November). From 1997 to 2001 and in 2006, the annual average mysid density and biomass at the deep stations were consistently higher in Lower Arrow (Fig. 5.22). From 2002 to 2005 and in 2007, the pattern changed and mysid density became higher in Upper Arrow. Both density and biomass in Upper Arrow increased progressively in each successive year from 1998 to 2000. In 2001 and 2002, stagnation in growth of the mysid population was noticed, followed by a further increase in 2003 and a steady decrease in 2004, 2005, and 2006. In 2007 mysid biomass continued to decrease despite an increase in density. In Lower Arrow, the mysid density and biomass increased from 1997 to 2001 and in the next four years both decreased to levels similar to the pre-fertilization period (1997-1998). In 2006, mysid density in Lower Arrow was more than twice as high as in 2005, and biomass was one and a half times higher, while in 2007 both density and biomass decreased slightly.

From 1997 to 2007, densities in both Arrow basins were generally below 500 individuals/m^2 at both deep and shallow sites throughout the year (Fig. 5.23). However, from 2000 to 2005, this level was exceeded more often than in previous years, particularly from May to August. During the study 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), while 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 basins 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 (Figs. 5.24 and 5.25). Over the study period, density at shallow sites was consistently higher in Upper Arrow than in Lower Arrow. However, there was no consistent trend among the stations in either basin. At the deep sites, there were usually two density peaks during the year, the first in May-June with high densities of juveniles (Figs. 5.26 and 5.27) and the second in August-October with high densities of immature males and females. There was no clear gradient of increasing density along the length of the lakes in the pre fertilization period (1997-1998). From 1999 to 2002, and again in 2006, there was a tendency toward higher densities at station AR7 in Lower Arrow. However, from 2003 to 2005, mysid density reached a distinct peak in Upper Arrow at AR3 (Fig. 5.28, annual averages from deep sites only). The highest seasonal mysid abundance at a deep site in 2007 was in July at station AR 2 in Lower Arrow with 916 ind/m^2 (mainly juveniles and immature males and females). The highest seasonal abundance of mysids at shallow sites occurred in July at station AR 2 in Upper Arrow with 816 ind/m^2 (mainly juveniles and immature males and females).

Throughout the year in 1997 and 1998, mysid biomass was generally below 1,000 mg/m^2 at all stations (Fig. 5.29). Likewise, in the period from 1999 to 2007, biomass was below 1,000 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 1,000 mg/m^2, with occasional values exceeding 2,000 mg/m^2 in September, October, and November. From 2000 to 2007, values frequently exceeded 1,000 mg/m^2 during the summer and fall. At the shallow site of AR2 in Upper Arrow, biomass increased significantly, exceeding 9,000 mg/m^2 in August 2000, 8,000 mg/m^2 in July 2001, and 13,900 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 (Figs. 5.30 and 5.31). Through the studied period 1997-2001, there was a tendency toward an increase in biomass at deep sites in both Upper and Lower Arrow (Figs. 5.29, 5.32, and 5.33). Unlike previous years, deep sites in Upper Arrow resulted in a decreasing trend from 2003 onward. At the same time mysid biomass in Lower Arrow was relatively stable and fluctuated around 600-700 ind/L. The highest seasonal mysid biomass at a deep site in 2007 was found in July at station AR 2 in Upper Arrow with 3,860 mg/m^2 (mainly immature males and females, and mature females). The highest seasonal biomass of mysids at shallow sites occurred in July also at station AR 2 with 2,376 ind/m^2 (mainly immature males and females).

Annual average density of mysids in Arrow Lakes Reservoir in 1997 trough 1999 was approximately half the density observed in Kootenay Lake in those years. Likewise, mysid biomass in Arrow was about half that of Kootenay Lake in 1999. From 2000 onward, densities and biomass in Lower Arrow were similar to Kootenay Lake, while mysid densities in Upper Arrow were higher than in Kootenay from 2002 to 2007. Despite a significant difference between density in Upper Arrow and Kootenay Lake, mysid biomass was significantly higher in only 2003 and 2004 (Fig. 5.34) (Schindler et al. 2007b).

From 1999 to 2007, mysid density in Okanagan Lake was higher than in either Upper or Lower Arrow, with the exception of 2003 when mysid density in Upper Arrow reached the highest number recorded during the study period (286 ind/m^2) (Fig. 5.34). Mysid biomass in Okanagan Lake greatly exceeded biomass in all other studied lakes, particularly in 2001 and 2004 when mysid biomass in Okanagan Lake increased to 3,361 mg/m^2 and 4,129 mg/m^2, respectively (Andrusak et al. 2006).

Life Stages

The mysid population in Arrow Lakes Reservoir has been composed of slightly more females than males. The density of developmental stages of *M. relicta* at deep sites is shown in Figs. 5.26 and 5.27. From April to July 2007, 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. In October and November, very few juveniles were observed, but mature and breeding males and females were common. The pattern of seasonal development at the deep stations in 2007 was very similar to that observed in previous years.

The timing of progression through the developmental stages at the shallow sites was similar to the deep sites (Figs. 5.24 and 5.25). However, in most months, the proportion of mature and breeding/brooding individuals was lower at the shallow sites compared to the deep sites. Brooding females were not at shallow sites during the 2007 sampling season; most individuals were juveniles and immature males and females. From April to June, juveniles dominated the distribution. From July to November, immature males and females dominated. The pattern observed in 2007 was similar to previous years.

Discussion

Zooplankton density in 2007, as well as in the previous study years, indicated higher zooplankton production in Lower Arrow than in Upper Arrow. In comparison to the previous year, the density of all zooplankton categories in the both basins decreased. Copepods had distinct peaks in July in Upper Arrow and in August in Lower Arrow. *Daphnia* reached its peak in September in Lower Arrow, while in Upper Arrow only a few individuals of *Daphnia* were found during the entire sampling season.

In Upper Arrow, total zooplankton biomass fluctuated during the study years. The highest total zooplankton biomass and *Daphnia* biomass in Upper Arrow was in 1999—the first year of fertilization—while the lowest *Daphnia* biomass was in 2007. The highest biomass of zooplankton and *Daphnia* in Lower Arrow was observed in 2000, while in 2004 *Daphnia* had the lowest biomass during the study period. In Lower Arrow, *Daphnia* made up the majority of biomass during 1998 - 2001and 2006 (60-74%). In the following years from 2002 to 2005, *Daphnia* comprised between 11% and 49% of total zooplankton biomass. In 2007, a decrease of *Daphnia* occurred in Lower Arrow, so *Daphnia* made up 25% of the total zooplankton biomass. In Upper Arrow, *Daphnia* made up the majority of biomass only in 1998 and 1999 (67% and 70%). From 2000 onward, the contribution of *Daphnia* to total zooplankton biomass decreased; in 2007 it was 4%, the lowest value during all study years.

The annual average mysid biomass data in 2007 (deep stations) suggest that Lower Arrow is slightly more productive than Upper Arrow, despite higher mysid density in the upper basin. From 1997 to 2001, mysid density and biomass were higher in Lower Arrow. The opposite trend of higher mysid density and biomass in Upper Arrow started in 2002 and continued to the 2005 season. In 2007, density of *Mysis relicta* was higher in Upper Arrow, where smaller individuals (juveniles or immature males and females) made up the majority of the population, resulting in lower biomass than in Lower Arrow.

The number of juvenile and immature mysids at the near-shore areas of Upper Arrow was significantly higher than in Lower Arrow in all ten years of the study. This resulted in an along-lake pattern of higher density and biomass in Upper Arrow relative to Lower Arrow. (Note that this pattern is for shallow, near-shore stations and is the opposite of the pattern for deep stations.) In 2007, density and biomass at shallow sites in Upper Arrow increased, while in Lower Arrow it remained at a similar level to 2006. 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 or less favourable for *Daphnia* spp, causing fluctuations in density and biomass not only in *Daphnia* but the entire zooplankton community. The flushing rate of the water in the narrows (the area of water that separates Upper Arrow from Lower Arrow) was highest in 2007 compared to the previous years of study (R. Pieters, pers. comm.). This could be an explanation for lower *Daphnia* biomass.

A significant decrease of *Daphnia* biomass in 2007 caused a decrease of total zooplankton biomass, especially in Upper Arrow. These changes have likely been due to a combination of predation, food availability, climatic changes and flushing rate of Arrow Lakes Reservoir. In conditions with insufficient favourable food, high water temperature, and high predation pressure, *Daphnia* growth could not be expected. The fluctuation in *Daphnia* biomass over the study years, which was mirrored in fluctuations of total zooplankton biomass, could be explained by the changes in kokanee numbers and heavy grazing pressure on zooplankton and especially on *Daphnia* populations (see Chapter 6 for kokanee information). Furthermore, average biomass of *M. relicta*, another predator of zooplankton, slightly decreased to ~700 mg/m^2 in both basins in 2007. This biomass can maintain predation pressure on larger zooplankton such as *Daphnia* and could have an impact on total zooplankton density and biomass.

Changes in zooplankton density in the fertilized years suggest that the system has been shifting towards more productive conditions. However, strong predation pressure by both kokanee and mysid populations has decreased *Daphnia* and zooplankton biomass. The higher *Daphnia* density and biomass in Arrow Lakes Reservoir during the first five years of the study may be explained by a lack of predation pressure on zooplankton by high mysid densities, as in Okanagan Lake, or high kokanee densities, as in Kootenay Lake. Also, Kootenay Lake contained approximately twice the density of *M. relicta* as seen in Arrow Lakes Reservoir between 1998 and 1999. However, in 2000 - 2002, mysid density in Arrow Lakes Reservoir was similar to that in Kootenay Lake, and from 2003 to 2007 the mysid population in Arrow was up to twice the density of mysids in Kootenay. 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. Secchi depths in 2007 suggests that water was relatively clear in July - August, the period when *Daphnia* populations usually start to appear and increase its density in the lake. As a result, high visibility of prey and higher predation pressure can be one possible explanation for low *Daphnia* density in 2007. In addition to predation, other factors such as changes in the availability of grazeable algae as well as climatic conditions affected zooplankton density and biomass. In 2007 the flushing rate of the reservoir increased possibly taking out nutrients from the lake necessary for phytoplankton growth and its further transport to the higher trophic levels.

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Appendix 5.1. Fecundity data for *L. ashlandi*, *D. bicuspidatus thomasi*, *Daphnia* spp. and *B. longirostris* in Upper and Lower Arrow 1998-2007. Values are seasonal averages, calculated for samples collected between April and October in 1998-2001, and April and November in 2002-2007.

L. ashlandi	Basin	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
% of Gravid Females	Upper Arrow	10	15	14	15	8	03	14	8	16	18
	Lower Arrow	9	18	9	7	12	14	1	6	17	15
# Eggs per Gravid Female	Upper Arrow	11.22	11.00	11.85	8.20	9.65	9.05	10.83	9.15	7.38	8.65
	Lower Arrow	8.58	10.99	8.91	8.55	8.35	10.92	8.00	7.67	9.33	8.26
# Eggs per Litre	Upper Arrow	0.17	0.56	0.80	0.35	0.11	0.07	0.11	0.06	0.24	0.28
	Lower Arrow	0.17	0.28	0.15	0.10	0.13	0.45	0.01	0.07	0.32	0.21
# Eggs per Capita	Upper Arrow	0.13	0.17	0.19	0.07	0.05	0.02	0.09	0.06	0.43	0.11
	Lower Arrow	0.10	0.25	0.07	0.04	0.05	0.21	<0.01	0.07	0.13	0.07

D. bicuspidatus	Basin	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
% of Gravid Females	Upper Arrow	18	13	13	13	14	15	11	12	19	14
	Lower Arrow	13	13	12	11	12	16	15	13	13	14
# Eggs per Gravid Female	Upper Arrow	15.41	18.18	16.24	16.87	15.54	16.81	15.10	23.29	19.26	21.92
	Lower Arrow	14.49	14.05	14.61	17.70	16.17	15.37	16.50	17.68	13.98	17.22
# Eggs per Litre	Upper Arrow	1.57	2.45	2.65	3.76	2.46	4.24	2.37	1.45	3.44	1.82
	Lower Arrow	1.46	3.26	3.50	2.62	3.05	4.90	3.47	2.17	3.00	3.53
# Eggs per Capita	Upper Arrow	0.61	0.61	0.50	0.55	0.35	0.73	0.37	0.55	0.68	0.65
	Lower Arrow	0.36	0.44	0.43	0.37	0.29	0.55	0.36	0.31	0.34	0.42

***Daphnia* spp.**	Basin	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
% of Gravid Females	Upper Arrow	14	10	16	21	15	21	22	12	14	5
	Lower Arrow	12	10	12	12	16	12	10	17	12	16
# Eggs per Gravid Female	Upper Arrow	2.76	3.64	4.33	3.40	3.13	2.42	2.92	3.08	3.77	3.22
	Lower Arrow	1.84	2.23	2.10	1.78	2.31	2.20	2.23	2.43	1.97	2.41
# Eggs per Litre	Upper Arrow	0.22	0.47	0.67	0.47	0.13	0.27	0.09	0.07	0.31	0.01
	Lower Arrow	0.25	0.31	0.53	0.54	0.22	0.60	0.12	0.34	0.50	0.21
# Eggs per Capita	Upper Arrow	0.44	0.44	0.69	0.82	0.50	0.51	0.80	0.42	0.56	0.14
	Lower Arrow	0.28	0.37	0.33	0.23	0.37	0.30	0.24	0.54	0.27	0.35

B. longirostris	Basin	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
% of Gravid Females	Upper Arrow	33	20	22	24	27	21	27	20	26	27
	Lower Arrow	22	19	07	13	26	19	28	31	24	27
# Eggs per Gravid Female	Upper Arrow	2.51	2.82	2.72	2.18	2.27	2.03	1.68	1.94	2.25	2.00
	Lower Arrow	2.28	2.40	2.36	1.81	2.12	1.96	2.16	2.26	2.72	2.68
# Eggs per Litre	Upper Arrow	0.36	0.31	0.42	0.76	0.43	1.40	0.54	0.03	0.47	0.09
	Lower Arrow	0.08	0.03	0.08	0.21	0.48	0.92	0.87	0.49	0.52	0.36
# Eggs per Capita	Upper Arrow	0.85	0.64	0.70	0.48	0.55	0.43	0.42	0.45	0.64	0.55
	Lower Arrow	0.56	0.40	0.17	0.28	0.57	0.38	0.56	0.73	0.62	0.69

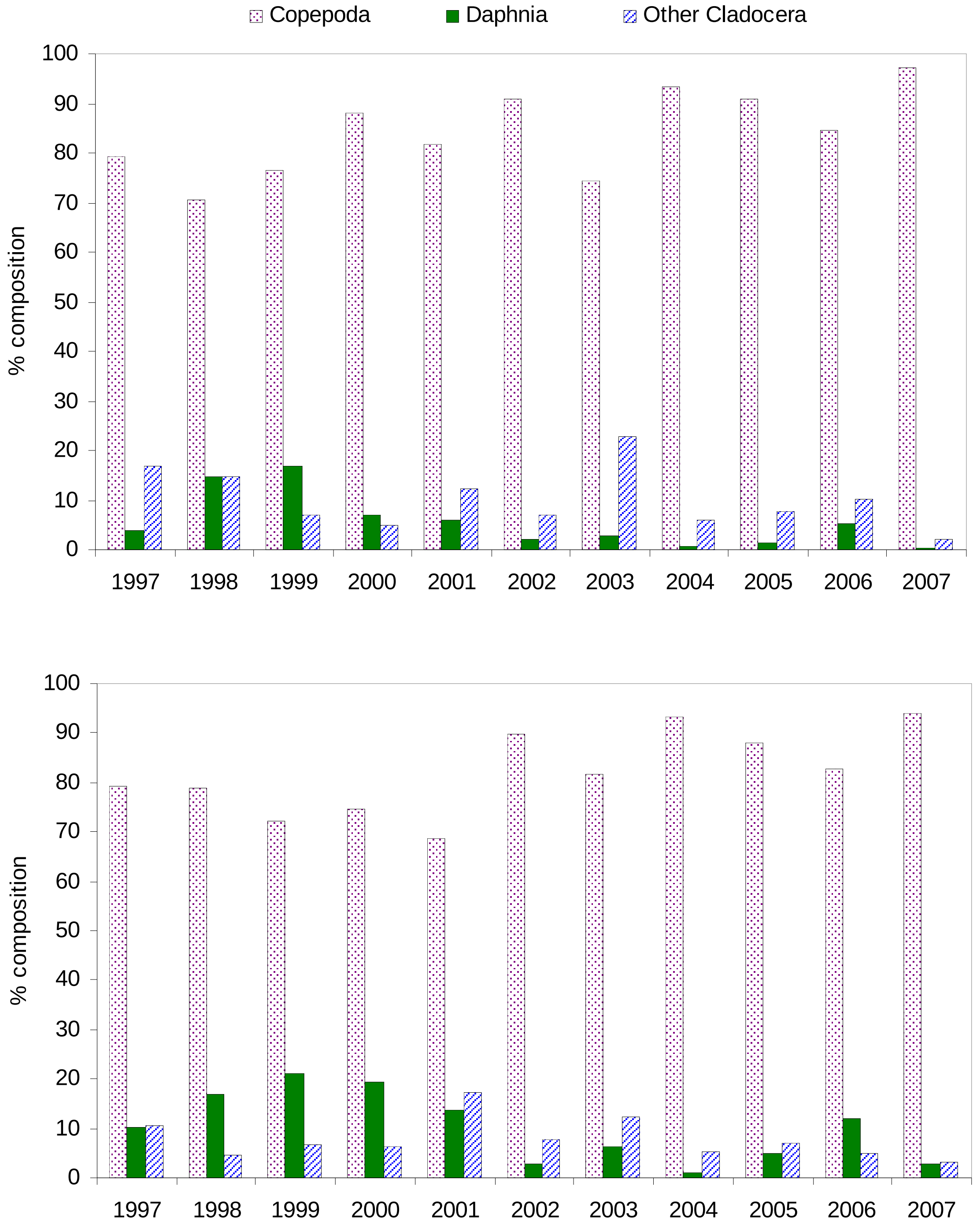


Figure 5.1. Seasonal composition of zooplankton as a percentage of average density in Upper Arrow (top) and Lower Arrow (bottom), 1997-2007.

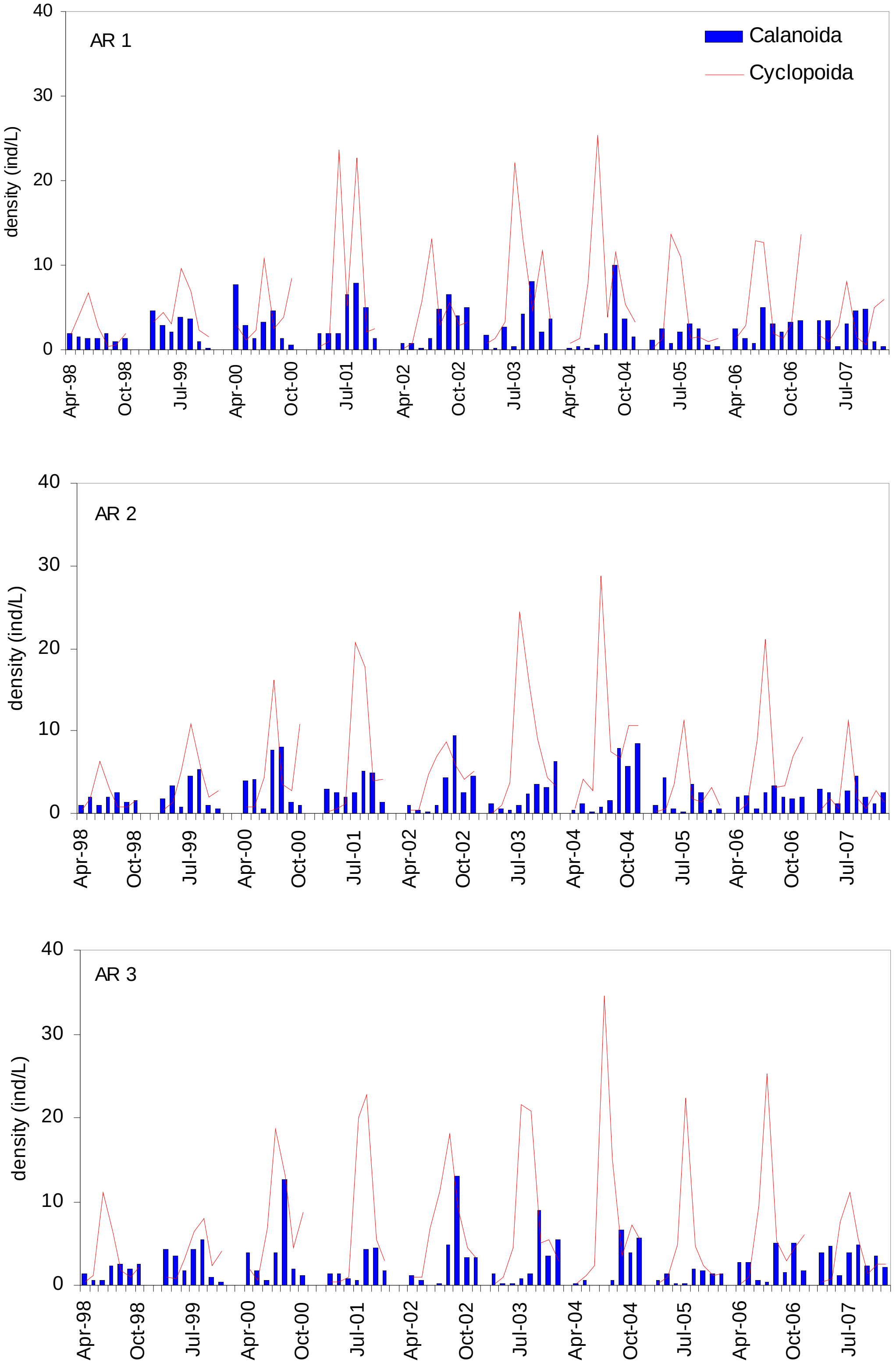
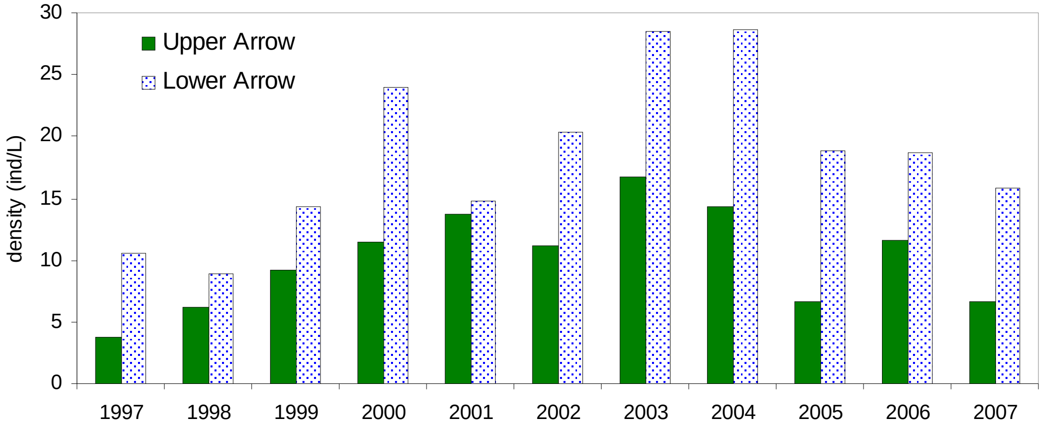
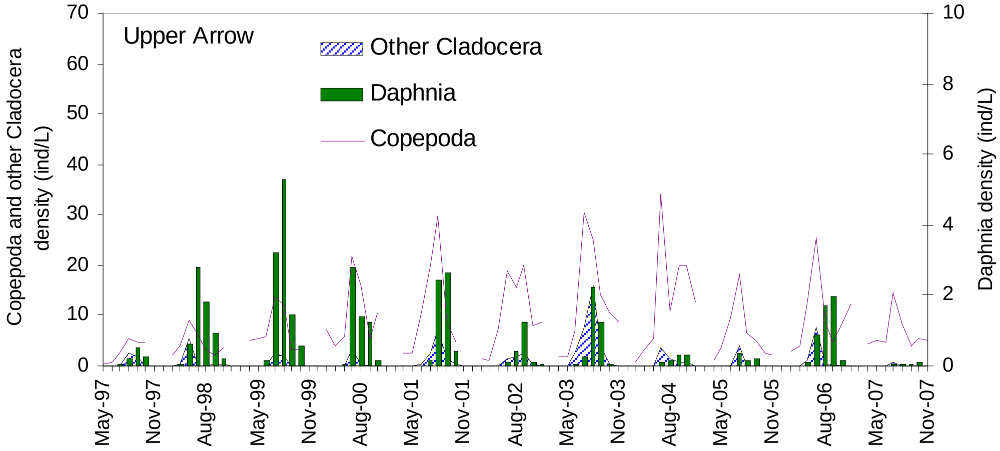


Figure 5.2. Density of calanoid and cyclopoid zooplankton in Upper Arrow 1998-2007.

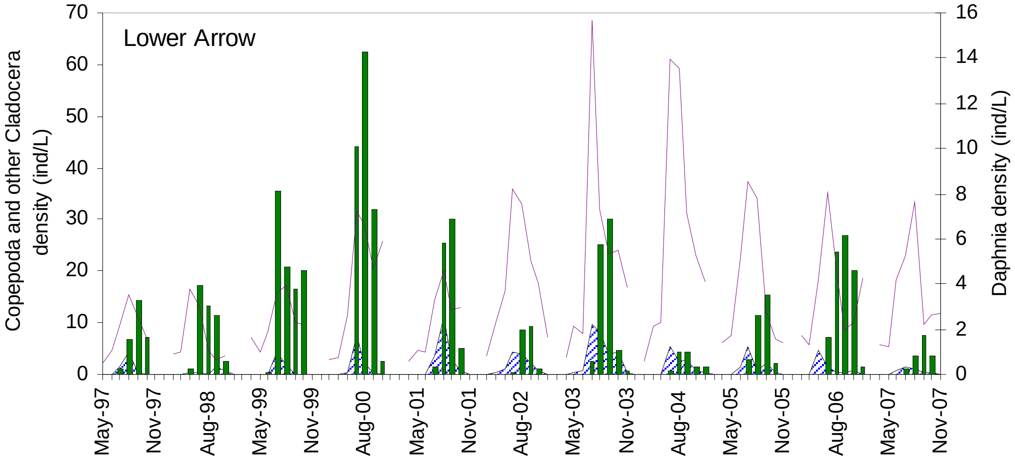
Figure 5.3. Density of calanoid and cyclopoid zooplankton in Lower Arrow 1998-2007.



a) Seasonal average density of zooplankton in Upper and Lower Arrow, 1997 to 2007.



b) Seasonal density of zooplankton in Upper Arrow, 1997 to 2007.



c) Seasonal density of zooplankton in Lower Arrow, 1997 to 2007.

Figure 5.4. Zooplankton density in Arrow Lakes Reservoir, 1997 – 2007.

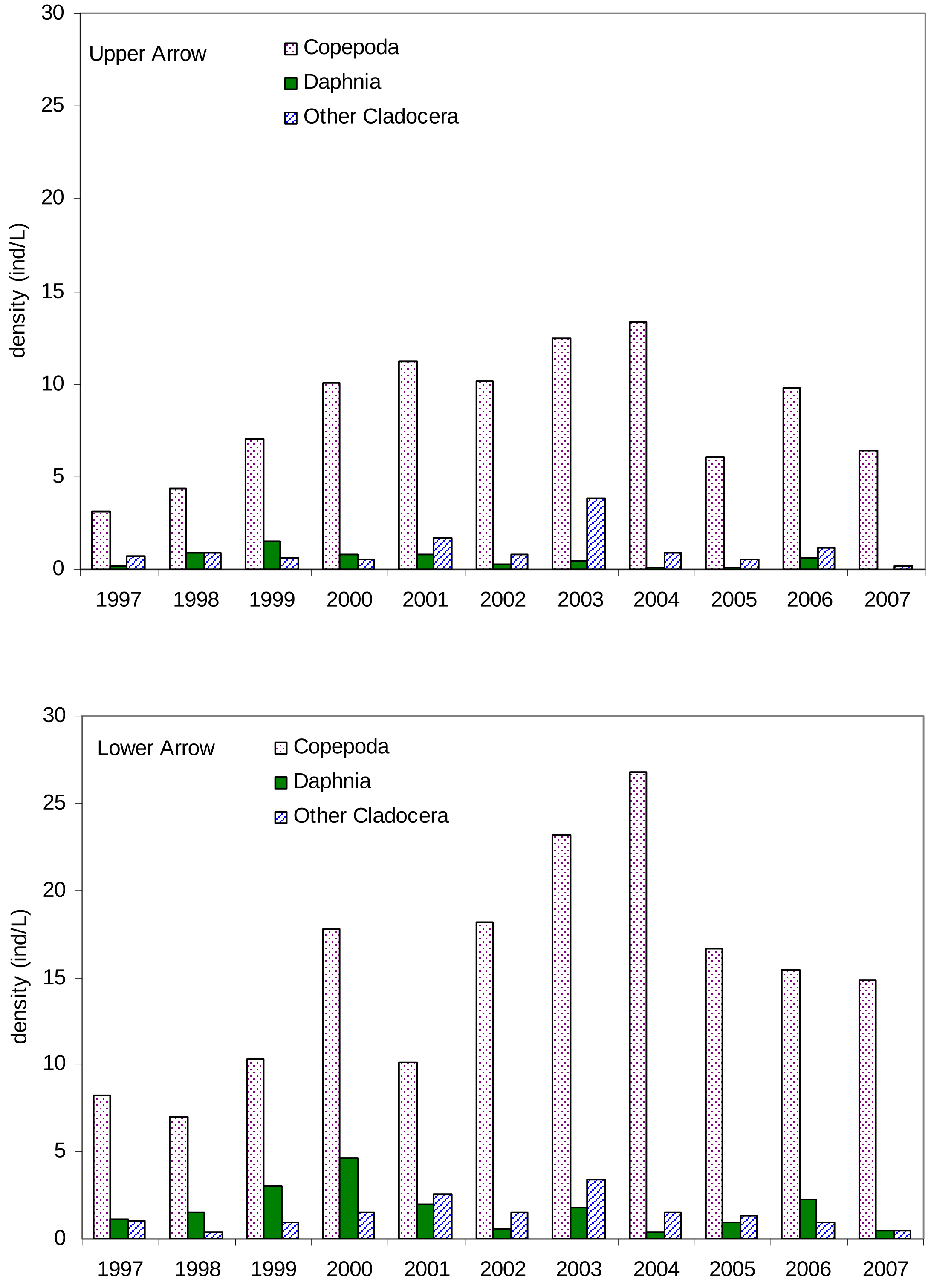
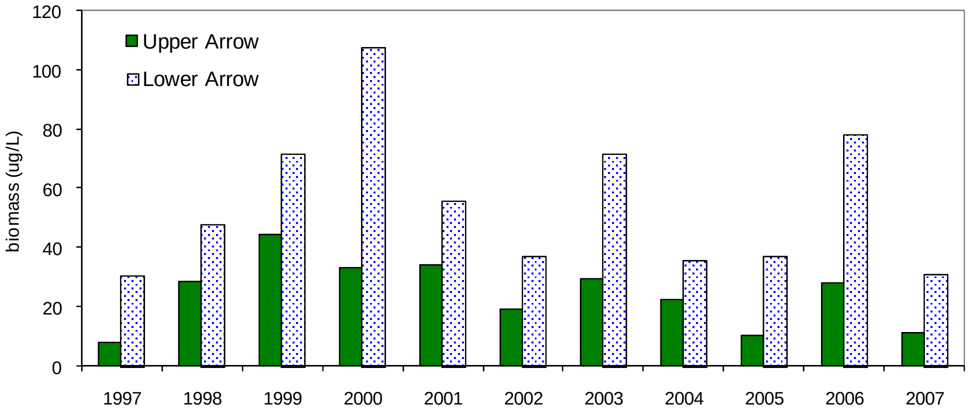
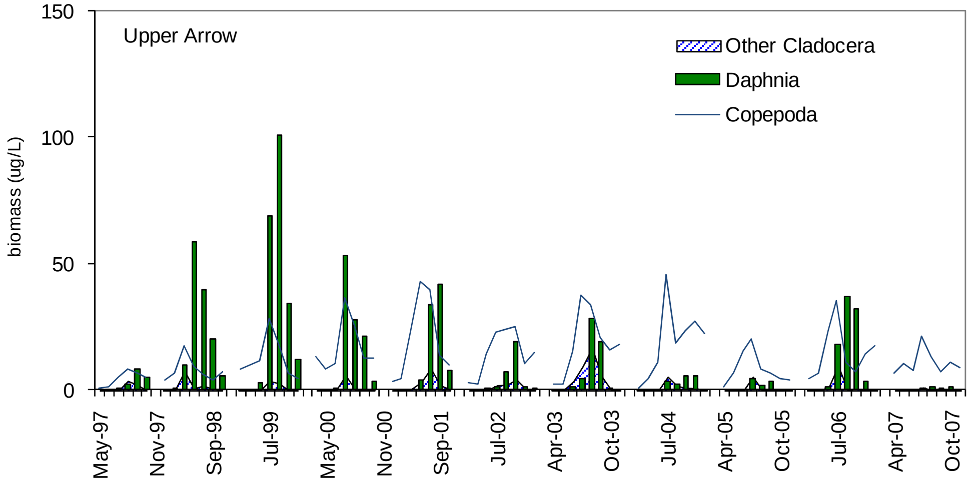


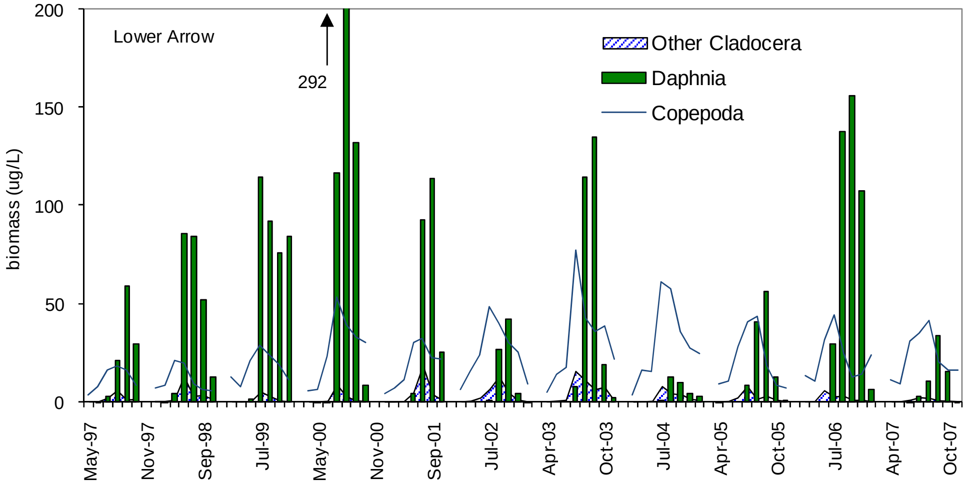
Figure 5.5. Seasonal average zooplankton density in Upper and Lower Arrow, 1997- 2007.



a) Seasonal average biomass of zooplankton in Upper and Lower Arrow, 1997 -2007.



b) Seasonal biomass of zooplankton in Upper Arrow, 1997 - 2007.



c) Seasonal biomass of zooplankton in Lower Arrow, 1997 - 2007.

Figure 5.6. Zooplankton biomass in Arrow Lakes Reservoir, 1997 - 2007.

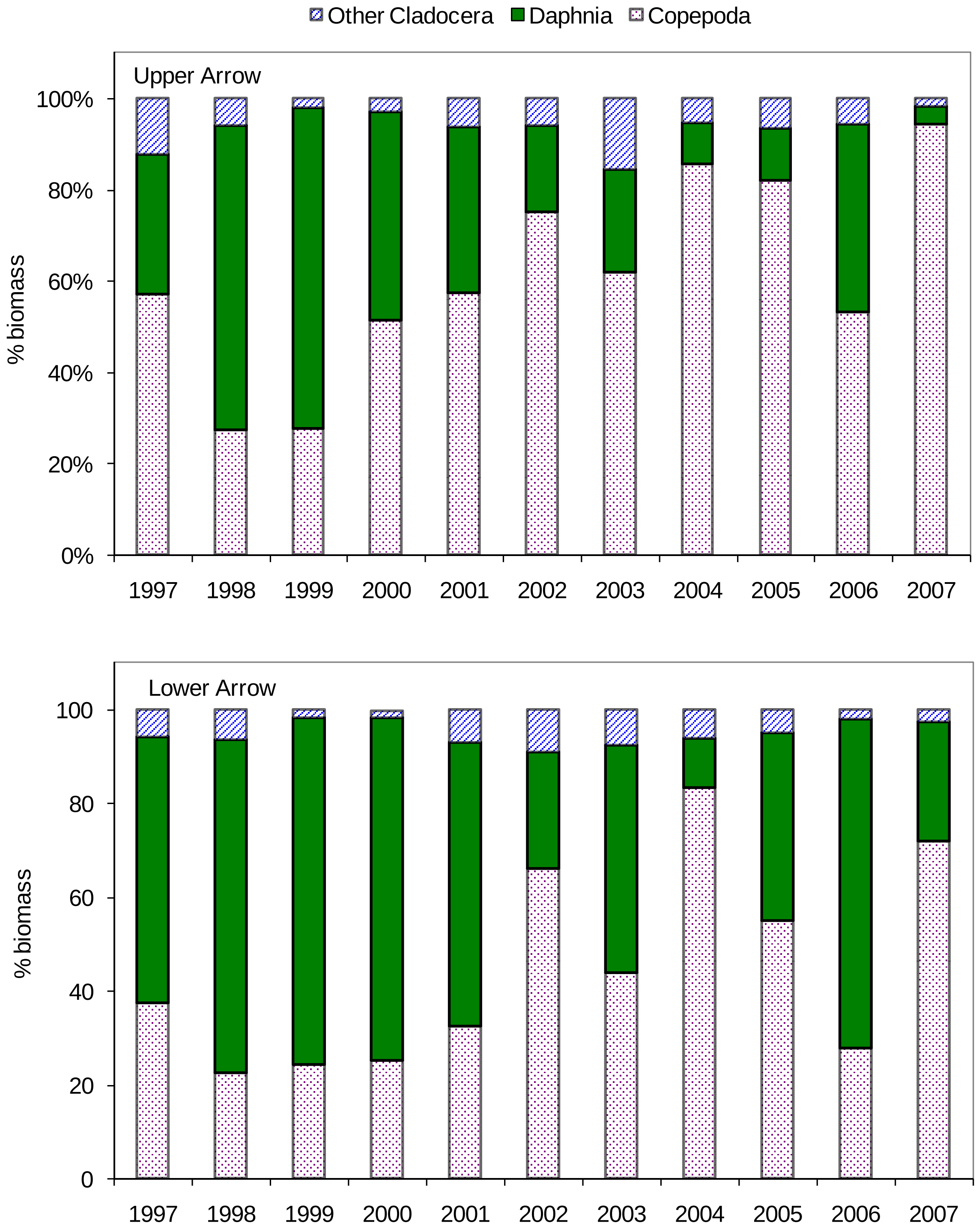


Figure 5.7. Seasonal composition of zooplankton as a percentage of average biomass in Upper Arrow (top) and Lower Arrow (bottom), 1997-2007.

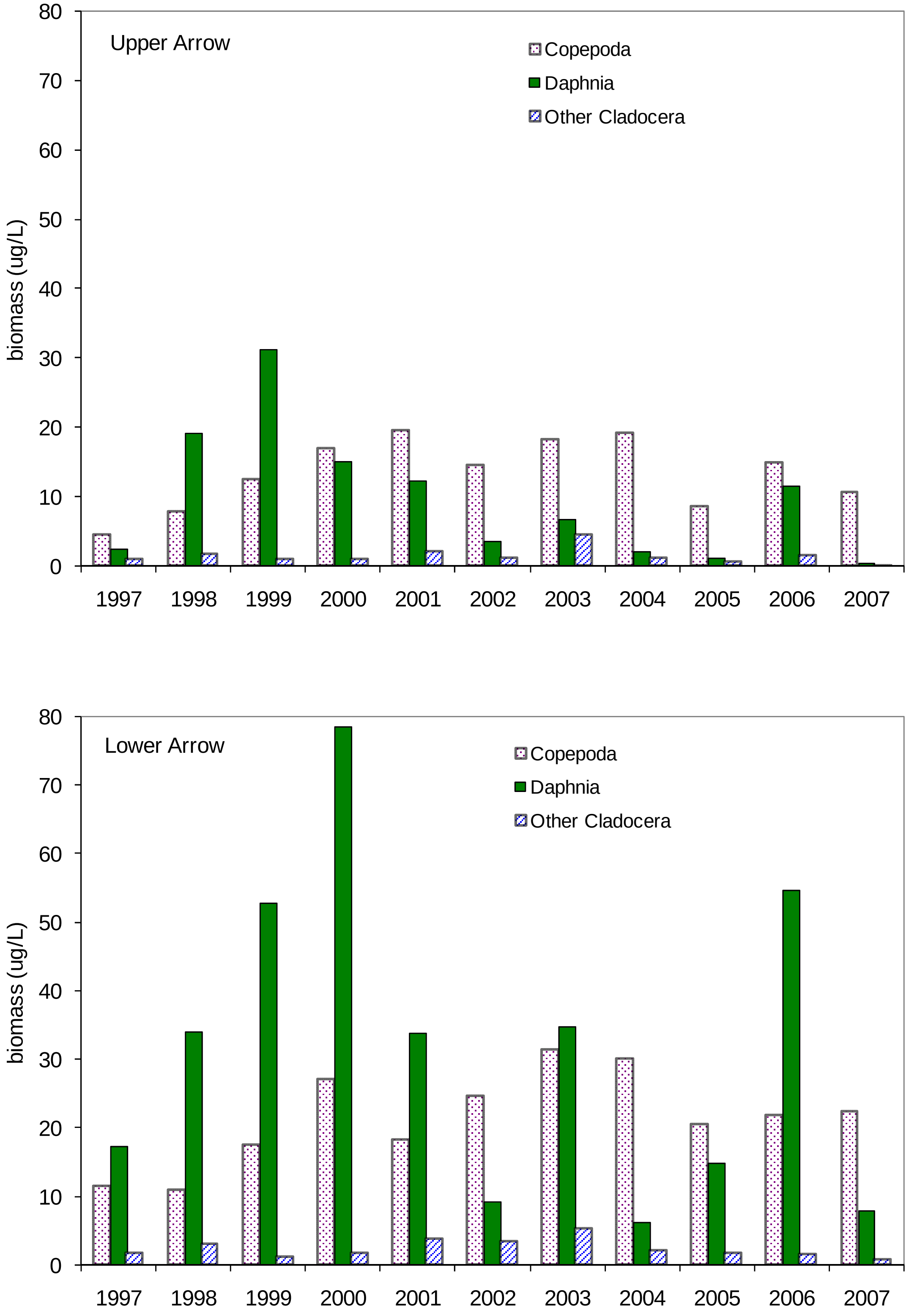


Figure 5.8. Seasonal average zooplankton biomass in Upper and Lower Arrow, 1997 – 2007.

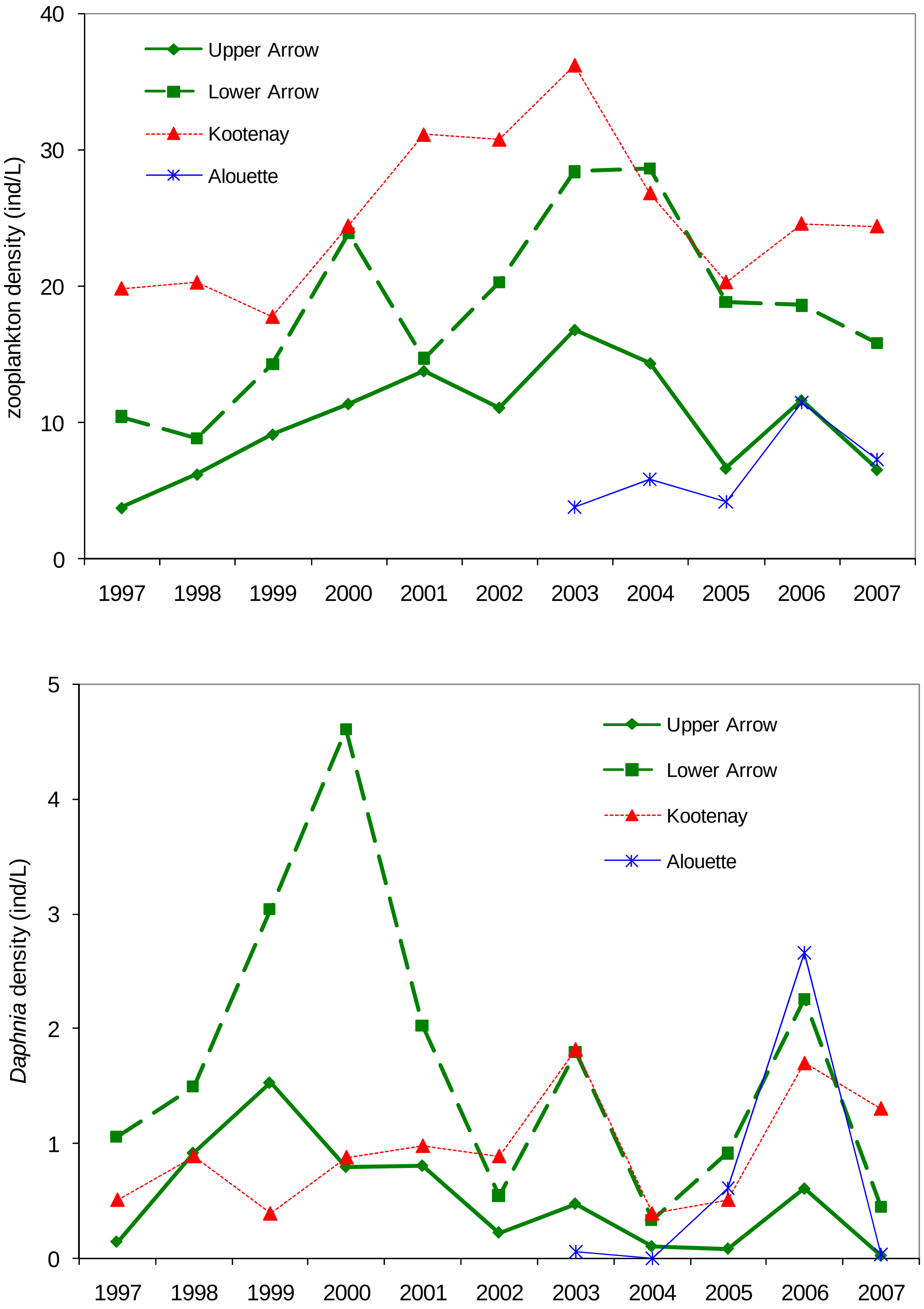
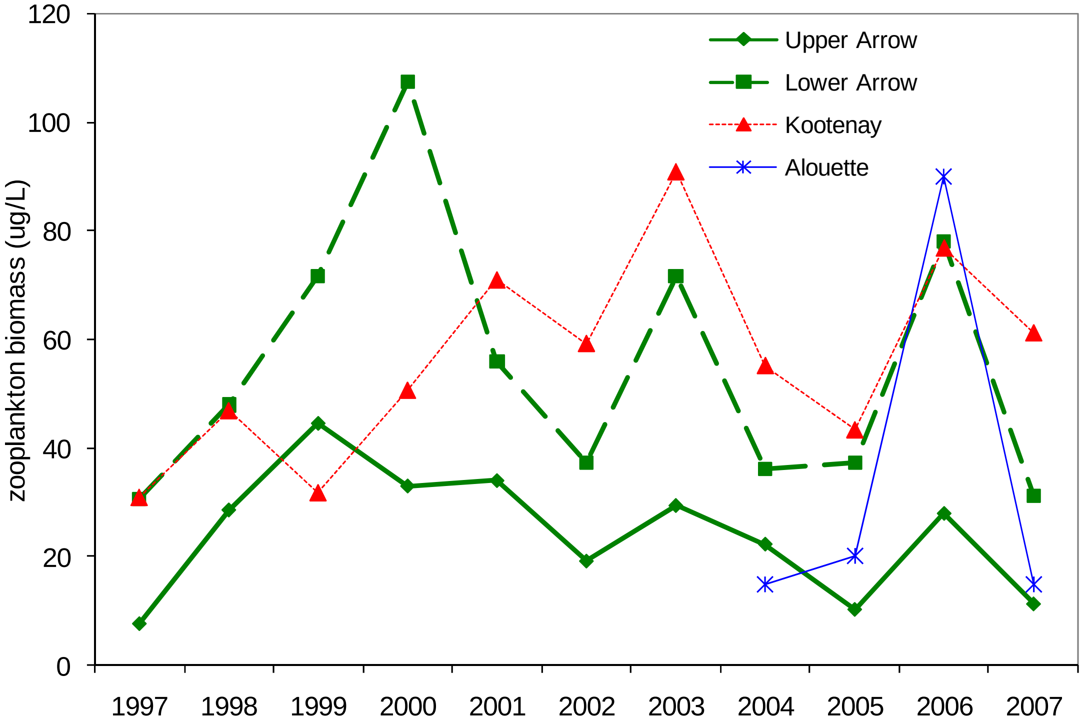


Figure 5.9. Seasonal average zooplankton density (top) and *Daphnia* density (bottom) in some British Columbia lakes.



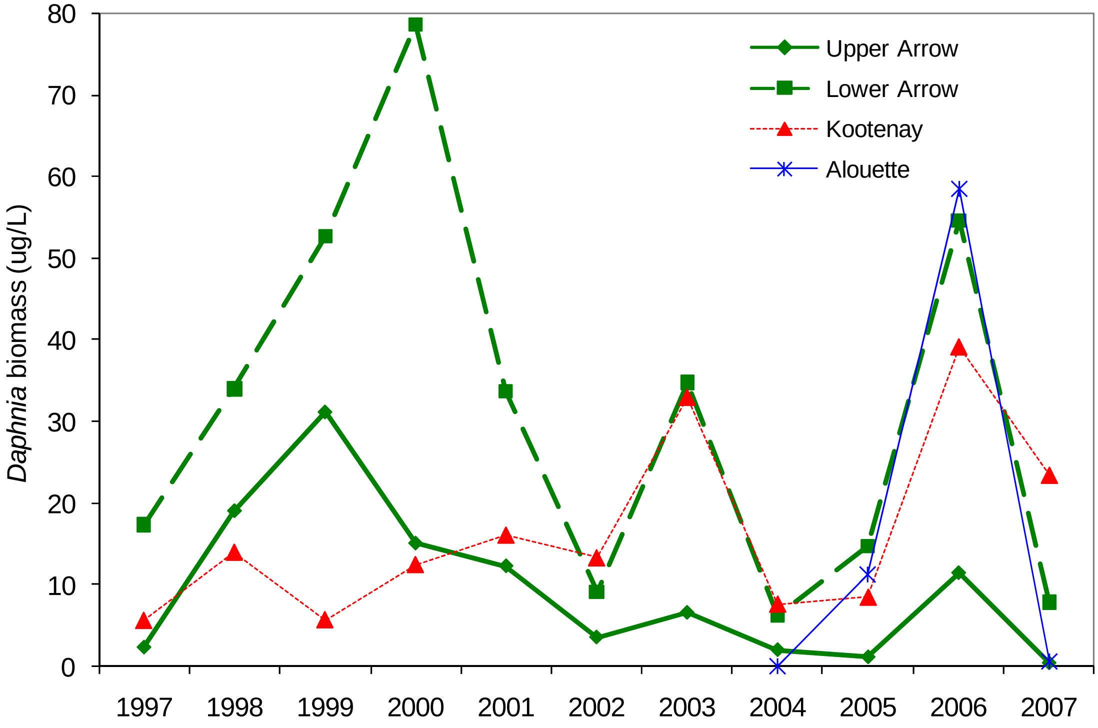


Figure 5.10. Seasonal average zooplankton biomass (top) and *Daphnia* biomass (bottom) in some British Columbia lakes.

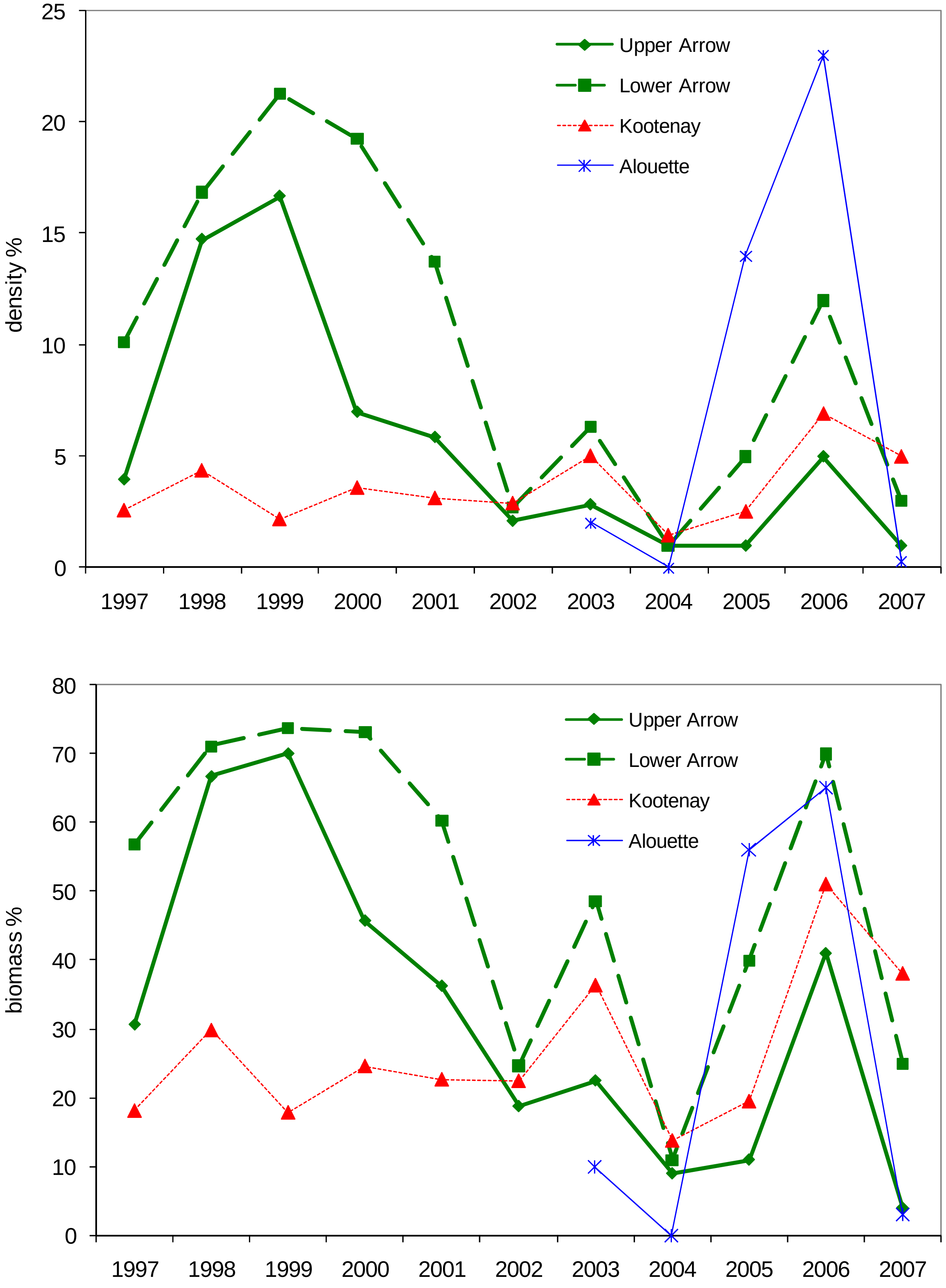


Figure 5.11. Percentage of *Daphnia* density and biomass in total zooplankton in some British Columbia lakes.

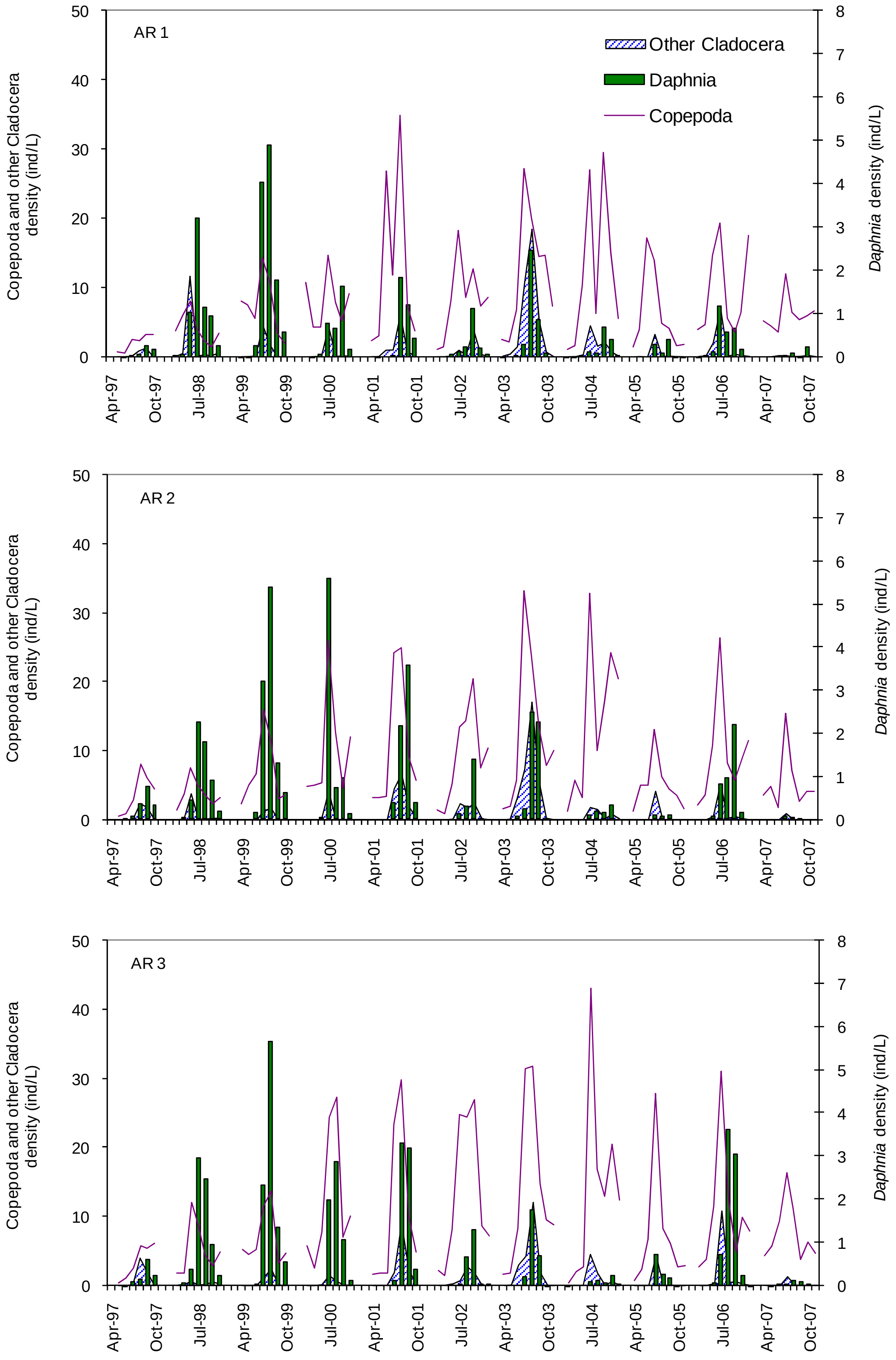


Figure 5.12. Density of cladoceran and copepod zooplankton, stations AR 1 to AR 3 in Upper Arrow, 1997 - 2007.

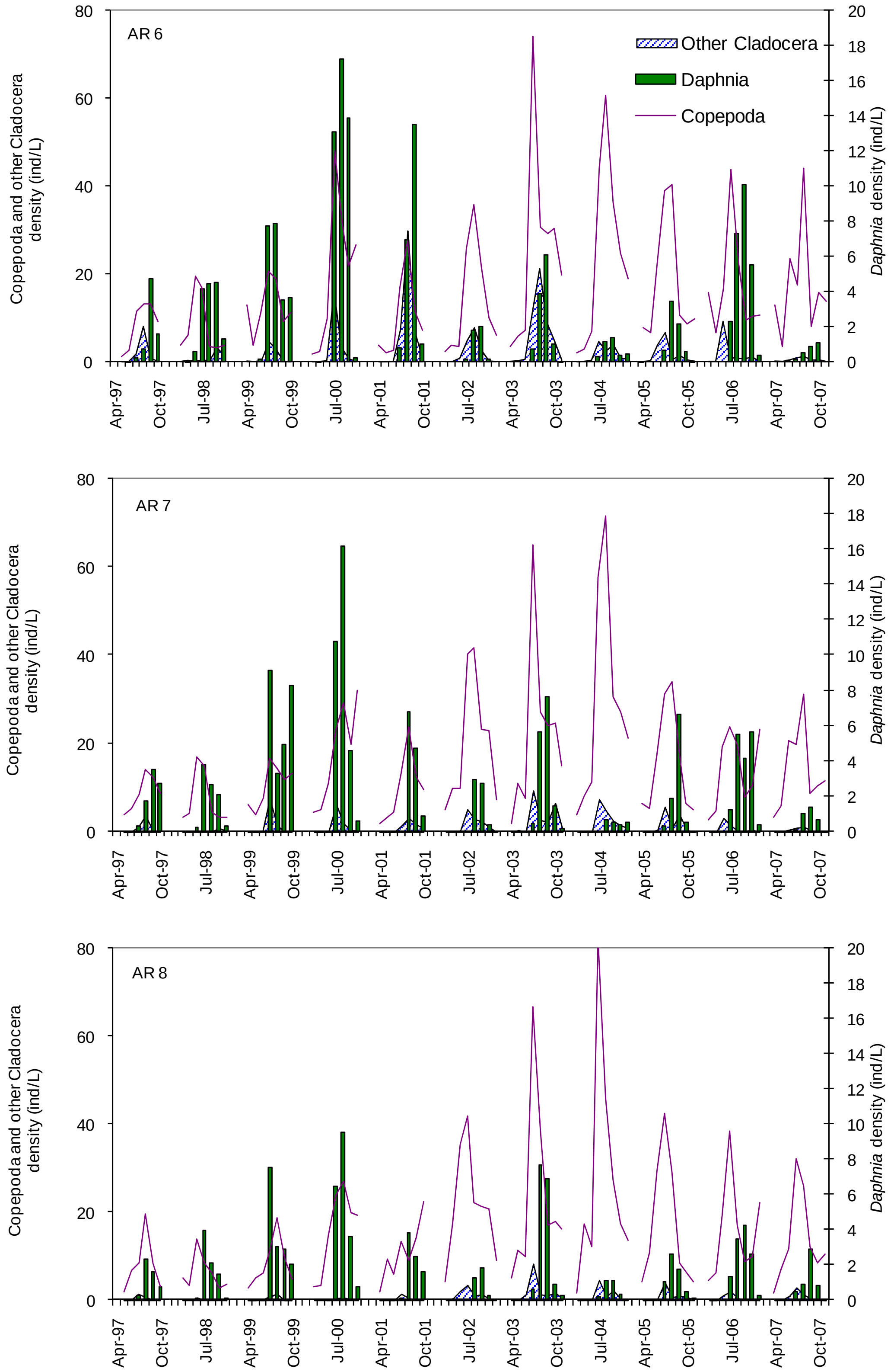


Figure 5.13. Density of cladoceran and copepod zooplankton, stations AR 6 to AR 8 in Lower Arrow, 1997 - 2007.

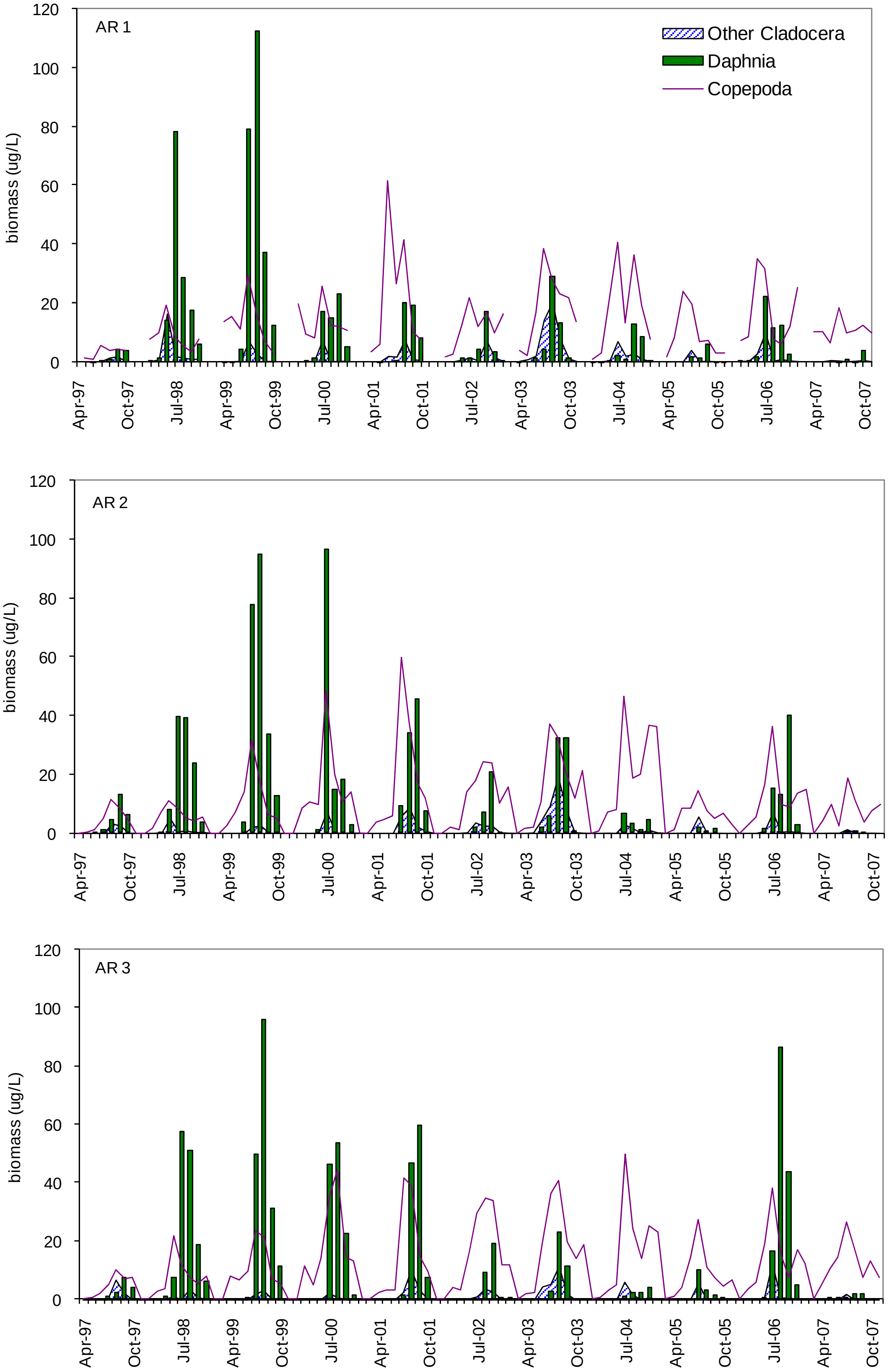


Figure 5.14. Biomass of cladoceran and copepod zooplankton, stations AR 1 to AR 3 in Upper Arrow, 1997 - 2007.

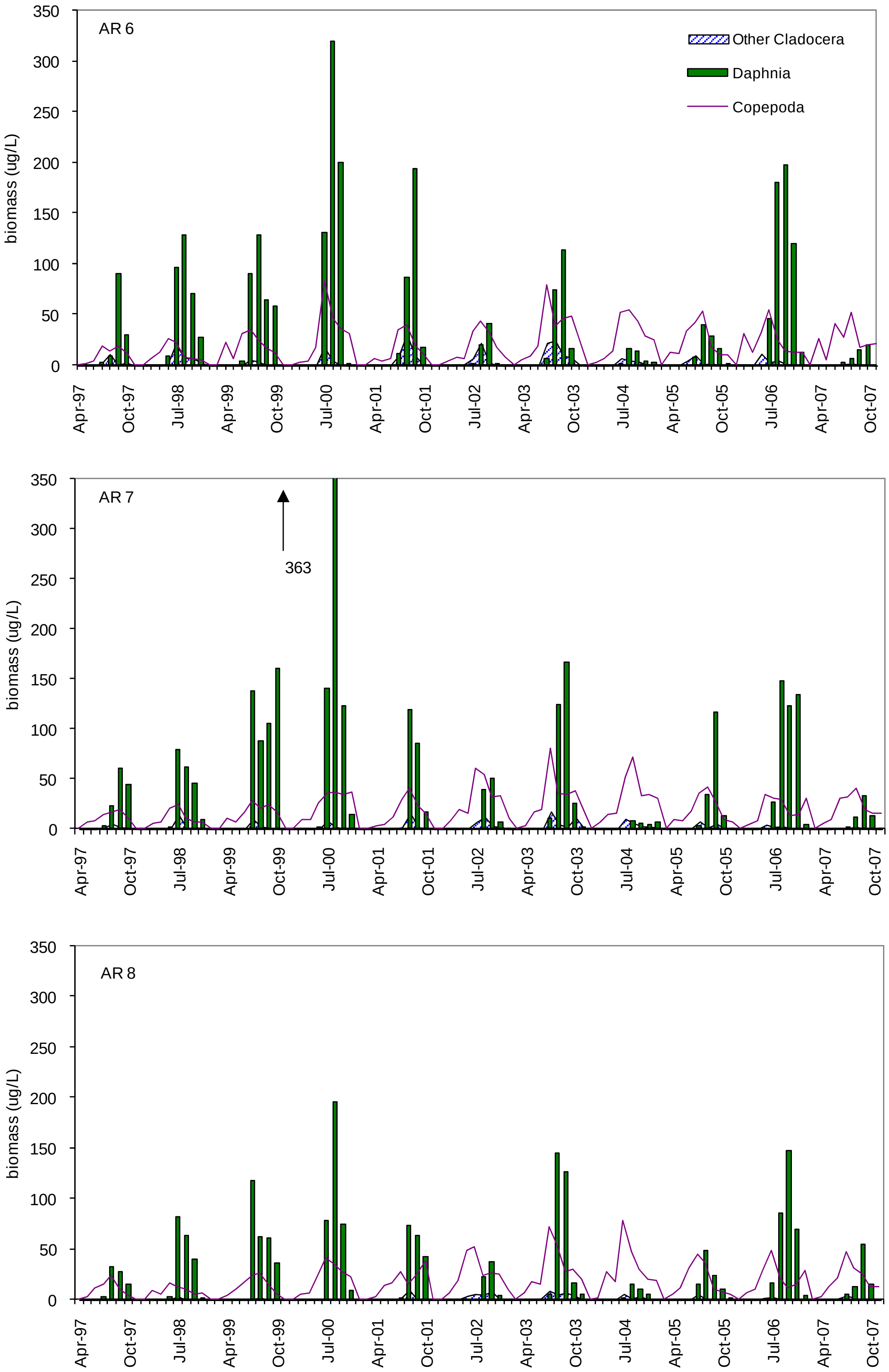


Figure 5.15. Biomass of cladoceran and copepod zooplankton, stations AR 6 to AR 8 in Upper Arrow, 1997 - 2007.

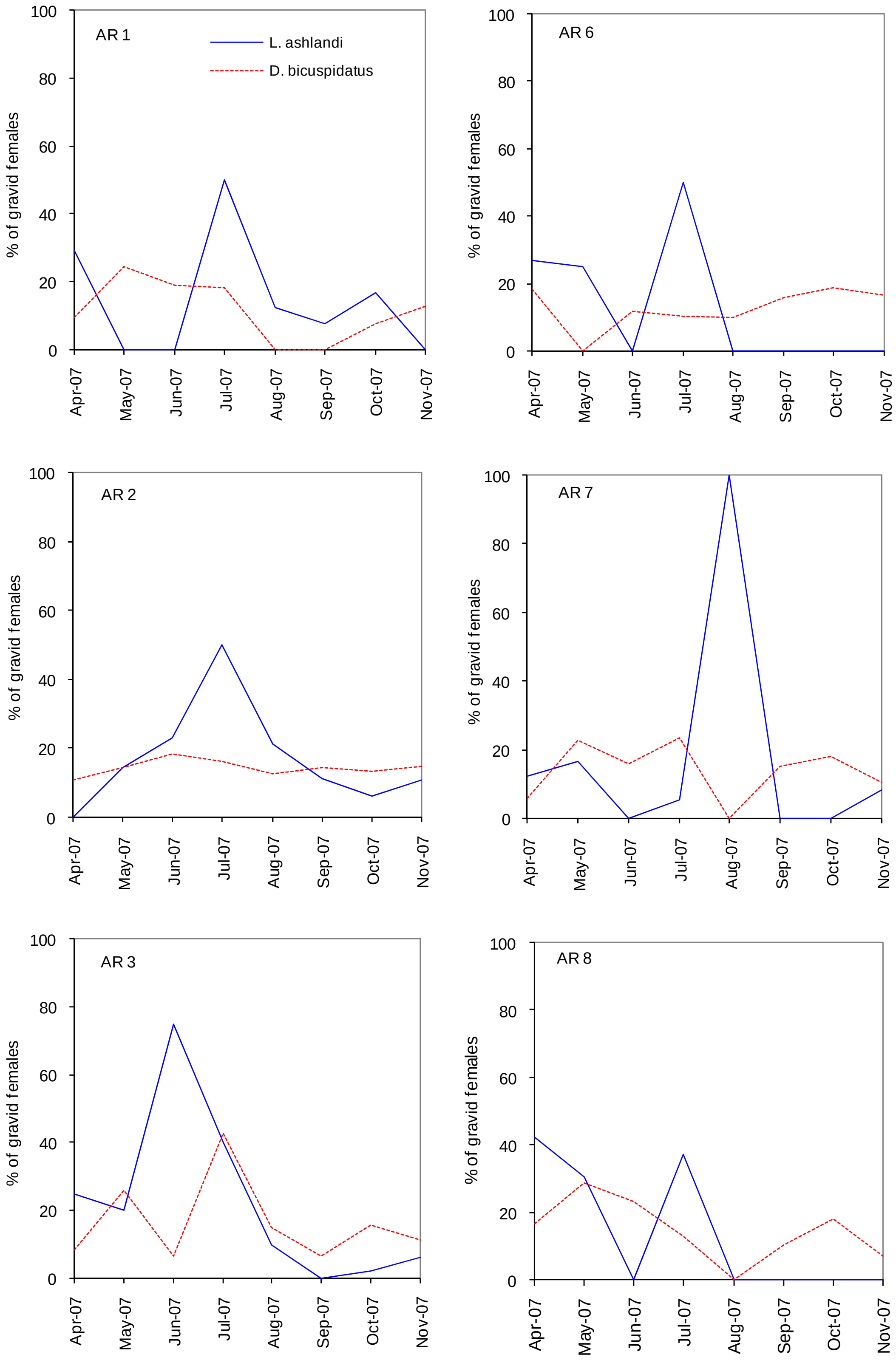


Figure 5.16. Percentage of gravid females in total number of females of two species of Copepoda in Arrow Lakes Reservoir, 2007.

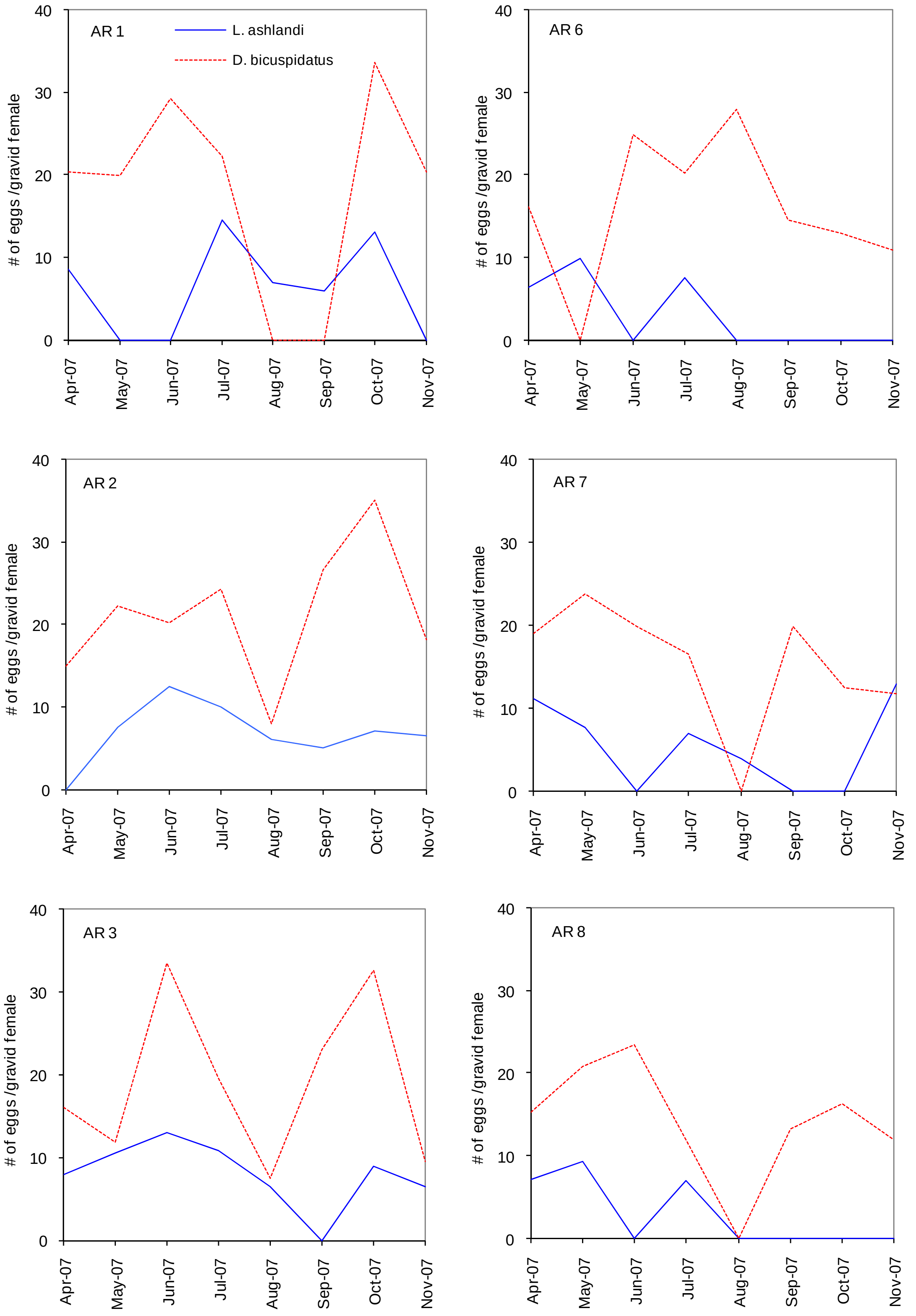


Figure 5.17. Number of eggs per gravid female in two species of Copepoda in Arrow Lakes Reservoir, 2007.

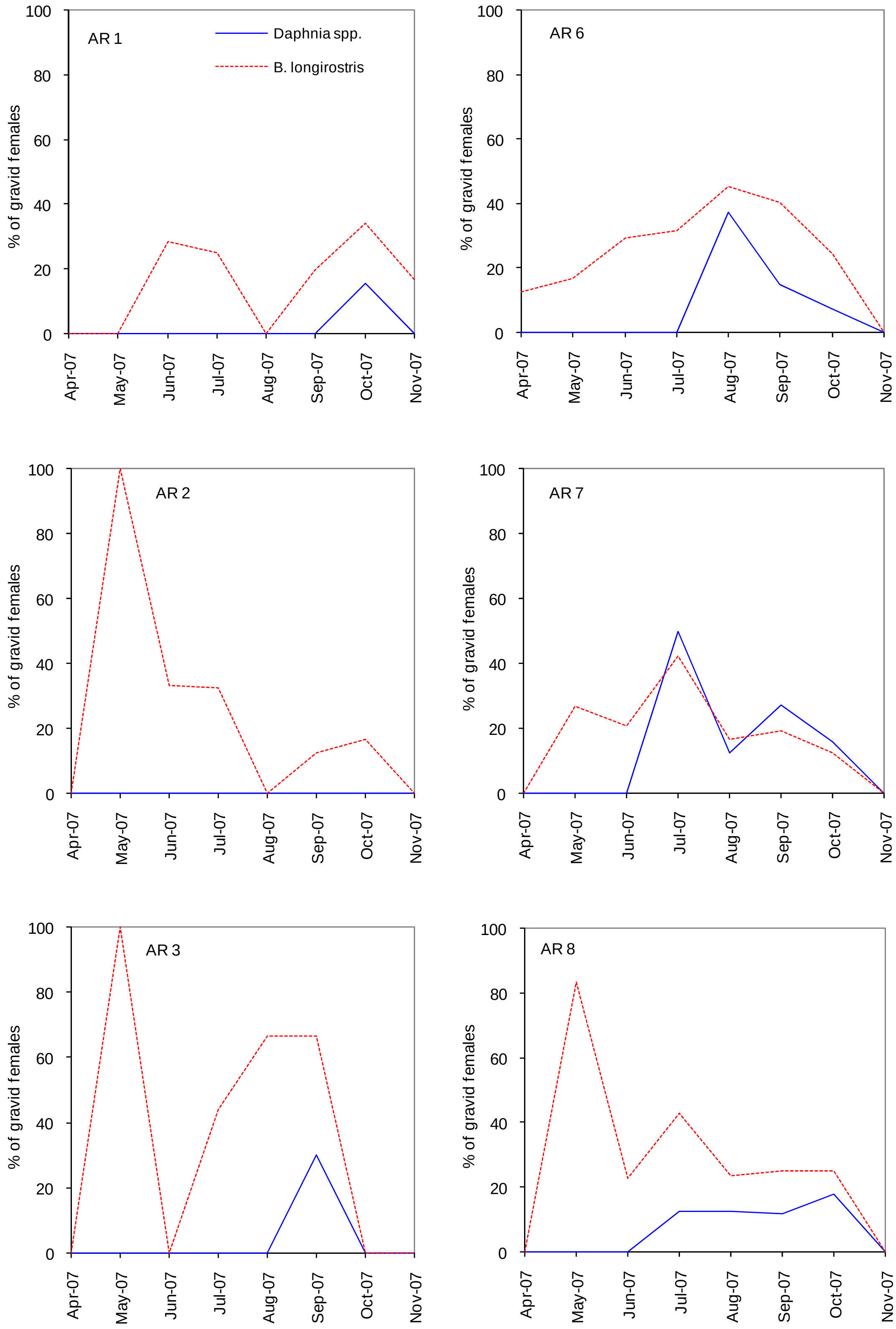


Figure 5.18. Percentage of gravid females in total number of females of two species of Cladocera in Arrow Lakes Reservoir, 2007.

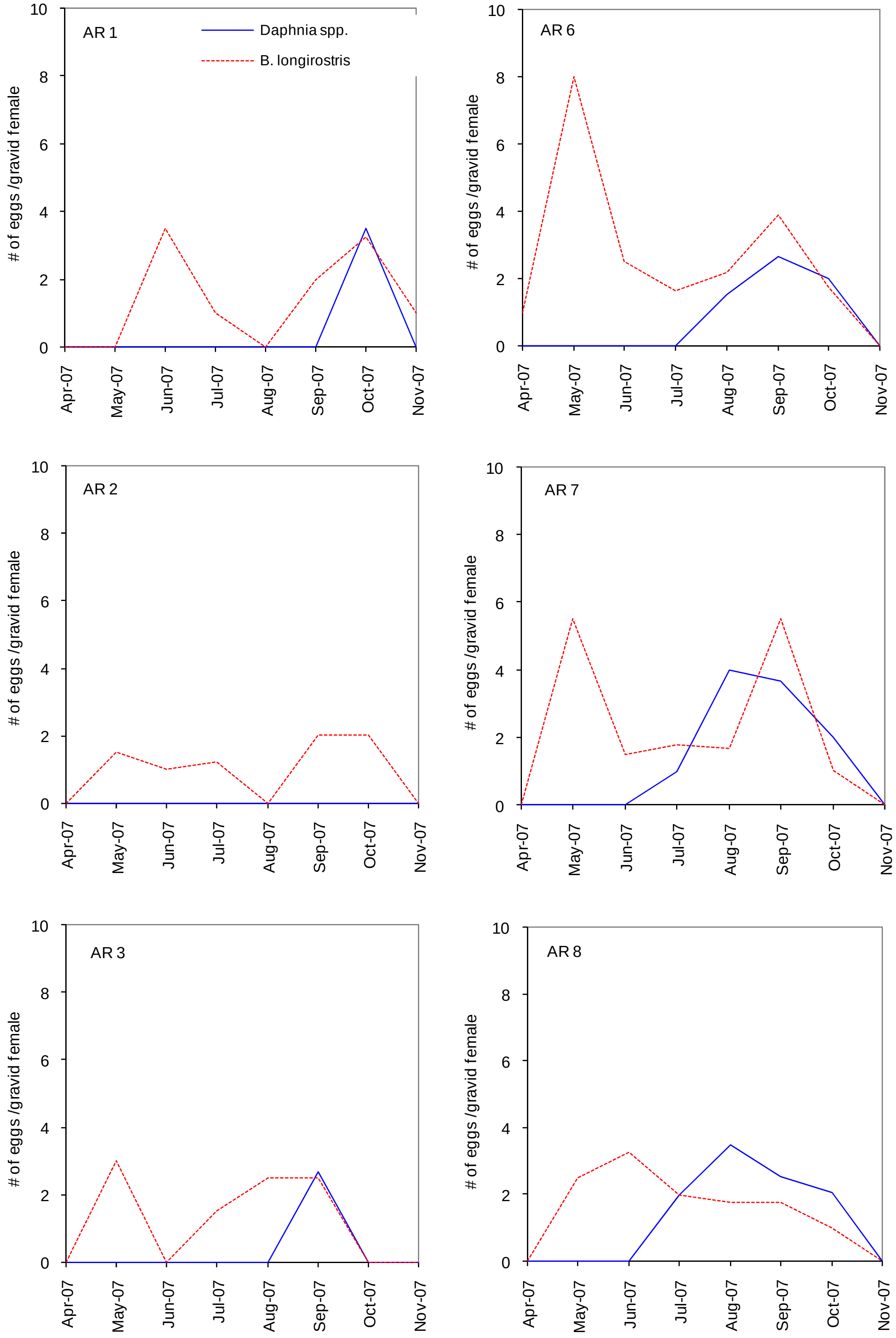


Figure 5.19. Number of eggs per gravid female in two species of Cladocera in Arrow Lakes Reservoir, 2007.

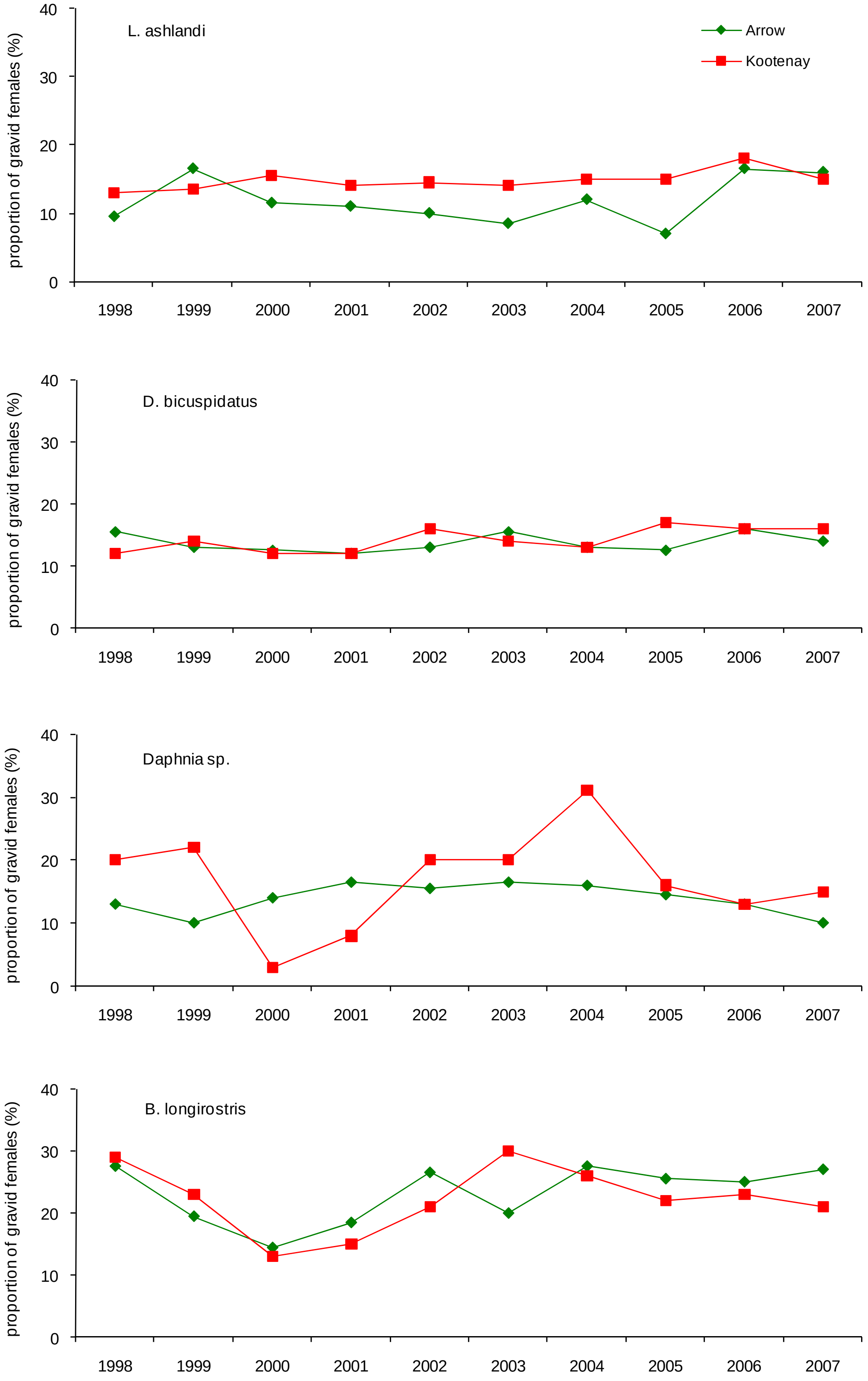


Figure 5.20. Proportion of gravid females of four most common zooplankton species in Arrow Lakes Reservoir and Kootenay Lake, 1997 – 2007.

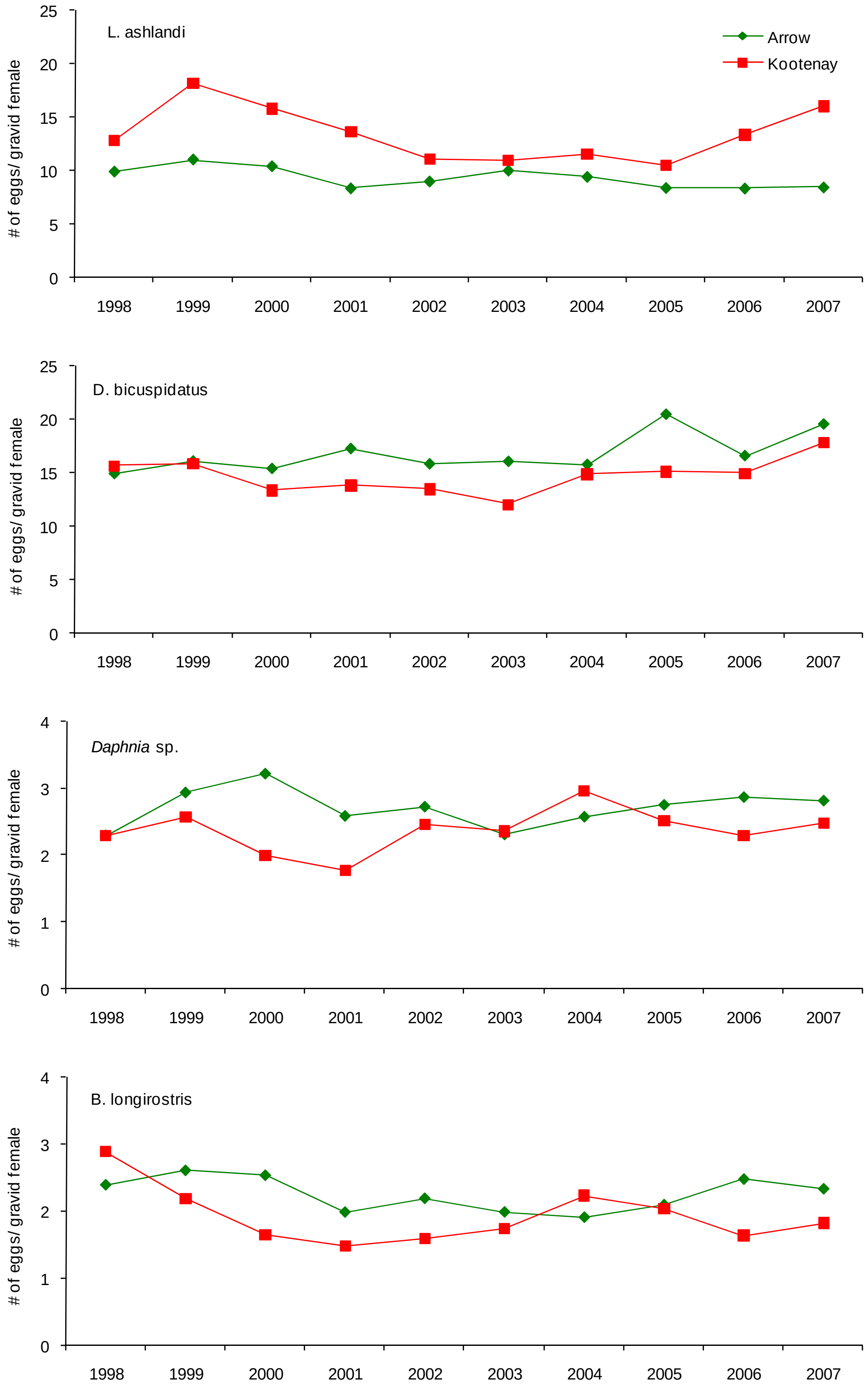
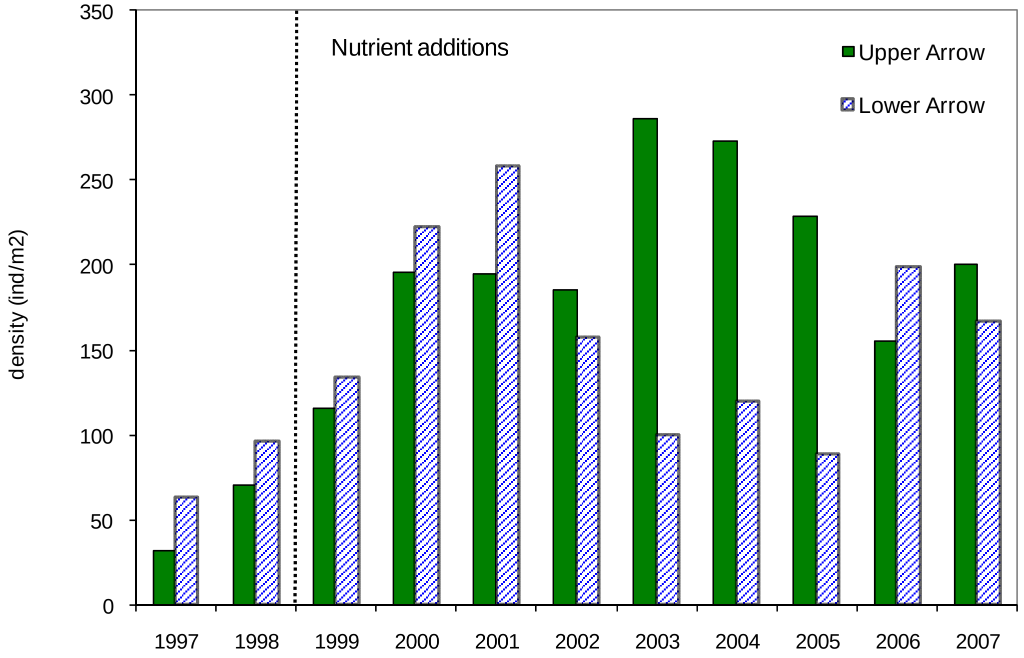


Figure 5.21. Number of eggs per gravid female of four most common zooplankton species in Arrow Lakes Reservoir and Kootenay Lake, 1997 – 2007.



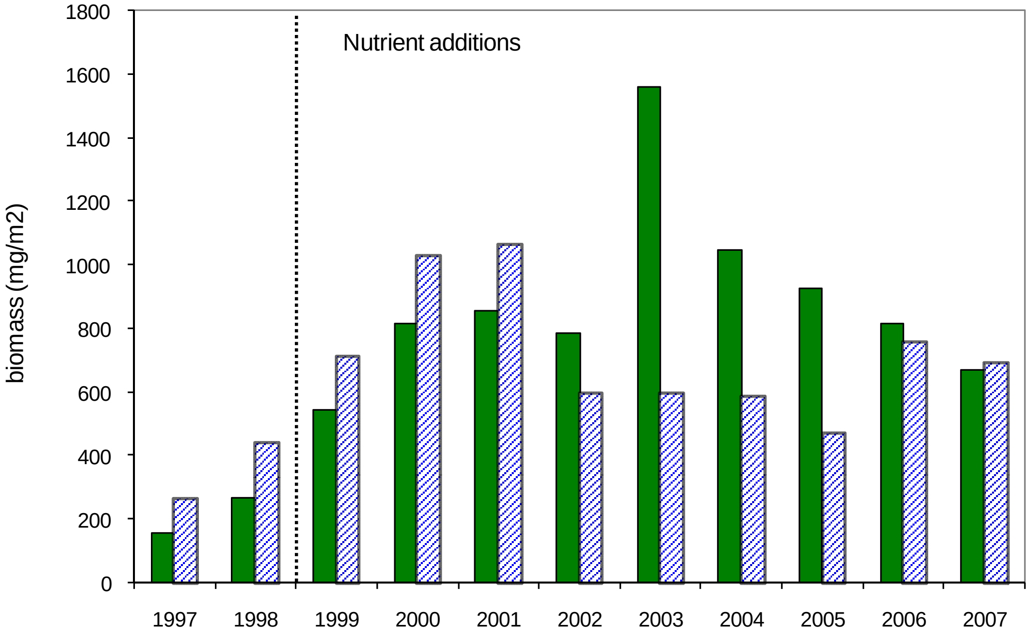
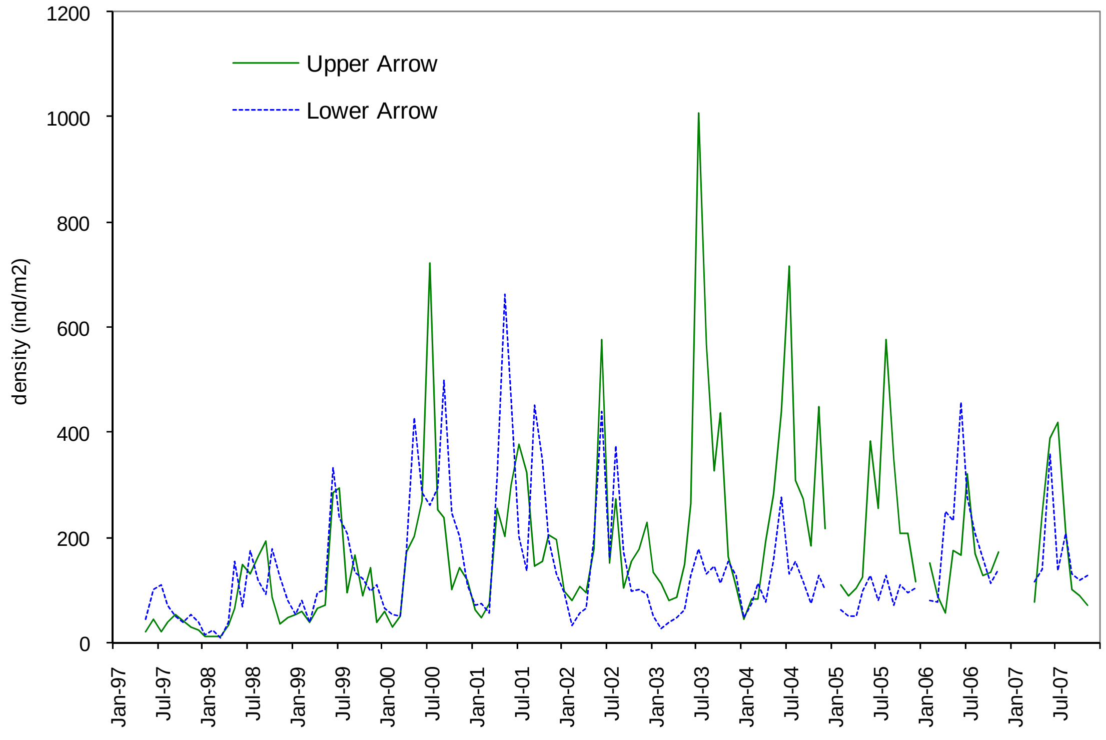


Figure 5.22. Annual average density (top) and biomass (bottom) of *M. relicta* in Arrow Lakes Reservoir, 1997 – 2007.



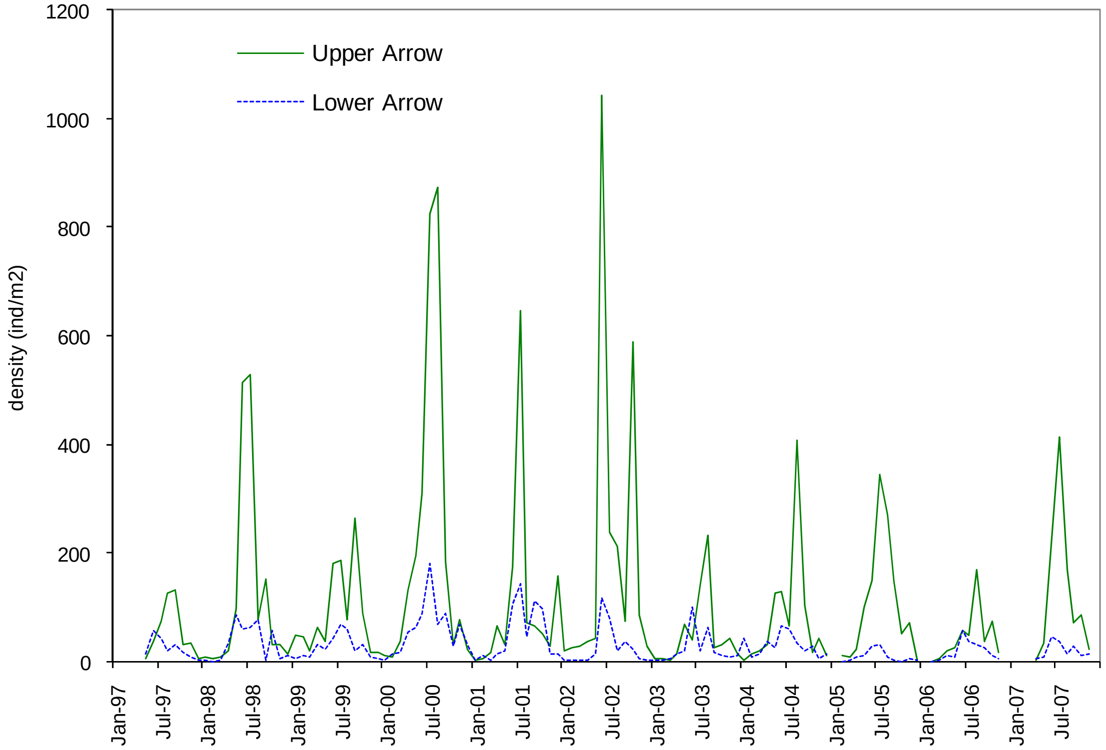


Figure 5.23. Seasonal average density of *M. relicta* in deep (top) and shallow (bottom) sites, Arrow Lakes Reservoir, 1997 – 2007.

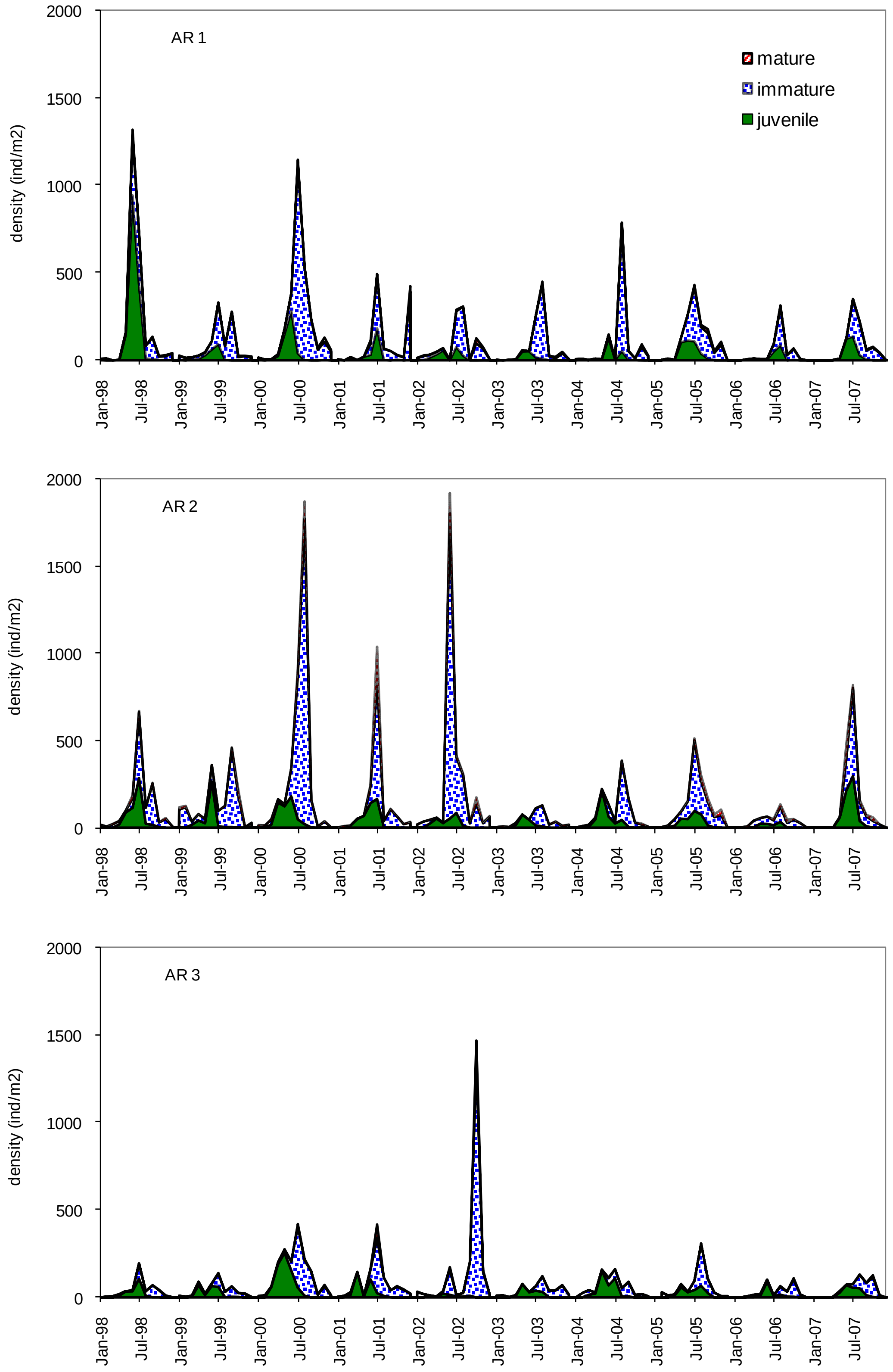


Figure 5.24. Density of developmental stages of *M. relicta* at shallow sites in Upper Arrow, 1998 – 2007.

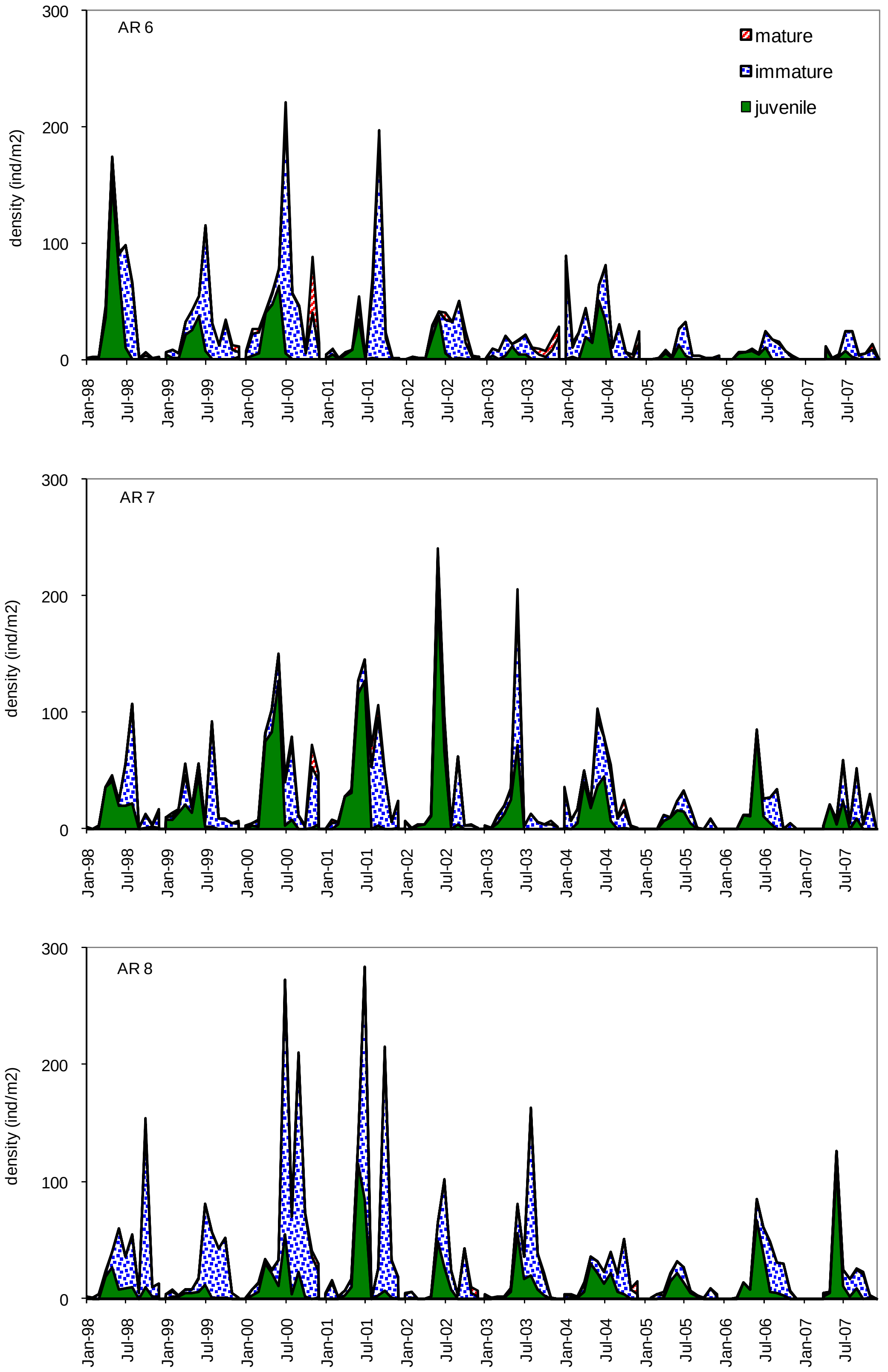


Figure 5.25. Density of developmental stages of *M. relicta* at shallow sites in Lower Arrow, 1998 – 2007.

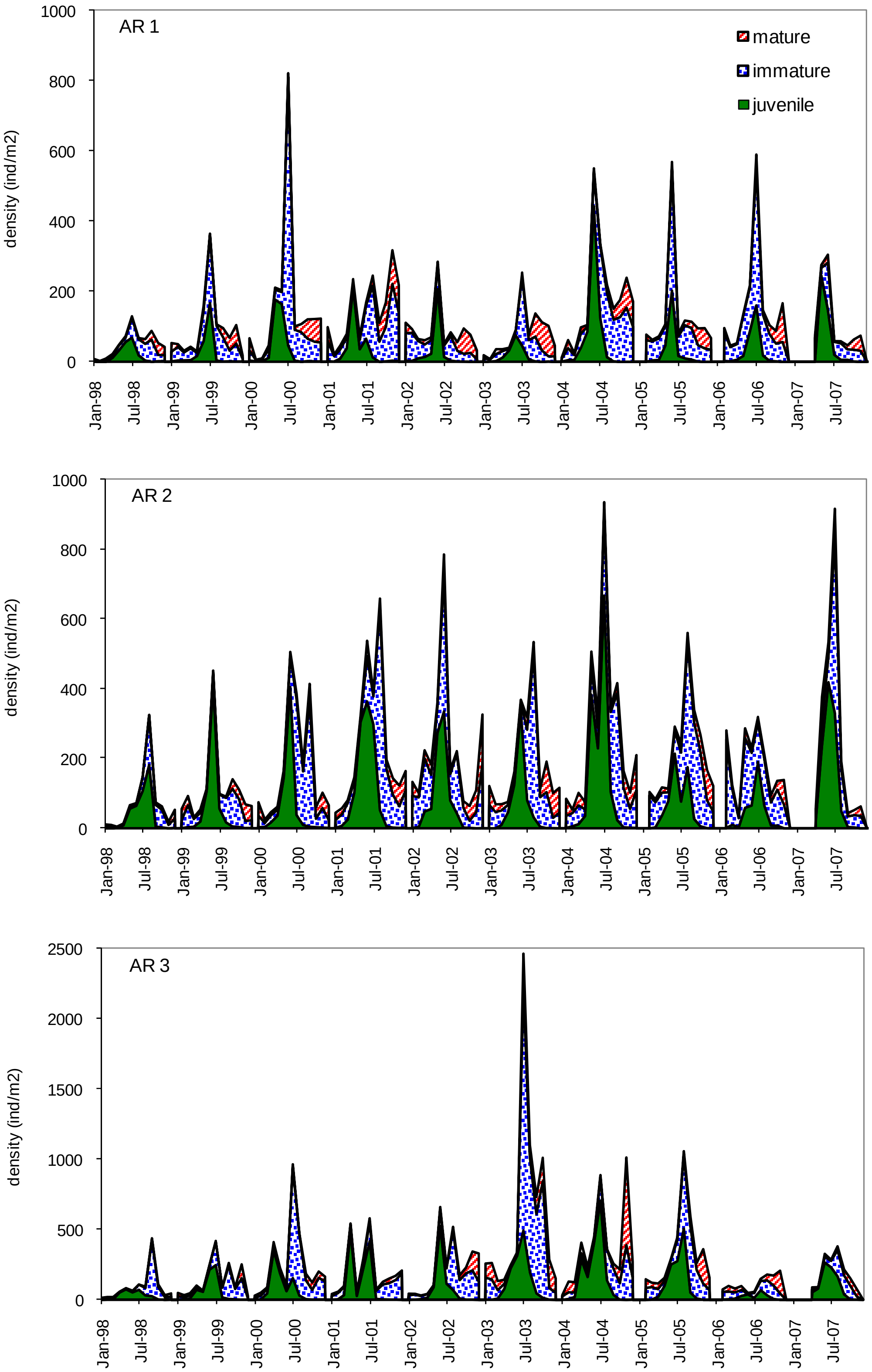


Figure 5.26. Density of developmental stages of *M. relicta* at deep sites in Upper Arrow, 1998 – 2007.

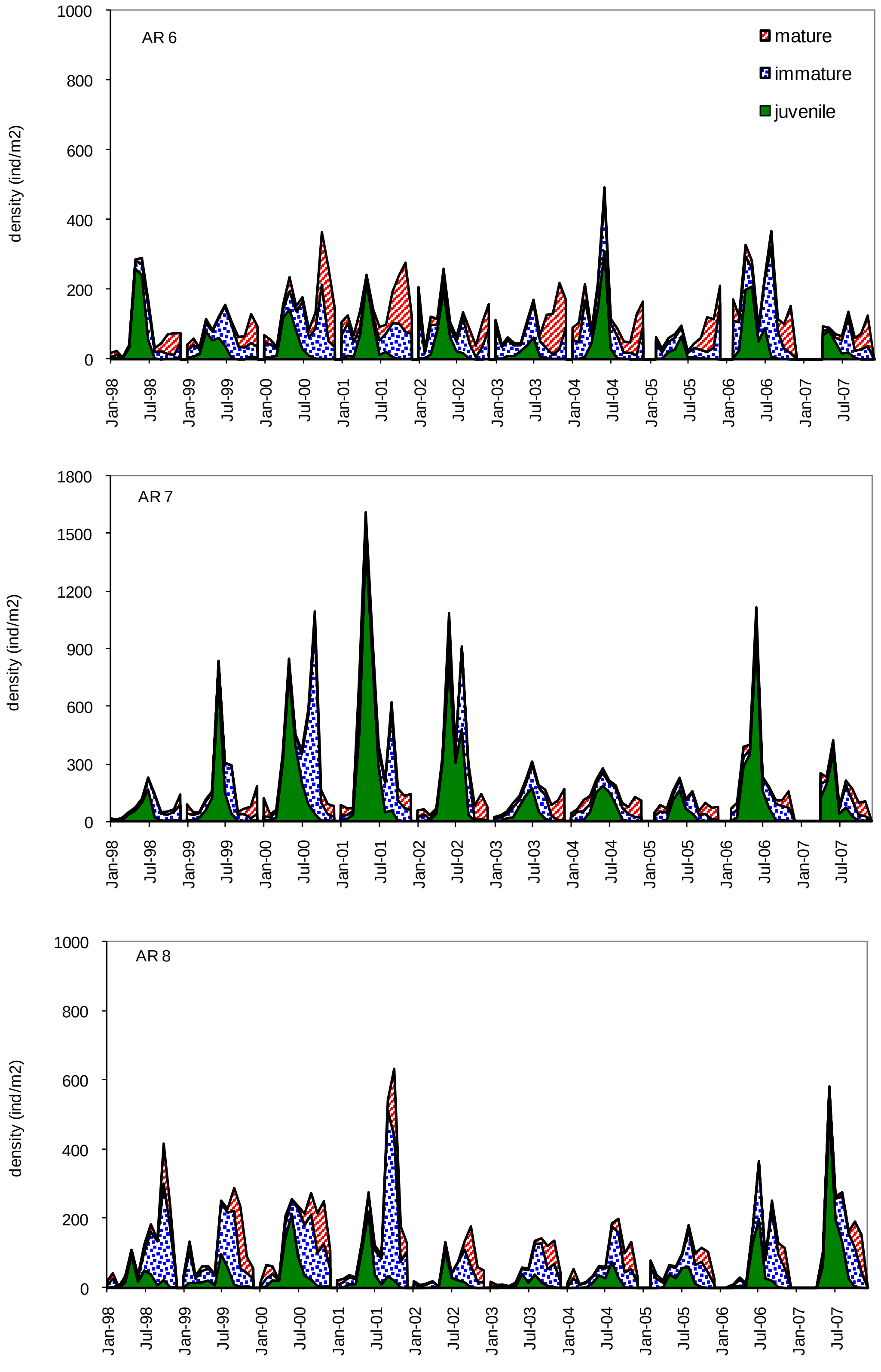


Figure 5.27. Density of development of *M. relicta* at deep sites in Lower Arrow, 1998 – 2007.

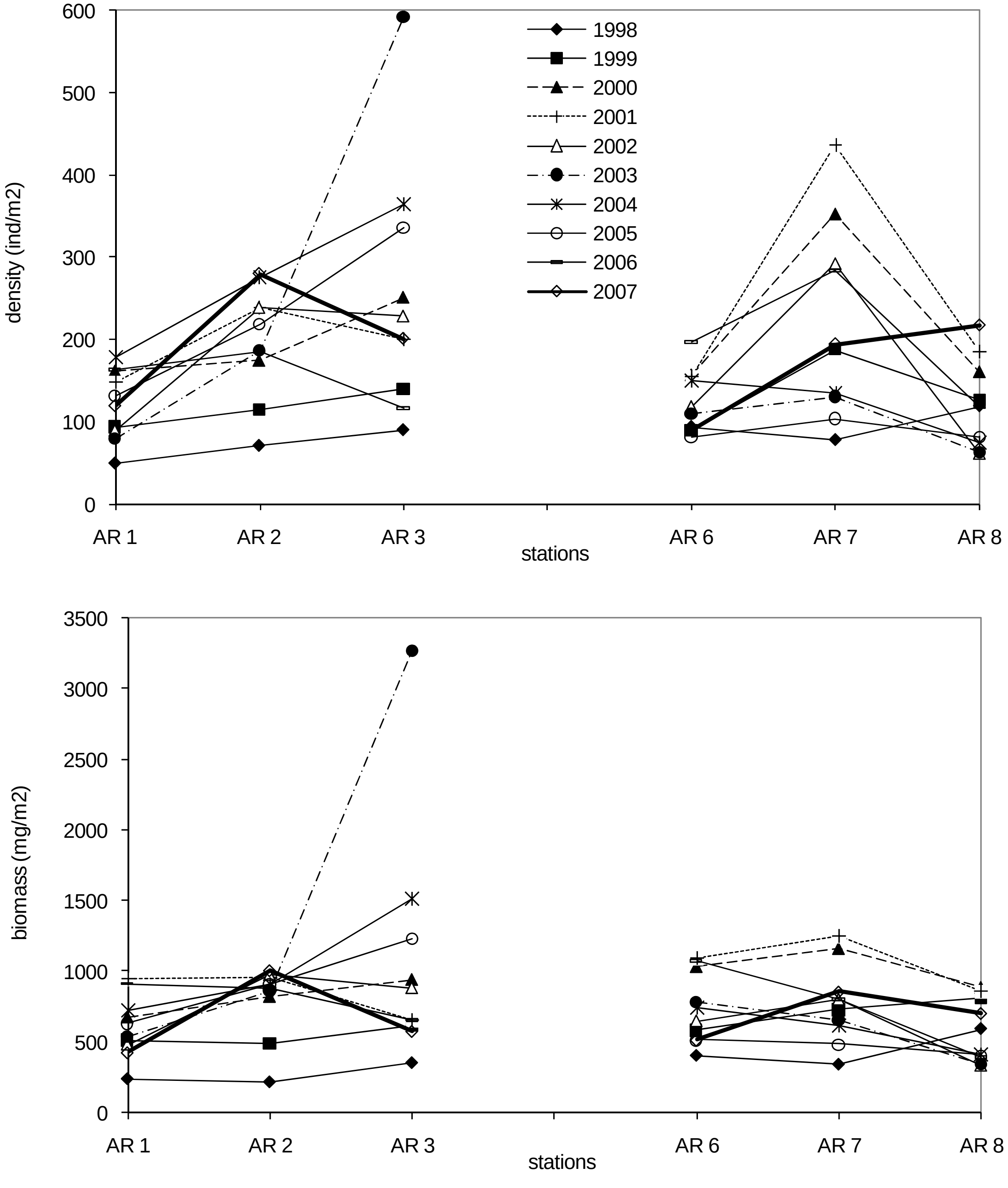
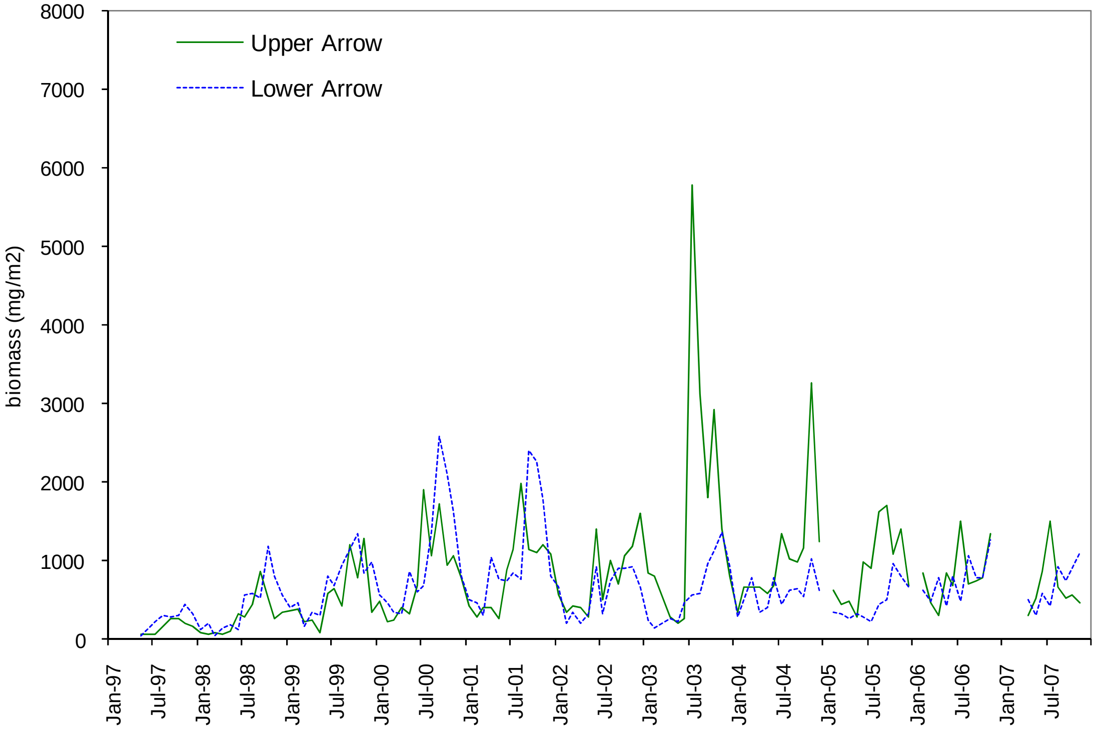


Figure 5.28. Annual average density (top) and biomass (bottom) of *M. relicta* from deep sites, along Arrow Lakes Reservoir, 1998 – 2007.



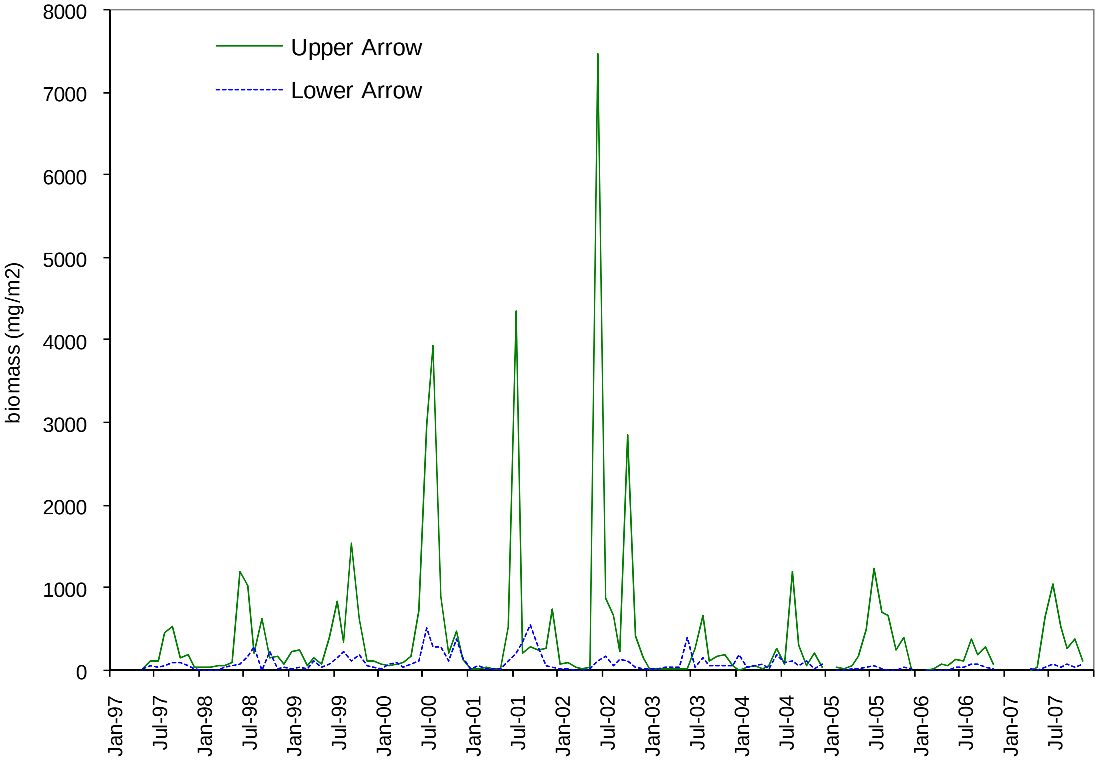


Figure 5.29. Seasonal average biomass of *M. relicta* in deep (top) and shallow (bottom) sites of Arrow Lakes Reservoir, 1997 – 2007.

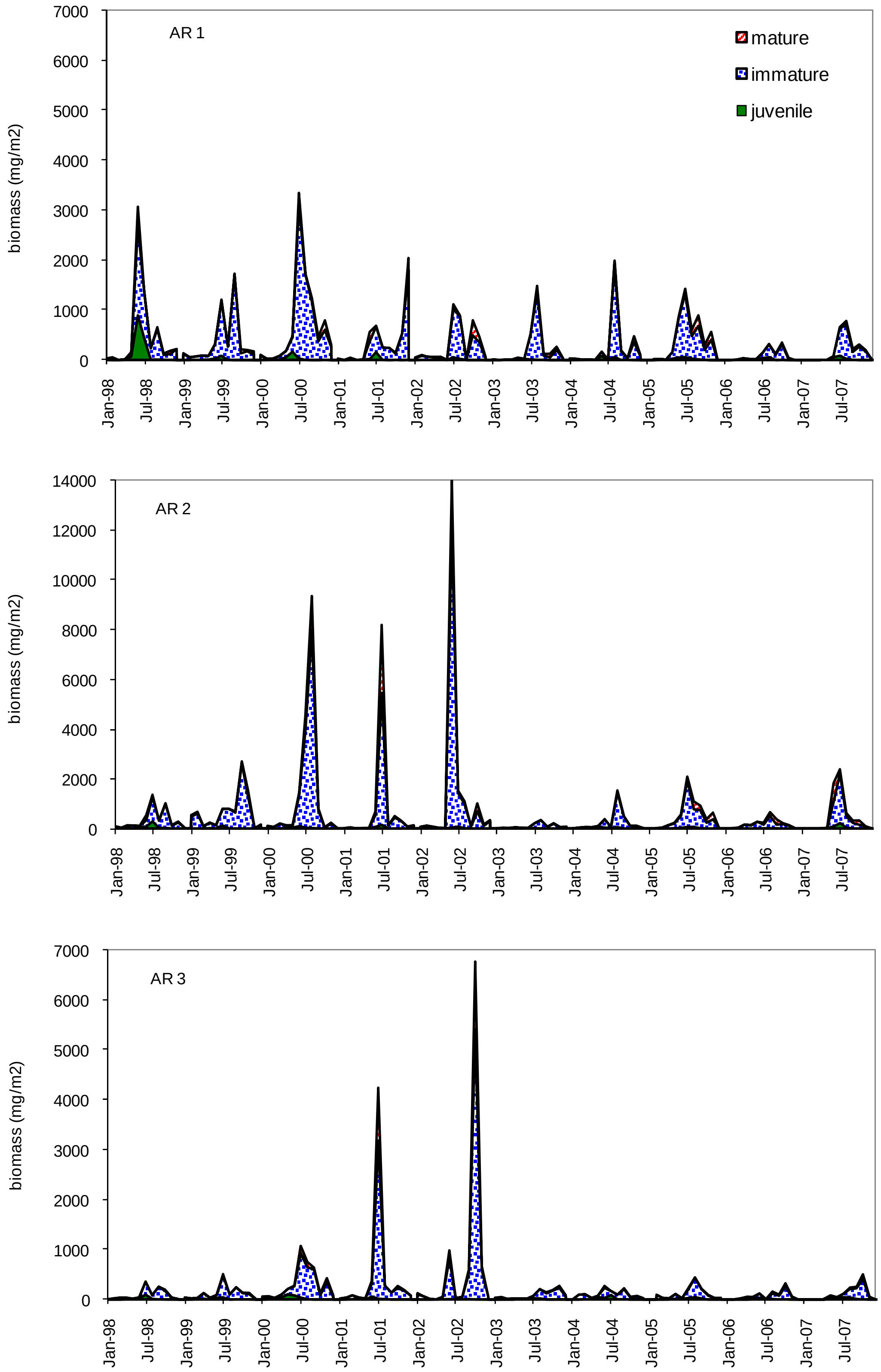


Figure 5.30. Biomass of developmental stages of *M. relicta* at shallow sites in Upper Arrow, 1998 – 2007.

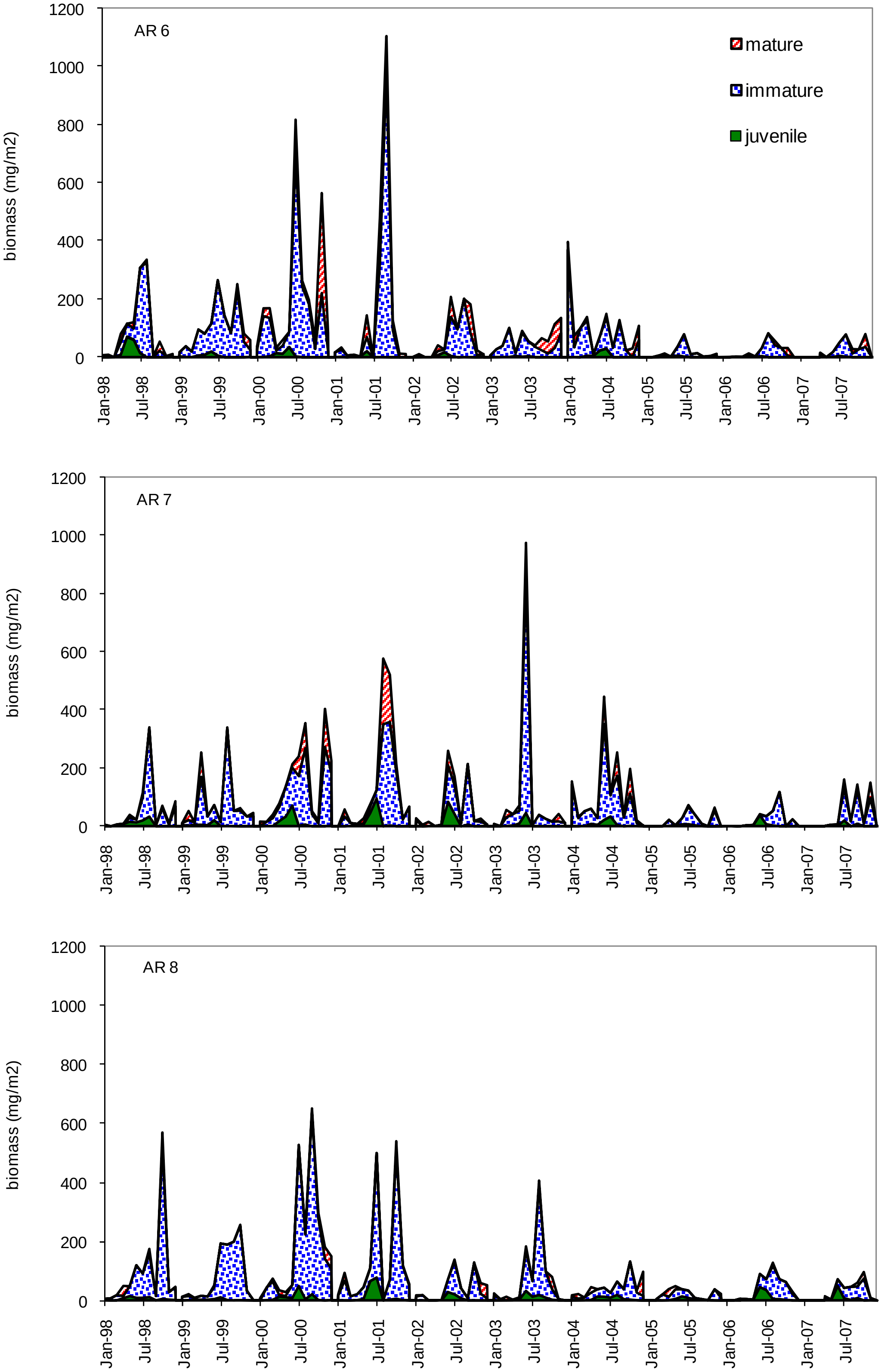


Figure 5.31. Biomass of developmental stages of *M. relicta* at shallow sites in Lower Arrow, 1998 – 2007.

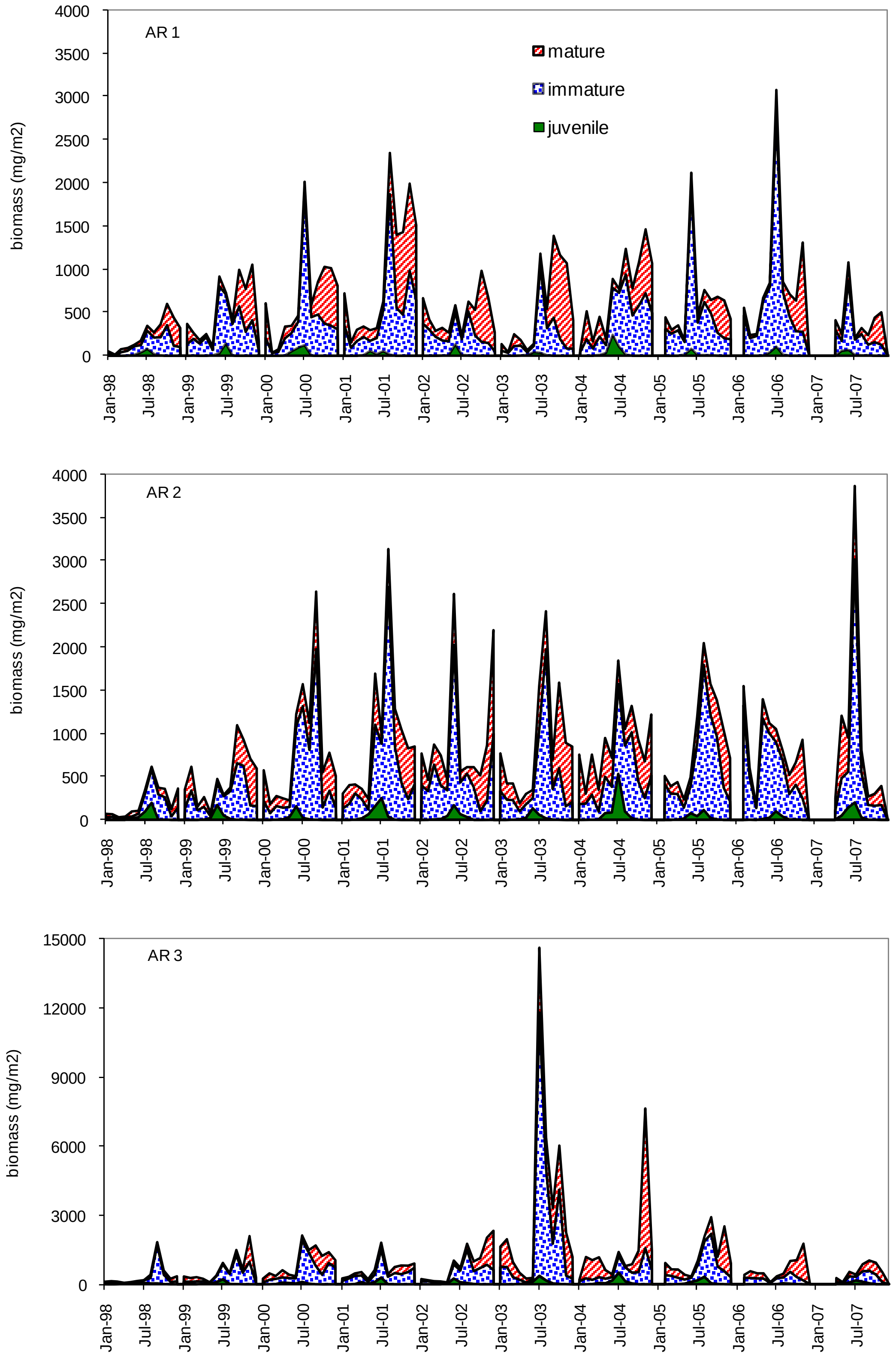


Figure 5.32. Biomass of developmental stages of *M. relicta* at deep sites in Upper Arrow, 1998 – 2007.

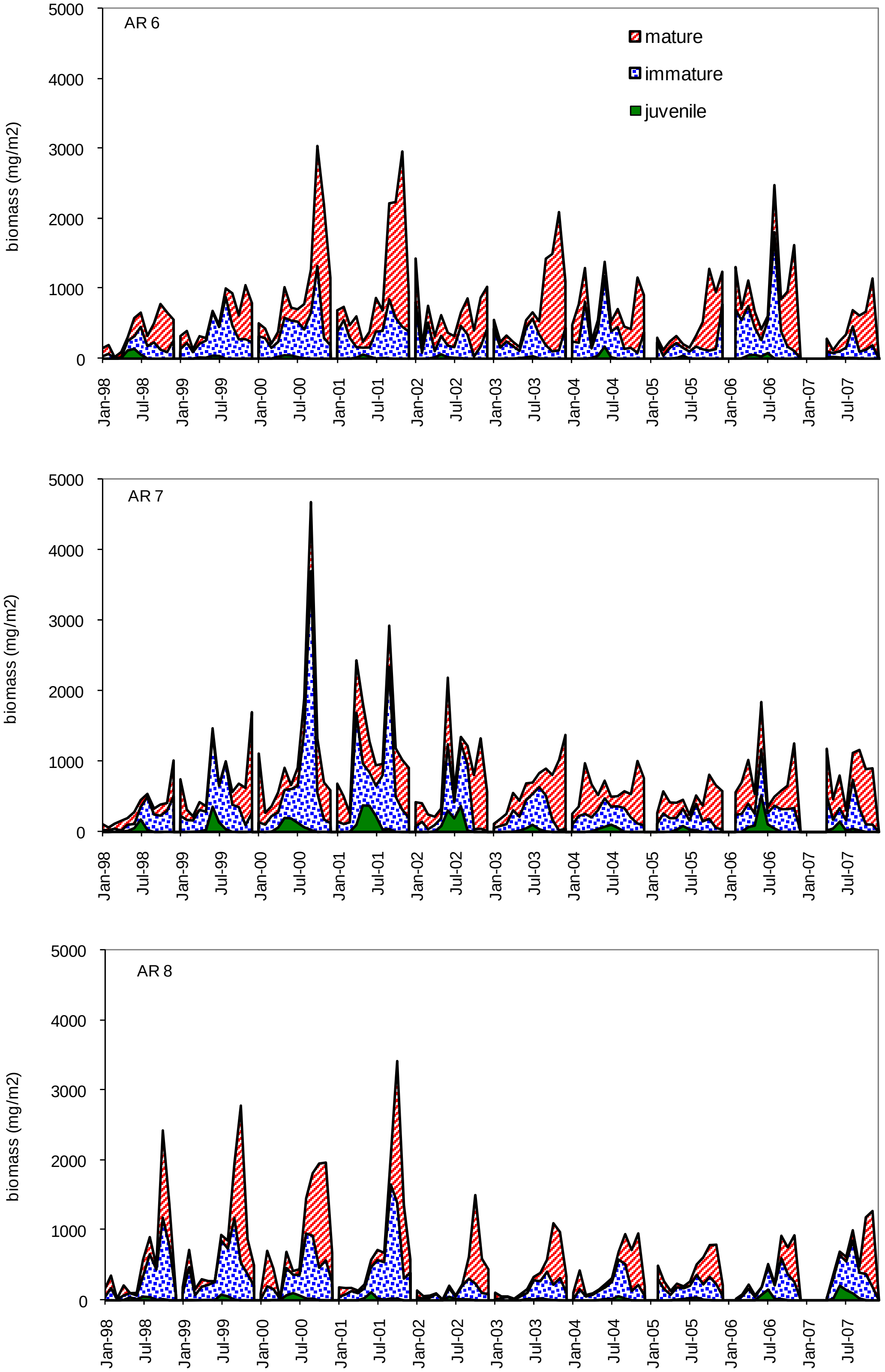
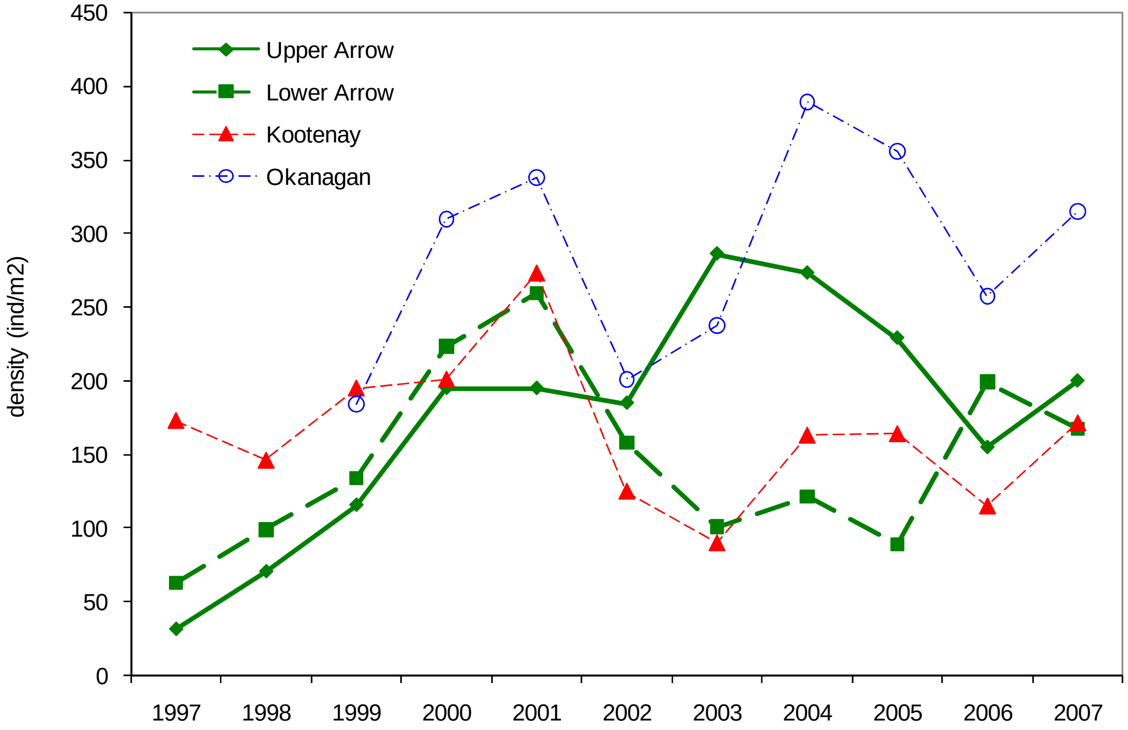


Figure 5.33. Biomass of developmental stages of *M. relicta* at deep sites in Lower Arrow, 1998 – 2007.



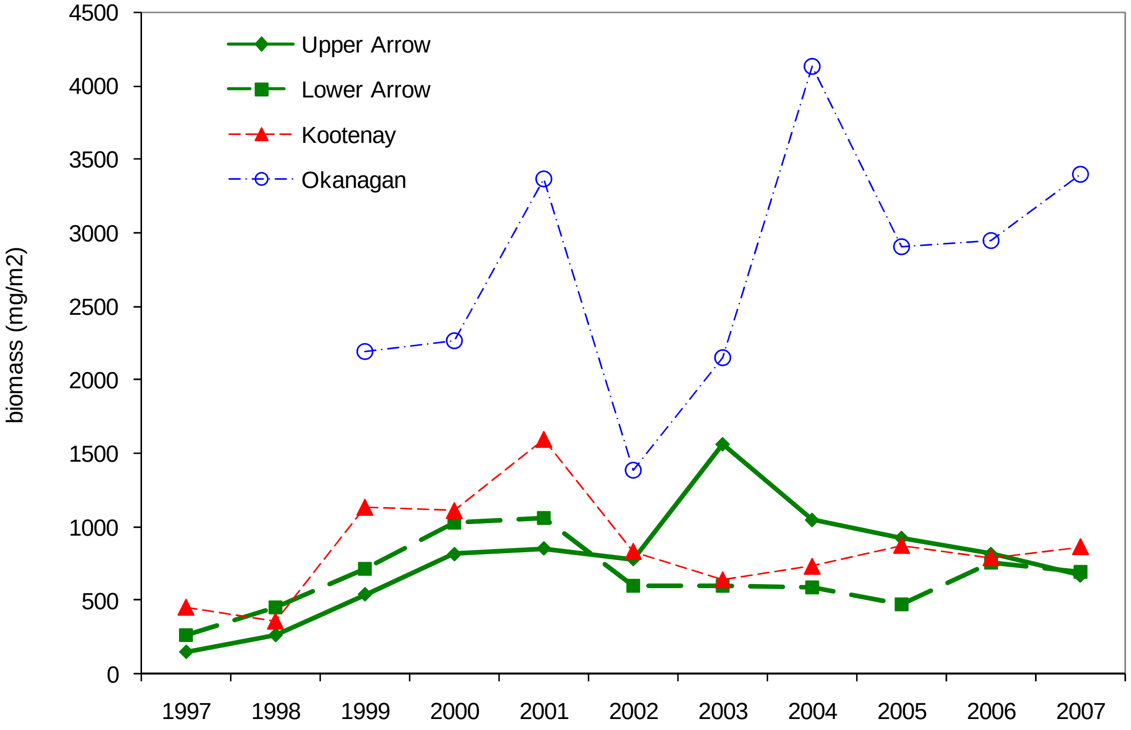


Figure 5.34. Seasonal average density and biomass of *M. relicta* in some British Columbia lakes, 1997 – 2007.

CHAPTER 6

RESPONSE OF ARROW LAKES RESERVOIR KOKANEE TO NUTRIENT ADDITIONS, YEAR 9 (2007)

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Introduction

The Arrow Lakes Reservoir (ALR) nutrient restoration program was modeled after the successful Kootenay Lake experiment that began over two decades ago. This reservoir was formed forty years ago when the Hugh Keenleyside Dam was constructed on the outlet of the former Lower Arrow Lake. Since then upstream reservoirs have further exacerbated the ALRs low productivity through retention of nutrients that formerly contributed to ALR production (Ney 1996, Pieters et al. 1999). As a consequence over the last two decades this reservoir has undergone oligotrophication primarily due to upstream reservoir nutrient uptake and wide seasonal variation in reservoir levels. In addition, Matzinger et al. (2007) modelled hydraulic alterations of the ALR caused by annual hydro plant water regulation. Their model predicted that hydraulic modifications such as deep water withdrawal or increased reservoir levels within the growing season can also reduce lake productivity by up to 40%. A further confounding factor to ALR fish production has been the introduction of *Mysis relicta* in 1968 (Sebastian et al. 2000) which is known to be a competitor with kokanee for macrozooplanktors. In response to these numerous perturbations the ALR kokanee (*Oncorhynchus nerka*) population verged on collapse in the late 1990s and a decision was made by the provincial government to initiate experimental fertilization of the Upper Arrow basin (Pieters et al. 2000). Pieters et al. (1999) described the background physical, chemical and biological data of Arrow Lakes Reservoir and the events leading to initial fertilization of the upper basin in 1999. Pieters et al. 2003 (*in* Stockner 2003) provides a summary of initial trophic level responses to the nutrient additions.

A number of technical reports have been written describing fish losses due to the dams on the ALR system upstream including Sebastian et al. (2000), Pieters et al. (2000) and Pieters et al. 2003 (*in* Stockner 2003). The diminishing numbers of ALR kokanee observed in the late 1990s responded to lake nutrient additions in a similar manner to Kootenay Lake kokanee where abundance and biomass increased about three fold (Schindler et al. 2009a). Since kokanee are often the keystone species in most southern British Columbia large lakes, their abundance usually determines 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 ALR once they achieve a size > 40 cm (Andrusak and Parkinson 1984; Arndt 2004a; Sebastian et al. 2003). Kokanee can also provide excellent fishing opportunities during the summer months.

Arndt (2004b) summarized ALR sport fish statistics and demonstrated improved growth and condition of 2003 rainbow trout and bull trout attributable to increased kokanee abundance (Arndt 2004a). Most recently Schindler et al. (2009a) compared a number of years pre-nutrient addition trophic level data with the first eight years of nutrient addition trophic level data and concluded that nutrient addition was highly beneficial to production at all trophic levels up to kokanee. However, this system is hydrologically and operationally complex thus close monitoring of trophic level responses to nutrient additions is essential. This report summarizes the 2007 status of ALR kokanee with the results compared with previous trend data summarized by Sebastian et al. (2000) and Schindler et al. (2009a). The impact on the kokanee population from nine years of experimental fertilization is discussed.

Kokanee assessment work on the ALR dates back to the early 1970s. The early years data provides the current ALR nutrient addition and monitoring program with a long term data set that shows trends over three decades in kokanee spawner abundance from several index streams and the Hill Creek spawning channel. Escapements approaching one million were observed in the 1960s and close to that into the 1970s. Hill Creek spawning channel was constructed in the early 1980s in an effort to replace ~ 0.5 million kokanee estimated lost due to the Revelstoke Dam blocking access to key spawning areas in the Upper Columbia River. Hill Creek initially experienced large escapements during the late 1980s possibly due to displaced Upper Columbia kokanee but the restoration target of 0.5 million has yet to be achieved. Hill Creek spawning channel data includes annual estimates of kokanee fry production and numbers of returning spawners as well as biological characteristics (eg., length, weight, fecundity, sex ratio and egg retention).

There are several partnerships involved in the ALR nutrient restoration 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, now called the Fish and Wildlife Compensation Program (FWCP) - Columbia Basin, administers the nutrient restoration project and most monitoring of the trophic levels with much of the technical support provided by MoE. Since 1999, the Columbia Power Corporation which operates the Arrow Lakes Reservoir Generating Station at Hugh Keenleyside Dam has also provided funding for the nutrient restoration program.

Methods

Each fall standardized trawl and acoustic surveys are conducted, index stream kokanee escapement estimates are made, and biological sampling is conducted at the Hill Creek spawning channel. The sport fishery is also monitored by the FWCP with the most recent results reported by Arndt (2004a). 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 between previously reported data and the revised database do not make any appreciable change to long-term trends in escapements or fish sizes. Kokanee spawner data in this report was obtained from the Nelson office of MOE using the 2007 data base.

Spawner Escapement, Size and Fecundity

ALR kokanee spawner numbers have been estimated for most streams dating back to 1966 with more rigorous enumerations made from 1988 onward (Sebastian et al. 2000). Estimates are made through a combination of several aerial surveys each fall and visual ground counts. During the 2000s three aerial surveys have been conducted at the time of known peak spawning (e.g. Hill Creek daily counts) thus ensuring a good estimation at or near peak of spawning. 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). Total counts are conducted at a fish fence located at the Hill spawning channel. A more complete description of methods employed for all kokanee enumerations can be found in Sebastian et al. (2000). Run timing generally occurs between late August and late September with the peak of spawning usually recorded during the third week of September. Streams surveyed and used as index sites for estimates of abundance are shown in Table 6.1. These index systems support approximately 85% of all the kokanee counted in the last three decades. Estimates from a number of smaller systems periodically enumerated can be found in Appendix 6.1.

Table 6.1 Upper and Lower ALR tributaries used as index sites for kokanee spawner estimates.

Upper Arrow	Lower Arrow
Hill Creek spawning channel	Burton/Snow Creeks
Bridge Creek spawning channel	Caribou Creek
Drimmie Creek	Deer Creek
Halfway River	Mosquito Creek
Kuskanax Creek	

Kokanee biological data is obtained each year from fish returning to the Hill Creek spawning channel. Redfish Consulting Ltd. (1999) described the operation and performance of this channel in detail. At Hill Creek the total number of fish in the system is estimated through a combination of manual channel fence counts and ground survey estimates of fish downstream of the channel. Kokanee are sub-sampled at the lower channel fence site for length, sex ratio, and fecundity. Annual egg deposition is estimated from the sex ratio and mean fecundity, less egg retention, determined from samples taken within the channel over the spawning period. Fry out-migration is determined each spring as described by Redfish Consulting Ltd. (1999).

Trends in kokanee fry-to-adult survival rates have previously been determined from spawning channel data for pre-fertilization years assuming that all the fish returned at age 3+ (Redfish Consulting Ltd. 1999; Sebastian et al 2000). Both length frequency distributions and otolith analyses have suggested however, that some years since nutrient additions, have included a mix of ages returning. Previous attempts to adjust for multiple spawner return years has led to some confusion and difficulty interpreting the results and assumptions when reported by adult return year. For simplicity, the fry to adult survival estimates in this report have been recalculated based on fry production years and cohorts have been followed through to the estimated number of adults of each age produced. No attempts have been made to estimate or compare fry to adult survival for age 2+ versus age 3+ spawners within the same cohort, but rather the combined percent return of all ages from that fry year has been reported. The data used for fry survival estimates are shown in Appendix 6.2 with highlights showing the data used to calculation a specific year. In the absence of otolith data, age proportions have been estimated from the length frequency distributions as described in the next section. Where otolith ages are in doubt as a result of combined length frequency and trawl age data or where there is disagreement between different aging specialists, the age proportions have defaulted to the length frequency method.

Previous attempts to adjust the spawner-recruitment ratio to account for multiple spawner ages some years did not appear to change the long-term trend appreciably. Therefore, we have returned to a simple trend assuming age 3+ returns accepting that some years may be misrepresented but that overall trends will be useful.

Age determination

Some uncertainty continues to exist regarding the age of ALR kokanee spawners although some previous age data is presented in this report. Age analysis of mature kokanee has been problematic on a number of large lake projects owing to scale resorption and or poor quality scales due to spawning condition. In recent years efforts have been made to resolve age determination by using otoliths but as with scale reading there have been mixed results. For example, in 2006 there was only 40% agreement between two investigators, so the ages defaulted to a single age at return (i.e. age 3+) represented by a single mode on the length frequency distribution. The most reliable data over the period of record has been derived from trawl captured fish that typically provide samples of all age groups that are easily distinguished by length frequency analysis and verified by scale interpretation. In the absence of otoliths, adult ages were estimated to be either one a single age (eg 3+) or a combination of two ages (eg. 2+ and 3+) based on the frequency distribution (i.e. unimodal or bimodal) and comparing the spawner mode with the mode of age 2+ trawl caught fish.

Note: ages of kokanee referred to in this report for example as age 3+ are fish that have grown through three winters and four summers.

Trawl sampling

In 2007 the annual trawl survey was not conducted in the fall owing to equipment failure. Except for 2007 standardized mid-water trawl samples have been collected in the fall of each year since 1999 to monitor annual variation in kokanee density, and obtain length and weight-at-age data. Scale samples have been collected from all age groups to confirm age. Trawling is always conducted during the new moon, when the fish are typically found in a layer at the thermocline and are least able to avoid the sampling gear. Three trawl stations are located within each of the two main basins (Chapter 1, Fig.1.1) and three trawls are usually conducted at each station. Stepped-oblique trawls ensure a representative sample of fish is obtained from each depth strata where fish are observed on an echosounder. The net is typically 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 is a 15 meter long beam trawl with a 5 m by 5 m square opening towed at 0.8 m s^{-1}. The net consists of graduated mesh panels from 10 cm (stretched mesh) at the head bar to 0.6 cm at the cod end. Net depths are estimated from the cable angle and the length of cable deployed. A geographic positioning system (GPS) is used to determine distances travelled and resulting boat speed and trawl sample volumes.

Captured fish are kept on ice until processed the following morning. The species, fork length, weight, scale code and stage of maturity are 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. (1995), kokanee lengths are adjusted to an October 1 standard enabling growth comparisons with previous fall surveys (also see Sebastian et al. *in* Pieters et al. 2003a).

Hydroacoustic survey

ALR hydroacoustic surveys in 2007 were conducted at night during October 17-20 in the limnetic area of the reservoir. Limnetic habitat for kokanee surveys was defined as habitat where water depth was greater than 20 meters depth at survey time (Pennak 1964). Acoustic surveys each consisted of 18 transects, 10 in the upper basin and 8 in the lower basin (Chapter 1, Fig. 1.1). All surveys have been conducted using standard methods as outlined in Sebastian et al. (1995) 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 several 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 6.3).

The Simrad 70 kHz survey data were digitized 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. 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 (Appendix 6.4). Limnetic habitat stratum areas were adjusted based on the reservoir water level at the time of the survey as outlined in Appendix 6.5. Mean transect fish densities are summarized in Appendix 6.6 and 6.7. 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 de-convolution 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+ to 3+ fish, respectively.

Previous years trawl captured fish lengths have been converted to the same acoustic scale using Love’s (1977) empirical relation (Appendix 6.8), and compared to acoustic size distributions in order to verify the age cut-off for the two size groups. Since it has not been 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.

Kokanee Biomass

Biomass estimates for pelagic habitat were determined from acoustic abundance proportioned into age groups based on both trawl and acoustic surveys (Appendix 6.9). Mean weights at age from the trawl data were applied to the total estimated numbers of fish at each age to determine total biomass in the reservoir. Lack of trawl samples in 2007 meant using the mean weights of age 0-3+ from 2006 and 2008[1] to estimate 2007 biomass estimates. In most years actual weights of spawners have been used to calculate Hill Creek spawner biomass (data on file MoE Nelson BC) and this was again the case in 2007. The sum of all weights for all age groups was then divided by the surface area of "pelagic habitat" to determine an average biomass density ($kg \cdot ha^{-1}$).

Results

2007 Spawner Escapement Estimates

The 2007 escapement estimate for Hill Creek was 113,339 (15,840 below channel; 97,499 in the channel) (Figs. 6.1, 6.2). The 2007 estimate for Upper ALR index streams including Hill Creek was approximately 126,000 while the Lower Arrow tributary estimate was about 96,000 **(**Figs. 6.1, 6.2). The lowest estimates on record were ~40,000 in the upper basin in 1996 and only 25,000 in the lower basin in 1997. The Upper Arrow streams including Hill Creek and spawning channel supported ~300,000-500,000 spawners during the late 1980s through to the early 1990s (Fig.6.1; Appendix 6.1). These escapements decreased through the 1990s with a similar declining pattern evident for the lower basin streams (Fig.6.2) with a record low escapement for these index streams in 1997. Upon commencement of nutrient additions in 1999 spawner numbers in both basins increased to peak numbers in 2004. However, for the third straight year the 2007 escapements declined to levels not observed since the mid 1990s.

Spawner Size and Fecundity

Hill Creek kokanee spawners have been monitored for numbers, length and sex ratio since 1977 and larger sample sizes (> 100) have been available since the spawning channel began operating in the early 1980s. Length frequency histograms representative of the last three decades are illustrated in Figure 6.3. There have been a series of major shifts in size frequencies that reflect density dependent increases/decreases in growth as a consequence of dam impacts that initially reduced spawning habitat and decreased reservoir productivity. For example, the average size of Hill Creek kokanee in the early 1980s (e.g. 1984) was slightly larger than the 1970s (data on file) most likely because overall numbers in the reservoir were lower due to the Revelstoke Dam which eliminated all kokanee spawning in the Upper Columbia River. At that time reservoir productivity had probably not yet begun to decline therefore growing conditions for fewer fish was most likely optimal. Bridge Creek kokanee also showed a similar upward shift in size frequency (Sebastian et al. *in* Schindler et al. 2009a). Mean size during most of the 1990s was small (e.g. 1997, Fig. 6.4) probably due to a combination of increased fry production from Hill Creek spawning channel and

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[1] Preliminary 2008 trawl results were available at the time of this writing.

reduced lake productivity due to nutrient retention in the upstream reservoirs. The large size reflected in the 2000 histogram demonstrates exceptionally good growth when in-lake abundance was relatively low but productivity had been increased significantly through nutrient additions. From 2002-2005 mean size was comparatively small ranging ~210- 230 mm as in-lake abundance was much higher (see below). The 2006 and 2007 size frequency distributions have again shifted to larger size fish as in-lake abundance has declined dramatically from 2004-2007 (see below).

Length frequency distributions for Hill Creek spawners displayed a single mode ranging between 200-270 mm for twenty of the last twenty-six years (Fig. 6.3). A very obvious change to a bimodal distribution was first seen in 1986 and 1987 following a single mode of very large individuals in 1985. A similar (bimodal) pattern became evident thirteen years later when nutrient additions began in 2000 that was even more pronounced in 2001 and carried into 2002 (Fig. 6.3). This pattern also followed a single mode of very large individuals in 1999. Age data (below) indicated that two age groups (i.e. age 2+ and 3+ fish) contributed to the spawning population from 2000-2002. Length frequency data for 2003-2005 (Sebastian et al. *in* Schindler et al. 2007a) illustrates a shift back to a single mode as mean size declined from 258 mm in 2001 to ~210 mm in 2004 and 2005. Starting in 2006 and again in 2007 there has been a shift to larger size fish presumably in response to good growing conditions and lower kokanee abundance in the reservoir. The 2007 histogram looks very similar to the 2000 and 2001 histograms in Figure 6.3.

Hill and Bridge creek spawners have undergone rather dramatic changes in average size and fecundity within the last twenty years (Note: biological data collection at Bridge Creek ceased after 2002). Two periods of high fecundities have occurred according to Figure 6.4. The first high growth and fecundity was in 1985 and may be tied to density of kokanee in the reservoir as described later in the discussion. Following a period of record low fecundities in 1996 and 1997 despite very low in-lake abundance, fecundity rose substantially to peak levels in 2000 that was >400 eggs /female (Figs. 6.4, 6.5). These changes are reflected in both Hill and Bridge creek data. In-lake abundance at this time was moderately high and building. Since the early 2000s female spawners returning to Hill and Bridge Creek channels have been smaller and their fecundities declined to < 240 eggs per female. During the mid 2000s when in-lake abundance was highest, Hill Creek mean fecundities have been only 189 (2004) and 214 (2005) but in 2006 and 2007 there were slight increases that coincided with a decline of in-lake abundance.

Age-at-maturity

It has become evident over the years that age of ALR kokanee spawners has varied between years and between basins depending on the status of reservoir productivity. Kokanee ages prior to lake fertilization were determined primarily by interpreting scale samples from trawl captured fish and comparing these with the size of spawners returning to Hill Creek. Between size frequency analysis, scale interpretation and limited otolith ageing it was concluded that these fish spawned predominately at age 3+. Further support of this ageing was provided by a small mark recapture experiment in 1997-98 where marked fed fry were recovered as adults from the channel and correctly interpreted as age

2+ fish using otoliths while the unmarked (wild) fish were mostly age 3+ (Sebastian et al. 2000).

During the last eight years a number of contractors have been used to determine age from otolith samples. There was confidence in the ageing especially for the 2001 fish since otolith ageing was consistent with the analysis from trawl and spawner length frequency distributions. Of 253 otoliths interpreted from the 2001 sample, 49% were age 2+, 51% were age 3+ and one fish was age 4+. Uncertainty of the 2003 ages from one contractor led to use of a different contractor who interpreted the 2004 and 2005 otoliths for Hill Creek and Lower basin streams as virtually all age 3+ (data on file). There were a few additional age 2+ spawners determined from the lower Arrow basin streams sample but still < 10% overall. Contractor availability has led to yet another contractor being used for the 2007 samples and there appears to be reasonable agreement between otolith ageing and size frequency analysis from previous trawl and spawner samples.

The 2006 ages were determined primarily from the trawl samples in combination with the size frequency of the spawners since the ageing of otoliths by two different contractors was inconclusive with only 40% agreement. Based on ageing and length frequency analysis of the trawl data it was concluded that the large majority of 2006 spawners were most likely one age group, i.e., age 3+ with possibly some age 4+ fish (Figs. 6.6-6.8; Table 6.2). Because trawl samples were not collected in 2007 age determination using the new contractor was relied upon. There appears to be reasonable agreement between otolith ageing and length frequency analysis for age 2+ and 3+ spawners (Figs. 6.3d, 6.4, 6.8), however, the length frequency method did not detect a component of 4+ fish given the considerable overlap in size distributions (Fig. 6.8). It is also worth noting that although all samples were randomly selected during the spawning run, the smaller sample of fish submitted for otolith analyses (n=100) had a higher proportion of smaller (i.e. age 2+ sized) fish than the larger sample of spawners measured for lengths (n=205). This can account for the slightly higher proportion of 2+ spawners suggested by the otolith analyses compared with the length frequency based on the larger sample size (Table 6.2). The shift in age-at-maturity from a predominately single age (3+) signals some important changes regarding the status of the reservoirs' productivity.

With commencement of lake nutrient additions in 1999, the age and size of Hill Creek spawners has been more variable including a temporary shift in the age of maturity. Based on length frequency distributions alone, a shift in size and age-at-maturity most likely occurred from 2000 to 2002, when bimodal length frequencies became evident (Fig. 6.3c). The data from 2003-2006 suggests a shift back to a dominance of age 3+ fish. The 2007 data indicates yet another shift in age-at-maturity with three age groups present although the majority still appears to be age 3+. The presence of age 2+ suggests good growing conditions in the reservoir for the early-maturing cohorts.

Reservoir pool elevation and habitat areas

A reservoir level of 432.8m or 7.4m below full pool during the October 2007 survey was ~2.5m higher than the three previous survey years. The areas of limnetic habitat (>20m depth) was estimated at 19,613 ha in Upper Arrow and 9,567 ha in Lower Arrow or

29,180 ha in total; an increase of ~500 ha over the three previous years (Appendix 6.5). Pool level at the time of survey is required to adjust habitat areas at depth for extrapolating fish densities to estimate total abundance.

Table 6.2 Age composition (%) of Upper and Lower Arrow basin kokanee spawners 1985-2007 based on otolith and length frequency analyses.

	Year	**Sample**	**% by otolith analysis**			**% by length frequency[1]**		
		(n)	**2+**	**3+**	**4+**	**2+**	**3+**	**4+**
Upper Arrow	1985					0	100	0
	1986					0	95	5
	1987					63	37	0
	1988					30	70	0
	1989					0	100	0
	1990					0	100	0
	1991					0	100	0
	1992					0	100	0
	1993					0	100	0
	1994					0	100	0
	1995					0	100	0
	1996					0	100	0
	1997					0	100	0
	1998					0	100	0
Hill Creek	1999	182	20	73	7	0	100	0
	2000	194	52	46	2	65	35	0
	2001	253	49	51	<1	54	45	1
	2002	200	50	50		79	21	0
	2003[2]	159	(94)	(6)		0	97	3
	2004	*99*	5	94	1	0	100	0
	2005	99	2	92	5	0	100	0
	2006[3]	100	0	(48)	(51)	0	100	0
	2007[4]	100	38	43	19	20	80	0
Lower Arrow								
Octopus Creek	1999	53	22	66	11			
	2000	29	7	90	3			
	2001	21	9.5	86	4.5			
	2002	22	41	59	0			
	2003	20	95		5			
	2004	30	3	94	3			
Deer Creek	2003	19	16	84	0			
	2004	30	3	97	0			
Caribou	2004	29	17	83	0			

1 Ageing based on length frequency analysis plus scale ages from trawling

2. Otolith analyses deemed to be out by one year based on trawl age 2+ size in Upper Arrow which did not overlap spawners

3. Only 40% agreement in otolith interpretation between two analysts so will default to length frequency proportions for survival calculations

4. Otolith determinations considered reliable based on Casselman ratings >5 even though different from length frequency analyses

2006 Trawl catch data

Since 1988 trawl surveys have been conducted on ALR but unfortunately in 2007 a major equipment breakdown occurred therefore trawling could not be conducted. Because three cohorts are typically sampled the 2006 data is shown to provide some supporting evidence for the ages of the 2007 spawners determined by the new contractor as described in the previous section. In fall 2006 the mean size of age 1+ fish in Upper Arrow was 145 mm and these grew to spawn as age 2+ in 2007 at a mean size of 215 mm. This is impressive growth from age 1+ to age 2+ and is discussed further below. The 2006 age 2+ fish mean size was 223 mm and these grew to spawn as age 3+ at a mean size of 246 mm. The mean size of age 3+ spawners was 259 mm suggesting these fish grew very little as age 4+ spawners in 2007 with a mean size of 266 mm.

Kokanee growth

Despite lack of 2007 trawl data it is informative to review previous trawl data and compare results with the known size of the three age groups that contributing to the 2007 spawner population. Size and growth of kokanee fry captured by trawl over the 18 years of record have been fairly constant similar to that observed on Kootenay Lake by Schindler et al (2009b). It does not appear that fry greatly benefit from lake nutrient additions as their size is similar before and after treatment (Fig. 6.9). However, growth has been quite variable for ALR age 1+ and 2+ fish and these age groups do appear to have responded to nutrient additions. Trends in mean length-at-age for all ages were relatively constant until 1995 when they decreased followed by large size increases, peaking in 1999. From 1999-2004 mean length-at-age for age 1-3+decreased only to again increase in 2005 and more so in 2006. Decline in size from 2001-2004 (Fig. 6.9) was most likely a result of the higher densities of age 1-3+ fish following initial nutrient additions. The levelling off of growth from 2002-2004 probably reflects a density growth response since densities of age 1-3+ fish had reached a maximum and levelled off. During 2005 and 2006 growth of age 1+ and age 2+ fish improved as expected due to low 2004 and 2005 fry production; i.e., positive density growth response. The growth of 2006 age 1-3+ fish to age 2-4+ in 2007 was impressive and reminiscent of the accelerated growth exhibited in 1999-2000 when nutrient additions commenced. Mean size of all 2007 spawners was slightly smaller than 2006 primarily due to the larger contribution of the smaller age 2+ fish to the spawning population. As discussed below there is however a concern that in-lake abundance during 2005-2007 was only roughly half that estimated in 2000-2001 even though nutrient loadings were similar.

Kokanee densities

In 2007 juvenile kokanee densities ($fish \cdot ha^{-1}$) varied considerably throughout the reservoir, both in depth and longitudinal distribution (Figs. 6.10, 6.11). The density contour plots illustrate how the depth of the fish layer changed from north to south over the length of the reservoir. At the most northern survey stations fish were found closer to the surface (e.g. Beaton Arm). The fish layer was deeper (e.g. 20-30m) in the main Upper Arrow basin compared with Beaton Arm and was deepest at the outlet areas of both the upper and lower basins (Fig. 6.10). Only in the vicinity of Beaton Arm at transect 2 were any fish recorded near the surface. This is important since fish found near the surface are difficult to enumerate with a downward looking acoustic survey therefore the night time surveys on ALR continue to be appropriate. In Lower Arrow the fish layer was found relatively deep and over a wide range of depths. Similar to 2006 the 2007 survey also detected somewhat higher densities of combined age 0+ and age1-3+ fish at the two most southerly stations. These fish may well be vulnerable to entrainment at the Hugh Keenleyside Dam.

Separating the kokanee densities into age 0+ and age1-3+ provides some additional insight into how the juveniles respond to general reservoir conditions such as internal flows, depth variation and food availability. There are two obvious patterns that appear from year-to-year. First, in the main Arrow basins where 99% of the trawl catches were kokanee, the highest fry densities were found at the northern or upstream ends of the Upper and Lower basins. This distribution was evident in 2006 as well as 2007 albeit far fewer fry were evident at the very southern end of the lower basin in 2007 (Fig. 6.11). Secondly, high densities are usually evident in the survey transects (# 19 & 20) located in the "narrows" between the two basins. Although highest fish densities were recorded in the narrows, previous years trawling indicated that kokanee were only 35% of the catch; i.e., other species were present and recorded.

It may be significant that the lowest densities of fry and age 1-3+ kokanee in 2007 were again found in the middle sections of the Upper and Lower Arrow basins (Fig. 6.11). This may indicate these areas are less productive for kokanee since it has been observed in Kootenay Lake that the highest densities of fry are often found in the vicinity of where the nutrients are added (Sebastian et al. *in* Schindler et al. 2009b). There was a noticeable absence of age 1-3+ fish at a number of transects in 2007, even less than in 2006 that was considered to be a low year. Also, the patchiness of age 1-3+ fish has not been seen previously to the degree evident in 2007.

Excluding the narrows, total transect densities in 2007 ranged from 75-498 fish$\cdot$ha^{-1}, much lower than the 2006 values of 218-638 fish$\cdot$ha^{-1} (Appendix 6.7). It should be noted that the last four years estimates have been far less than those made during 2001-2002 when a number of transects exceeded 1000 fish$\cdot$ha^{-1} with record numbers up to 3800 fish$\cdot$ha^{-1} at transect 18 in 2002. Kokanee distributions appear to be highly variable both seasonally and from year to year, presumably in response to recruitment levels and food availability.

Abundance

Hydroacoustic surveys on ALR have estimated total kokanee abundance since 1991 with additional manual echo counts made in 1988 and 1989. Prior to nutrient additions, kokanee abundance in the reservoir were less than 5 million dropping as low as 2.5 million in 1997. However, coincidental with lake nutrient addition beginning in 1999, kokanee numbers increased fourfold to ~20 million in 2001-02. Since then total abundance has declined to a low of ~5 million in 2005 and 2007 with a slightly higher number in 2006 (Figs. 6.12, Table 6.5). Estimates of total spawner abundance appear to track reasonably well with acoustic abundance estimates, particularly the abundance of age 1-3+ but with a lag-time (Figs. 6.13, 6.14). Production problems at the Hill Creek spawning channel during the winters of 2003-04 and 2004-05 but also poor egg-to-fry survival in tributaries is believed to account for 2004 and 2005 declines when relatively low numbers of fry were produced. The 2006 increase in age 1-3+ was unexpected and difficult to explain given the low production from Hill Creek. It is possible that survival improved that year due to good in-lake conditions but this did not carry through into 2007 when both age 0+ and age 1-3+ declined. The upper basin has consistently supported more kokanee than the lower basin since nutrient additions began. For example, in 2007 ~65% of total production was estimated in the upper basin (Table 6.3). Prior to nutrient addition, Upper Arrow produced ~50% of the total numbers of kokanee although it has about 2/3 of the pelagic habitat area. Since nutrient addition, it appears that kokanee abundance and biomass per unit area in Upper Arrow has become almost equal to Lower Arrow, which has also increased since nutrient additions began. Evidently both basins have benefited from nutrient addition but undoubtedly the high fry production from Hill Creek accounts for higher numbers in the upper basin.

Table 6.3. Comparison of maximum likelihood abundance estimates (and 95% C. L.) for kokanee by basin and year for Arrow Lakes Reservoir during the nutrient addition period, 1999-2007.

Nutrient addition 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	7.6 (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)
6	2004	October	4.6 (4.0-5.0)	2.8 (2.5-3.2)	7.3 (6.7-8.0)
7	2004	October	3.3 (2.8-3.7)	1.8 (1.5-2.1)	5.0 (4.5-5.6)
8	2006	October	6.3 (5.9-6.8)	2.4 (2.2-2.7)	8.8 (8.4-9.2)
9	2007	October	3.6 (3.0-4.2)	1.9 (1.6-2.3)	5.5 (5.0-6.0)

There are a number of indicators that illustrate the influence of nutrient addition on ALR kokanee. Hill Creek fry production during the pre-nutrient addition years (1991-98) ranged from 0.7 - 3.4 million while acoustic estimates of fry for the entire reservoir remained very low at 1.3-4.2 million (Table 6.6; Fig. 6.13). With commencement of nutrient additions, total acoustic fry estimates increased dramatically, exceeding 15 million in 2001. These peak fry numbers coincides with peak production at Hill Creek, indicating the importance of Hill Creek to the entire reservoir. The same pattern is observed for the age 1-3+ fish which increased following initial nutrient addition and peaked in 2002-03 or 1-2 years after fry numbers peaked. The end result has been much larger escapements to Hill Creek (and other streams) since nutrient additions began. Spawner numbers follow the increase in fry numbers with a lag of 3 years and follow age 1-3+ abundance with a lag of 1-2 years peaking in 2004 (Figs. 6.13 and 6.14). The downward trend in both fry beginning in 2003 and age 1-3+ fish beginning in 2004 foreshadows lower spawner returns for 2006-2009 that was initially believed to be due solely to low spawning channel fry production in 2004 and 2005. However the much lower fry estimates in 2006 and 2007 despite improved fry production at Hill Creek after 2005 and lower escapements to the tributary streams for both upper and lower basins in 2006 and 2007 (Figs. 6.1, 6.2) suggest something else may have occurred (see discussion).

Kokanee biomass

Kokanee biomass estimates have been made for the entire reservoir's pelagic area based on acoustic abundance estimates proportioned by age group and expanded by the average weight of fish in each group. Total biomass divided by the area of pelagic habitat provides an estimate of biomass per unit area in kg·ha^{-1}. These estimates should be considered preliminary as they rely on estimating age structure (i.e. proportion by age) from trawl catches which can be problematic due to low numbers caught. Since no trawl data was available for 2007 the mean weights of the 2006 and 2008 trawl samples were used to estimate 2007 biomass. After nutrient additions began, in-lake biomass of all age groups increased during 1999-2001 (Appendix 6.9 Fig. 6.15). Biomass density prior to nutrient addition (n=6 years) averaged 2.8 kg·ha^{-1} whereas the nutrient addition era (n=9 years) has produced an average of 10 kg·ha^{-1} representing an increase of about three times (Fig. 6.15). Spawner biomass is additional to the in-lake biomass estimates which were measured after the spawners had left the reservoir. The additional spawner biomass was estimated at 1.4 kg·ha^{-1} and 3.2 kg·ha^{-1} for pre- and post nutrient addition periods respectively. Despite these changes it should be emphasized that kokanee biomass estimates have been on the decline since 2001 although the 2007 in-lake estimate of 4.7 kg·ha^{-1} remained above pre-nutrient addition levels. In terms of standing metric tonnes of kokanee, biomass prior to nutrient addition averaged 81 tonnes; since nutrient additions began the average has increased to 290 tonnes, over a threefold increase (Appendix 6.9b).

Fry-to-Adult Survival Rates

Further insight into how kokanee have responded to reservoir nutrient additions can be considered through estimates of kokanee fry-to-adult survival rates. Fry survival estimates depend on reliable estimates of fry outmigration, adult returns and the aging of spawners. It should be recognized that fry survival estimates are more useful as trends rather than individual values since they integrate survival conditions over a 2-4 year period and it is not known at what stage mortality occurs. Prior to nutrient additions, fry to adult survival rates in both Hill and Bridge Creeks had fallen to <2% by the early to mid 90's (based on fry years) and had reached minimum values of <1% (Fig. 6.16). This declining trend changed beginning with the 1996 fry cohort and survivals climbed to nearly 9% in Bridge Creek and 11% in Hill Creek over the next 3-4 years. The initial increase (i.e. 1996 fry year) may be tied to the beginning of the nutrient addition program in 1999. A somewhat surprising result from the initial year of nutrient addition in 1999 was that age 3+ fish benefitted in their final summer of growth with spawner size increasing (Fig. 6.4) and survival rates increasing to about 6% based on the 1996 fry year (Fig. 6.16). The fry survival rates then declined during a period of higher kokanee densities in the reservoir as would be expected. A second significant rise in fry survival occurred with the 2004 fry as a result of the extremely low fry recruitment reported for Hill Creek Channel in 2004 and presumably as a result of the low kokanee abundance years that followed. An estimated 43% of the 113,500 spawners or 48,800 fish were estimated to be age 3+ fish in 2007 originating from the 229,000 fry in 2004 (Appendix 6.2). The resulting survival estimate of 21.3% suggested for the 2004 cohort seems high for kokanee since it would require annual survival rates in the reservoir averaging ~60% over the previous three year period. One would expect that fry to adult survival rates for tributary produced fry would also have experienced similarly high survival conditions as the spawning channel fish and resulted in increased returns to tributaries. On the contrary, spawner returns to tributaries in 2007 were extremely low. With the lack of spawner counts in 2003 one can only speculate that fry production from tributaries in 2004 must have been dismal with the main reason being an extreme high flow event in November 2003 as mentioned by Porto (2006). A problem with this argument is that fall fry estimates from hydroacoustic surveys in 2004 suggested total in-lake population of 4.62 million. If they didn't come from tributaries, then they must have come from the spawning channel, again bringing the low fry estimates reported in 2004 for the spawning channel into question.

Spawner–Recruit Relationship

Recruits produced by a group of spawners can be highly variable and is usually dependent on several density dependent factors from the egg stage through to adults. Walters and Martell (2004) describe a lake where recruit growth and survival occurs as foraging arenas where feeding and predation shape the number and size of fish returning to spawn. Since kokanee grow primarily based on the production of the secondary trophic level (zooplankton) the spawner-recruit relationship can be one 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 consecutive cycles. Except for 2003 and 2004 egg-to-fry survival rates have been reasonably constant over the last decade and harvest has been low thus minimizing potentially major sources of error. Predation is still an unknown factor but may cycle following the kokanee with a couple of years lag time.

When spawner numbers equal their parental numbers the spawner: recruit ratio (S/R) is one (1.0). The ALR kokanee S/R trend over time can be characterized as having two peaks and two troughs (Fig. 6.17). There were several cycles in the 1980s that had S/R ratios > 1 but starting with the 1990-1993 cycle and the subsequent 5 cycles through to 1998 the S/R was < 1.0 indicating that the recruits were unable to replace their parental numbers. During this period Hill and Bridge creek escapements fell to very low levels with some S/R ratios calculated between 0.1-0.4. Concurrent with these low ratios was low in-lake abundance (Fig. 6.12) that led to the decision to fertilize the Upper Arrow basin. The downward trends of the S/R ratios initially changed in 1999 when both Hill and Bridge creek spawning runs reached replacement levels and since then have easily replaced themselves except for Bridge Creek in 2003 until another change occurred in 2006. The second peak has been followed by another trough with the S/R ratios < 1 in 2006 and 2007 for both Hill and Bridge creeks. These estimates were made on the assumption that the vast majority of spawners return at age 3+. It should be noted that occasional years where there is a mix of spawner ages may not be well represented by this approach, however, the long-term trends will indicate in a general way whether stocks are in a building or declining state.

Discussion

An extensive monitoring program of ALR trophic levels has been continuous since experimental nutrient addition of the ALR commenced some nine years ago. The details of how the nutrients are dispensed by the Highway ferry that operates between Shelter Bay and Galena Bay BC can be found in Chapter 2 of this report. As a consequence of nutrient addition that began in 1999 and continued through 2007, there have been profound changes observed in kokanee populations of Upper Arrow Lakes Reservoir (Schindler et al. 2009a). Increased spawner numbers, increased growth, higher fecundity, higher fry-to-adult survival rates, and spawner-recruit ratios > 1 in most years all support the notion that improved growing conditions have existed within the reservoir. Unfortunately the most recent data (2006 and 2007) provide some signals that undesirable changes have occurred and reservoir production is in decline to near pre-nutrient addition conditions.

For the third consecutive year escapements to Hill Creek and virtually all other tributaries declined, an unexpected result since nutrient loadings have remained nearly constant throughout the last nine years. Of particular concern is the 2007 escapement level to the index streams in both basins. The upper basin index stream escapements were nearly as low as the pre-nutrient addition years of the mid 1990s. The lower basin index stream numbers in 2007 were also very low; the lowest level since nutrient additions began. The extremely low returns to Upper Arrow tributaries in 2007 can possibly be traced to a combination of low adult returns, the small size of spawners (low fecundity and egg deposition) and poor incubation conditions in the fall of 2003. There is cause to believe that incubation conditions and egg-to-fry survival may have been well below average as a result of an extreme fall freshet in 2003 which exceeded previous historical maximums for the month of November (Water Survey of Canada stream flow Records). Unfortunately, the adult counts were not completed in either Upper or Lower Arrow tributaries in 2003 due to the unavailability of helicopters during a year of extreme drought and forest fires. Although it seems reasonable that the mortality occurred prior to fry emigration, the hydroacoustic surveys provide evidence that 4.6 million fry were present in the reservoir during fall 2004.

During the last two years the derived spawner-recruit ratio for the Hill Creek Spawning Channel was <1.0 for the first time since nutrient additions began. This low value however was anticipated for the spawning channel in 2007 due to extremely low egg-to-fry survival experienced during the winter of 2003 and resulting low fry production estimate for 2004. What is surprising is the higher than expected return to Hill Creek in 2007 compared with other tributaries. Potential explanations for the higher than expected returns to Hill Creek in 2007 include: (1) Fry production from Hill Creek and spawning channel was under-estimated in 2004, (2) density-dependent population dynamics resulted in unusually high fry to adult survival in the reservoir, (3) a substantial amount of straying into Hill Creek occurred from other index streams, perhaps related to low tributary flows in 2007. Scenario 3 (excessive straying) seems very unlikely since there have been no previous incidents of straying to the extent needed to explain Hill Creek escapements in 2007. Scenario 2 seems unlikely as it suggests very high fry to adult survival (i.e. >20%) occurred in the reservoir which would have benefited both tributary and spawning channel stocks and appears to contradict the system wide downward trend in kokanee returns in 2006 and 2007. We believe that scenario 1 (i.e. higher than reported fry production from Hill Creek in 2004) is the most credible explanation to account for observed returns to Hill Creek compared with tributaries in 2007 and also helps to explain the system wide estimate of 4.6 million fry in fall 2004.

Size-at-maturity of Hill Creek spawners can also be used to interpret to some extent what dynamics are at play in the reservoir. When nutrient addition began in 1999 spawner mean size increased reflecting a positive density growth response. Size increased through to 2000 then began to decrease as in-lake abundance increased. Grover (2006) has also observed a negative size-abundance relationship in kokanee that reside in Bucks Lake California. After 2001 Hill Creek spawner size levelled off for three years until a considerable increase occurred in 2006. At the time it was felt that this increase may be due to another density growth response as the in-lake numbers of age 1-3+ fish had declined to a low level by 2005 (Fig. 6.13). The 2007 mean size decreased slightly compared to 2006 yet in-lake abundance decreased in 2007. The decrease in size is attributable to a shift in age at maturity with the 2007 spawning run comprised of a larger proportion of the smaller age 2+ fish as in-lake growth conditions improved. The fact that abundance is decreasing rather than increasing is reason for real concern for the managers of the nutrient restoration program. There are clearly some other factors at play within the reservoir. All of the above described changes emphasize the importance of continuous monitoring of the key biological parameters. Forecasting shifts in size, fecundity and spawner numbers is especially important for spawning channel management where fry production is a primary objective.

Age determination of ALR kokanee continued to be problematic especially since lake nutrient additions began and large changes in growth rates are evident. Kokanee ageing is particularly important in overall monitoring of their status in response to nutrient addition but remains a challenge for fisheries managers on ALR and other large lakes. Many attempts at conventional ageing using scales or otoliths of mature fish have been unsatisfactory and problematic not only on ALR but also for Okanagan Lake kokanee (Andrusak *in* Andrusak et al. 2005). The most reliable ageing method is to use trawl length frequencies aided by scale analyses to determine early ages with reasonable certainty. Spawner ages are then estimated by overlaying their length distribution with the younger fish of known age. It should be mentioned that recent ALR otolith interpretations usually have agreed (except 2006) with the above method in determining that the majority of kokanee are currently spawning at age 3+ (Sebastian et al. *in* Schindler et al. 2007a). Although ageing of otoliths in 2007 was considered good and lacking trawl data meant accepting the ages without secondary evidence (from the trawl) the proportion of age 2-4+ spawners is somewhat in question since it appears contradictory to have fast growing age 2+ fish in the same spawner population as slow growing age 4+ fish. We believe it is most likely that some of the ages assigned as 4+ were actually age 3+ fish.

There is a fairly strong relationship between ALR spring spawning channel fry estimates and fall fry abundance estimates (Fig. 6.18). This relationship gives some confidence in reliability of both fry enumeration and hydroacoustic estimates of fry. It also provides some confidence in annual fry recruitment levels that can be tracked through to adult returns. Since 2001, fry abundance declined for four years due to density dependent growth leading to smaller sized females throughout the Arrow system and more recently low fry production from Hill Creek spawning channel and tributaries in 2004 and 2005. The 2006 abundance estimates signalled the first increase in all ages since 2001(fry) and 2002 (age 1-3+). Despite good production from Hill Creek in 2007 of nearly 7 million fry, the 2007 acoustic estimate declined as a result of lower survival and contribution of fry from tributaries in 2007 compared to 2006. The prediction from the acoustic and trawl data is for further declines in spawner returns during 2008 and possibly 2009 given the very low estimate of ages 1-3+ fish in 2007. The current lower in-lake abundance should result in a positive density growth response resulting in another upward cycle in growth, fecundity and fry abundance similar to the 1998 and 1999 response providing that higher productivity levels can be maintained with the continued application of nutrients. There is gathering evidence that other factors such as high flow-through due to high summer discharges from upstream dams (see Chapter 4 of this report) are negatively impacting the bottom up response that nutrient additions provided in the early years of the nutrient restoration program.

Hill Creek spawning channel kokanee fry production is of fundamental importance to restoration of fish in ALR and is a primary goal of the Ministry of Environment and the Fish and Wildlife Compensation Program (Sebastian et al. 2000). Prior to construction of the spawning channel Hill Creek supported ~10,000-13,000 kokanee spawners (Lindsay 1977). The channel was completed in 1980 and spawning kokanee initially used the channel in 1984 (Lindsay 1982; Sebastian et al. 2000). The channel is approximately 3.2 km long and 6.1 m wide, designed to support a theoretical number of 150,000 kokanee spawners at a spawning density of ~7.7 $spawner \cdot m^{-2}$. Kokanee numbers returning to spawn in Hill Creek and the spawning channel rose dramatically during the late 1980s following channel construction, and declined during the 1990s. Following the beginning of the nutrient program there were increases through the early 2000s until decreased numbers in 2006 and 2007 primarily because of low fry production in 2004 and possibly low fry survival in 2007 (Fig. 6.1). The goal has been to produce 0.5 million spawners but the highest returns to date have only been ~ 300,000. None the less, Hill Creek is a substantial producer of all kokanee in the reservoir. For the upper basin Hill Creek escapement numbers represent ~72% of the total enumerated in the major (index) spawning streams (Fig. 6.1). The extremely poor index stream escapement in 2007 meant that Hill Creek represented almost 90% of the total. For the whole reservoir from 1995-2007, Hill Creek spawners represents ~30% of the entire total for all the major spawning streams. In 2007 this percentage increased to ~48%.

Fry production at the Hill Creek spawning channel increased substantially following the first year of nutrient addition as a result of increased escapements of larger fish with higher fecundity which led to a 5-10 fold increase in the egg deposition starting in fall 1999 (Table 6.4). Fry production was close to 8.5 million in 2001 and 2002 but due to two consecutive low production years in 2004 and 2005 production fell to 0.23 million followed by 0.67 million in 2006 and 5.5 million in 2007. Redfish Consulting Ltd. (1999) demonstrated that up to 1998 the spawning channel was not producing maximum fry numbers largely because the channel performance had not been tested by deliberately loading spawner numbers to determine the asymptote of the relationship between spawners (eggs) and fry.

Table 6.4. Kokanee fry production from Hill Creek spawning channel 1992-2007.

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-to-fry survival (%)
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	102,400	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
2003	133,951	233	9	48	14.43	0.23	1.6
2004	199,820	189	4	35	9.53	0.67	7.0
2005	142,755	214	5	48	12.99	4.66	36
2006	91,649	240	8	48	10.21	5.46	52
2007	97,731	236	4	46	10.07	6.96	69

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.

Two metrics, fry-to-adult survival and the spawner-recruit relationship, provide further insight on how the Arrow Resevoir kokanee population has responded to reservoir nutrient addition. During initial years of nutrient addition, fry to adult survival rates increased substantially at a time when kokanee abundance was low. In-lake abundance rose from pre-nutrient addition estimates of ~ 5 million (all age groups) to highs of ~ 20 million in 2001 and 2002. After 2000 fry-to-adult survival rates (represented by 1999-2001 fry years) fell, a clear sign of increased mortality in the reservoir due to a density dependent response to the high abundance of age 1-3+ kokanee during 2001-2003 (Fig. 6.13). However, the survival rates remainded low for another two years even though by 2004 abundance was much lower. An increase in the 2006 abundance estimate did occur only to be followed in 2007 by a drop to only 5.5 million. The considerable increase in the fry-to-adult survival rate of the 2004 fry year represented by the 2007 adult return could be a signal that there has been an initial density dependent response to lower abundance of the last three years but this estimated rate is confounded by the uncertainty around the 2004 fry estimate from Hill Creek spawning channel and some question of the proportion of the 2007 spawner ages. If the survival rate remains high and mean size decreases then a shift upwards in kokanee abundance would be expected in 2008. However, the 2007 acoustics data (i.e. age 1-3+) already foreshadows probable continued low abundance in 2008. It is fairly clear the mid 2000s population is not responding to nutrient additions in the same manner as it did during the initial years of nutrient additions.

It is speculated that the high(er) spawner–recruit ratios (S/R >1) for the late 1980s were probably due to lower in-lake numbers in the reservoir in the mid 80s resulting from significant habitat loss and subsequent reduced fish production from construction of the Revelstoke Dam. Fewer kokanee in the upper basin due to loss of production from the Upper Columbia River above Revelstoke Dam would have resulted in improved growing conditions in the upper basin for those kokanee produced below Revelstoke and is consistent with spawner size and survival data reported at Hill Creek during the mid 80s. However, declining lake productivity began to be reflected in the kokanee population by the early 1990s and S/R ratios fell to < 1. During this period kokanee fry production from the Hill Creek spawning channel was rapidly expanding creating a density dependant response in the face of a much lower reservoir carrying capacity. The positive spawner-recruitment ratios for both spawning channel populations from 1999-2005 was a signal of a reversal of the downward trend that began in the early 1990s (Fig. 6.17). The declining S/R rates in recent years are not surprising since the parental numbers increased considerably during this period (Fig. 6.1). However, the S/R ratios in the last two years have fallen below one, an unexpected result that also points to in-lake survival problems.

Kokanee biomass estimates calculated before and after nutrient additions provide convincing data supportive of positive influence of nutrient additions on ALR kokanee in the early years (Fig. 6.15**)**. There has been nearly a fourfold increase in average biomass since 1999 and the escapement numbers reflect this increase. However, the declining trend since 2001 also supports the notion that something is amiss within the reservoir. The 2007 estimate was only slightly higher than the pre-nutrient addition era. Biological data presented in this report provide clear evidence that lake nutrient addition was initially successful in restoring kokanee, albeit not to an initial target of ~0.5 million kokanee returning to Upper Arrow. The data also indicates that in the most recent years, kokanee have not responded nearly as well. The recent addition of kokanee biomass to the annual suite of monitoring indicators will assist in determining if the initial restoration targets are achievable through a combination of nutrient addition and fry production at Hill Creek spawning channel by providing another metric for determining when the system carrying capacity for kokanee has been reached.

A key question has been “was the original adult target of 500,000 spawners achievable at Hill Creek”? The question can be broken down into two parts as follows: what is the potential for the spawning channel to produce fry, and do the survival rates in the reservoir enable returns to reach the target of a half million adults? A plot of egg deposition vs. fry produced from the channel (only) shows a linear relationship (Fig. 6.19) that strongly suggests maximum fry production has yet to be achieved. It is recommended that the channel be loaded with adults to determine what its’ capacity is to produce fry. The second question examines the relationship between fry production levels and resulting survival in the reservoir, since it is non-linear. With limited data for the fertilized regime, it appears that the relation between fry production and survival can be described with a power model (Fig.6.20). Unfortunately, in the absence of high fry outputs, the limitations on survival can only be extrapolated outside the bounds of existing data so remains highly speculative. Some predictions for increased production are presented in Table 6.5. Preliminary results suggest that fry production could reasonably be increased to 20 million to produce a theoretical adult return of 400,000. Beyond this, it appears that survival in the reservoir may become a limiting factor to the extent that fry outputs cannot achieve replacement levels. For example, the power model suggests you might need a fry production of 32 million to achieve a return of 500,000 adults to the spawning channel as fry survival rate declines to 1.57%. This level would not be sustainable if 32 million fry would only result in a maximum production of 25 million fry from the channel. This simplistic analysis suggests that the target of 0.5 million adults may not be achievable unless survival in the reservoir can be further improved.

Table 6.5. Theoretical return rates and resulting fry production from increased fry production at Hill Creek spawning channel based on preliminary survival relation in Figure 6.20.

Fry Production (millions)	Predicted survival Rate in reservoir[1]	Potential adult returns to channel[2]	Future Fry production[3] (millions)
10	2.88%	288,000	14.4
15	2.33%	349,000	17.5
20	2.00%	400,900	20.0
25	1.78%	446,000	22.2
32	1.57%	501,000	25.0

1. Based on power model in Figure 6.20
2. Fry x Predicted survival rate
3. Theoretical fry production in channel based on 1:1 sex ratio, fecundity of 200 eggs/female and 50% egg-to-fry survival

There are a number of similarities between results of nutrient addition to Upper Arrow Reservoir and nutrient addition to the North Arm of Kootenay Lake. The results from Kootenay Lake show some dramatic changes to the kokanee population over the last two decades. Kootenay Lake kokanee responded almost immediately after nutrient addition began with rapid growth, increased fecundity (e.g. 200 to 400 eggs/female) and a shift in the average age at maturity from age 3+ to age 2+ (Sebastian et al. 2009). Escapements increased similar to what has been observed on ALR over the first five years of nutrient addition. When the nutrient additions were deliberately reduced in Kootenay Lake in 1997 the in-lake abundance declined which led to three consecutive low escapement years in 2000-02. When nutrient additions were restored to original levels in 2000, in-lake abundance increased leading to near record escapement levels by 2004 and 2005 while age-at-maturity returned to age 3+ and the average spawner size declined (Schindler et al. 2009b). A similar response has occurred on ALR for but reasons appear to be different. Nutrient loadings on ALR have not been reduced, yet in recent years in-lake abundance, S/R ratios and biomass have all declined to near pre-nutrient addition levels. What has been reduced in ALR is fry recruitment levels over three consecutive cohorts (2003-2005 fry years) through a combination of spawning channel management and natural causes (e.g., extreme fall flows and egg mortality). Given that recovery from this period has not yet been seen, these results are troubling with all evidence pointing to a decline in lake productivity. A longer time series is required to determine what levels of kokanee can be sustained in

ALR with continued nutrient additions and increased fry output from Hill Creek spawning channel.

Differences in fry-to-adult survival rates between ALR (Bridge and Hill creeks) and Kootenay Lake (Meadow Creek) are worth mentioning. It can be misleading to look at individual (survival) years since this can vary depending on the average age at maturity and ageing has been difficult. It may be more reliable to compare average survival rates over a few consecutive years as this will tend to average out any errors due to spawner ageing problems. Both Arrow and Kootenay showed comparable responses during the initial four year period of nutrient addition with average survivals increasing by roughly threefold to nine to ten percent. These increases in survival (and certainly the peaks) may be largely related to the younger average age at maturity during this initial nutrient addition (i.e. rapid growth) phase. On Kootenay Lake the average fry-to-adult survival just prior to nutrient additions was ~6% compared with only ~2% on ALR. The first four years after initial nutrient additions to Kootenay showed an average increase of fry-to-adult survival to ~10% followed by a decline to ~4% but with much higher spawner numbers than prior to treatment. This probably indicates the lake in the late 1990s was likely approaching a new carrying capacity. Based on Hill Creek data, the ALR kokanee fry-to-adult survival averaged only 2.2% throughout the 1990s during a period with very low in-lake abundance and spawner returns. This supports the notion that carrying capacity of ALR prior to nutrient addition was limiting. Upon nutrient addition, the average survival in ALR increased to ~8% during the first four years and then returned to 3% but with much higher numbers of spawners returning. The rise in the ALR 2007 survival rate shown by the 2004 fry year is most interesting but has some uncertainty due to ageing and spawning channel production problems as discussed previously. This may be an anomaly and reinforces the point that individual survival rates should not be interpreted as singularly important. It may also suggest there is a lower critical limit of fry production below which stocks have difficulty recovering even though the system is nutrient enriched and the survival rates are very high.

The role of predation in maintaining and possibly exacerbating cycles in kokanee response to nutrient addition is beginning to be of interest in both systems as evidence of predator cycles becomes available. Developing reliable methods for tracking predator populations will also be important in assessing the overall impact of nutrient addition on fish populations in these systems. The top down effect of predators on kokanee may be different between Arrow and Kootenay Lake as a result of the fishery; a more intensive fishery on Kootenay Lake may serve to limit or “control” predator numbers as they increase. Creel census should provide more insight into the effects of the fisheries on kokanee in Arrow and Kootenay.

The response of ALR kokanee to lake nutrient addition reflects the positive responses of the lower trophic levels in this large scale experiment that has been documented in other BC reservoirs (Perrin et al 2006; Stockner and Ashley *in* Stockner, 2003). The overall biomass of kokanee has increased on average by nearly four times indicating that restoration has initially been successful. However the most recent data on ALR points to in-lake productivity problems such as effective transfer of nutrients from one trophic level to another and or suspected changed physical conditions due to increased discharge during the growing season which may increase entrainment of both zooplankton and kokanee.

Recommendations

1. More attention needs to be directed to the question of reservoir flow through to determine if this is a causative factor in the recent decline in the ALR productivity as reflected in the recent decline in the kokanee population.

2. The Hill Creek spawning channel should continue to be evaluated annually for fry production, spawner numbers and associated biological data annually including sex ratio, length, weight, fecundity and egg retention.

3. The original target of 150,000 spawners for Hill Creek Spawning Channel did not consider the small size and low fecundities of kokanee that occur at higher densities. Spawner numbers permitted into the spawning channel should be increased well beyond the original target of 150,000 in order to test the channel capacity to produce fry (eg. Is producing 20 million fry even feasible?). Fecundity estimates must be done weekly during the spawning period to ensure egg deposition targets are met or exceeded.

4. The density-dependent relationship between kokanee density and fry to adult survival in the reservoir should be tested with higher fry output levels from Hill Creek spawning channel to help determine reservoir carrying capacity with continued nutrient enrichment.

5. Lower Arrow kokanee spawners need to be sampled annually from three streams to determine size and age-at-maturity. A minimum of 30 samples per stream should be collected for otolith analyses.

6. The acoustic and trawl surveys provide some key information for monitoring the response of kokanee to nutrient addition. This time series needs to be continued into the future.

7. The role of predation on kokanee cycles is not well understood. Some discussion and planning around monitoring of predator populations is recommended.

Acknowledgements

Thanks to staff listed in Chapter 1, Table 1.1 for assisting with the various tasks associated with understanding kokanee in Arrow Lakes Reservoir. Thanks to Steve Arndt of the Fish Wildlife Compensation Program – Columbia Basin for reviewing this report.

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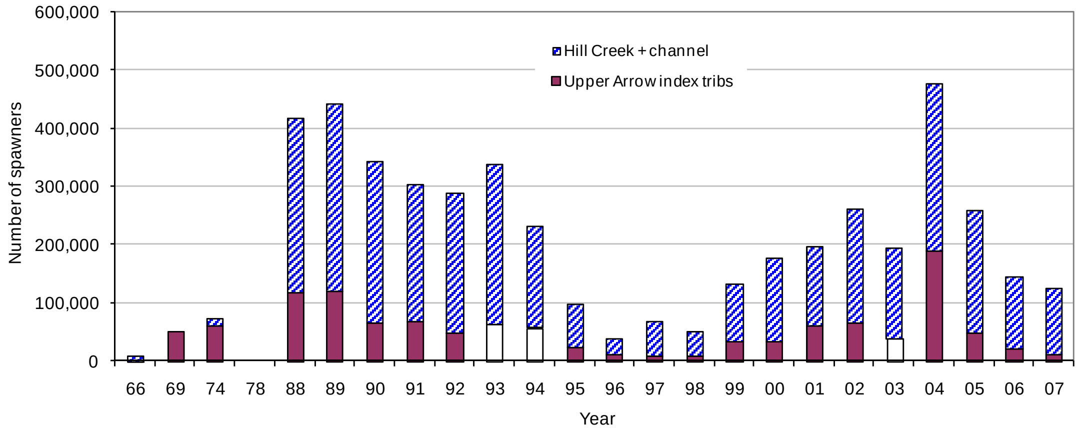


Figure 6.1. Trends in kokanee spawner returns to Hill Creek and four other index streams (Drimmie, Halfway, Kuskanax and Bridge) in the Upper Arrow Reservoir, 1966-2007. Note: estimates for 1993, 1994 and 2003 for index streams based on average escapements in previous four years. Index stream estimates have been expanded by 1.5 (including Hill Creek below channel).

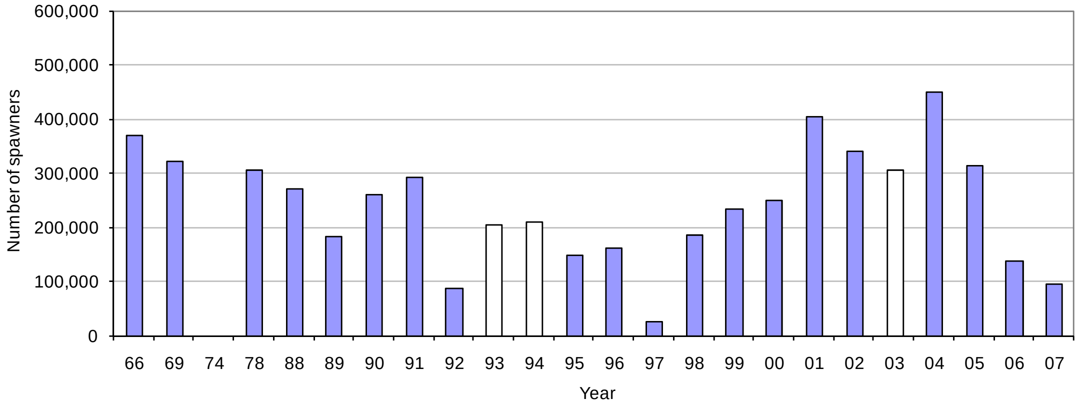


Figure 6.2. Trends in kokanee spawner returns to four index streams (Burton/Snow, Caribou, Deer and Mosquito) in the Lower Arrow Reservoir 1966-2007. Note: estimates for 1993, 1994, and 2003 for index streams based on average escapements in previous four years. All index stream estimates were expanded by 1.5 to approximate total run size.

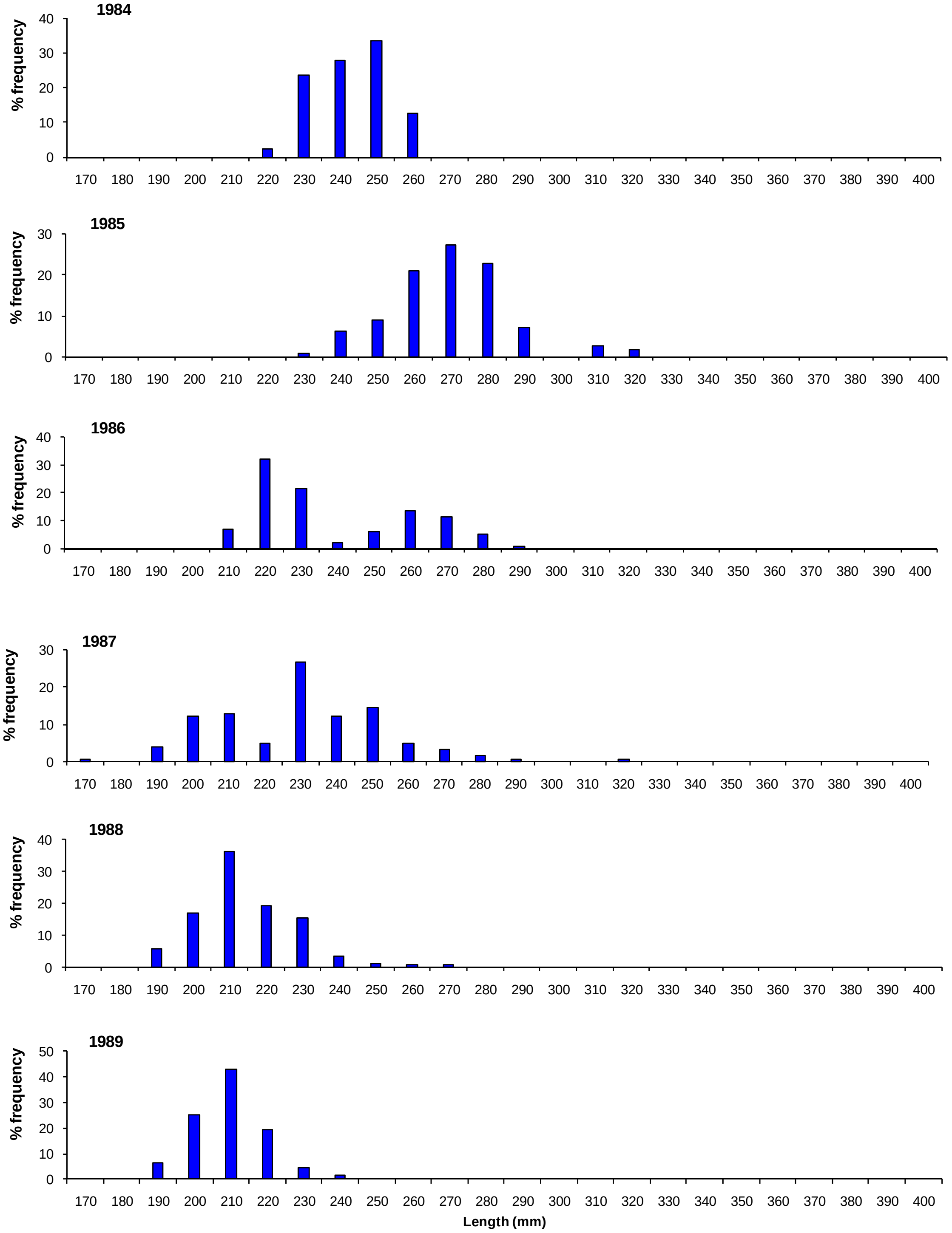


Figure 6.3a. Length frequency histograms of Hill Creek kokanee spawners for select years during 1984-1989. Sample size ranged from 97-175 per year.

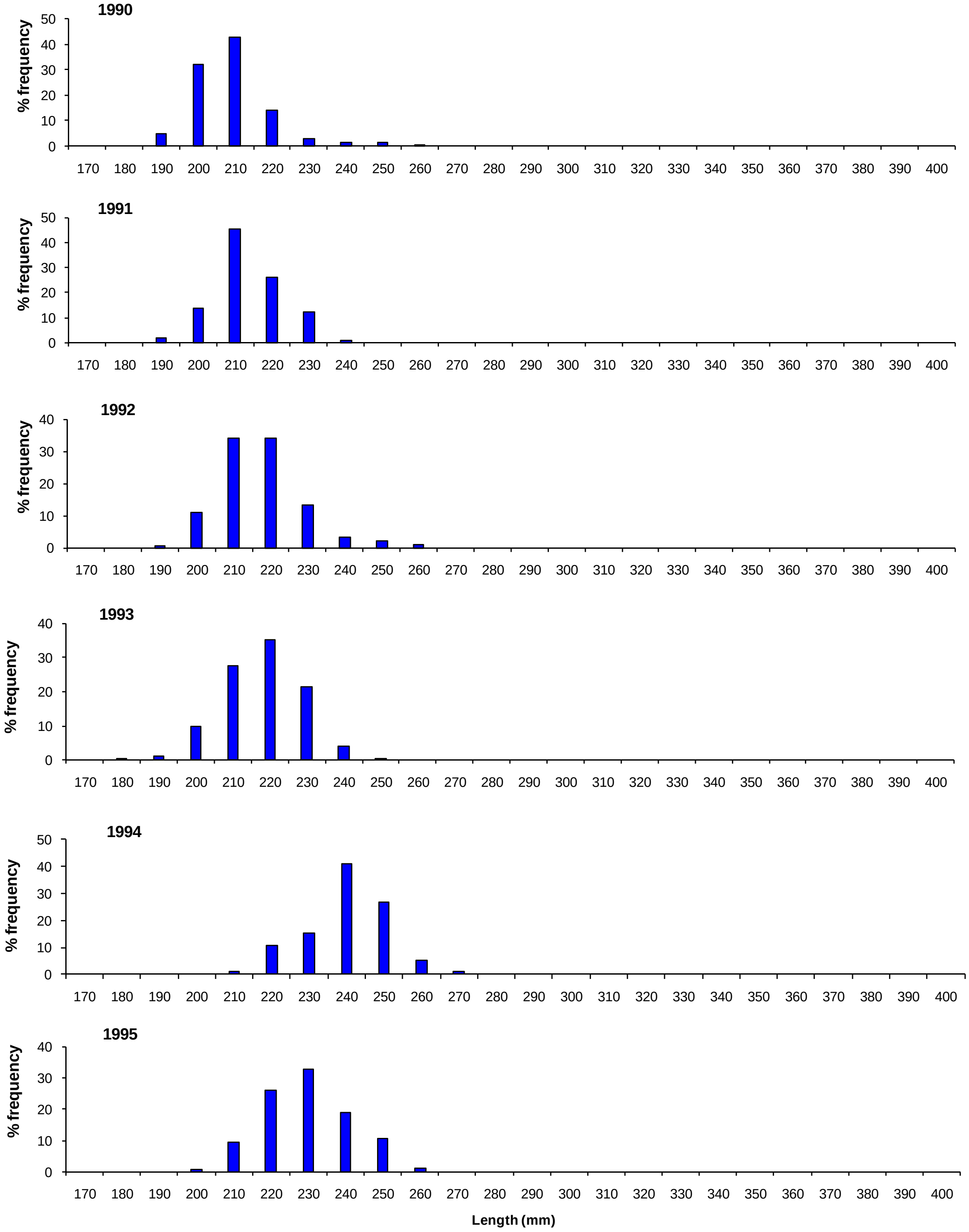


Figure 6.3b. Length frequency histograms of Hill Creek kokanee spawners for 1990-1995 Sample size ranged from 100-300 per year.

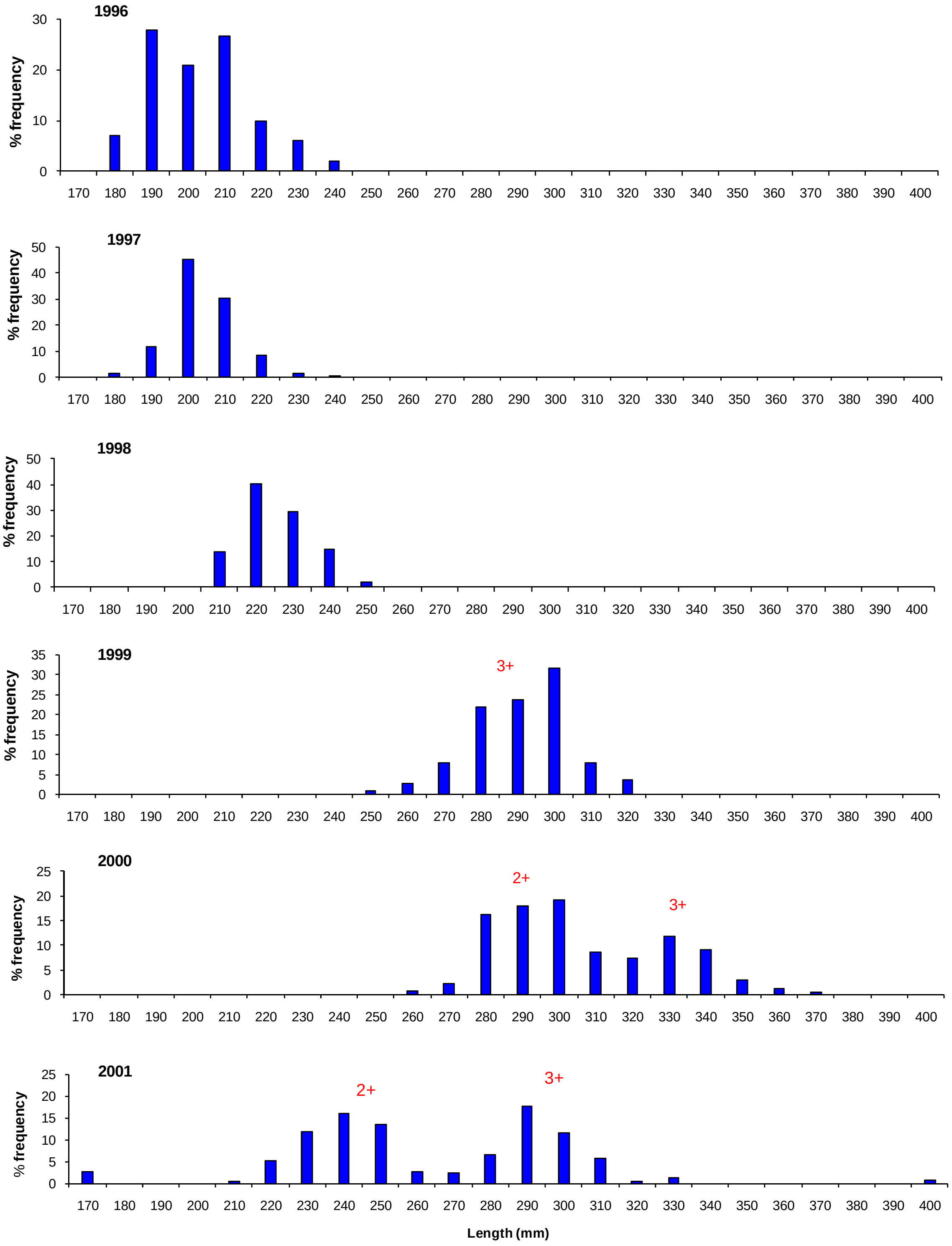


Figure 6.3c. Length frequency histograms of Hill Creek kokanee spawners for 1996-2001 with otolith ages. Sample size ranged from 114-287 per year.

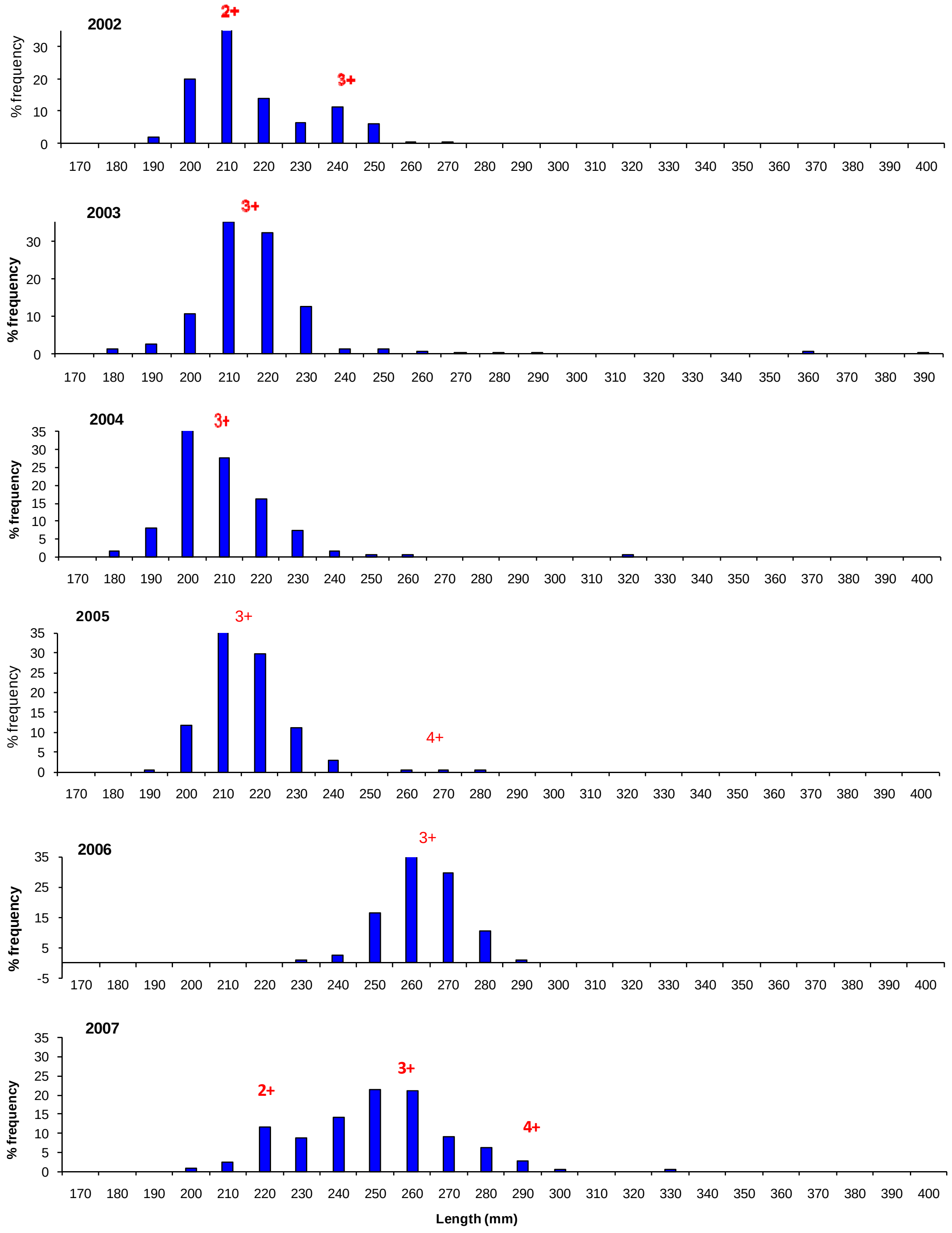


Figure 6.3d. Length frequency histograms of Hill Creek kokanee spawners for 2002-2007 with otolith ages. Sample size ranged from 114-287 per year.

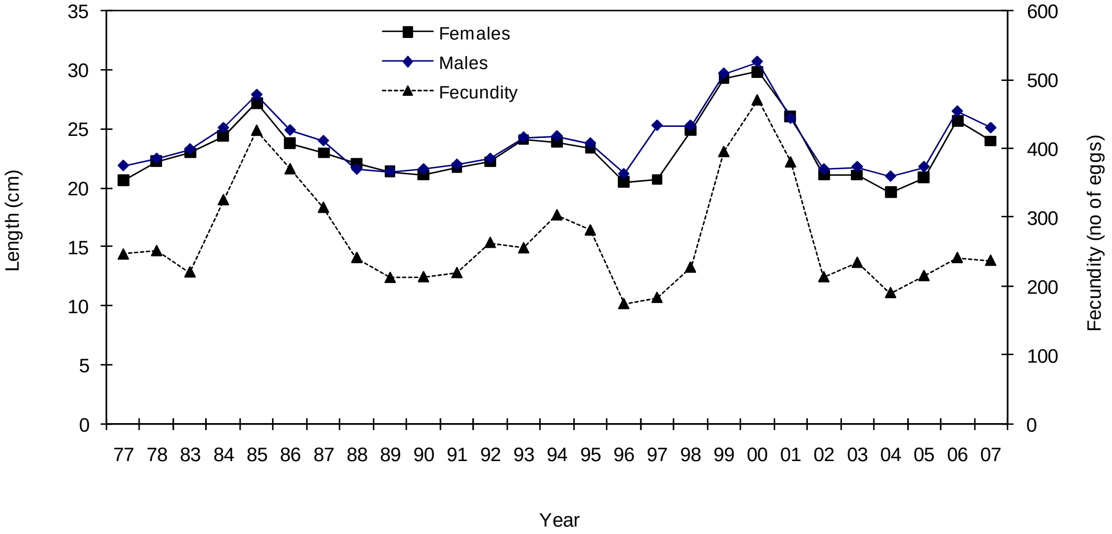


Figure 6.4. Trends in spawner mean length and fecundity at Hill Creek Spawning Channel from 1977-2007.

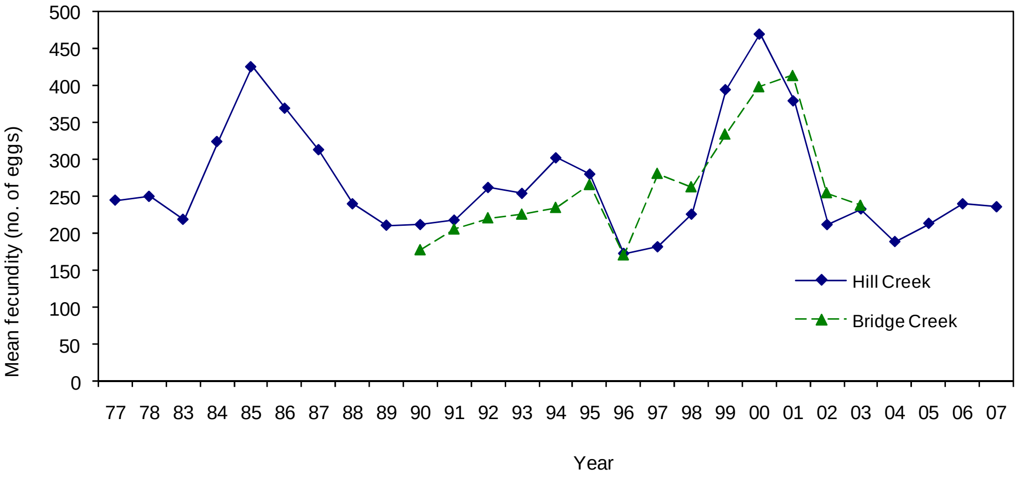
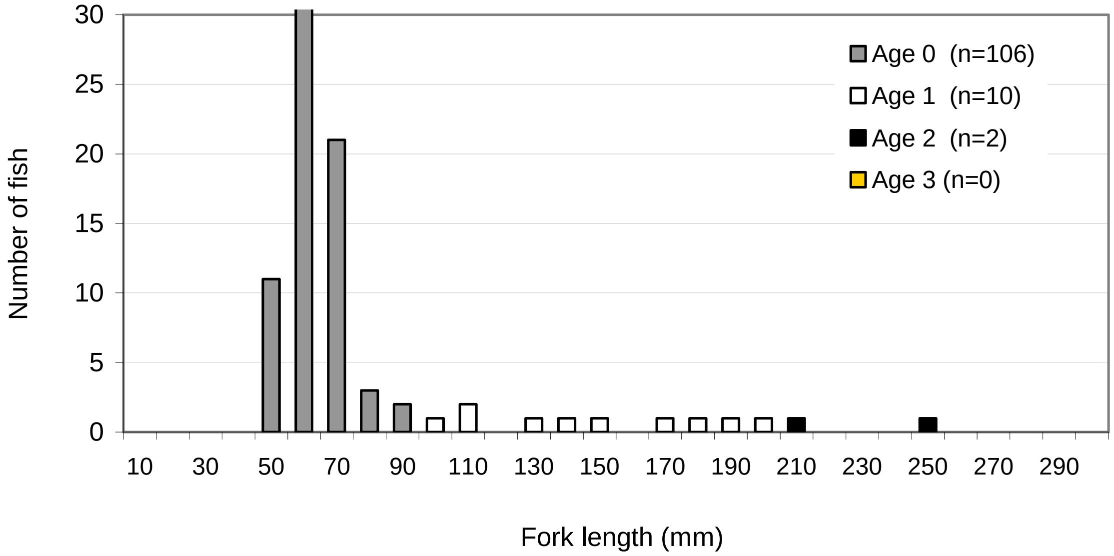


Figure 6.5. Comparison of average fecundity of Hill Creek (1977-2007) and Bridge Creek spawners (1990-2003). Note: sample sizes were usually >100 fish.

a) Upper Arrow



b) Lower Arrow

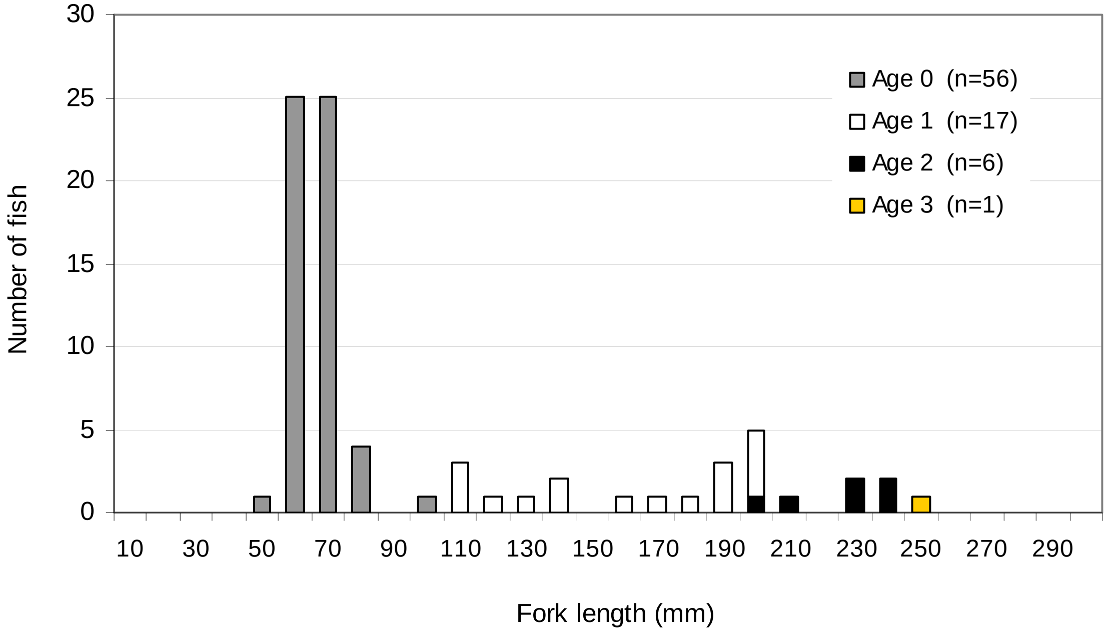
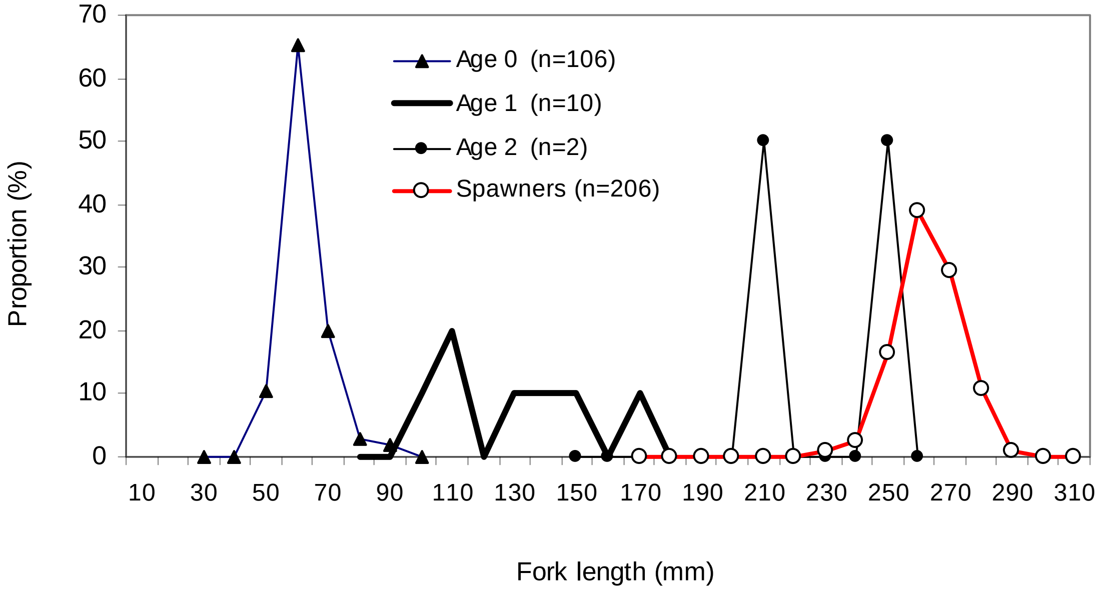


Figure 6.6. Kokanee length frequency by age from 2006 trawl sampling. Ages verified by scale interpretations. Note: no trawl data available in 2007.

a) Upper Arrow 2006 trawl and Hill Creek spawners



b) Lower Arrow 2006 trawl

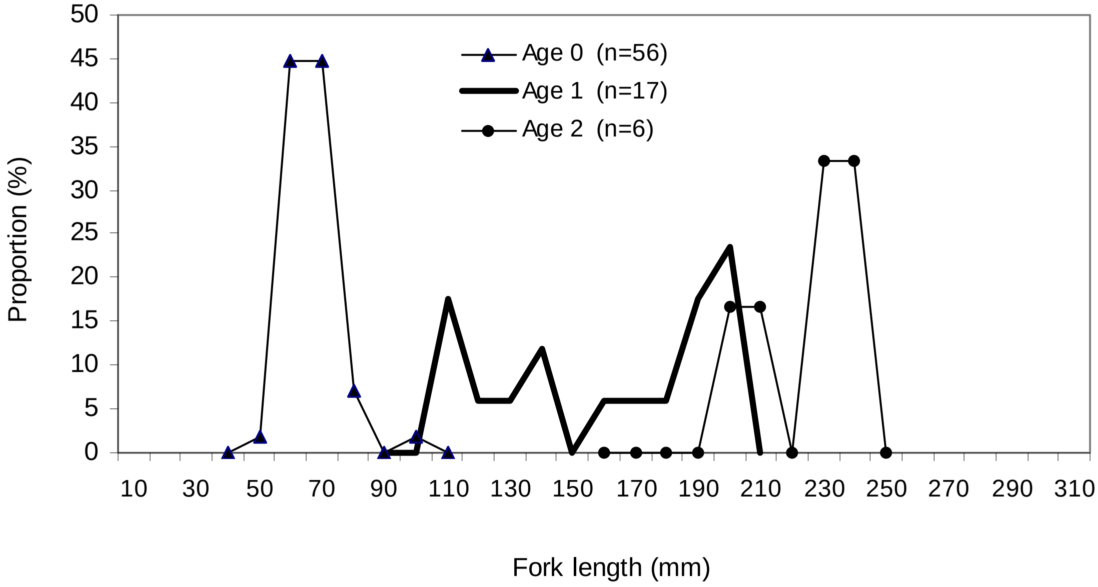
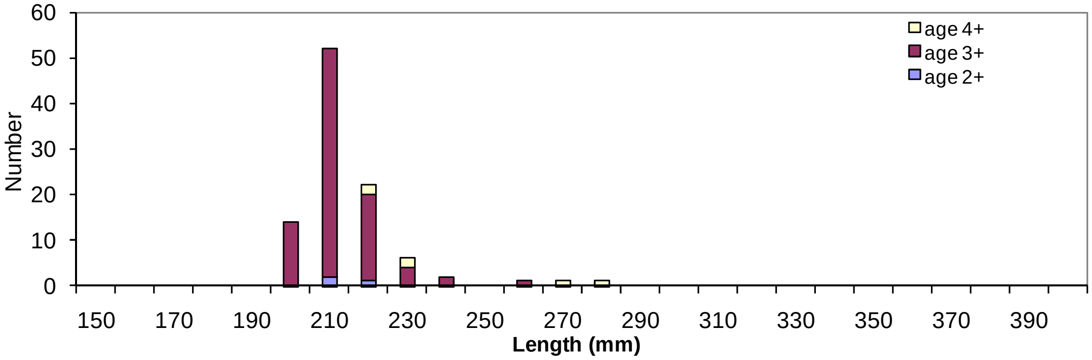
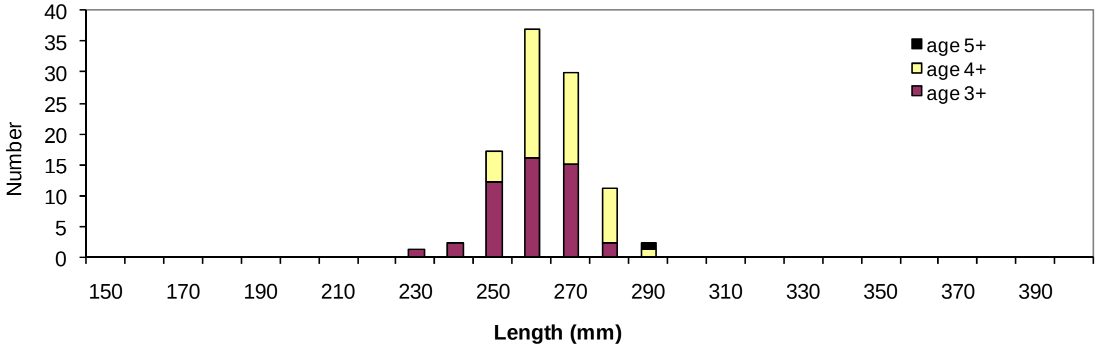


Figure 6.7. Kokanee length frequency by age with Hill Creek spawners overlaid.

a) Hill Creek 2005



b) Hill Creek 2006



c) Hill Creek 2007

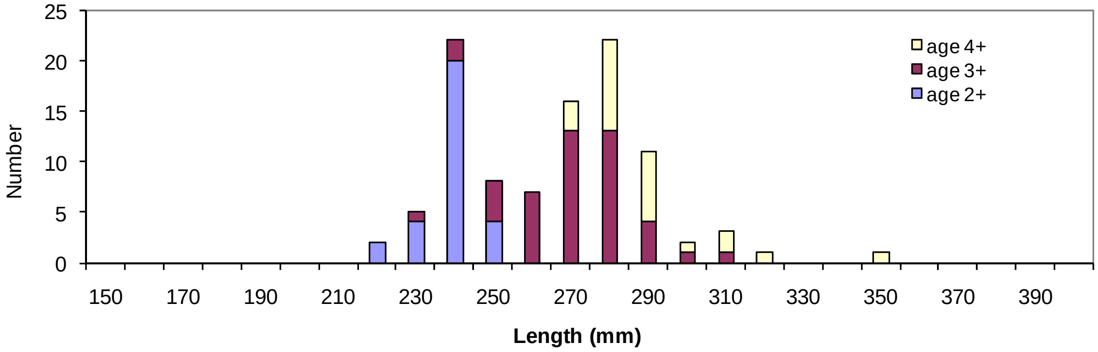
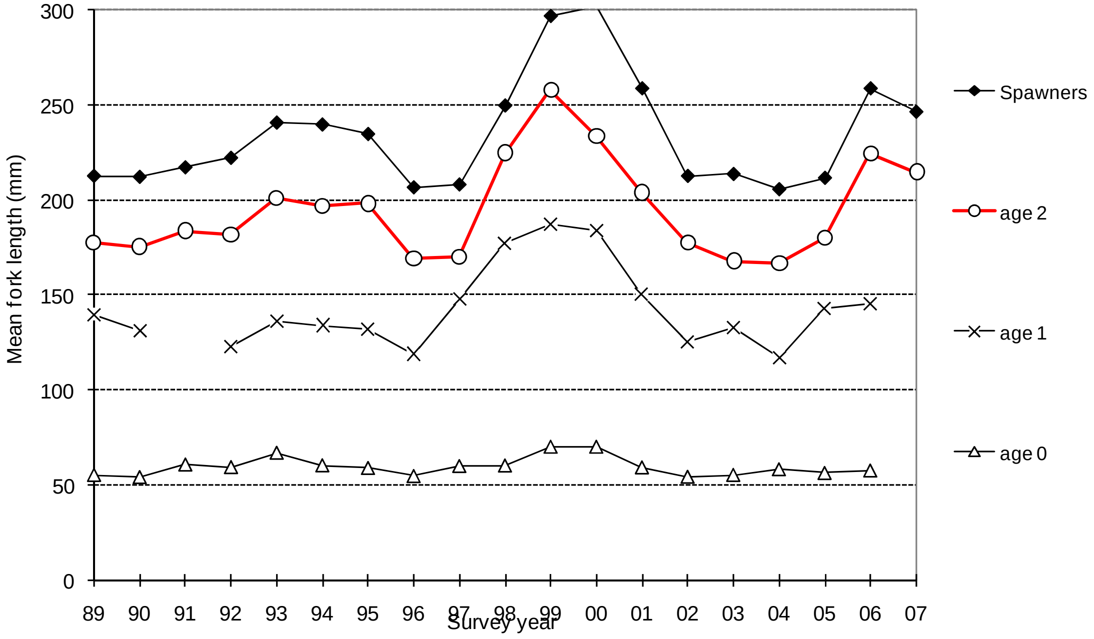


Figure 6.8. Kokanee spawner length frequency by age based on otolith analyses for Hill Creek in a) 2005 b) 2006 and c) 2007.

(a) Upper Arrow



(b) Lower Arrow

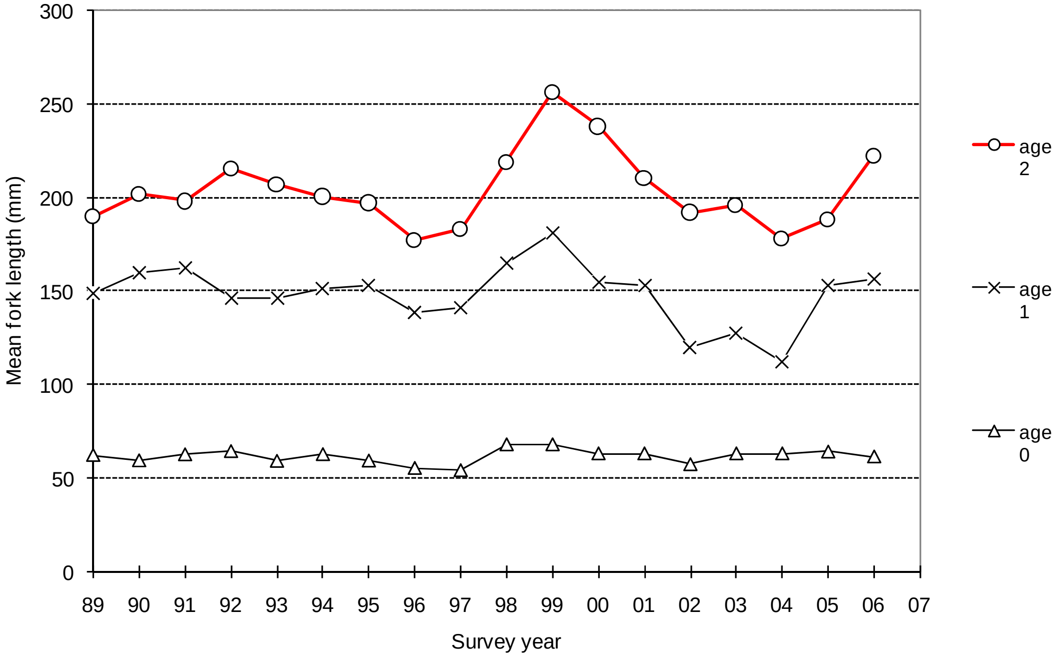


Figure 6.9. Trends in kokanee length at age adjusted to October 1 for a) Upper and b) Lower Arrow based on trawl survey data (1989-2007).

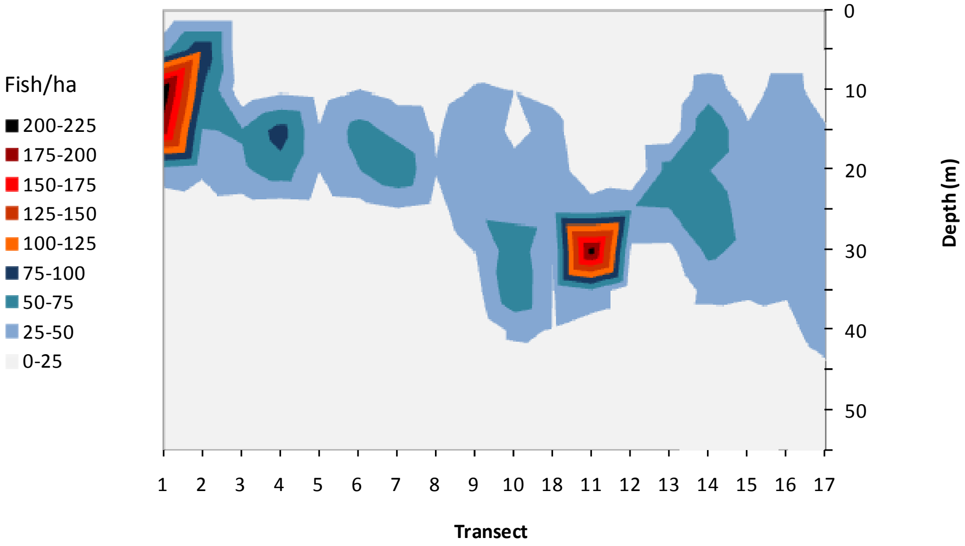


Figure 6.10. Contour plot showing depth and distribution of the night time kokanee layer over the length of Arrow Reservoir based on hydroacoustic surveys in October 2007. Note colour density indicates fish density in no·ha^{-1} as shown in legend

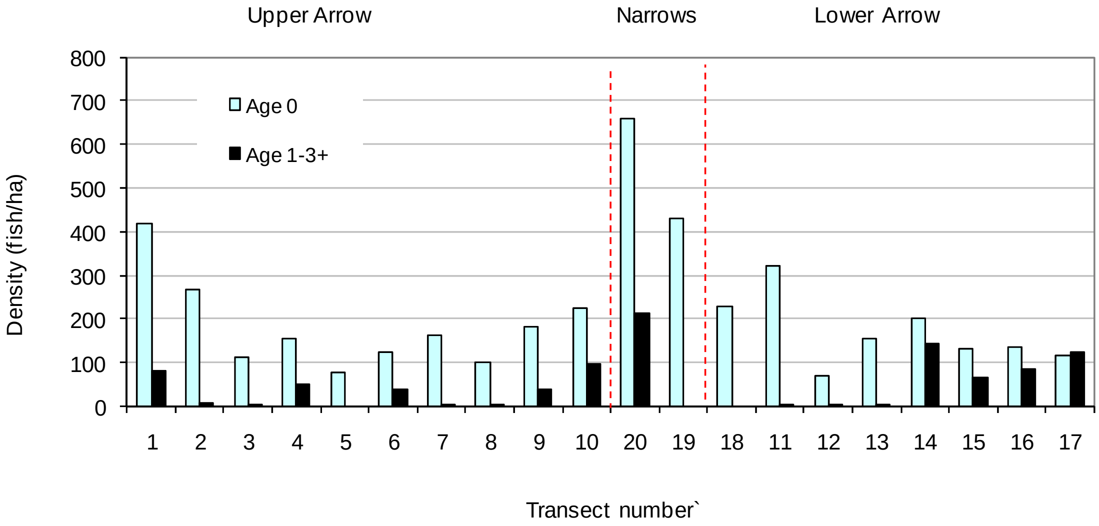
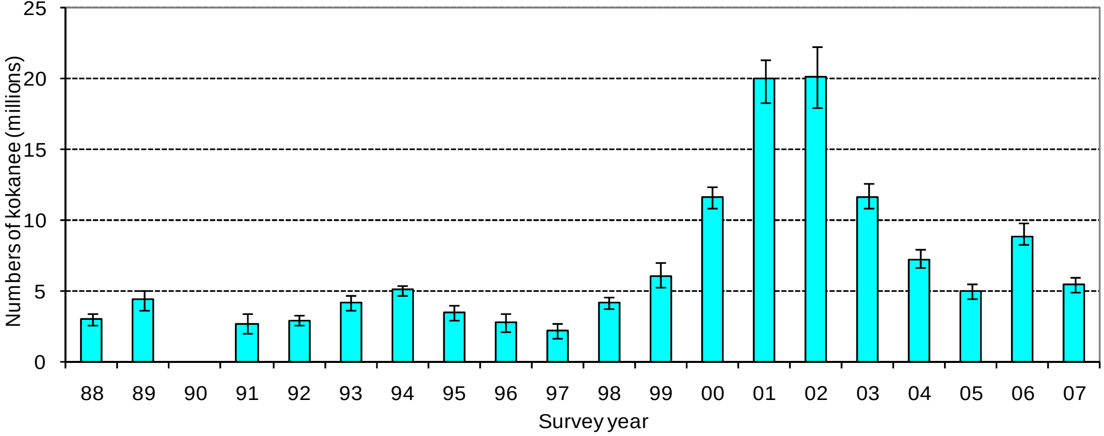
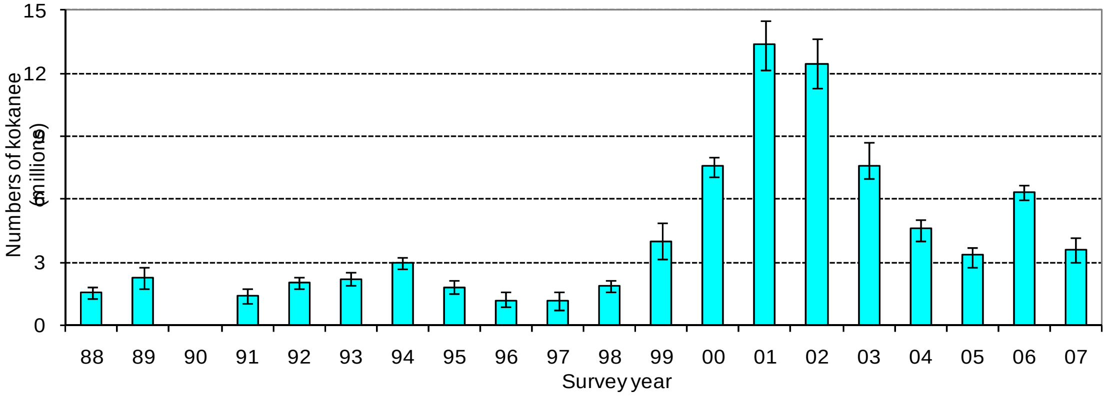


Figure 6.11. Longitudinal distribution of age 0+ and age 1-3+ kokanee in ALR during October 2007 based on acoustic surveys. Note transects 19 and 20 in the narrows can contain up to 65% non-kokanee (mostly pygmy whitefish).

a) Arrow Reservoir - hydroacoustic estimates (all ages combined)



b) Upper Arrow



c) Lower Arrow

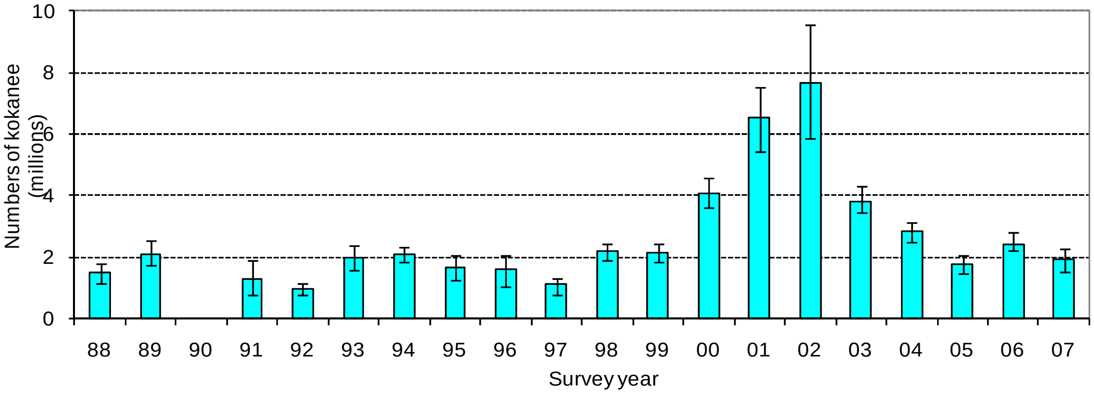


Figure 6.12. Kokanee abundance estimates of all ages for a) ALR (combined Upper and Lower Arrow), b) Upper Arrow and c) Lower Arrow based on fall acoustic surveys, 1988 – 2007.

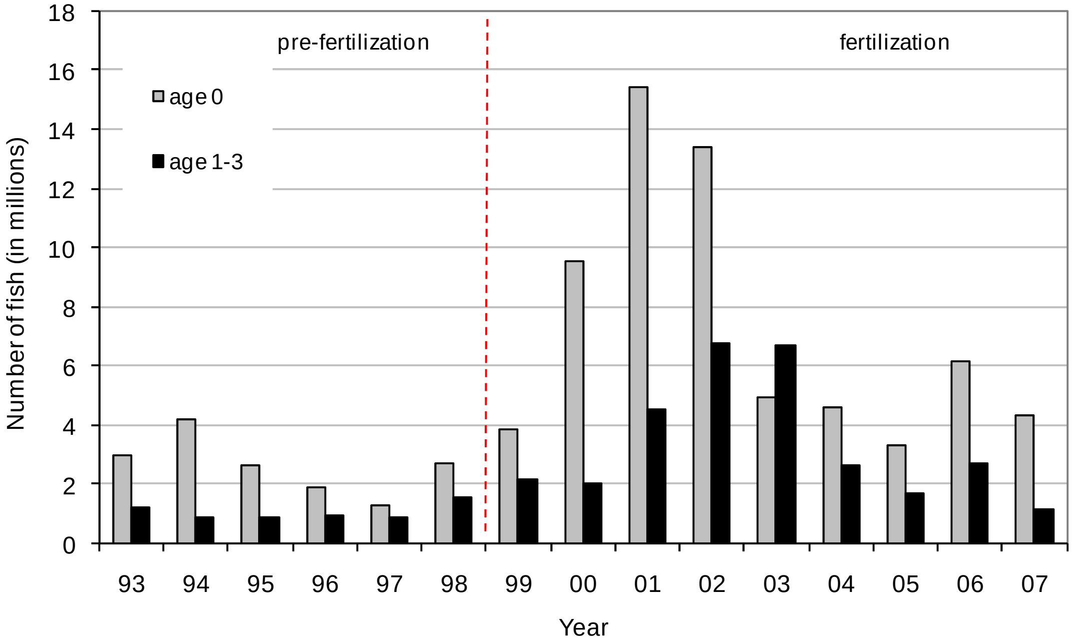


Figure 6.13. Trends in age 0+ and age 1-3+ kokanee abundance for Arrow Lakes Reservoir based on fall hydroacoustic surveys during 1993-2007.

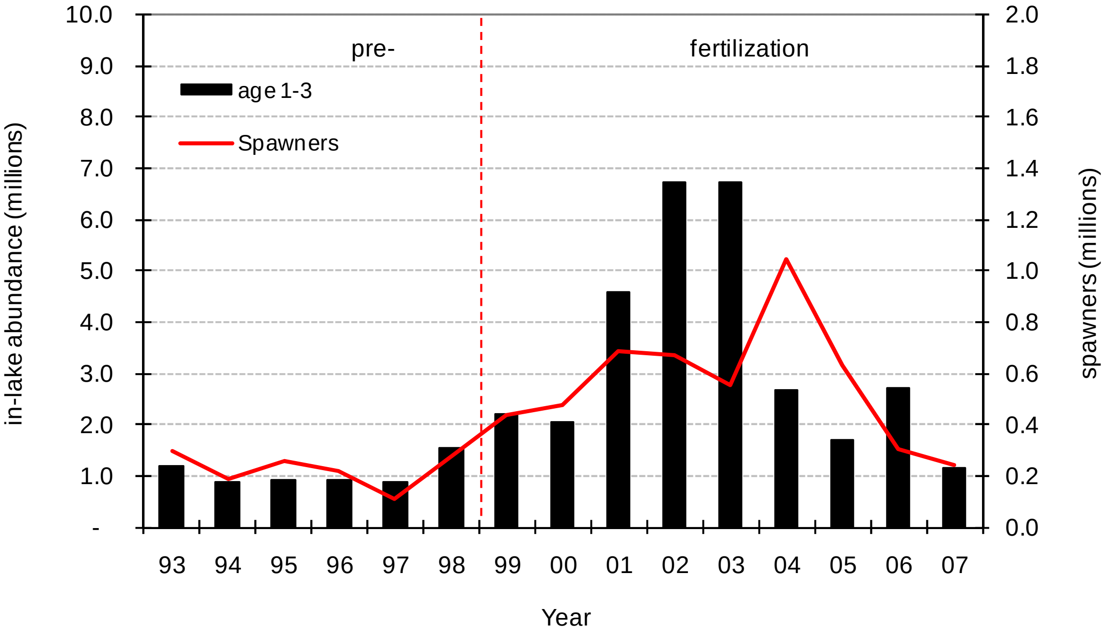


Figure 6.14. Trends in age 1-3+ kokanee abundance and estimated spawner returns to Arrow Lakes Reservoir tributaries including Hill Creek during 1993-2007.

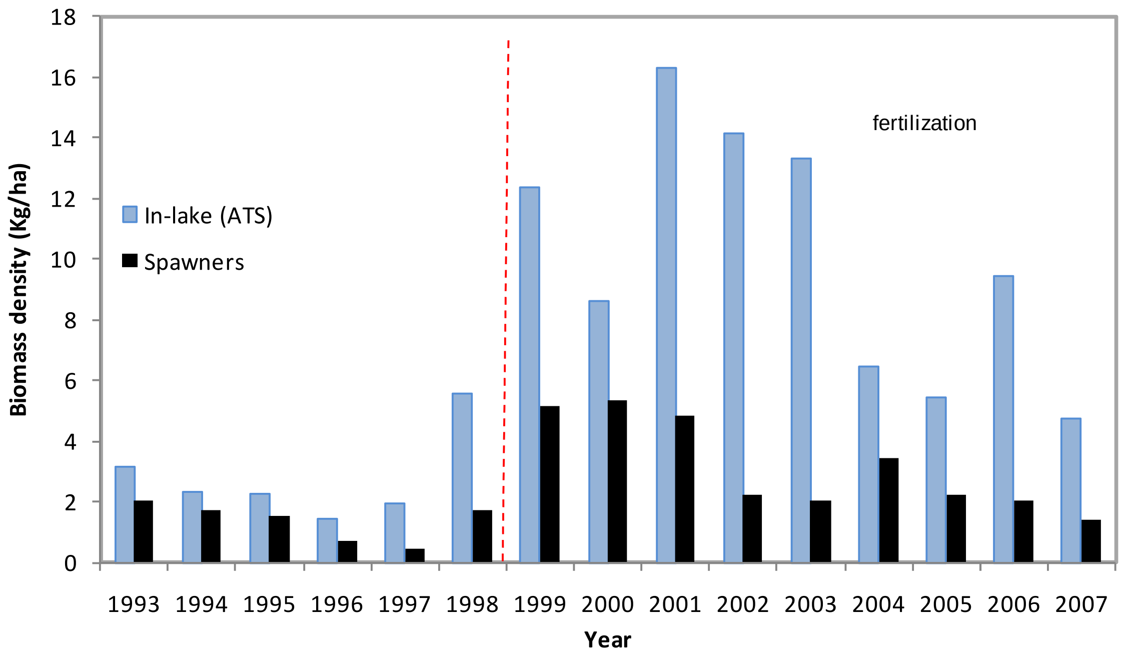
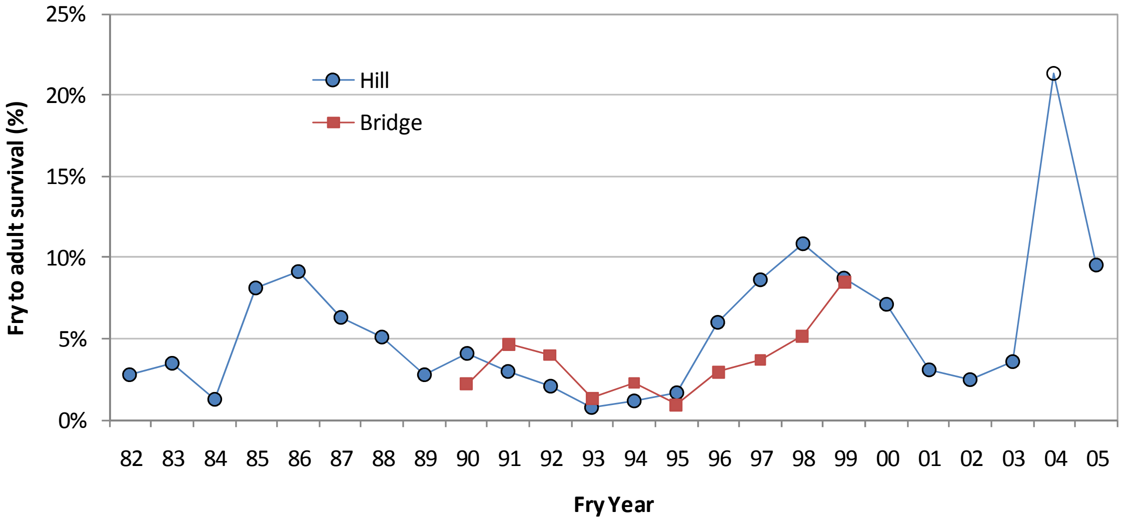


Figure 6.15. Preliminary estimates of in-lake and spawner biomass density for Arrow Lakes Reservoir kokanee. Note: In-lake biomass estimates were made after spawners had left the reservoir to spawn in tributaries. ATS refers to acoustic and trawl surveys.



`**Figure 6.16.** Fry to adult survival estimates from Hill and Bridge Creek spawning channels by fry year adjusted for age at return.

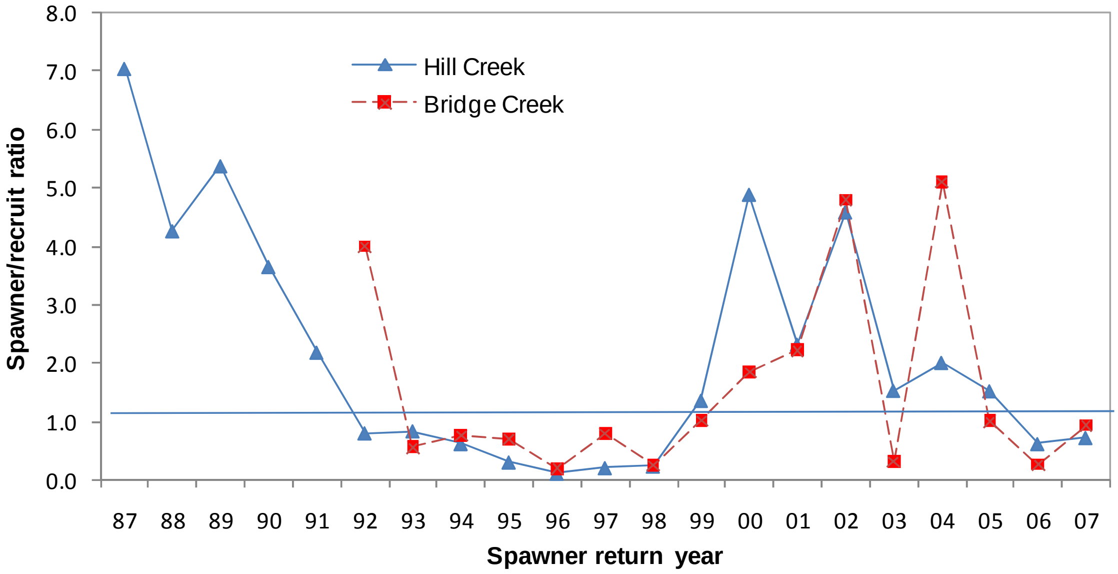


Figure 6.17. Spawner/recruit relationships for Hill and Bridge Creeks assuming spawners return at age 3+.

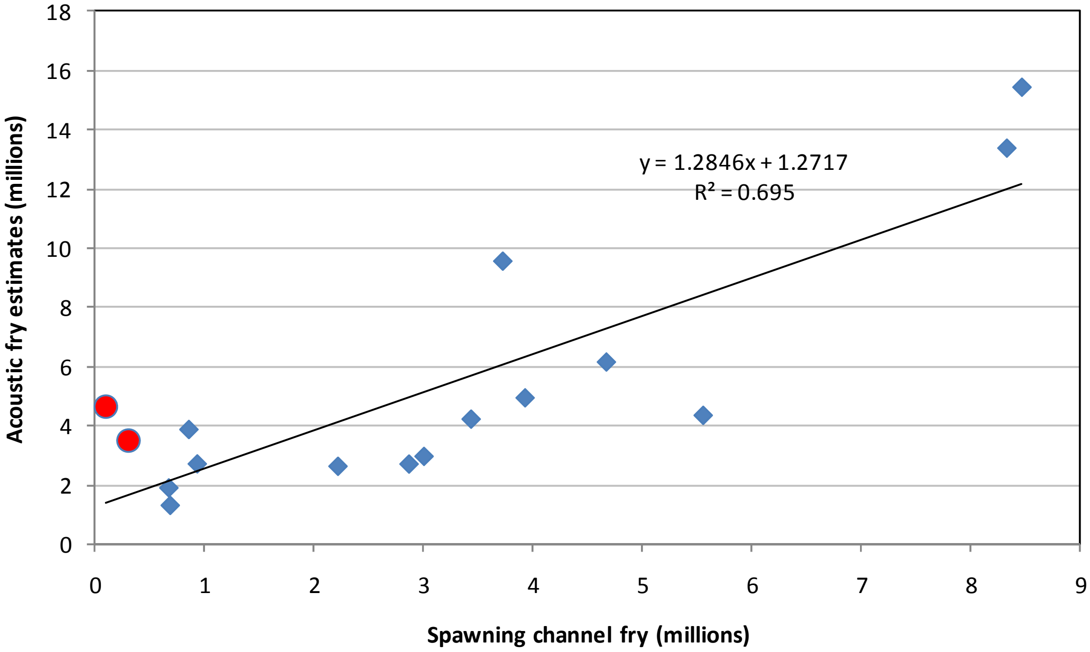


Figure 6.18. Relationship between Hill Creek spawning channel fry production and late summer fry hydroacoustic estimates 1992-2006. Two outliers indicated represent the 2004 and 2005 poor fry production years.

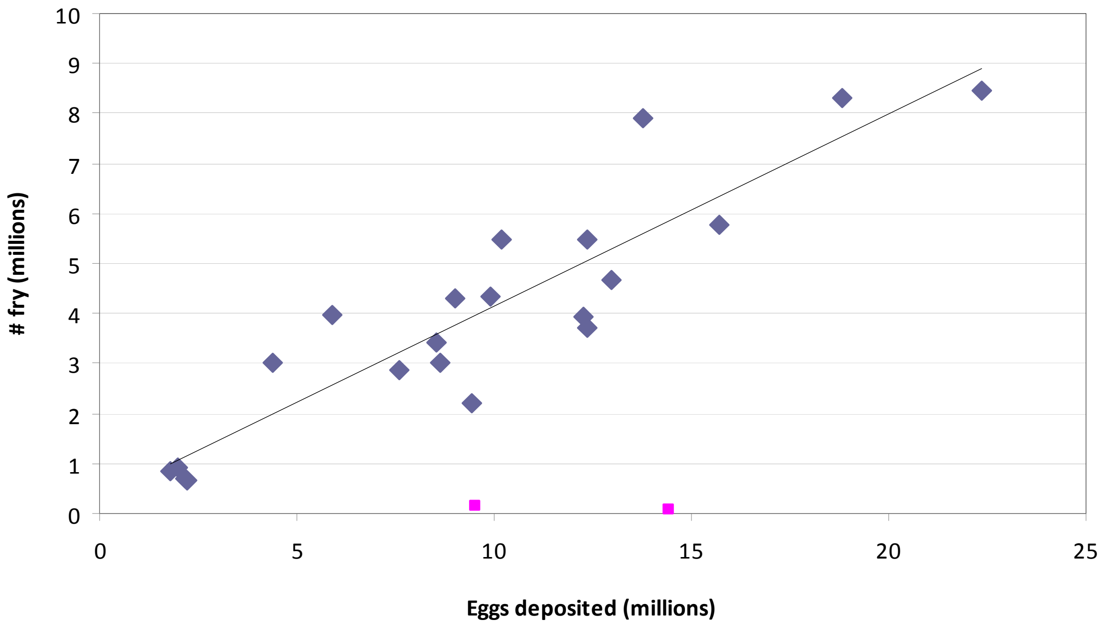


Figure 6.19. Relationship between number of eggs deposited at the Hill Creek spawning channel and the number of fry produced 1984-2006.

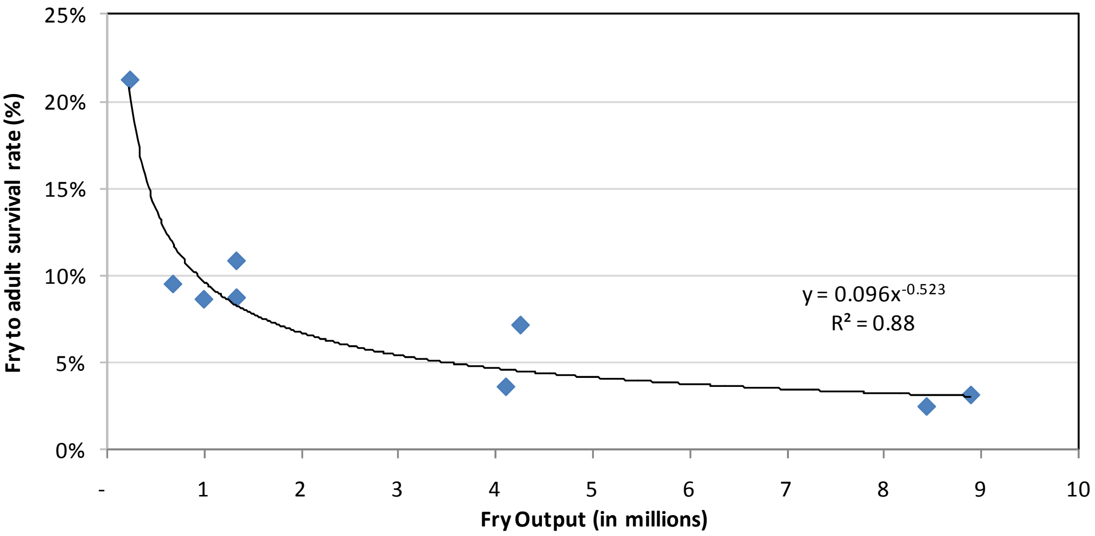


Figure 6.20. Relationship between fry output from Hill Creek Spawning Channel and the fry to adult survival rate.

Apprendix 6.1. Arrow Lakes Reservoir estimated total kokanee spawner numbers (peak counts expanded)

Index systems highlighted in green

Expansion factor = 1.5

Upper Arrow	**1966**	**1969**	**1974**	**1978**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
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	199,820	142,755	92567	97,499
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	86,370	67,050	29880	15,840
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	54,260	14,500	4740	4,000
Alkokolex	12,000																							
Bannock					150									0	0	0	128	53	0		1,200			
Blanket					150	3,000	1,200	300	750				555	1,395	750	30	2,255	530	4,818	227	240			
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	40,920	2,445	1677	389
Crawford					3,750				825				270	45	900	90	2,130	1,500	3,246		4,523			
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	27,015	18,770	6807	4359
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		46,050	4,305	3150	1912.5
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		2,400	2,385	3945	1995
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		63,600	11,595	7980	2820
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		9,120	28,877	1938	1030.5
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	1,050	3,306	240	90
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		25,350	8,805	1875	8145
Upper Index streams only		51,300	60,810	0	111,750	105,750	48,450	50,550	20,100	***56,213***	***43,828***	11,385	5,100	4,982	5,622	20,025	24,533	46,838	49,946	***35,336***	136,665	34,670	17937	9091.5
Upper Index tribs+SPChannel		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	477,115	258,975	145124	126430.5
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		561,918	304,792	154799	138079.5
Lower Arrow	**1966**	**1969**	**1974**	**1978**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2006**
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		179,700	113,850	56,100	24,075
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		120,750	81,000	23,400	16,650
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	32,273	12,542	10,938	11,477
Dog				9,750			150		75					500		396								
Eagle				24,750		750		750	300					2,175	915	6,029	5,624	0	345	0	13,875	0	0	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		117,600	106,050	47,700	43,650
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		1,184	680	740
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	17,400	11,976	6,834	5,132
Lower Arrow Index	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		450,323	313,442	138,138	95,852
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		481,598	326,601	145,652	101,723
Columbia tribs u/s	500,000	500,000	500,000																					
Overall Arrow Inde	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	*500,000*	927,438	572,416	283,262	222,282
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		1,043,515	631,393	300,451	239,802

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 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.

Note: Index counts in bold red italics were based on an average of the four previous years as no data was available (eg 1993, 1994 and 2003)

Appendix 6.2 Hill Creek Spawning Channel production data (fry and adult returns by age and year) and calculated fry to adult survival by cohort

Yellow highlighting shows example of which numbers are used in calculating fry surivival

Blue highlights indicates age proportions have been adjusted

Fry Year	Total Estimated Fry Production				Adult Return Data		Age Class Proportions[9]			Returns by Age Class			Age Data Source	Brood Year	Fry Year	Fry-Adult Survival
	EE	FF	Wild[7]	TOTAL[8]	Year	#	2+	3+	4+	2+	3+	4+				
	-	-	-	-												
1981	-	-	-	-			-		-							Hill
1982	1,000,000	-	1,284,026	2,284,026			-		-					1981	82	2.80%
1983	900,000	-	1,147,503	2,047,503	1983	15,277	-	1.00	-	-	15,277	-	assumed all age 3 from length frequency	1982	83	3.52%
1984	-	-	-	3,000,000	1984	69,936	-	1.00	-	-	69,936	-	assumed all age 3 from length frequency	1983	84	1.33%
1985	-	175,000	3,229,652	3,404,652	1985	60,176	-	1.00	-	-	60,176	-	assumed all age 3 from length frequency	1984	85	8.12%
1986	-	-	4,511,267	4,511,267	1986	75,889	-	0.95	0.05	-	72,095	3,794	estimated from bimodal frequency distribution	1985	86	9.15%
1987	87,000	-	4,312,695	4,399,695	1987	107,528	0.63	0.37	-	67,743	39,785	-	estimated from bimodal frequency distribution	1986	87	6.30%
1988	-	-	4,586,296	4,586,296	1988	298,112	0.30	0.70	-	89,434	208,678	-	estimated from bimodal frequency distribution	1987	88	5.13%
1989	-	-	8,601,185	8,601,185	1989	323,437	-	1.00	-	-	323,437	-	assumed all age 3 from length frequency	1988	89	2.81%
1990	-	-	6,592,040	6,592,040	1990	277,239	-	1.00	-	-	277,239	-	assumed all age 3 from length frequency	1989	90	4.15%
1991	-	-	5,802,397	5,802,397	1991	235,443	-	1.00	-	-	235,443	-	assumed all age 3 from length frequency	1990	91	3.00%
1992	-	-	3,610,373	3,610,373	1992	241,871	-	1.00	-	-	241,871	-	assumed all age 3 from length frequency	1991	92	2.05%
1993	-	-	3,883,792	3,883,792	1993	273,679	-	1.00	-	-	273,679	-	assumed all age 3 from length frequency	1992	93	0.75%
1994	250,000	123,695	4,550,957	4,924,652	1994	174,224	-	1.00	-	-	174,224	-	assumed all age 3 from length frequency	1993	94	1.20%
1995	-	59,077	2,805,952	2,865,029	1995	73,840	-	1.00	-	-	73,840	-	assumed all age 3 from length frequency	1994	95	1.73%
1996	54,000	125,582	1,100,706	1,280,288	1996	29,072	-	1.00	-	-	29,072	-	assumed all age 3 from length frequency	1995	96	5.98%
1997	155,000	129,514	705,130	989,644	1997	58,977	-	1.00	-	-	58,977	-	assumed all age 3 from length frequency	1996	97	8.65%
1998	57,750	172,745	1,094,284	1,324,779	1998	42,540	-	1.00	-	-	42,540	-	assumed all age 3 from length frequency	1997	98	10.86%
1999	-	357,784	968,743	1,326,527	1999	100,939	0.20	0.73	0.07	20,188	73,685	7,066	Andrusak, Arrow fert report	1998	99	8.74%
2000	-	347,462	3,903,039	4,250,501	2000	142,103	0.52	0.46	0.02	73,894	65,367	2,842	Andrusak, Arrow fert report	1999	00	7.16%
2001	-	-	8,888,753	8,888,753	2001	137,096	0.49	0.51	-	67,177	69,919	-	Andrusak, Arrow fert report	2000	01	3.15%
2002	-	-	8,433,296	8,433,296	2002	195,062	0.79	0.21	-	154,099	40,963	-	estimated from bimodal frequency distribution	2001	02	2.48%
2003	-	-	4,100,045	4,100,045	2003	155,279	-	0.95	0.05	-	147,515	7,764	Carder plus 1 year based on trawl 2+ size	2002	03	3.62%
2004	-	-	229,231	229,231	2004	286,190	0.05	0.94	0.01	14,310	269,019	2,862	based on ages by J. DeGisi	2003	04	21.26%
2005	-	-	671,233	671,233	2005	209,805	0.02	0.93	0.05	4,238	194,970	10,596	based on ages by J. DeGisi	2004	05	9.52%
2006	-	-	5,009,523	5,009,523	2006	122,447	-	1.00	-	-	122,447	-	default to spawner lfreq	2005	06	
2007	-	-	5,634,460	5,634,460	2007	113,339	0.38	0.43	0.19	43,069	48,736	21,534	Lidstone (Casselman rating >5)	2006	07	
2008	-	-	7,042,421	7,042,421	2008	82,061	0.78	0.22		64,008	18,053	-	Lidstone (Casselman rating >5)	2007	08	

Example calculation: fry to adult survival for year 2000 fry equals the sum of cohort returns (highlighted in yellow) divided by fry production in 2000.
Note that this method requires reliable ages for three consecutive years of adult returns

APPENDIX 6.3. 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 (O 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 October 19, 2006 Upper and Lower 4100mV, sphere at 20m; threshold 240mV
Lab calibration	July 8 1998, Applied Physics Laboratory UWA

APPENDIX 6.4. **a)** Maximum likelihood estimates and bounds for all fish in October 2007 Arrow Reservoir surveys based on Monte Carlo Simulations. Note: LB=Lower bounds, UB=Upper bounds, MLE=Maximum likelihood estimate.

October 2007 Systat coefficients for fish >-62 dB in 3 zones (zone 1: transects 1-2; zone 3-8: transects 9-18)

Zone[*]	**Depth**	**N**	**R^2**	**Density**	**Std Dev**	**Area**	**Stratum population**	**Statistic**	Abundance
1	10	2	0.94	46.2	12.09	2,819	130,303		
1	15	2	0.96	207.3	40.39	2,696	559,034		
1	20	2	0.97	180.1	32.95	2,574	463,713	LB=	4,954,000
1	25	2	0.99	36.3	3.51	2,452	88,935	Total MLE=	5,512,000
1	30	2	0.95	9.2	2.19	2,329	21,492	UB=	5,988,000
2	10	6	0.35	3.8	2.33	13,515	51,885		
2	15	6	0.87	17.8	3.06	13,351	238,209		
2	20	6	0.84	46.0	8.85	13,248	609,259		
2	25	6	0.88	43.9	7.19	13,146	576,886		
2	30	6	0.93	13.9	1.65	13,043	181,435		
2	35	6	0.41	2.3	1.22	12,941	29,480		
3	15	10	0.46	13.6	4.94	13,582	184,875		
3	20	9	0.82	33.6	5.50	13,058	438,259		
3	25	10	0.87	38.0	4.89	12,534	476,284		
3	30	10	0.94	43.6	3.60	12,010	523,867		
3	35	9	0.85	34.8	5.13	11,486	400,027		
3	40	9	0.83	25.0	3.97	10,962	273,716		
3	45	10	0.69	14.5	3.25	10,386	151,068		
3	50	9	0.75	6.6	1.35	9,798	64,588		
3	55	9	0.14	0.7	0.65	9,209	6,658		

October 2007 Systat coefficients for fish >-62 dB in 3 zones (zone 1: transects 1-2; zone 3-8: transects 9-18)

Zone[*]	**Depth**	**N**	**R^2**	**Density**	**Std Dev**	**Area**	**Stratum population**	**Statistic**	Abundance
1	10	2	0.95	3.4	0.80	2,819	9,587		
1	15	2	0.91	30.4	9.38	2,696	81,862		
1	20	2	0.94	37.7	9.44	2,574	96,986	LB=	949,400
1	25	2	0.84	3.7	1.61	2,452	9,079	Total MLE=	1,168,400
2	15	6	0.25	1.4	1.09	13,351	18,958	UB=	1,376,700
2	20	6	0.38	5.3	3.04	13,248	70,257		
2	25	6	0.41	7.3	3.92	13,146	96,163		
2	30	6	0.37	2.0	1.21	13,043	26,674		
2	35	6	0.22	0.1	0.10	12,941	1,553		
3	15	10	0.18	0.6	0.46	13,582	8,747		
3	20	10	0.54	7.5	2.29	13,058	97,698		
3	25	10	0.61	8.6	2.27	12,534	107,553		
3	30	9	0.74	9.3	1.92	12,010	111,307		
3	35	10	0.68	16.2	3.68	11,486	186,139		
3	40	10	0.81	14.5	3.55	10,962	159,308		
3	45	10	0.56	5.5	1.62	10,386	56,626		
3	50	10	0.52	2.2	0.71	9,798	21,673		

*. Zones are determined using Figure 6.10. Zones typically, though not always, correspond to the Upper and Lower Arrow basins. For example, in 2007, Beaton Arm, was treated as a separate zone and the lower

two transects of Upper Arrow were combined with Lower Arrow. Reservoir level elevation was 432.8 m in October 2007. Depths indicate upper bounds of 5 meter depth strata. Areas in October of 2007 were based on 7 m below full pool plus 2 m to center of strata (down 9 m in total).

APPENDIX 6.5. 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
2004	Oct 3	430.04	194	93	287
2005	Oct 21	430.30	194	93	287
2006	Oct 19	430.50	194	93	287
2007	Oct 17	432.80	196	96	292

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)	**Pieters et al** (1998) (ha)	**Fisheries** 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

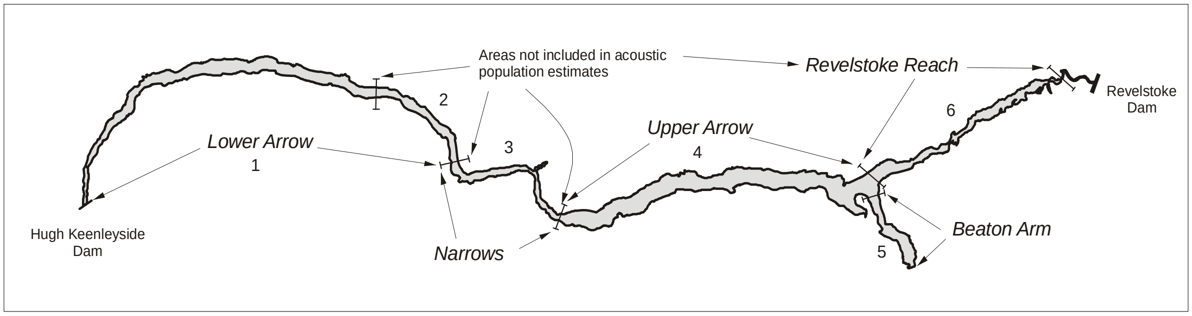
1 These estimates were used for expanding the acoustic/ trawl populations.

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 6.5 continued

c) Habitat area estimates by depth stratums used for acoustic population estimates.

Depth (m) from surface	Revelstoke Reach	Upper Arrow	Narrows	Lower Arrow
full pool	6437	22,582	5,500	12,193
1		22,456		12,092
2		22,330		11,991
3		22,205		11,890
4		22,079		11,789
5		21,953		11,688
6		21,827		11,587
7		21,702		11,486
8		21,576		11,385
9		21,450		11,284
10		21,324		11,183
11		21,198		11,082
12		21,073		10,981
13		20,947		10,880
14		20,821		10,779
15		20,695		10,678
16		20,570		10,577
17		20,444		10,476
18		20,318		10,375
19		20,192		10,274
20		20,055		10,173
21		19,992		10,086
22		19,929		10,000
23		19,866		9,913
24		19,803		9,827
25		19,739		9,740
26		19,676		9,653
27		19,613		9,567
28		19,550		9,480
29		19,487		9,394
30		19,424		9,307
31		19,360		9,220
32		19,297		9,134
33		19,234		9,047
34		19,171		8,961
35		19,108		8,874
36		19,045		8,787
37		18,981		8,701
38		18,918		8,614
39		18,855		8,528
40		18,792		8,441
41		18,729		8,354
42		18,665		8,268
43		18,602		8,181
44		18,539		8,095
45		18,476		8,008
46		18,413		7,921
47		18,350		7,835
48		18,286		7,748
49		18,223		7,662
50		18,160		7,575
51		18,068		7,511
52		17,977		7,447
53		17,885		7,384
54		17,794		7,320
55		17,702		7,256
56		17,611		7,192
57		17,519		7,129
58		17,427		7,065
59		17,336		7,001
60		17,244		6,937
61		17,153		6,874
62		17,061		6,810
63		16,969		6,746
64		16,878		6,682
65		16,786		6,619
66		16,695		6,555
67		16,603		6,491
68		16,512		6,427
69		16,420		6,364
70		16,328		6,300
71		16,237		6,236
72		16,145		6,172
73		16,054		6,109
74		15,962		6,045
75		15,870		5,981
76		15,779		5,917
77		15,687		5,853
78		15,596		5,790
79		15,504		5,726
80		15,413		5,662

Data interpolated from Canadian Hydrographic Service charts: # 3056, 3057 and 3058,
Areas are in Hectares (Ha.); Full pool elevation reference 440.24 m

APPENDIX 6.6. Summaries of fish density (number/ha) by transect for age 0 and age 1-3 fish during October 2007 acoustic surveys.

Survey Year	Transect No.	All ages	Age 0	Age 1-3
2007	1	498	417	81
2007	2	275	268	7
2007	3	115	114	2
2007	4	206	157	49
2007	5	78	78	0
2007	6	162	124	38
2007	7	168	164	5
2007	8	104	103	2
2007	9	223	184	38
2007	10	324	226	98
2007	11	323	322	1
2007	12	75	71	4
2007	13	161	156	5
2007	14	344	202	142
2007	15	196	130	66
2007	16	222	137	85
2007	17	241	117	124
2007[a]	18	227	227	0
2007[b]	19	429	429	0
2007[b]	20	872	659	213

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 in the vicinity of the Narrows and are used for qualitative information only at this time.

APPENDIX 6.7. Total transect fish density (number/ha) 1995 to 2007.

Transect	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	63	197	474	420	376	696	300	160	160	301	498
2	134	179	459	441	643	1448	480	566	285	359	275
3	277	97	263	733	923	721	330	260	142	274	115
4	87	50	231	389	295	1306	184	253	77	275	206
5	29	141	160	298	505	873	214	180	139	224	78
6	114	93	158	442	605	375	561	217	348	218	162
7	39	91	130	320	1073	311	574	304	185	255	168
8	49	70	151	434	775	440	629	359	149	337	104
9	38	111	167	427	830	372	439	304	210	367	223
10	36	97	134	280	773	1245	284	240	254	318	324
20			1335	807	1109	1606	898	564	497	672	872
21			1666								
19				2191	647	1507	613	664	422	1668	429
18			389	711	1593	3818	540	624	249	638	227
11	101	198	204	502	2621	587	391	490	357	363	323
12	146	534	313	408	705	731	173	238	92	255	75
13	102	218	231	637	1181	1662	302	162	197	294	161
14	107	144	178	483	528	473	729	368	234	296	344
15	139	135	261	926	1682	1238	500	331	255	528	196
16	305	145	203	408	941	734	844	266	285	480	222
17	196	301	253	194	781	621	938	693	231	269	241
UpperArrow	87	112	233	418	680	779	399	284	195	293	215
Lower Arrow	156	239	254	534	1254	1233	552	396	237	390	246

Note: Upper Arrow is represented by transects 1-10
Lower Arrow is represented by transects 11-18
Narrows area is represented by transects 19-21 (not included in annual kokanee population as it includes unknown proportion of other species and represents a very small area

APPENDIX 6.8. 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).

APPENDIX 6.9. Preliminary estimates of kokanee biomass for Arrow Lakes Reservoir.

a) Estimated number of fish at each age based on acoustic abundance and trawl proportions and mean weights by year and age based on trawl samples

	Estimated number of fish				**Mean weight (g)**			
Year	**Age 0+**	**Age 1+**	**Age 2+**	**Age 3+**	**Age 0+**	**Age 1+**	**Age 2+**	**Age 3+**
1993	2,960,000	664,151	520,755	15,094	2.2	39.1	111.3	118.2
1994	4,200,000	538,043	357,065	4,891	2.5	40.3	94.5	112.2
1995	2,630,000	450,000	450,000	-	2.7	38.7	91.8	
1996	1,910,000	430,986	469,014	-	1.8	23.2	58.6	
1997	1,272,000	336,000	564,000	-	1.5	34.6	74.3	
1998	2,660,000	768,504	831,496	-	2.8	61.7	131.7	
1999	3,860,000	1,330,233	869,767	-	4.9	103.1	238.9	
2000	9,600,000	1,405,405	540,541	54,054	4.9	74.8	169.3	171.5
2001	15,400,000	2,592,063	1,861,905	146,032	3.5	54.9	124.9	169.9
2002	13,420,000	4,312,644	2,387,356	-	2.7	30.4	101.1	
2003	4,956,000	4,738,122	1,887,845	74,033	3.1	37.3	97.7	136.6
2004	4,640,000	850,617	1,669,136	80,247	3.7	28.5	80.4	95.9
2005	3,290,000	670,635	777,937	241,429	3.5	56.7	97.1	121.5
2006	6,150,000	2,005,714	617,143	77,143	4.0	63.4	167.4	202.0
2007[1]	4,344,000	661,440	496,080	-	3.6	59.7	160.5	-

[1] No trawl data in 2007. Mean weights were derived from means of 2006 and 2008 trawl data

b) Calculated biomass (metric tons) in pelagic habitat and biomass density (kg/ha) for pelagic areas surveyed. Note: bottom rows compare average biomass during pre-fertilization (1993-1998) and fertilization years (1999-2007).

	Biomass (metric tonnes)					**Biomass Density (kg/ha)**				
Year	**Age 0+**	**Age 1+**	**Age 2+**	**Age 3+**	**Total**	**Age 0+**	**Age 1+**	**Age 2+**	**Age 3+**	**Total**
1993	6.6	26.0	57.9	1.8	92	0.22	0.88	1.96	0.06	3.1
1994	10.3	21.7	33.7	0.5	66	0.36	0.75	1.16	0.02	2.3
1995	7.1	17.4	41.3	-	66	0.24	0.59	1.40	-	2.2
1996	3.4	10.0	27.5	-	41	0.12	0.34	0.94	-	1.4
1997	1.9	11.6	41.9	-	55	0.06	0.39	1.41	-	1.9
1998	7.5	47.5	109.5	-	164	0.25	1.59	3.68	-	5.5
1999	18.9	137.2	207.8	-	364	0.64	4.63	7.01	-	12.3
2000	46.6	105.2	91.5	9.3	253	1.59	3.55	3.09	0.31	8.5
2001	53.5	142.3	232.6	24.8	453	1.90	5.06	8.27	0.88	16.1
2002	36.0	131.2	241.4	-	409	1.23	4.50	8.27	-	14.0
2003	15.6	176.9	184.5	10.1	387	0.53	6.03	6.29	0.33	13.2
2004	17.2	24.3	134.2	7.7	183	0.60	0.84	4.65	0.27	6.3
2005	11	38.0	75.6	29.3	154	0.40	1.32	2.63	1.02	5.4
2006	24.4	127.2	103.3	15.6	271	0.85	4.43	3.60	0.55	9.4
2007	15.8	39.5	79.6	-	135	0.54	1.35	2.73	-	4.6
Pre	6	22	52	0.4	**81**	0.2	0.8	1.8	0.0	**2.8**
Fert	27	102	150	11	**290**	0.9	3.5	5.2	0.4	**10.0**