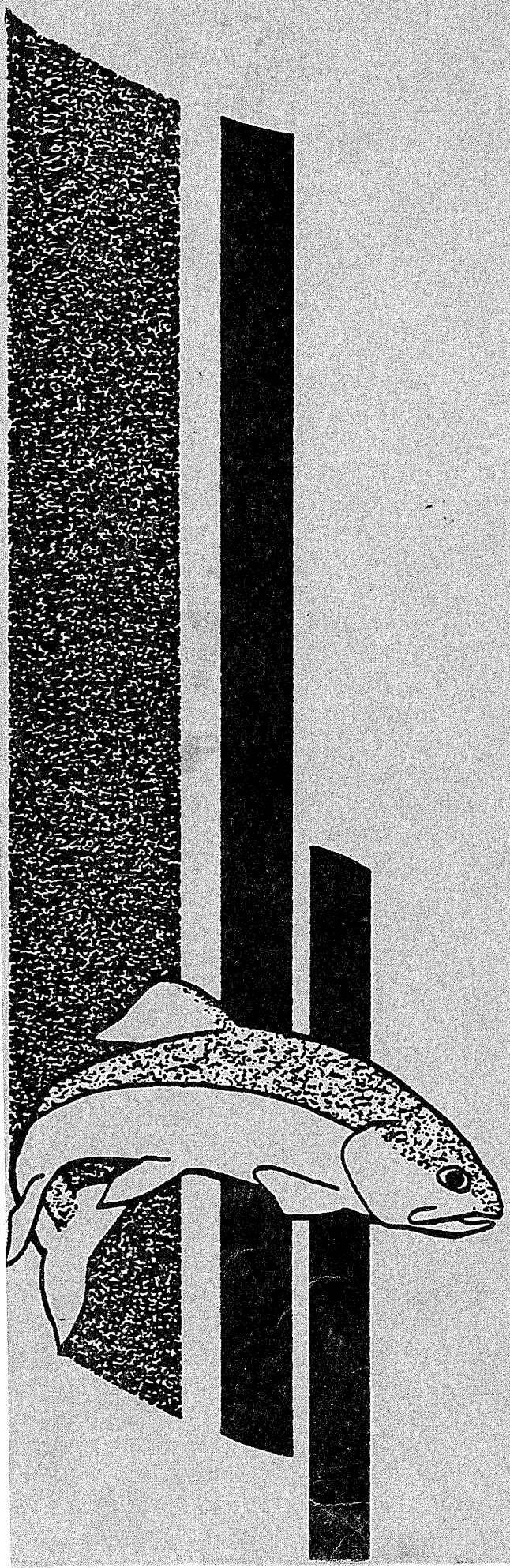


ARROW RESERVOIR FERTILIZATION EXPERIMENT YEAR 3 (2001/2002) REPORT

by

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Fisheries Project Report No. RD 103
2003

Province of British Columbia
Ministry of Water, Land and Air Protection

Major Funding By

Columbia Basin Fish and Wildlife Compensation Program

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Roger Pieters[1,2], Lidija Vidmanic[1,3], Shannon Harris[1,2]

John Stockner[3,4], Harvey Andrusak[5], Mark Young[6]

Ken Ashley[7], Bob Lindsay[8], Greg Lawrence[1]

Ken Hall[1,9], Amin Eskooch[1], Dale Sebastian[10]

George Scholten[10], Patricia Woodruff[11]

[1] Department of Civil Engineering
2324 Main Mall, University of British Columbia, Vancouver, B.C. V6T 1Z4

[2] Department of Earth and Ocean Sciences
6339 Stores Road, University of British Columbia, Vancouver, B.C. V6T 1Z4

[3] Fisheries Centre
2204 Main Mall, University of British Columbia, Vancouver, B.C. V6T 1Z4

[4] Eco-Logic Ltd., 2614 Mathers Avenue, West Vancouver, B.C. V7V 2J4

[5] Redfish Consulting Ltd., 5244 Highway 3A, Nelson, B.C., V1L 6N6

[6] Kootenay Wildlife Service, RR#3, S-21, C-10, Nelson, B.C. V1L 5P6

[7] Fisheries Research and Development Section, Ministry of Fisheries, Province of B.C.
2204 Main Mall, University of British Columbia, Vancouver, B.C. V6T 1Z4

[8] Ministry of Water, Land and Air Protection, Province of B.C.
333 Victoria Street, Suite 401, Nelson, British Columbia V1L 4K3

[9] Institute for Resources and Environment
2206 East Mall, University of British Columbia, Vancouver, B.C. V6T 1Z3

[10] Biodiversity Branch, Ministry of Water, Land and Air Protection, Province of B.C.
2975 Jutland Road, Victoria, British Columbia V8T 5J9

[11] British Columbia Conservation Foundation
206-17564 56th A Ave. Surrey B.C. V3S 4X5

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Executive Summary

Arrow Reservoir Fertilization Experiment Year 3 (2001/2002) Report

This report reviews the third year (2001) of a five-year fertilization experiment on the Arrow Lakes Reservoir (1999-2004) with the goal of restoring historic kokanee salmon populations. It includes the ongoing limnological work being done to monitor the response of the system to the nutrient additions. This work follows two years of pre-fertilization study (1997 and 1998) described in Pieters et al. (1998, 1999). Results from the first two years of fertilization (1999 and 2000) are given in Pieters et al. (2000, 2003a, 2003b).

An examination of the limnology and tropic status of the Arrow Reservoir was driven by rapidly declining stocks of kokanee, a native land-locked sockeye salmon (*Oncorhynchus nerka*) and keystone species of the local ecosystem. Arrow Reservoir was formed from the Upper and Lower Arrow Lakes by completion of the Hugh Keenleyside Dam in 1967. Arrow Reservoir is part of the Columbia River with two upstream dams, Mica (1973) and Revelstoke (1984). The resulting upstream reservoirs act as nutrient traps, reducing the already naturally low levels of nutrients in the Arrow Reservoir. Unlike its neighbour Kootenay Lake, which is one of the most studied in British Columbia, Arrow Reservoir had received little or no limnological attention prior to 1997.

The overall Arrow Reservoir budget expenditure for the 2001/2002 fiscal year was $812,000 including $323,000 for fertilizer purchase. Contributed was $625,000 by the Columbia Basin Fish and Wildlife Compensation Program, $175,000 by the Columbia Power Corporation and $12,000 by the B.C. Ministry of Water, Air and Land Protection. These direct contributions do not include significant in-kind contributions from these and other agencies.

From April 25th to September 6th, 1058 metric tonnes of agricultural grade fertilizer was applied to Upper Arrow between Galena Bay and Shelter Bay, from the Ministry of Transportation and Highways' ferry the DEV Galena. The fertilizer consisted of a seasonally adjusted blend of liquid ammonium polyphosphate (10-34-0) and urea-ammonium nitrate (28-0-0) delivering 52.8 MT of phosphorus and 232 MT of nitrogen. The seasonal loading and timing of the fertilizer application was modelled after the Kootenay Lake fertilization experiment (Ashley et al. 1999).

Hydrological conditions in 2001 were dominated by a very low snowpack (~60% of normal). This resulted in both low spring and summer inflow to Arrow and a very low summer water level. Summer water levels in 2001 were 8.3 m below average, the third lowest since 1969. Sunlight in April and June 2001 was slightly below average, but sunlight in July and August was above average reflected in above average air temperatures during that time. Surface water temperatures in 2001 peaked at 21-24 °C in July and August, significantly higher than the 16-20 °C seen in 1997, 1999 and 2000. Surface water temperatures were comparable to 1998 when high sunlight, low inflow (but average water level) resulted in surface water temperatures reaching 26 °C in the Upper Arrow.

Water quality parameters and nutrients measured in 2001 were generally similar to those observed in 1997 to 2000. Rivers, streams and the reservoir had orthophosphate (OP) levels at the detection limit (1 μg/l). Values of total dissolved phosphorus (TDP) were low with means ranging from 2-4 μg/l in the intensively sampled streams and 2.4 μg/l in the reservoir. As in 1998 to 2000, mean TDP concentrations in 2001 were lower than in 1997. Total phosphorus (TP) in the streams was highly variable because of particulates in contrast to the reservoir where TP was relatively low and uniform (averaging 3.2 μg/l) as a result of particle settling. Ammonia in stream inputs and in the reservoir was low with most values at or near detection level (5 μg/l). Slightly higher values of ammonia (up to 26 μg/l) were seen in the 0-30 m integrated samples through summer. Nitrate ranged from a mean of 20 to 260 μg/l in the streams and averaged 147 μg/l in the reservoir. However, drawdown of nitrate and silica below limiting values was observed in the top 10 m from July through September (in profiles of discrete samples for dissolved nutrients, done for the first time in 2001). Low orthophosphate levels coupled with generally high dissolved nitrogen concentrations result in a high N:P ratio which suggests oligotrophic conditions and phosphorus limitation of organic production, with possible nitrogen co-limitation at times.

Beside the rivers and streams that were sampled intensively (9-13 samples/year), nine additional rivers and streams were sampled twice during May and August in 1998 to 2001. These streams were generally consistent in chemical character with streams that are currently being monitored. The exceptions were three small streams (Deer, Little Cayuse and Syringa Crs.) at the southern end of Lower Arrow, which showed elevated OP and TDP.

Fertilization had little impact on the reservoir water quality parameters that were monitored. Orthophosphate remained at the detection limit. Total phosphorus and total dissolved phosphorus remained low. Nutrient additions in an oligotrophic system are expected to be taken up in less than a day. Secchi depths were shallow in 2001, though not unprecedented (record low of 2.1 m at AR1 observed in both June 1997 and July 2001). Chlorophyll *a* biomass has, however, increased steadily through the fertilized years.

The fifth year of phytoplankton enumeration in 2001 was consistent with previous observations (1997-2000) of an oligotrophic community with low mean abundance and biomass and lacking a clear spring bloom. However, 2001 also showed a shift in species composition to colonial diatoms in August, not typically found in an oligotrophic system. In 2001 the mean abundance for the Arrow Reservoir was 6,200 cells/mL, higher than the previous observations which ranged from 4,000 cells/mL in 1998 to 5,700 cells/mL in 1997. More striking was the increase in biomass to 0.67 mm^3/L up from the prior maximum of 0.46 mm^3/L in 1997 and 2000 but still within the oligotrophic range of <1 mm^3/L. This increase in biomass reflects a change in species composition and seasonal succession in 2001. In the untreated and first two treated years (1997-2000) the small picoplankter *Synechococcus* was numerically dominant. In the first treated year blooms of *Synechococcus* were observed close to the fertilizer application zone, a typical response seen in fertilization of other interior and coastal systems. In 2000, increases in the picoplankter *Synechococcus* were not as conspicuous as in 1999, instead increased densities of microflagellates were observed together with large populations of diatoms in Upper Arrow in the late summer to late autumn. In 2001, picoplankton populations declined at all

stations, populations of micro-flagellates began to decline for the first time and very large populations of colonial diatoms (esp. *Fragilaria spp.*) were observed from mid-June to October at *all* stations. A large response in diatoms has not been observed before in fertilized coastal or interior sub-alpine lakes. The colonial diatom species form long chains or star shapes which render them less grazable to most zooplankton and may short circuit energy/carbon flows to kokanee. Not known is the extent to which this resulted from the unusual low water conditions observed in 2001.

Upper Arrow zooplankton density increased again in 2001, to 13.8 individuals/L, continuing the increases observed from 1997-2000. In contrast, Lower Arrow zooplankton density declined sharply from a high of 23.9 individuals/L in 2000 to 14.8 individuals/L in 2001, ending a trend of increasing density observed from 1997-2000. Zooplankton biomass shows a similar pattern with Upper Arrow increasing slightly to 34.0 µg/L in 2001. In contrast, Lower Arrow biomass decreased from a high of 107 µg/L in 2000 to 56.0 µg/L in 2001. This decline in Lower Arrow was primarily due to declines in biomass of *Daphnia spp*. Zooplankton standing stock suggests Lower Arrow remains more productive than Upper Arrow, though the contrast is diminished in 2001.

From 2000 to 2001, the density and biomass of the zooplankton *Daphnia* spp., the preferred food of both kokanee and mysids, was similar in Upper Arrow and decreased in Lower Arrow. While there was a sharp decline in *Daphnia* density and biomass in Lower Arrow, both density and biomass remained more than double that of Kootenay Lake. In terms of the proportion of *Daphnia spp*. to other zooplankton, 2001 saw a second year of decline. However, the proportion of *Daphnia* in density and biomass remains high relative to other lakes. In 2001, the proportion of *Daphnia* biomass to total zooplankton biomass was 60% in Lower Arrow, 36% in Upper Arrow, 23% in Kootenay Lake and only 13% in Okanagan Lake. While copepod fecundity is comparable in Upper and Lower Arrow, cladoceran fecundity, including *Daphnia* spp., is somewhat higher in Upper Arrow than Lower Arrow in 2001.

Mysid (*Mysis relicta*) population density and biomass at the deep sites increased progressively from 1997 to 2000 in both the Upper and Lower Arrow. In 2001, density and biomass was the same or increased slightly from 2000. Density in 1997, 1998, 1999, 2000 and 2001 was 32, 71, 116, 195 and 195 individuals/m^2 in Upper Arrow, respectively, and 63, 99, 134, 223 and 259 individuals/m^2 in Lower Arrow, respectively. For comparison, annual mean densities in Kootenay Lake ranged from 146 to 273 individuals/m^2 for 1997-2001 and varied from 184 to 338 individuals/m^2 in Okanagan Lake in 1999-2001. The 2001 data suggest Upper Arrow is less productive than Lower Arrow though the contrast has diminished in the fertilized years, 1999-2001. The proportion of gravid females was similar to that of previous years and similar between Upper and Lower Arrow.

Kokanee data in 2001 support data from 1999 and 2000 to provide strong evidence that a change occurred in Upper Arrow following the start of annual nutrient additions in 1999. Evidence comes from higher escapements, higher size-at-maturity, increased fecundity, higher fry-to-adult survival rates and spawner-recruit ratios above one. Following almost a decade of declines, kokanee escapements increased in both basins in 1999, 2000 and again

in 2001, to 235,000 and 360,000 fish for the Upper and Lower Arrow, respectively. (Totals provisional as escapements from several minor tributaries are currently under review, see forthcoming 2002/03 report.) Mature fish size at the Hill Creek spawning channel was 25.9 cm in 2001, a slight decrease from the record size of nearly 30 cm in 2000. This decrease is likely a density dependent growth response as expected with higher numbers and as observed in response to fertilization in Kootenay Lake. Fecundity at the Hill and Bridge Creek spawning channels remained high in 2001. Compared with a 20 year mean of less than 300 eggs/female, the fecundity at Hill Creek was 369 eggs/female in 2001, a decline from a record high of 469 eggs/female in 2000. Based on otolith readings, which can be subjective, the age of kokanee spawners at Hill Creek has shifted from 20% age 2+ in 1999 to 52% age 2+ in 2000. (Age data for 2001 was not available at time of writing.) This indicates a shift in the dominant age at maturity from 3+ to 2+, which is also reflected in the size-frequency data. The age of spawners at Octopus Creek in Lower Arrow remained dominantly age 3+ (i.e., 4 years old) in 2000. For the fry-to-adult survival rate and spawner-recruit relationship, it was assumed that all age 3+ fish and 50% of the age 2+ fish contributed to the spawner numbers in both 2000 and 2001. In 2001, the resulting estimate of the fry-to-adult survival rate was over 6% at Hill Creek, close to the highest estimated survival rate on record. For a third consecutive year, the recruit-spawner ratio at Hill Creek and Bridge Creek was greater than the replacement value of one, after 7 years of values less than one.

Hydroacoustic surveys for kokanee were done in July and October. The July survey of Upper Arrow was not considered reliable for age 0 fish only, due to significant numbers of age 0 fish positioned near the surface which is sub-optimal for the echosounder. The October abundance estimate for the reservoir was 20.0 million (18.3-21.4 million, 95% C. L.) which is up from 2.3, 4.4, 6.1 and 11.6 million in 1997, 1998, 1999 and 2000, respectively. A comparison of echograms from October 1998, 1999 and 2001 from Upper Arrow mid-basin illustrates the change (Figure 14.4). Basin average densities in October were 711 and 805 fish/ha for Upper and Lower Arrow, respectively. Sampling south of the Narrows, at transects additional to those of the annual survey (transects 19 and 20), gave densities of up to 2,860 and 1,100 fish/ha in July and October. Limited trawl sampling at these locations in July 2001 suggested that almost all these fish were kokanee, up from 16% in 1998.

Primary productivity was measured monthly from April through October at AR2 and AR7, the central stations in Upper and Lower Arrow. Primary productivity in Upper Arrow was 132 $mgC/m^2/day$ in pre-fertilization year, 1998, and increased to 202, 190 and 163 $mgC/m^2/day$ in fertilized years 1999, 2000 and 2001, respectively. Primary productivity in Lower Arrow was 132 $mgC/m^2/day$ in 1998, but in contrast to Upper Arrow, decreased to 74, 59 and 100 $mgC/m^2/day$ in 1999, 2000 and 2001. (Annual averages for May to September and integrated from 0-15m for comparison with 1998 and 1999 results). Size-fractionated samples in 2001 indicate that nanoplankton, the preferred food source of *Daphnia*, account for about a third of the primary productivity and just under a third of the biomass, a decrease from the proportion seen in 2000. The fraction of nanoplankton primary productivity and biomass in 2001 were similar to those observed in Kootenay Lake. Dividing the daily rate of photosynthetic carbon productivity by the biomass of

phytoplankton (chlorophyll *a*) provides a measure of the specific growth rate or assimilation number of the phytoplankton community. The specific growth rates were 2.3 and 1.6 mg·C/mg·Chl *a*/hr for the Upper and Lower basins, respectively, and these values are still low relative to a range of fertilized and unfertilized B.C. lakes with values from 6.3 to 14.2 mg C/mg Chl *a*/hr.

The third year of a five-year fertilization experiment was completed with nutrient additions to the Upper Arrow in 2001. Results collected in the past four years – two baseline years 1997 and 1998 and two fertilized years 1999 and 2000 – confirm that Arrow productivity was low at all levels of the food web. Results in 2001 were generally consistent, e.g. pelagic orthophosphate was at or below detection throughout the year. However, the shift to dominance of colonial diatoms in 2001 and the accumulation of phytoplankton biomass suggests that the system may be shifting to a higher trophic level. The extent to which this was the result of the unusual low inflow and water levels is not known. *Daphnia* biomass dropped in both Upper and especially Lower Arrow, likely as a result of the grazing pressure of ever increasing numbers of kokanee and mysids, though the rate of mysid population growth did slow considerably in 2001. The proportion of *Daphnia* to total zooplankton, while high, is declining as *Daphnia* may be caught in a squeeze of less-edible forage (diatoms) and high grazing pressure. Three successive years of spawner and pelagic data provide strong evidence that kokanee are benefiting from the nutrient additions. Monitoring and analysis should be continued in order to assess the effectiveness and optimal use of these nutrient additions for the restoration of kokanee stocks.

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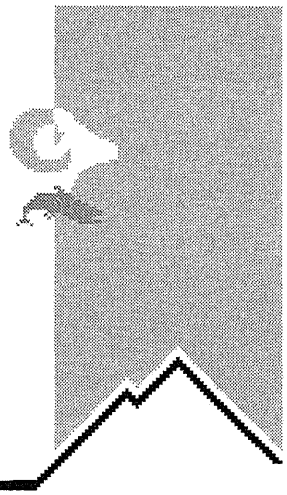
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Introduction

CHAPTER 1
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1.1 Introduction

This report describes the third year (2001) of a five-year (1999-2004) fertilization experiment on the Arrow Lakes Reservoir, with the results and preliminary analysis of ongoing monitoring. Concern over the dramatic decline in kokanee, a landlocked sockeye salmon (*Oncorhynchus nerka*) and keystone of the local ecosystem, resulted in a comprehensive study of the Upper and Lower Arrow Reservoir commencing in 1997. Funding for 1997/98, 1998/99, 1999/00, 2000/01 and 2001/02 was provided by the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP), with additional funding from the B.C. Ministry of Water Land and Air Protection (MWLAP). Funding was also provided in 1999/00, 2000/01 and 2001/02 by the Columbia Power Corporation (CPC). The two years of pre-fertilization monitoring, 1997 and 1998, are described in Pieters et al. (1998, 1999) and the first two years of fertilization, 1999 and 2000, are described in Pieters et al. (2000, 2003a). All four years are summarized in Pieters et al. (2003b).

1.2 Fertilization Experiment

The 5 year (1999-2004) fertilization of Arrow Reservoir is modelled on the Kootenay Lake fertilization experiment which commenced in 1992 and which has been highly successful in restoring kokanee stocks (Ashley et al. 1997, 1999a,b). As with the Kootenay Lake fertilization experiment, an adaptive management approach has been adopted. The fertilization of Arrow is undertaken as a large-scale experiment and as such is subject to the risk of failure. Adaptive management requires that adequate information be collected to assess the progress of the experiment so that necessary changes can be made in a timely fashion.

Fertilizer type. The fertilizer was 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). The fertilizer is purchased from a Canadian supplier, Agrium Ltd., and is federally certified for agricultural use.[1]

Seasonal loading. The seasonally adjusted blend of fertilizer (Appendix 1.1) is modelled on the Kootenay Lake fertilization experiment (Ashley et al. 1997, 1999a,b). The application schedule for 2001 is given in Appendix 1.2.

The seasonal loading of fertilizer application was intended to approximate pre-impoundment spring freshet conditions for phosphorus (P) loading, (i.e., following a natural hydrograph) and to compensate for biological uptake of dissolved inorganic nitrogen (DIN) as the summer progressed. Phosphorus loading peaked in late spring and declined through the summer (see figures in Appendix 1.1). Weekly nitrogen loading began at low rates in the spring and increased through the summer in an attempt to minimize the occurrence of cyanobacteria (blue-green algae) which can be associated with low N:P ratios (Smith, 1983; Pick and Lean, 1987).

Fertilizer treatment started on April 25 and ended on September 6, 2001. The fertilizer N:P ratio (weight to weight basis) was modified at 3-4 week intervals and increased from 0.67:1 (i.e., 10-34-0 only) in the initial spring applications to 7.5:1 in the late summer applications. The fertilizer N:P ratio expressed in terms of molar concentrations ranged from 1.5:1 to 16.7:1. Based on an in-lake area of 193 km^2 (Appendix 14.6), this corresponds to a loading of phosphorus that ranged from 7.5-22.5 mg/m^2/week.

Application System. The fertilizer was dispensed from the Ministry of Transportation & Highways ferry, the DEV Galena. This ferry runs between Galena Bay and Shelter Bay on the Upper Arrow Reservoir, approximately 30 km south of Revelstoke on Hwy 6 (in the vicinity of hydroacoustic track 3 in Figures 1.1 or 14.1). The DEV Galena is 50.3 m long, 18.0 m wide, has a draft of 2.4 m and displaces 518 tonnes.

The propulsion units on the DEV Galena are two Voith Schneider cycloidal propellers powered by two 1460 shp (shaft horsepower) engines, located on opposing corners (the 'drive' corners). The propellors have been described as akin to egg beaters. They have four vertically mounted blades that are 1.6 meters in length. The blades are attached to a turntable. As the turntable spins the blades are rotated in the vertical plane to give thrust in whatever direction is required. The propulsion units are powered by electric motors which in turn get their power from diesel powered generators (a diesel electric vessel, DEV).

[1] One kg 10-34-0 contains 0.1484 kg phosphorus. At 15 °C the density of 10-34-0 is 1.415 kg/L, and 28-0-0 is 1.28 kg/L.

Two fertilizer diffuser units were located in opposing corners of the DEV Galena. The diffusers were bolted to the rub rail on the long side of the ferry such that the diffusers discharged the fertilizer blend directly into the propeller wash. The fertilizer diffuser pipe was 12 feet (3.6 m) long, 3 inches (7.6 cm) in diameter and had 0.25 inch (0.63 cm) holes at 12 inch (30 cm) spacing.

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

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

The ferry crossing time is about 25 minutes, travelling a distance of approximately 6 km. The pump is generally activated 5 minutes after leaving each ferry terminal to prevent application of fertilizer in the shallower shore regions, yielding roughly 15 minutes of actual fertilizer distribution per ferry crossing. Initially, half of the fertilizer in the trailer tank was applied on the trip from Galena Bay to Shelter Bay. Then on reaching Shelter Bay the truck was turned around, re-boarded the ferry and the tank was connected to the diffuser in the opposite drive corner and the remaining fertilizer was dispensed on the return trip. More recently, the entire load of fertilizer has been dispensed on the outgoing trip due to high traffic volumes on the ferry.

Two to 15 fertilizer trips were made each week depending on the amount of fertilizer to be released. A record of fertilizer trips is given in Appendix 1.3. A total of 214 trips were made. Several trips were made each day throughout the week, including weekends. A major consideration was traffic volume on the ferries, which during the summer would only allow 2 loads during weekdays (one in early morning and one in the early evening); weekend traffic volume was generally less than during the week. The fertilizer was applied consistently through the summer with several daily applications the norm. The fertilizer trip record indicates a cumulative total of 801,888 L of fertilizer was applied. This is consistent with the fertilizer schedule of 802,913 L (99.9% of target application volume) and within the accuracy of volume measurement of the fertilizer delivery system.[2]

[2] The supplier meters the fertilizer on the basis of weight. Volume measurement is here based on density at 15 °C.

1.2 Fish Stocks

1998 Public Participation Program, Nelson Conference

On October 24/25, 1998 a public conference, which attracted 175 public, government, scientist and academic participants, was held at the Baker Street Inn in Nelson on "The State of Fisheries in Kootenay Lake and Arrow Reservoir". The Columbia Basin Trust, BC Environment, CBFWCP and Westland Television sponsored the conference. Westland Television produced a documentary, which was aired on the Knowledge Network television program in 1999.

Mike Halleran of Westland chaired the conference and John Stockner, an internationally known limnologist and scientist, was the keynote speaker. The first day of the conference provided an update on Kootenay Lake fisheries after seven years of fertilization and, on the second day, presented results of two years of intensive Arrow Reservoir studies (1997 and 1998) addressing declining productivity levels.

In summary, the research conducted on Arrow Reservoir suggested that the current state of fisheries required immediate attention to prevent a collapse of the kokanee stocks. The recommendation was to proceed with a five-year fertilization experiment on Upper Arrow Reservoir to restore productivity levels similar to the fertilization project being carried out on Kootenay Lake. The participants at the conference supported this recommendation.

Background

The Arrow Reservoir originally consisted of two large oligotrophic lakes, the Upper and Lower Arrow Lakes, which lie between the Selkirk and Monashee Mountain ranges in southeastern British Columbia (Fig. 1.1). They were transformed into a reservoir when the Keenleyside Dam (near Castlegar) was constructed in 1969 as part of the Columbia River Treaty. The Arrow Reservoir is dominated by the inflowing Columbia River near Revelstoke and the outflowing Columbia River near Castlegar. At full pool the Arrow Reservoir has a surface area (mean elevation of 432.4 m) of approximately 46,450 ha (Upper Arrow 29,557 ha and Lower Arrow 16,893 ha)[3]. The Upper Arrow has six major tributaries and 25 minor tributaries; the Lower Arrow has four major tributaries and 26 minor tributaries. The communities of Revelstoke, Nakusp and Castlegar are located on or near the reservoir.

The most common concern in lakes and reservoirs around the world is an excess of nutrients (eutrophication[4]) which results in high algal productivity leading to 'green and slimy' or 'polluted' water. In contrast the Arrow Lakes Reservoir was naturally low in

[3] With Narrows included in Upper Arrow; see Appendix 3.3 for detail.

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

nutrients and is suffering from a further reduction of these nutrients (oligotrophication, Ney 1996). Further introduction to nutrients can be found in Sections 9.1-9.3.

Fish Stocks

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

Fish and Habitat Losses

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

Arrow Lakes kokanee have been severely influenced as a result of dam development, i.e., impoundment, loss of tributary habitat, drawdown, entrainment, etc. The Keenleyside Dam flooded 30% of their spawning habitat (Lindsay and Seaton 1978) while the Revelstoke Dam blocked upstream passage to 500,000 spawners (Martin 1976). The pre-impoundment annual escapement in the Upper and Lower Arrow Lakes derived from hydroacoustic surveys was estimated at 0.8 to 1.6 million kokanee, whereas the current ten year average escapement (1991-2000) is approximately 0.3 million. Nutrient retention by upstream impoundments (Revelstoke and Mica dams) has substantially reduced reservoir productivity particularly in the Upper Arrow. Nutrients (mainly phosphorus) that formerly entered the Arrow Lakes from the Columbia River are now settling out and/or being utilized in the Revelstoke and Mica reservoirs resulting in decreased productivity in the Arrow Reservoir. Kokanee, being pelagic planktivores, are typically the first species to respond to decreased reservoir productivity resulting from aging impoundments, a process known as oligotrophication (Ney 1996). The current status of Arrow kokanee is outlined in Chapters 13 and 14.

Sebastian et al. (2000) believe there may be four separate strains of rainbow trout that inhabit Arrow Reservoir watershed including two adfluvial forms, a steam resident form and a fluvial form below the Revelstoke dam. The Arrow Lakes previously supported a trophy rainbow trout fishery for the large, piscivorous yellow finned rainbow trout, which are an ecological analogue of the Gerrard rainbow trout in Kootenay Lake. An estimated 3,000 adults were lost following dam construction (1,000 spawners and 2,000 fish from the sport fishery). The spawner estimate is based on the return of 500 fish to the base of the Revelstoke Dam (Martin 1976) and an additional 500, which according to area residents, spawned in the narrows between the two lakes. The sport harvest estimate is loosely based on Kootenay Lake data where the annual harvest is twice the escapement. These fish were large (up to 14 kg in size) but quite distinct in appearance from Gerrard rainbow trout by their yellow-orange color on their stomachs as well as on their pectoral, pelvic and anal fins. The flooding of the lakes almost completely eradicated this stock, and from the mid-1970's through the early 1980s, very few of these fish were caught. From 1979 through 1981, attempts were made by the Fisheries Section (Kootenay Region Ministry of Environment) to preserve and enhance this stock by collecting spawning adults blocked at the Revelstoke Dam. Some yearling releases from the Hill Creek hatchery resulted from these collections, however, this program was too labour-intensive and too few adults were collected to justify its continuation. Attempts were made again from 1992 through 1996 to collect spawning adults to preserve this unique stock but too few fish were captured and the program was discontinued. A remnant population remains in the Arrow system, and signs have been placed at major boat launches identifying the differences between Gerrard and yellow-fin trout and requesting that the public voluntarily release any yellow-fin rainbow trout captured while angling.

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

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

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

At least three different strains of bull trout are thought to inhabit the Arrow Reservoir including an adfluvial, fluvial, and resident form (Sebastian et al. 2000). Adfluvial bull trout are highly dependent upon kokanee as a food source (Sebastian et al. 2000). Bull trout were traditionally one of the main species targeted by anglers in the Arrow Lakes. The impacts from dam construction on this species have been dramatic primarily because of flooding and blocked access to spawning and rearing habitat. As a result of the Revelstoke Dam, it was estimated that 4,000 adult spawners (13 spawners·km^{-1} of stream habitat) were lost (Martin 1976). The number of kilometers of habitat lost in comparison with remaining habitat in the Arrow system represented a loss of 66% of the total adult spawning population in the lake (Lindsay 1977). The total bull trout spawning population was estimated at approximately 5,000-10,000 adults (Sebastian et al. 2000, p38).

Clearly, dam construction has had a large impact with 2/3 loss of spawning habitat and the significant numbers of fish observed at the base of Mica and Revelstoke Dams for several years after closure of these dams. However, because of the low level of fishing effort, catch statistics have not provided sufficiently accurate population and size estimates to define these changes over time. See Sebastian et al. (2000) for further discussion.

A bull trout stocking program commenced on the Arrow with the construction of the Revelstoke Dam in 1981 with annual releases of juveniles ranging from 5,000 to 130,000. In 1996, a report by Winsby and Stone reviewed bull trout production from the Hill Creek Hatchery and suggested adult brood capture only take place every second year (commencing in 1996) and that the release program incorporate release of both yearling and two year old fish in an attempt to improve survival to adult sized fish. The evaluation of this program is ongoing (see e.g. Arndt 2002).

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

Compensation

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

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

areas. The upper 0.2 km of the channel has larger gravel suitable for spawning rainbow trout although kokanee also spawn in this area.

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

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

At present there are a number of limnological and fisheries studies being conducted on the Arrow Reservoir to better understand it's fish populations and limnological characteristics. Most of these studies are being funded by the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) which is a joint program between BC Hydro and the Ministry of Environment, Lands and Parks. This report summarizes the results of the third year of fertilization and of studies conducted in 2001/02.

1.2 Personnel, Affiliation and Responsibilities

Table 1.1 Listing of 2001/02 Arrow Reservoir project focus, personnel and affiliation

Project Focus	Personnel	Affiliation
Senior Scientist	Dr. Greg Lawrence	Civil Engineering, UBC
Fertilization Coordinator	Dr. Beth Wright	MWLAP, Nelson
Fertilizer application	Grant Thorp Bob Millar Heather Cooke	MWLAP, Hill Creek and Nakusp
Reservoir physical, chemical, phytoplankton and zooplankton sampling	Mark Young Don Miller Steve Arndt	Kootenay Wildlife Services Ltd. Kootenay Wildlife Services Ltd. CBFWCP, Nelson

Columbia River at Revelstoke (year round), Illecillewaet and Akolkolex rivers water chemistry and temperature sampling	Karen Bray	CBFWCP, Revelstoke
Incomappleux R., Halfway R., St. Leon Cr. and Cape Horn Cr. Kuskanax Cr.: water chemistry and temperature sampling	Diana Koller	Hill Creek Hatchery, MWLAP, Hill Creek
Slewiskin, Mosquito, Caribou, Burton, Barnes, Eagle and Inonoaklin Creeks, Whatshan River, Whatshan powerhouse discharge and Halcyon Hotsprings: water chemistry and temperature sampling	Grant Thorp	Fish and Wildlife, MWLAP, Nakusp
Columbia River (year round) d/s Keenleyside Dam, and Deer, Little Cayuse and Syringa Creeks: water chemistry and temperature sampling	Dan Gebhart	Aquatic Resources Limited
Kokanee acoustic surveys	Dale Sebastian George Scholten Patricia Woodruff	Fisheries Branch, MWLAP, Victoria Fisheries Branch, MWLAP, Victoria B.C. Conservation Foundation
Mysid net sampling	Mark Young Don Miller Steve Arndt	Kootenay Wildlife Services Ltd. Kootenay Wildlife Services Ltd. CBFWCP, Nelson
Kokanee trawling	Don Miller and KWS staff	Kootenay Wildlife Services Ltd.
Hill Creek kokanee adult enumeration	Grant Thorp Bob Millar	Fish and Wildlife, MWLAP, Nakusp Hill Creek Hatchery, MWLAP, Hill Creek
Hill Creek kokanee fry enumeration	Grant Thorp Bob Millar	Fish and Wildlife, MWLAP, Nakusp Hill Creek Hatchery, MWLAP, Hill Creek
Zooplankton analysis and reporting	Dr. Lidija Vidmanic	Fisheries Centre, UBC Civil Engineering, UBC

Mysid analysis and reporting	Dr. Lidija Vidmanic	Fisheries Centre, UBC, Civil Engineering, UBC
Kokanee analysis and reporting	Harvey Andrusak	Redfish Consulting Ltd.
Phytoplankton analysis and reporting	Dr. John Stockner	Ecologic Ltd.
Primary Productivity	Shannon Harris Dr. Ken Hall	Civil Engineering, UBC Civil Engineering, UBC
Stream and reservoir chemistry reporting	Dr. Roger Pieters Amin Eskooch	Civil Engineering and EOS, UBC
Arrow Reservoir nutrient budget	Dr. Roger Pieters Dr. John Stockner	Civil Engineering and EOS, UBC Ecologic Ltd.
Paleolimnology	Dr. Ken Ashley Dr. Lidija Vidmanic	Fisheries Branch, MF, UBC Civil Engineering, UBC
Meteorological data	Dr. Roger Pieters	Civil Engineering and EOS, UBC
Regional support and logistics	Grant Thorp Les Fleck Bob Lindsay Jay Hammond	Fish and Wildlife, MWLAP, Nakusp Fish and Wildlife, MWLAP, Nelson
CBFWCP Technical Committee	Jay Hammond Dr. Ken Ashley Gary Birch Dave Wilson	Fish and Wildlife, MWLAP, Nelson; Fisheries Branch, MF, UBC B.C. Hydro, Castlegar B.C. Hydro, Vancouver
Project co-ordination and scientific liaison	Dr. Ken Ashley Bob Lindsay	Fisheries Branch, MWLAP, UBC Fish and Wildlife, MWLAP, Nelson
Annual report preparation	Dr. Roger Pieters	Civil Engineering and EOS, UBC
Contract administration	Harald Manson	CBFWCP, Nelson

Table 1.2 Arrow Reservoir physical, chemical and plankton sampling program for 2001/02[5]

Parameter sampled	Sampling frequency	Sampling technique
Temperature, dissolved oxygen, pH, ORP, specific conductance, turbidity	Apr - Nov/01 monthly, Jan/02 and March/02	(a) Hydrolab at 8 AR sampling stations at 1 m intervals from 0 to 50 m, and at 5 m intervals from 50 to 100 m (b) same sampling at Hydrolab sites 1-4

[5] Table 1.2 describes sampling for fiscal year 2001/02 which ran from April 1, 2001 to March 31, 2002. Subsequent chapters report on data collected from January 1 to December 31, 2001.

Transparency	Apr - Nov/01 monthly, Jan/02 and March/02	Secchi disk (without viewing chamber) at 8 AR sampling stations
Water chemistry: Specific cond., pH, silica, alkalinity and nutrients (TP, TDP, LL SRP, NO_3+NO^2, NH_3); Total metals (Ca, Mg, Na, K, Cl, SO_4, CO_3, HCO_3) were added to June and September analysis for AR 2 and 7 only	Apr - Nov/01 monthly, Jan/02 and March/02	(a) Integrated sampling tube at 0 - 30 m at 8 AR sampling stations plus a bottle sample 5 m off the bottom at Stns. 1-3, 6-8 (b) (June and August only) bottle samples every 50 m as depth allows.
Water chemistry: Specific cond., pH, nutrients (TP, TDP, LL SRP, NO_3+NO_2, NH_3) and temperature sampling	(a) Columbia River at Revelstoke and Keenleyside; monthly from Jan./01 to March/02 and twice in April, May and June (b) Illecillewaet, Akolkolex, Incomappleux, Kuskanax, Mosquito, Burton, Caribou and Inonoaklin rivers monthly from April to October, twice in April, May and June	Sampling bottle
Water chemistry: Specific cond., pH, nutrients (TP, TDP, LL SRP, NO_3+NO_2, NH_3) and temperature sampling	Two samplings on Halfway R., St. Leon, Cape Horn and Slewiskin Crs, Whatshan River and powerhouse discharge, Eagle, Deer, Little Cayuse and Syringa Crs.; May and July	Sampling bottle
Chlorophyll *a* (not corrected for phaeophytin)	Apr - Nov/00 monthly (bi-monthly in June and Aug); Jan + March 01.	Integrated sampling tube at 0 - 30 m at AR 1-4, 6-8 sampling stations (no samples at AR 5)

Primary Productivity	Vertical profiles at stations AR2 and 7 Apr-Oct/01	Sample bottle
Phytoplankton	Apr - Oct/01 monthly (twice in June and Aug)	Integrated sampling tube at 0 - 20 m at AR 1-4, 6-8 sampling stations (no samples at AR 5)
Macrozooplankton	Apr - Oct/01 monthly	3 oblique Clarke-Bumpus net hauls (3-minutes each) from 40 to 0 m at AR 1-3, 6-8 sampling stations (150 µm net) (no samples at AR 4 and 5)
Mysid net sampling	Apr-Dec/01 monthly; Jan/02 and March/02	3 replicate hauls with mysid net, two deep and one shallow at AR 1-3, 6-8 (no samples at AR 4 and 5)
Kokanee acoustic sampling	2 surveys; summer and fall/01	Standard MWLAP Simrad and Biosonics hydroacoustic procedure at 20 transects in Upper and Lower Arrow
Kokanee trawling	Fall trawl series	Standard trawl series using oblique hauls at AR 1-3 and 6-8 in Upper and Lower Arrow
Adult kokanee enumeration	Fall spawning period at Hill Creek channel and selected streams	Standard Region 4 MWLAP procedure
Kokanee fry enumeration	Spring monitoring at Hill creek	Standard Region 4 MWLAP procedure
Meteorological data	year round April-Oct/01	Lower Arrow shore station Upper Arrow sunlight station

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APPENDIX 1.1
FERTILIZER SPECIFICATIONS, 2001

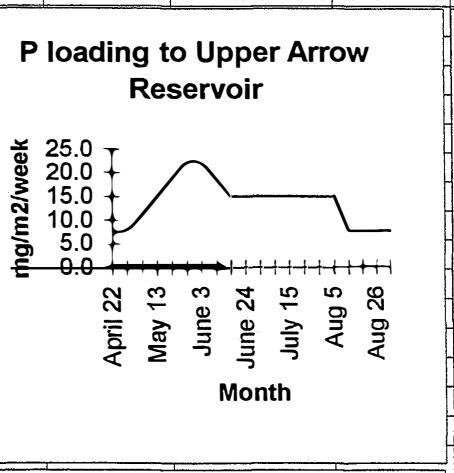
	A	B	C	D	E	F	G	H	I
1	Timing, fertilizer load and N:P ratios for Upper Arrow Reservior - K. Ashley, Feb 22/00								
2	Reconstructed from 2000 load sheet and 2001 schedule - R. Pieters July 21/2003								
3	Fertilizer: blend of 10-34-0 (ammonium polyphosphate) and 28-0-0 (urea-ammonium nitrate)								
4	Density of 10-34-0 is 1.415 kg/L, and 28-0-0 is 1.28 kg/L @ 15 C								
5	Note: N:P ratios are increased during application period					**Year 3 of 5 - 2000 for ARF**			
6									
7	**Note: All areal calculations based on 1992-96 Kootenay Lake North Arm loadings**								
8	**total area = 192.82 km2 (no Beaton Arm)**								
9									
10	**Week**	**Nutrient**	**N / P Loading**	**Amount**	**Amount**	**Form**	**N:P ratio**	**Expected**	**Expected**
11	**Dates**	**P or N**	**mg/m2/wk**	**N or P kg**	**Fert (mt)**	**fertilizer**	**wt:wt**	**P (ug/L)**	**Chlor a**
12	April 22	P	7.5	1,448	9.7	10-34-0	0.67	1.1	0.8
13		N	5.1	975		10-34-0			
14		N	0.0	0		**28-0-0**			
15	April 29	P	7.5	1,448	9.7	10-34-0	0.67	1.3	0.8
16		N	5.1	975		10-34-0			
17		N	0.0	0		**28-0-0**			
18	May 6	P	11.3	2,171	14.6	10-34-0	0.67	1.5	0.9
19		N	7.6	1,462		10-34-0			
20		N	0.0	0		**28-0-0**			
21	May 13	P	15.0	2,895	19.5	10-34-0	0.67	1.8	0.9
22		N	10.1	1,950		10-34-0			
23		N	0.0	0		**28-0-0**			
24	May 20	P	18.8	3,619	24.4	10-34-0	3.00	2.2	1.0
25		N	12.6	2,437		10-34-0			
26		N	43.7	8,425	30.1	**28-0-0**			
27	May 27	P	22.5	4,343	29.2	10-34-0	3.00	2.6	1.1
28		N	15.2	2,925		10-34-0			
29		N	52.3	10,100	36.1	**28-0-0**			
30	June 3	P	22.5	4,343	29.2	10-34-0	3.00	3.1	1.2
31		N	15.2	2,925		10-34-0			
32		N	52.3	10,100	36.1	**28-0-0**			
33	June 10	P	18.8	3,619	24.4	10-34-0	4.50	3.5	1.3
34		N	12.6	2,437		10-34-0			
35		N	71.8	13,850	49.5	**28-0-0**			
36	June 17	P	15.0	2,895	19.5	10-34-0	4.50	3.8	1.4
37		N	10.1	1,950		10-34-0			
38		N	57.4	11,075	39.6	**28-0-0**			
39	June 24	P	15.0	2,895	19.5	10-34-0	4.50	4.1	1.4
40		N	10.1	1,950		10-34-0			
41		N	57.4	11,075	39.6	**28-0-0**			
42	July 1	P	15.0	2,895	19.5	10-34-0	4.50	4.4	1.5
43		N	10.1	1,950		10-34-0			
44		N	57.4	11,075	39.6	**28-0-0**			
45	July 8	P	15.0	2,895	19.5	10-34-0	6.00	4.7	1.6
46		N	10.1	1,950		10-34-0			
47		N	79.9	15,425	55.1	**28-0-0**			
48	July 15	P	15.0	2,895	19.5	10-34-0	6.00	5.0	1.6
49		N	10.1	1,950		10-34-0			
50		N	79.9	15,425	55.1	**28-0-0**			

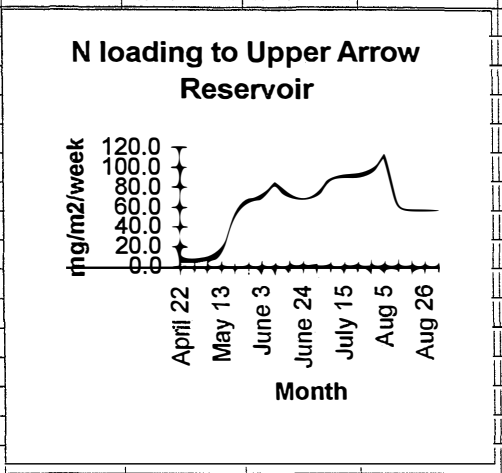
APPENDIX 1.1
FERTILIZER SPECIFICATIONS, 2001 (CONTINUED)

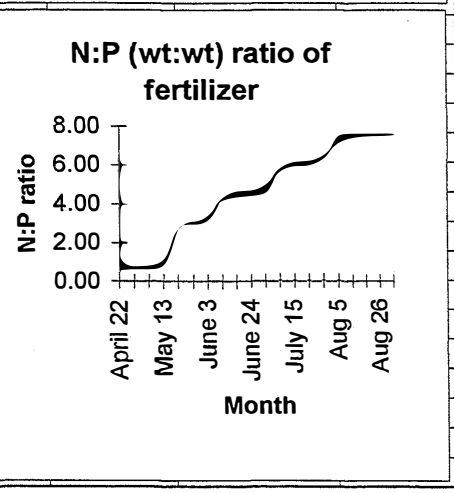
	A	B	C	D	E	F	G	H	I
51	July 22	P	15.0	2,895	19.5	10-34-0	6.00	5.3	1.7
52		N	10.1	1,950		10-34-0			
53		N	79.9	15,425	55.1	**28-0-0**			
54	July 29	P	15.0	2,895	19.5	10-34-0	6.00	5.6	1.8
55		N	10.1	1,950		10-34-0			
56		N	79.9	15,425	55.1	**28-0-0**			
57	Aug 5	P	15.0	2,895	19.5	10-34-0	7.50	5.9	1.8
58		N	10.1	1,950		10-34-0			
59		N	102.3	19,750	70.5	**28-0-0**			
60	Aug 12	P	7.5	1,448	9.7	10-34-0	7.50	6.0	1.9
61		N	5.1	975		10-34-0			
62		N	51.2	9,875	35.3	**28-0-0**			
63	Aug 19	P	7.5	1,448	9.7	10-34-0	7.50	6.2	1.9
64		N	5.1	975		10-34-0			
65		N	51.2	9,875	35.3	**28-0-0**			
66	Aug 26	P	7.5	1,448	9.7		7.50	6.3	1.9
67		N	5.1	975		10-34-0			
68		N	51.2	9,875	35.3	**28-0-0**			
69	Sept 2	P	7.5	1,448	9.7	10-34-0	7.50	6.5	2.0
70		N	5.1	975		10-34-0			
71		N	51.2	9,875	35.3	**28-0-0**			
72									
73									
74		**Total P**	273.8	52.8	355.8	$138,781			
75		**load**	mg/m2	metric ton	metric ton	Cost of P			
76			in 20 weeks	of P	of 10-34-0	@$390/mt	(estimated cost)		
77									
78									
79		**Total N**	1203.3	232.2	702.3	$158,022			
80		**load**	mg/m2	metric ton	metric ton	Cost of N			
81			in 20 weeks	of N	of 28-0-0	@$225/mt	(estimated cost)		
82									
83									
84	Total	weight	1058.2		Total cost	$296,804			
85		of N and P	metric tons		of fertilizer				
86		fertilizer							
87				**Summary**					
88			**Phosphorus**			**Nitrogen**			
89		**Load**	**Amount**	**10-34-0**	**Load**	**Amount**	**28-0-0**	**N:P Ratio**	**No.**
90		**mg/m2**	**kgs**	**M. Tons**	**mg/m2**	**kgs**	**M. Tons**	**Wt:Wt**	
91	April 22	7.5	1,448	9.7	5.1	975	0.00	0.67	1
92	April 29	7.5	1,448	9.7	5.1	975	0.00	0.67	2
93	May 6	11.3	2,171	14.6	7.6	1,462	0.00	0.67	3
94	May 13	15.0	2,895	19.5	10.1	1,950	0.00	0.67	4
95	May 20	18.8	3,619	24.4	56.3	10,862	30.09	3.0	5
96	May 27	22.5	4,343	29.2	67.5	13,025	36.07	3.0	6
97	June 3	22.5	4,343	29.2	67.5	13,025	36.07	3.0	7
98	June 10	18.8	3,619	24.4	84.4	16,287	49.46	4.5	8
99	June 17	15.0	2,895	19.5	67.5	13,025	39.55	4.5	9
100	June 24	15.0	2,895	19.5	67.5	13,025	39.55	4.5	10

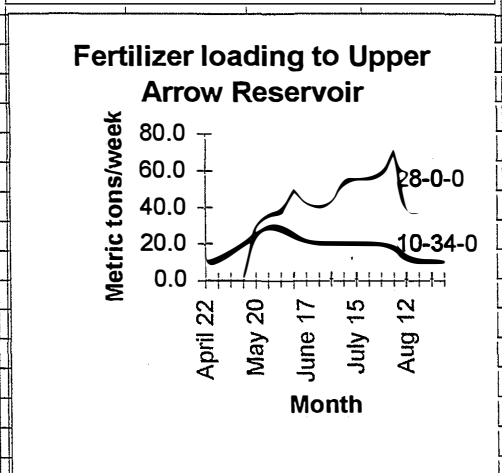
APPENDIX 1.1
FERTILIZER SPECIFICATIONS, 2001 (CONTINUED)

	A	B	C	D	E	F	G	H	I
101	July 1	15.0	2,895	19.5	67.5	13,025	39.55	4.5	11
102	July 8	15.0	2,895	19.5	90.0	17,375	55.09	6.0	12
103	July 15	15.0	2,895	19.5	90.0	17,375	55.09	6.0	13
104	July 22	15.0	2,895	19.5	90.0	17,375	55.09	6.0	14
105	July 29	15.0	2,895	19.5	90.0	17,375	55.09	6.0	15
106	Aug 5	15.0	2,895	19.5	112.4	21,700	70.54	7.5	16
107	Aug 12	7.5	1,448	9.7	56.2	10,850	35.27	7.5	17
108	Aug 19	7.5	1,448	9.7	56.2	10,850	35.27	7.5	18
109	Aug 26	7.5	1,448	9.7	56.2	10,850	35.27	7.5	19
110	Sept 2	7.5	1,448	9.7	56.2	10,850	35.27	7.5	20
111									
112			**Phosphorus**			**Nitrogen**			
113		**Load**	**Amount**	**10-34-0**	**Load**	**Amount**	**28-0-0**	**N:P Ratio**	**No.**
114		**mg/m2**	**kgs**	**M. Tons**	**mg/m2**	**kgs**	**M. Tons**		
115									
116		273.8	52.8	355.8	1203.3	232.2	702.3		
117		mg/m2	P	10-34-0	mg/m2	N	28-0-0		
118		in 20 weeks	metric ton	metric ton	in 20 week	metric ton	metric ton		









APPENDIX 1.2
FERTILIZER SCHEDULE, 2001

Upper Arrow Reservoir Fertilization Schedule - April 22 to Sept 2/01.									E. Wright - Feb. 2/01						
Year 3 of 5		2001 Schedule - Daily applications, (Mon to Fri only), 25 minute travel time, one-way application													Trips/wk
		M. tons	% of	% of	litres	M. Tons	% of	% of	litres	Total	Blend (%)	N:P ratio	Appl. rate	Total	1,000 g
Week	Date	10-34-0	10-34-0	10-34-0	10-34-0	28-0-0	28-0-0	28-0-0	28-0-0	M. Tons	N-P2O5-K2O	wt:wt	litres/min	litres	tank
			in total	in blend			in total	in blend					(25 min. travel)		
1	22-Apr	9.7	100.0	34.0	6,929	0.0	0.0	10.0	0	9.7	10-34-0	0.67	55	6,929	2
2	29-Apr	9.7	100.0	34.0	6,929	0.0	0.0	10.0	0	9.7	10-34-0	0.67	55	6,929	2
3	6-May	14.6	100.0	34.0	10,429	0.0	0.0	10.0	0	14.6	10-34-0	0.67	83	10,429	2
4	13-May	19.5	100.0	34.0	13,929	0.0	0.0	10.0	0	19.5	10-34-0	0.67	111	13,929	3
5	20-May	24.4	44.8	15.2	17,429	30.1	55.2	19.9	23,516	54.5	19.9 - 15.2 - 0	3.00	328	40,944	9
6	27-May	29.2	44.7	15.2	20,857	36.1	55.3	20.0	28,203	65.3	20.0 - 15.2 - 0	3.00	392	49,060	11
7	3-Jun	29.2	44.7	15.2	20,857	36.1	55.3	20.0	28,203	65.3	20.0 - 15.2 - 0	3.00	392	49,060	11
8	10-Jun	24.4	33.0	11.2	17,429	49.5	67.0	22.1	38,672	73.9	22.1 - 11.2 - 0	4.50	449	56,100	12
9	17-Jun	19.5	33.0	11.2	13,929	39.6	67.0	22.1	30,938	59.1	22.1 - 11.2 - 0	4.50	359	44,866	10
10	24-Jun	19.5	33.0	11.2	13,929	39.6	67.0	22.1	30,938	59.1	22.1 - 11.2 - 0	4.50	359	44,866	10
11	1-Jul	19.5	33.0	11.2	13,929	39.6	67.0	22.1	30,938	59.1	22.1 - 11.2 - 0	4.50	359	44,866	10
12	8-Jul	19.5	26.1	8.9	13,929	55.1	73.9	23.3	43,047	74.6	23.3 - 8.9 - 0	6.00	456	56,975	13
13	15-Jul	19.5	26.1	8.9	13,929	55.1	73.9	23.3	43,047	74.6	23.3 - 8.9 - 0	6.00	456	56,975	13
14	22-Jul	19.5	26.1	8.9	13,929	55.1	73.9	23.3	43,047	74.6	23.3 - 8.9 - 0	6.00	456	56,975	13
15	29-Jul	19.5	26.1	8.9	13,929	55.1	73.9	23.3	43,047	74.6	23.3 - 8.9 - 0	6.00	456	56,975	13
16	5-Aug	19.5	21.7	7.4	13,929	70.5	78.3	24.1	55,078	90.0	24.1 - 7.4 - 0	7.49	552	69,007	15
17	12-Aug	9.7	21.6	7.3	6,929	35.3	78.4	24.1	27,578	45.0	24.1 - 7.3 - 0	7.54	276	34,507	8
18	19-Aug	9.7	21.6	7.3	6,929	35.3	78.4	24.1	27,578	45.0	24.1 - 7.3 - 0	7.54	276	34,507	8
19	26-Aug	9.7	21.6	7.3	6,929	35.3	78.4	24.1	27,578	45.0	24.1 - 7.3 - 0	7.54	276	34,507	8
20	2-Sep	9.7	21.6	7.3	6,929	35.3	78.4	24.1	27,578	45.0	24.1 - 7.3 - 0	7.54	276	34,507	8
MT of	10-34-0	355.5			MT of 28-0-0	702.7				1058.2	Total MT of 10-34-0 and				

APPENDIX 1.2
FERTILIZER SCHEDULE, 2001 (CONTINUED)

	MT of P	52.8				MT of N	196.8						28-0-0												
						in 28-0-0																			
						MT of N	35.6																		
Litres 10-34-0	253,929					in 10-34-0																			
						Total MT	232.3																		
Litres 28-0-0	548,984					of N																			
Total litres	802,913																								
Note: Density of 10-34-0 is 1.4 kg/L, 28-0-0 is 1.28 kg/L at 15 deg. C																									

APPENDIX 1.3
FERTILIZER TRIP SCHEDULE

Date yy/mm/dd	Time	Liters	Cum. Subtotal	Cum. Total
01/04/25	9:30 AM	3,780	3,780	
01/04/26	7:30 PM	3,024	6,804	6,804
01/04/30	7:30 PM	3,780	3,780	
01/05/05	7:30 PM	3,024	6,804	13,608
01/05/08	7:30 PM	3,780	3,780	
01/05/09	8:30 AM	3,780	7,560	
01/05/11	7:30 PM	3,024	10,584	24,192
01/05/13	7:30 PM	3,780	3,780	
01/05/14	7:30 PM	3,780	7,560	
01/05/15	7:30 PM	3,780	11,340	
01/05/16	7:30 PM	3,780	15,120	39,312
01/05/20	5:30 AM	3,780	3,780	
01/05/20	7:30 AM	3,780	7,560	
01/05/21	5:30 AM	3,780	11,340	
01/05/21	7:30 AM	3,780	15,120	
01/05/22	7:30 PM	3,780	18,900	
01/05/23	7:30 PM	3,780	22,680	
01/05/24	5:30 AM	3,780	26,460	
01/05/24	7:30 AM	3,780	30,240	
01/05/25	7:30 AM	3,780	34,020	
01/05/26	7:30 AM	3,780	37,800	
01/05/26	9:30 AM	3,144	40,944	80,256
01/05/27	7:30 AM	3,780	3,780	
01/05/27	7:30 PM	3,780	7,560	
01/05/28	8:30 PM	3,780	11,340	
01/05/29	7:30 AM	3,780	15,120	
01/05/29	9:30 AM	3,780	18,900	
01/05/30	9:30 AM	3,780	22,680	
01/05/30	7:30 PM	3,780	26,460	
01/05/31	6:30 AM	3,780	30,240	
01/05/31	8:30 AM	3,780	34,020	
01/06/01	7:30 AM	3,780	37,800	
01/06/01	7:30 PM	3,780	41,580	
01/06/02	7:30 AM	3,780	45,360	
01/06/02	9:30 AM	3,780	49,140	129,396
01/06/03	8:30 AM	3,780	3,780	
01/06/03	7:30 PM	3,780	7,560	
01/06/04	6:30 PM	3,780	11,340	

Date yy/mm/dd	Time	Liters	Cum. Subtotal	Cum. Total
01/06/04	8:30 PM	3,780	15,120	
01/06/05	5:30 PM	3,780	18,900	
01/06/05	7:30 PM	3,780	22,680	
01/06/06	6:30 PM	3,780	26,460	
01/06/06	8:30 PM	3,780	30,240	
01/06/08	7:30 AM	3,780	34,020	
01/06/08	7:30 PM	3,780	37,800	
01/06/09	6:30 AM	3,780	41,580	
01/06/09	8:30 AM	3,780	45,360	174,756
01/06/10	7:30 AM	3,780	3,780	
01/06/10	6:30 PM	3,780	7,560	
01/06/10	8:30 PM	3,780	11,340	
01/06/11	6:30 PM	3,780	15,120	
01/06/11	8:30 PM	3,780	18,900	
01/06/12	7:30 AM	3,780	22,680	
01/06/12	9:30 AM	3,780	26,460	
01/06/13	6:30 PM	3,780	30,240	
01/06/13	8:30 PM	3,780	34,020	
01/06/14	5:30 AM	3,780	37,800	
01/06/14	7:30 AM	3,780	41,580	
01/06/15	6:30 AM	3,780	45,360	
01/06/15	8:30 AM	3,780	49,140	
01/06/16	6:30 AM	3,780	52,920	
01/06/16	8:30 AM	3,024	55,944	230,700
01/06/17	6:30 PM	3,780	3,780	
01/06/17	8:30 PM	3,780	7,560	
01/06/18	7:30 AM	3,780	11,340	
01/06/18	9:30 AM	3,780	15,120	
01/06/19	6:30 PM	3,780	18,900	
01/06/19	8:30 PM	3,780	22,680	
01/06/20	12:30 PM	3,780	26,460	
01/06/20	9:30 PM	3,780	30,240	
01/06/21	6:30 AM	3,780	34,020	
01/06/21	8:30 AM	3,780	37,800	
01/06/23	6:30 PM	3,780	41,580	
01/06/23	8:30 PM	3,286	44,866	275,566
01/06/24	6:30 PM	3,780	3,780	
01/06/24	8:30 PM	3,780	7,560	
01/06/25	7:30 AM	3,780	11,340	
01/06/25	9:30 AM	3,780	15,120	
01/06/26	6:30 PM	3,780	18,900	

Date yy/mm/dd	Time	Liters	Cum. Subtotal	Cum. Total
01/06/26	8:30 PM	3,780	22,680	
01/06/27	4:30 PM	3,780	26,460	
01/06/27	6:30 PM	3,780	30,240	
01/06/27	9:30 PM	3,780	34,020	
01/06/28	5:30 PM	3,780	37,800	
01/06/28	7:30 PM	3,780	41,580	
01/06/30	5:30 AM	3,286	44,866	320,432
01/07/01	8:30 AM	3,780	3,780	
01/07/01	11:30 AM	3,780	7,560	
01/07/02	5:30 PM	3,780	11,340	
01/07/02	7:30 PM	3,780	15,120	
01/07/02	9:30 PM	3,780	18,900	
01/07/03	7:30 PM	3,780	22,680	
01/07/03	9:30 PM	3,780	26,460	
01/07/04	6:30 AM	3,780	30,240	
01/07/04	8:30 AM	3,780	34,020	
01/07/04	11:30 AM	3,780	37,800	
01/07/05	5:30 PM	3,780	41,580	
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01/07/10	7:30 AM	3,780	18,900	
01/07/10	12:30 PM	3,780	22,680	
01/07/11	7:30 AM	3,780	26,460	
01/07/11	9:30 AM	3,780	30,240	
01/07/11	11:30 AM	3,780	34,020	
01/07/12	7:30 AM	3,780	37,800	
01/07/12	9:30 AM	3,780	41,580	
01/07/13	7:30 AM	3,780	45,360	
01/07/13	9:30 AM	3,780	49,140	
01/07/13	11:30 AM	3,780	52,920	
01/07/14	5:30 AM	3,780	56,700	421,998
01/07/15	5:30 AM	3,780	3,780	
01/07/15	7:30 AM	3,780	7,560	
01/07/15	9:30 AM	3,780	11,340	
01/07/16	5:30 PM	3,780	15,120	
01/07/16	7:30 PM	3,780	18,900	
01/07/17	6:30 AM	3,780	22,680	
01/07/17	8:30 AM	3,780	26,460	
01/07/18	6:30 PM	3,780	30,240	
01/07/19	8:30 AM	3,780	34,020	
01/07/19	10:30 AM	3,780	37,800	
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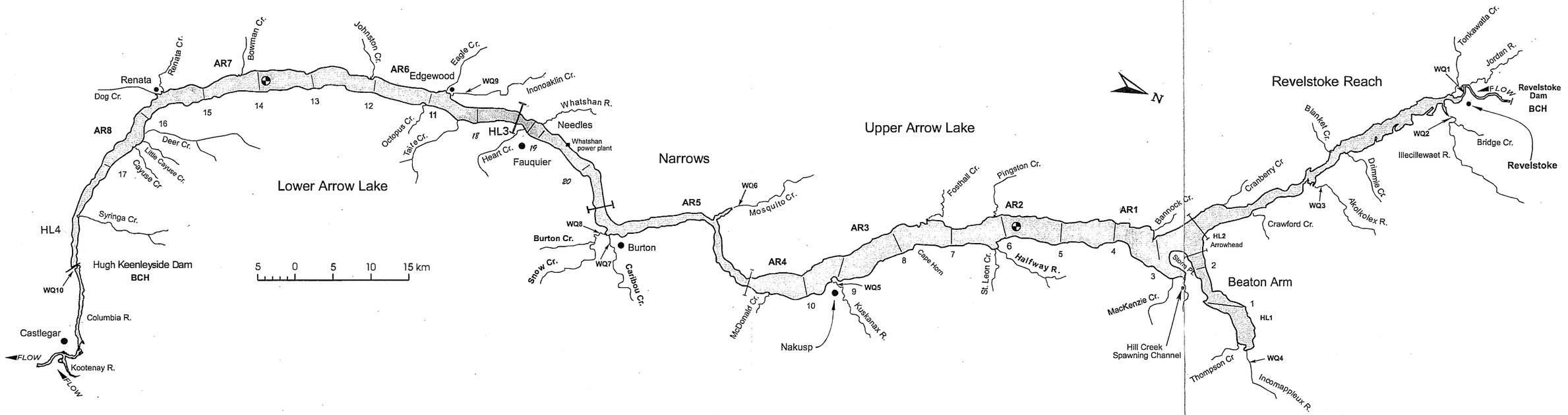
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01/07/21	7:30 AM	3,780	56,700	478,698
01/07/22	5:30 AM	3,780	3,780	
01/07/22	5:30 PM	3,780	7,560	
01/07/22	7:30 PM	3,780	11,340	
01/07/23	6:30 AM	3,780	15,120	
01/07/23	8:30 AM	3,780	18,900	
01/07/24	5:30 PM	3,780	22,680	
01/07/24	7:30 PM	3,780	26,460	
01/07/25	5:30 AM	3,780	30,240	
01/07/25	7:30 AM	3,780	34,020	
01/07/26	6:30 PM	3,780	37,800	
01/07/26	8:30 PM	3,780	41,580	
01/07/27	5:30 AM	3,780	45,360	
01/07/27	7:30 AM	3,780	49,140	
01/07/27	9:30 AM	3,780	52,920	
01/07/28	5:30 AM	3,780	56,700	535,398
01/07/29	5:30 AM	3,780	3,780	
01/07/29	5:30 PM	3,780	7,560	
01/07/29	7:30 PM	3,780	11,340	
01/07/30	5:30 AM	3,780	15,120	
01/07/30	5:30 PM	3,780	18,900	
01/07/31	6:30 PM	3,780	22,680	
01/07/31	8:30 PM	3,780	26,460	
01/08/01	5:30 AM	3,780	30,240	
01/08/01	7:30 AM	3,780	34,020	
01/08/01	9:30 AM	3,780	37,800	
01/08/02	7:30 AM	3,780	41,580	
01/08/02	9:30 AM	3,780	45,360	
01/08/03	9:30 PM	3,780	49,140	
01/08/03	11:30 PM	3,780	52,920	
01/08/04	5:30 AM	3,780	56,700	
01/08/04	7:30 AM	3,780	60,480	595,878
01/08/05	7:30 PM	3,780	3,780	
01/08/05	9:30 PM	3,780	7,560	
01/08/05	11:30 PM	3,780	11,340	
01/08/06	5:30 AM	3,780	15,120	
01/08/06	7:30 AM	3,780	18,900	
01/08/06	8:30 PM	3,780	22,680	
01/08/07	5:30 PM	3,780	26,460	
01/08/07	7:30 PM	3,780	30,240	
01/08/07	9:30 PM	3,780	34,020	
01/08/08	6:30 AM	3,780	37,800	

Date yy/mm/dd	Time	Liters	Cum. Subtotal	Cum. Total
01/08/08	8:30 AM	3,780	41,580	
01/08/08	5:30 PM	3,780	45,360	
01/08/08	7:30 PM	3,780	49,140	
01/08/08	9:30 PM	3,780	52,920	
01/08/09	6:30 PM	3,780	56,700	
01/08/09	8:30 PM	3,780	60,480	
01/08/10	7:30 AM	3,780	64,260	
01/08/11	9:30 PM	3,780	68,040	663,918
01/08/12	5:30 PM	3,780	3,780	
01/08/12	7:30 PM	3,780	7,560	
01/08/15	5:30 PM	3,780	11,340	
01/08/15	7:30 PM	3,780	15,120	
01/08/15	9:30 PM	3,780	18,900	
01/08/17	5:30 AM	3,780	22,680	
01/08/17	7:30 AM	3,780	26,460	
01/08/18	7:30 AM	3,780	30,240	
01/08/18	4:30 PM	3,780	34,020	697,938
01/08/19	5:30 AM	3,780	3,780	
01/08/19	7:30 AM	3,780	7,560	
01/08/20	5:30 PM	3,780	11,340	
01/08/21	5:30 PM	3,780	15,120	
01/08/22	5:30 PM	3,780	18,900	
01/08/22	7:30 PM	3,780	22,680	
01/08/24	5:30 AM	3,780	26,460	
01/08/24	7:30 AM	3,780	30,240	
01/08/25	7:30 AM	3,780	34,020	731,958
01/08/26	7:30 AM	3,780	3,780	
01/08/26	9:30 AM	3,780	7,560	
01/08/27	5:30 PM	3,780	11,340	
01/08/28	5:30 PM	3,780	15,120	
01/08/29	7:30 AM	3,780	18,900	
01/08/29	9:30 AM	3,780	22,680	
01/08/30	5:30 PM	3,780	26,460	
01/08/31	7:30 AM	3,780	30,240	
01/08/31	9:30 AM	3,780	34,020	765,978
01/09/02	6:30 AM	3,780	3,780	
01/09/02	8:30 AM	3,780	7,560	
01/09/03	5:30 AM	3,780	11,340	
01/09/03	7:30 AM	3,780	15,120	
01/09/04	5:30 AM	3,780	18,900	
01/09/04	7:30 AM	3,780	22,680	
01/09/05	5:30 PM	3,780	26,460	
01/09/05	7:30 PM	3,780	30,240	
01/09/06	7:30 AM	3,780	34,020	

Date yy/mm/dd	Time	Liters	Cum. Subtotal	Cum. Total
01/09/06	10:30 AM	1,890	35,910	801,888

* On July 19, the 6:30 AM trip is recorded after the 10:30 AM trip. It is not known if they were recorded out of sequence or if the second trip should read 6:30 PM.

Figure 1.1 Plan view of Arrow Reservoir and sampling stations. See also Figure 14.1.



Project Stations AR#

Location and related studies

- **AR1** Albert Point, studies 1 - 6
- **AR2** Ann Point, studies 1 - 7
- **AR3** Turner Cr., studies 1 - 6
- **AR4** McDonald Cr. studies 3, 5, 6
- **AR5** Mosquito Cr., studies: 5, 6, 8
- **AR6** Johnson Cr., studies 1 - 6
- **AR7** Bowman Cr., studies 1 - 7
- **AR8** Cayuse Cr., studies 1 - 6

Studies

1 - Kokanee life stages (trawling)
2 - Zooplankton (tows)
3 - Phytoplankton (tube sampling)
4 - Mysid (net hauls)
5 - Hydrolab data profiles
6 - Water sample collections
7 - Paleolimnology (coring)
8 - Acoustic current profile

Metrological Station

Collection of continuous ambient and sub - surface conditions

- Surface wind speed and direction
- Air temperature
- Sunshine

- Water temperature
- Current profile (surface to bottom)

Spawner Enumerations

Upper Arrow	Lower Arrow
Bannock Cr.	Burton Cr.
Blanket Cr.	Caribou Cr.
Bridge Cr.	Deer Cr.
Cape Horn Cr.	Dog Cr.
Cranberry Cr.	Eagle Cr.
Crawford Cr.	Heart Cr.
Drimmie Cr.	Mosquito Cr.
Halfway R.	Octopus Cr.
Hill Cr.	Snow Cr.
Jordan R.	Taite Cr.
Kuskanax R.	
McDonald Cr.(Slewiskin Cr.)	
McKay Cr.	
MacKenzie Cr.	Spawning Channels
St. Leon Cr.	Hill Cr.
Thompson Cr.	Bridge Cr.
Tonkawatla	

Hydrolab HL# 1 - 4

locations of additional data collection

Water Quality WQ# 1 - 10

location of additional sample collections
- general ions & nutrients
- temperature
- limited sampling at sites 6,7,8,9

Flow Data BCH

BC Hydro dam operation records
- discharge
- temperature

Hydroacoustic Transects

Existing 1 - 17

New 18 - 20

plan view / profile view

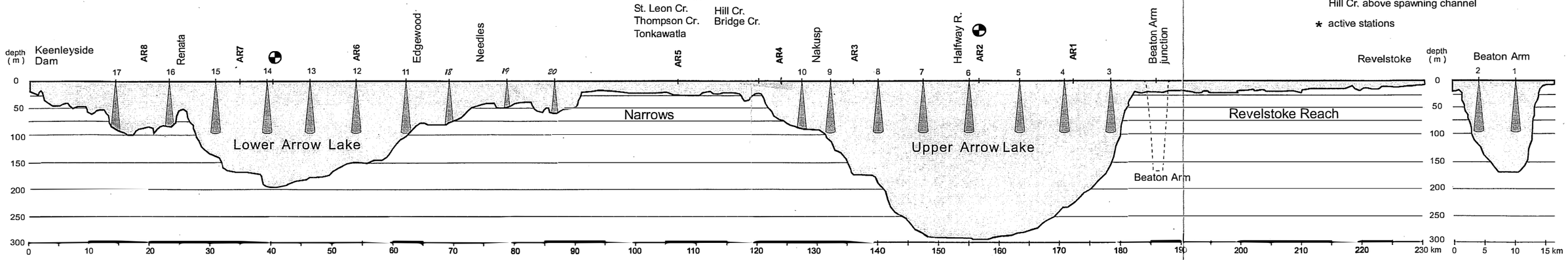
Simrad 70 kHz and Biosonics 420 kHz data collections

Study area reach breaks

Environment Canada Discharge stations

Columbia R. at Revelstoke
* Illecillewaet R. near Revelstoke
* Jordan R. near Revelstoke
* Incomappleux R. near Beaton
Columbia R. at Castlegar
* Cranberry Cr. at Corsier Lk.
* Barns Cr.
Caribou Cr. near Burton
* Kuskanax R. near Nakusp
Nakusp Cr. near Nakusp
Beaton Cr. near Beaton
* Inonoaklin Cr. near Edgewood
Renata Cr. near Renata
Heart Cr. near Fauquier
Whatshan R. at Needles
* Deer Cr. at Deer Park
Hill Cr. at Mill Road bridge
MacKenzie Cr.
Hill Cr. above spawning channel

* active stations



GHS 981014

FIGURE 1.1 ARROW LAKES / RESERVOIR FISHERIES INVESTIGATION SAMPLING LOCATIONS

2

Bathymetry

CHAPTER 2
BATHYMETRY

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2.3 Area of the draw-down zone.....2-3
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2.1 Introduction*

Before impoundment of the Columbia River's Arrow system, Upper and Lower Arrow Lakes were two distinct basins separated by a river channel. After completion of the Hugh Keenleyside Dam in 1967, the mean water level increased by 12 m (see Section 3.5), flooding the connecting river channel, which is now known as the Narrows. Both the original lakes and the subsequent reservoir are examples of 'fjord-type' basins as they are long, narrow and deep, and lie within a steep-sided and well defined glacially contoured mountain valley. The maximum depth of the upper and lower basins is now 287 m and 194 m below chart datum of 434 m, respectively (see Figure 1.1).

Two sources of bathymetric data are examined here: the Canadian Hydrographic Service charts (Section 2.2) and storage-elevation curves from B.C. Hydro (Section 2.3). For kokanee habitat areas see Appendix 14.6.

2.2 Bathymetric charts

Methods. The primary source of Bathymetric data for the Arrow Reservoir is the series of Canadian Hydrographic Service (CHS) charts listed in Table 2.1. The old river bed between Arrowhead and Revelstoke, which is part of the Upper Arrow, is here called the "Revelstoke Reach."

For CHS charts 3056, 3057 and 3058, chart datum is 434.0 m above geodetic datum. The exception is the side of chart 3058 near Revelstoke which has a datum of 435.6 m. Note that datum on a chart is normally at mean low water level, but the datum for these "*was selected to show the features as they will usually appear during the recreational boating season.*" Chart datum is 11 m above mean low water level and 4.5 m below mean high water level. For discussion of water level refer to Section 3.5.

* This chapter is the same as that given in previous reports and is provided for reference.

Table 2.1 Canadian Hydrographic Service charts

Chart	Title	Description
3055	Waneta to Hugh Keenleyside Dam	-below Keenleyside Dam
3056	Hugh Keenleyside Dam to Burton	-Lower Arrow Reservoir
3057	Burton to Arrowhead	-Narrows, mainstem Upper Arrow Reservoir, Beaton Arm
3058	Arrowhead to Revelstoke	-riverine "Revelstoke Reach"

An electronic form of charts 3056 and 3057 were obtained from the CHS vendor Nautical Data International, Inc., St. Johns, Newfoundland. Paul Hamblin enlisted the kind help of CHS staff at the Canadian Centre for Inland Waters (CCIW), Burlington, to convert electronic data to extract only the shoreline and contour segments. Paul Hamblin then sorted and joined all curve segments for the shoreline and the 10, 50, 100 and 200 m contours (the 200 m contour is for the upper basin only). The area was computed inside each closed curve using Green's theorem. Finally, the area was integrated over depth to give the volume of the reservoir. The division between the Upper and Lower Arrow was approximately located at the boundary between charts 3056 and 3057, near Burton, at the south end of the narrows. Chart 3058, for the Revelstoke Reach, was not available in digital form from NDI.[1]

On a CHS chart, shoreline demarks the highest observed water level. In tidal waters a shoreline is not necessarily a true contour. Rob Hare, CHS Sydney, determined that the charts for the Arrow Reservoir (from Revelstoke to the Hugh Keenleyside Dam) were constructed from 12 field sheets. For all twelve the sounding datum was 434 m above geodetic datum and the high water level is marked as 7 m above the sounding datum. Thus, for the Arrow reservoir the shoreline is a true contour and the shoreline is 7 m above datum throughout.

Results. Areas and volumes are given in Tables 2.2 and 2.3, while Figures 2.1 and 2.2 show contours for the Upper and Lower Arrow, respectively. (Hypsographic or depth-area curves are plotted in Hamblin, 1998a,b). The major features of the Lower Arrow are,

- a shallow basin between Syringa Creek and the Hugh Keenleyside Dam (with a small 59 m hole, but otherwise 37 m),[2]
- an intermediate basin between Syringa and Creek Renata (97 m),
- a deep basin (194 m),
- a shallow basin between Needles and Burton (53 m).

The narrows at the north end of the Lower Arrow is generally 15-20 m deep. The major feature of the Upper Arrow is a single deep basin (287 m). At the north end of the main basin of the Upper Arrow is Beaton Arm (171 m)[3] connected to the main basin by a shallow sill of about 14 m. From Arrowhead to Revelstoke is a flooded river bed, the deepest part of which is approximately 10 m below datum.

[1] Digital field sheets with raw soundings may be available from CHS, Sydney office.
[2] All depths are below datum.
[3] Known as Beaton Arm on the CHS charts but as Northeast Arm on the topographic and other maps.

Table 2.2 Upper Arrow Reservoir*, (Area and volume with depth)**

Depth below datum (m)	Height above bottom (m)	Area (km^2)	Volume (km^3)
Shoreline***	294	306.	30.55[4]
10	277	218.31	26.091
50	237	155.16	18.62
100	187	115.45	11.86
200	87	65.08	2.83
287	0	0	0

*Does not include Revelstoke Reach. Cf Appendix 3.3.
**Narrows included with Upper Arrow. See text.
***Shoreline is 7 m above datum.

Table 2.3 Lower Arrow Reservoir* (Area and volume with depth)

Depth below datum (m)	Height above bottom (m)	Area (km^2)	Volume (km^3)
Shoreline**	201	177.24	12.33[1]
10	184	154.81	9.505
50	134	64.69	5.115
100	94	48.58	2.283
194	0	0	0

*Narrows included with Upper Arrow. See text.
**Shoreline is 7 m above datum.

2.3 Area of the draw-down zone

Methods. An indirect source of bathymetric data is provided by the storage-elevation curve described in Section 3.6. From this curve, reservoir surface area can be determined for water levels through the range of active water storage. By comparing surface areas with those determined from the topographic maps, it was determined that the storage-elevation curve divides the Upper and Lower Arrow near the south end of the Narrows (see Appendix 3.3). A summary of reservoir surface areas is given in Table 2.4.

Results. At mean high water level the surface area of the Arrow Reservoir is 514 km^2. As the water level drops to the mean low water level the surface area of the reservoir decreases to 391 km^2, a difference of 123 km^2 which is 26% of the mean surface area. Of this difference, 80% takes place in the Upper Arrow, which includes the Revelstoke Reach. Determining the fraction of this area which occurs in the Revelstoke Reach must await further processing of chart 3058.

[4] This is the volume to the shoreline elevation of datum plus 7 m. The volume for mean post-impoundment water level can be found by subtracting the volume above 432.4 m, which can be determined using data from the storage-elevation curve (Table A3.3.2). The volume of the Upper and Lower Arrow at a water level of 432.4 m is 27.76 and 10.83 km^3, respectively.

Before construction of the Hugh Keenleyside Dam the mean water level of the lakes was close to the pre-impoundment mean low water level, which suggests that lake water levels remained low through most of the year with a peak during spring. In contrast, the post-impoundment mean water level is closer to the post-impoundment mean high water level: in other words, water levels now remain high throughout most of the year with a major drop in level during winter. Thus, before impoundment, spring flows briefly covered a vegetated 'flood zone' while now under normal operating conditions, winter release gradually exposes a large, non-vegetated draw-down zone.

Table 2.4 Surface areas

Description	Elevation m	A(Up) km^2	A(Lo) km^2	A(Tot) km^2
Pre impoundment				
Pre, Mean High	425.4	250.86	158.43	409.29
Pre, Mean	419.8	219.19	148.03	367.22
Pre, Mean Low	417.4	209*	142.34	351*
Mean High-Mean Low	8.0	42	16	58
Post impoundment				
Post, Mean High	438.5	337.22	176.89	514.12
Post, Mean	432.4	295.57	168.93	464.50
Post, Mean Low	423	236.65	154.29	390.94
Mean High-Mean Low	15.5	100.6	22.6	123.2

Upper Arrow area includes Revelstoke Reach unlike Table 2.2 which excludes it.
*These values were extrapolated from the data in the elevation-storage curve.
See Appendix 3.3 for a complete list.

This annual exposure and erosion of the reservoir's littoral slope (draw-down zone) is one of the contributing factors in the oligotrophication of impoundments, affecting reservoir epibenthic production and nutrient fluxes in the near shore region (Ney, 1996).

Acknowledgements

Thanks to Ron Bell, CHS , Sidney, B.C. for pre-release of the electronic CHS charts, Paul Hamblin and the CHS staff at CCIW for the laborious processing of the digital charts, Kelvin Ketchum, B.C. Hydro, Burnaby for the storage-elevation curve, and Tim Fisher for help in preparation of the figures.

References

Hamblin, 1998a,b. Baseline physical limnology of the Lower (Upper) Arrow Lake Reservoir, unpublished report, NWRI, Burlington, Ontario.

Ney, J. I., 1996. Oligotrophication and its discontents: effects of reduced nutrient loading on reservoir fisheries, American Fisheries Society Symposium, 16: 285-295.

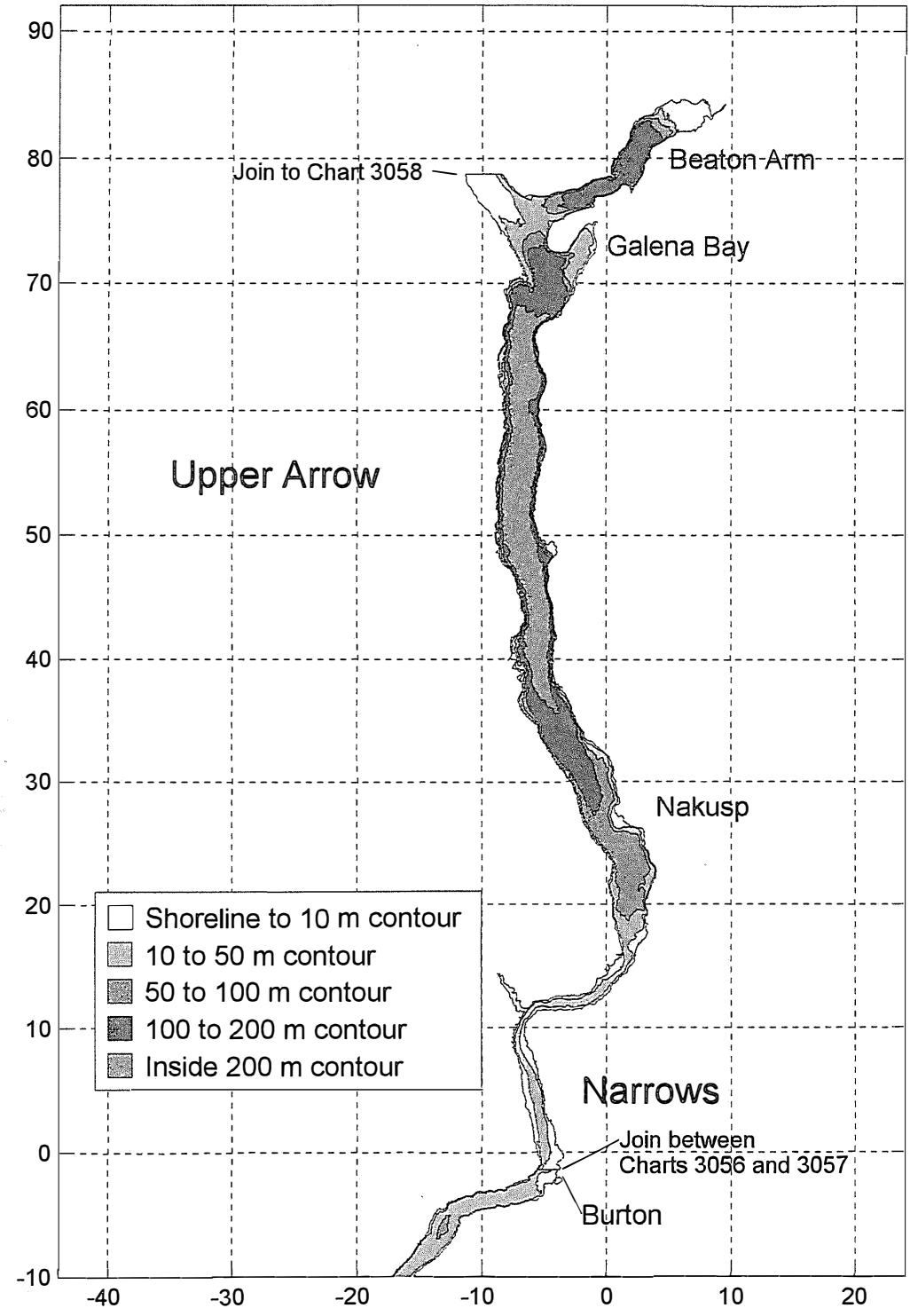


Figure 2.1 Upper Arrow showing the shoreline at 7 m above datum and the contours for 10, 50, 100 and 200 m below datum. The x and y axis are in kilometers with the origin at 117° 50' longitude and 50° 00' latitude, near Burton. Some small features may not be shown.

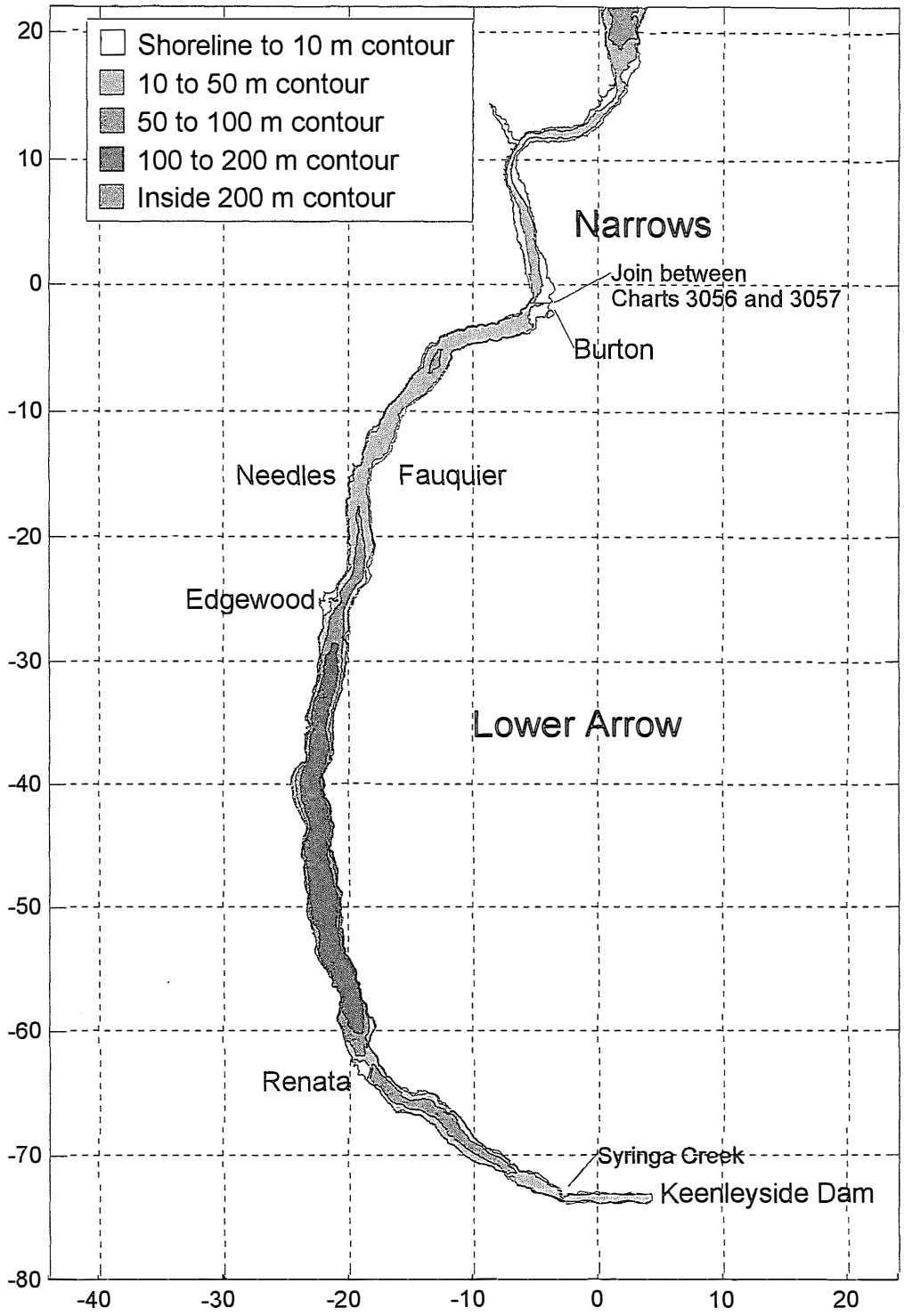


Figure 2.2 Lower Arrow showing the shoreline at 7 m above datum and the contours for 10, 50, and 100 m below datum. The x and y axis are in kilometers with the origin at 117° 50' longitude and 50° 00' latitude, near Burton. Some small features may not be shown (e.g. the island near Needles). Between Edgewood and Burton some segments of the contour labeled 10 m are given by the 5 m contour. This makes little difference in sections where the sides of the reservoir are steep, but results in the mismatch of the 10 m contours at the join near Burton.

3

Hydrology

CHAPTER 3
HYDROLOGY

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3.1 Introduction

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

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

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

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

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

Some basic hydrologic and morphometric features of the major lakes, reservoirs and dams in the Upper Columbia River basin are given in Table 3.1. The Whatshan Dam impounds

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

the Whatshan River and drains into the north end of the Lower Arrow at Needles. The Whatshan Reservoir is connected to a powerhouse north of Needles by a 3.4 km tunnel.

This chapter includes discussion of flows used in the nutrient budget in Chapter 9. For ease of comparison, flows for 1997 to 2001 will be discussed.

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

Lake or Reservoir	Dam	Date[1]	Area	Outflow		Vol.	Max Depth	Mean Depth
			km^2	m^3/s	km^3/yr	km^3	m	m
Kinbasket	Mica	1976	310[5]	586[3]	18.5			
Revelstoke	Revelstoke	1983	115[3]	749[10]	23.6			
Whatshan	Whatshan	1951[3]		9.3[3]	0.29			
Up. Arrow	-	-	275[7]	1,022[13]	32.3	27.8[8]	287	101[11]
Lo. Arrow	-	-	190[7]	-	-	10.8[8]	194	57[11]
Arrow	Keenleyside	1967[18]	465[7]	1,080[9]	34.1	38.6[8]	287	83[11]
Koocanusa	Libby	1973	186[4]	352[4]	11.1[4]	7.2[4]	107[4]	38[4]
Duncan	Duncan	1967	75[4]	91[4]	2.9[4]	3.0[4]	147[4]	40[4]
Kootenay L.	Corra Lynn	1931[2]	390[4]	780[4]	24.6[4]	36.7[4]	154[4]	94[4]

Table 3.1.b Hydrologic and morphometric characteristics continued

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

Notes to Table 3.1.a and 3.1.b:

1. Date given is the year in which filling of the reservoir commences.
2. Lake level regulation began in 1939 (Daley *et. al.*, 1981, p10).
3. B.C. Hydro: http://eww.bchydro.bc.ca/html/lib_comp_psupp_columbia.html.
4. From Daley *et.al.*, 1981.
5. Estimated from (active storage)/(lake level variation).
6. Active storage between mean high and low water levels from elevation-storage curve, Section 3.6.
7. Surface area for mean post-impoundment water level of 432.4 m with narrows included with the Lower Arrow. This area is from the storage-elevation curve, (Table A3.3.2) with 21 km^2 subtracted from (added to) the Upper (Lower) Arrow area, as the storage-elevation curve includes the narrows in the Upper Arrow (Section A3.3.1).

8. As determined in Section 2.2, footnote 1, for mean water level. Volume of the Upper Arrow does not include the riverine section between Revelstoke and Arrowhead.
9. Corrected Arrow Reservoir Outflow 1973-1990; see Section 3.2.
10. Water Survey Canada: Columbia R. above Steamboat 73-85, Revelstoke Project Outflow 86-90.
11. Estimated from volume/surface area both at mean post-impoundment water level of 432.4 m.
12. Section 3.5.
13. Revelstoke outflow plus 82% (Sect. 3.8) of the local flow of 333 m^3/s which enters Upper Arrow.
14. Length of main stem Upper Arrow (68.4 km) plus Revelstoke Reach (55.3 km); see Figure 1.1 and Section 3.9 for definition. Beaton Arm and Galena Bay are 17 km and 4.7 km long, respectively.
15. Length of Lower Arrow (92.0 km) and narrows (24.0 km). Distances given are length of the curve following the deepest part of the channel.
16. Mean post-impoundment area (275 km^2) divided by the sum of the lengths of the main stem Upper Arrow, Galena Bay, Beaton Arm and Revelstoke Reach.
17. Mean post-impoundment area (190 km^2) divided by the length of the Lower Arrow and narrows.
18. From WSC station "Columbia River at Castlegar" (see Section 3.3), the Keenleyside Dam began controlling flow in July 1968.

3.2 Main Inflow (Qin)

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

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

Daily flow data for 1986-1994 were obtained from WSC Station 08ND025, entitled "Revelstoke Project Outflow". Data for 1995-2001 was provided by Dan Nixon and Stan Matthews, B.C. Hydro, Burnaby.

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

The mean annual pre-impoundment flow for 1955-1964 was 818 m^3/s. This flow for 1986-1994 is 780 m^3/s or 5% lower than the flow for 1955-1964. There are two potential sources for this difference: measurement error and climatic variation. Open river gauging, such as the station above Steamboat Rapids, is generally considered accurate to 5%. The Revelstoke outflow is based on total power generated and considerable effort generally goes into establishing turbine ratings by the turbine manufacturer. As a result this flow is considered good to 1%. Climatic variation will be examined briefly in Section 3.11.

For the period after the completion of the Mica Dam in 1973 but before the completion of the Revelstoke Dam in 1983, the mean hydrograph for 1975-1982 (not shown) is similar to that shown in Figure 3.2.2 for 1986-1994. This is expected, as the Revelstoke dam is operated as run-of-the-river, and should have little impact on the shape of the annual hydrograph.

The daily mean Revelstoke outflow for 1997 to 2001 is shown in Figure 3.2.2, along with the mean pre- and post-impoundment hydrographs. Mean seasonal and yearly flows are summarized in Table 3.2.1. The inflow for all five years generally followed the mean post-impoundment hydrograph. All five years show above average flow especially in the fall with the exception of 2001. Average or below average flow were only recorded in the winter of 1997, 1999, 2000 and 2001, the spring of 2001, and the summer of 1998 and 2001.

Table 3.2.1 Mean seasonal inflow (m^3/s) from Revelstoke Dam.

Season	Winter* Nov21-Apr10	Spring Apr11-Jun15	Summer Jun16-Sep21	Fall Sep22-Nov20	Year* Nov21-Nov20
Mean*	736	620	1063	593	779
1997	733 (0%)	697 (+12%)	1166 (+10%)	1087 (+83%)	901 (+16%)
1998	853 (+16%)	690 (+11%)	1022 (-4%)	839 (+41%)	866 (+11%)
1999	663 (-10%)	669 (+8%)	1198 (+13%)	1053 (+78%)	872 (+12%)
2000	735 (-0.2%)	671 (+8%)	1105 (+4%)	873 (+47%)	845 (+8%)
2001	734 (-0.3%)	555 (-11%)	694 (-35%)	627 (+6%)	673 (14%)

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

3.3 Outflow (Qout).

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

Methods. There are two sources of WSC outflow data. The first is WSC station 08NE002, entitled "Columbia River at Castlegar" which was operational from 1913-1915

and 1961-1972. This record spans the construction of the Keenleyside Dam completed in 1967. This station is located approximately 7.5 km downstream of the Dam, just above Norns Creek, which is about one kilometer above the confluence with the Kootenay River. This station is a good representation of flow at the Keenleyside Dam because the Columbia River between the Keenleyside Dam and this station drains only ~30 km^2. The second source of outflow data is that computed from the Keenleyside operational record, reported by WSC as station 08NE126 entitled "Arrow Reservoir Outflow" from 1973 onward.

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

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

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

Corrected flows, for WCS station "Columbia River at Castlegar" for 1961-1972 and for WSC station "Arrow Reservoir Outflow" for 1973-1990 were obtained from K. Ketchum, B.C. Hydro, Burnaby. The data at the station "Columbia River at Castlegar" was corrected by reducing the flow by 4.7% or a mean of 58 m^3/s. The Arrow Reservoir Outflow for 1973-1990 was corrected by reducing the flow by 3.4-5.5%, or a mean of 52 m^3/s. Additional study is currently underway to improve Arrow outflow data quality in conjunction with construction of the power project on Keenleyside Dam (Stan Matthews, Power Supply Resource Management, B.C. Hydro, Burnaby).

Data for 1997-2000 were provided by Dan Nixon and Stan Matthews, B.C. Hydro, Burnaby.

Results. The Columbia River flow near the Hugh Keenleyside Dam is shown in Figure 3.3.2(a). The change in flow due to the completion of the Hugh Keenleyside Dam in 1967 is clearly visible. The spring peaks are reduced and day to day variability in increased. The mean daily pre-impoundment hydrograph given by the corrected daily data for the station "Columbia River at Castlegar" for 1961-1966 is shown in Figure 3.3.2(b). The mean annual outflow for this period was 1,151 m^3/s. The post-impoundment hydrograph given by the corrected daily data for the Keenleyside discharge for 1973-1990, is shown in Figure 3.3.2(c). The mean annual outflow for this period was 1,079 m^3/s. This value is 72 m^3/s lower than the mean flow for 1961-1966.

Similar to that seen for the pre-impoundment inflow at Revelstoke, the pre-impoundment outflow shows a dramatic spring peak of 4,000 m^3/s which declines through summer and fall until it reaches a low winter baseline of around 200 m^3/s. Post-impoundment outflow shows flow distributed more evenly throughout the year with minor peaks in summer and winter.

The Keenleyside outflow for 1997 to 2001 is given in Figure 3.3.3, together with the mean pre- and post-impoundment hydrographs. The mean seasonal and yearly flows are summarized in Table 3.3.1. Each of 1997 to 2001 generally follows the mean post-impoundment hydrograph. Above average flows are seen through most of 1997, 1999, 2000, and 2001 with below average flow through most of 1998 and summer of 2001.

Table 3.3.1 Mean seasonal outflow (m^3/s) from Hugh Keenleyside Dam.

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

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

3.4 Local Metered Stream Flow

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

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

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

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

Table 3.4.1 Mean seasonal flow (m^3/s) for the Illecillewaet River at Greeley.

Season	Winter* Nov21-Apr10	Spring Apr11-Jun15	Summer Jun16-Sep21	Fall Sep22-Nov20	Year* Nov21-Nov20
Mean*	10.2	90.7	105	25.8	52.7
1997	10.6 (+3%)	108 (+19%)	108 (+3%)	48.6 (+88%)	60.5 (+15%)
1998	11.0 (+7%)	105 (+15%)	77.6 (-26%)	14.9 (-42%)	46.5 (-12%)
1999	9.1 (-11%)	76.3 (-16%)	133 (+27%)	37.8 (+46%)	59.1 (+12%)
2000	15.1 (+45%)	81 (-11%)	119 (+14%)	27.3 (+6%)	57(+8%)
2001	9.8 (-4.0%)	75.8 (-16.5%)	84.7 (-19%)	21.8 (-16%)	43.7 (-17%)

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

3.5 Lake and Reservoir Levels

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

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

Table 3.5.1 Summary of water level measurement

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

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

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

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

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

Normal full pool 440.13 m. Minimum pool 420 m. (BC Hydro Keenleyside web site.)

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

Figure 3.5.2 shows the 1997 to 2001 Fauquier and Nakusp water levels located in the Lower and Upper Arrow, respectively. Mean seasonal and yearly flows are summarized in Table 3.5.3. The water levels generally follow the Fauquier post-impoundment mean. In winter of 1998, 1999 , 2000 and 2001, water levels stayed higher than average through mid-winter and were drawn lower than average at the end of winter. The seasonal water level averages are generally higher than the mean values. The exception was 2001, where water levels were well below seasonal average for May onward; 8-10 m below average in summer and fall.

For the four years 1997-2001 the Upper and Lower Arrow water levels are generally the same though there is some difference around day 90 in both 1998 and 1999 and around day 140 in 2001. A difference between the post-impoundment water levels can occur when water levels are low in combination with high flow through the narrows. As an example, the water levels for 1991 (Figure 3.5.3) show a significant difference between Upper and Lower Arrow levels from days 75-150. Separation between the Upper and Lower Arrow began in 1991 when water levels dropped below 428 m above datum. In general, the water level at which separation begins will also depend on the flow rate through the narrows.

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

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

* Bracketed values give water level difference (m) from the mean.
** Winter level for 1997 is for Nov. 21, 1996 to Apr. 10, 1997. Likewise the Year level for 1997 is from Nov. 21, 1996 to Nov. 20, 1997. See also Section 3.13.1. The mean levels are for 1970-1994.

3.6 Flow to Storage (Qstor)

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

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

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

3.7 Computing the Local Flow (Qloc).

Introduction

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

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

Equation for the local flow

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

Qin + Qloc = Qout + Qstor

where;
Qin Revelstoke Project Outflow,
Qloc Local inflow,
Qout Flow out from the Keenleyside Dam,
Qstor Flow to storage.

It should be noted that Qloc is the small difference between relatively large quantities (Qin, Qout and Qstor) and therefore Qloc is subject to considerable error.

Mean annual local flow

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

For Arrow Reservoir, the local drainage area accounts for 28% of the total drainage area above the Keenleyside Dam and the local inflow accounts for 31% of the total flow through Keenleyside. Two examples are given for the Arrow Reservoir, showing the differences that result from averaging over different periods. There are two possible sources for these differences, either errors or climatic variability. The Illecillewaet at Greeley for the first period 1973-1990 (52.0 m^3/s) was 6% lower than that for the second period 1986-90, 95-97 (55.3 m^3/s). Compare this to a 9% decrease in Qloc, between these two periods. Thus, it appears that a good part of the variance is accounted for by climate.

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

Table 3.7.1 Mean annual local flow determined from water balance

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

ARROW RESERVOIR: 1986-1990,1995-1997[6]		Area km^2	Flow m^3/s	Yield[5] m/yr
Qin	Revelstoke Project Outflow	as above	785.7	
Qout	Corrected Arrow Reservoir Outflow		1,148.6	
Qstor	Storage Flow		+13.5	
Qloc	**Local Inflow to Arrow**		**376.4**	
	Qloc/Qout		31%	

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

Notes to Table 3.7.1:

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

5. Yield or "effective" precipitation (m/yr) is [flow (m^3/s)*31.5575]/[area (km^2)], where 31.5775 m/yr = (1 m^3/s)/(1 km^2). See also Section 3.9.
6. This period was chosen to use the relatively more accurate Revelstoke discharge data from 1986 and because the corrected Arrow discharge is not currently available for 1991-1994.
7. Duncan R. below Duncan Dam, 08NH126, 1964-1986. Lardeau is the difference, $181^3 - 100 = 81$ m^3/s. The B.C. Hydro web site[4] reports the Duncan flow as 102 m^3/s.

Data for Kootenay Lake are shown in Table 3.7.1 for comparison. Kootenay Lake has three arms: the North, South and West Arms. The North and South Arms form the main basin of Kootenay Lake. Flow drains out of Kootenay Lake along the West Arm. The local inflow to the main basin of Kootenay Lake accounts for 13% of the total inflow to the main basin. This is substantially smaller than the 31% for Arrow Reservoir. Note, however, that this comparison depends on the definition of the local flow. For example, in Kootenay Lake, the Lardeau River is considered part of the main inflow: the Lardeau joins the outflow from the Duncan Dam to form the Lower Duncan River which then enters the North Arm of Kootenay Lake. It could be argued that the main inflow to Arrow Reservoir should be the flow entering the main basin of Upper Arrow at Arrowhead.

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

Daily local flow

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

Results. Local flow to the Arrow Reservoir for 1973 to 2001 is shown in Figure 3.7.1(a). The 8 year mean from 1986-1990 and 1995-1997 is shown in Figure 3.7.1(b). The average local flow for this period was 376.4 m^3/s.

Local flow for 1997 to 2001 is given in Figure 3.7.2. Mean seasonal and yearly flows are summarized in Table 3.7.2. Note that Qloc is highly variable, as it is a difference between large values. Negative values of the local flow correspond to a local drain rather than a local source of water, which is erroneous. Negative flows generally occur next to large

positive flows: smoothing of the daily data results in a physical hydrograph (smoothed data not shown). The local flow generally follows that of the Illecillewaet (Section 3.4). While early spring flows for 1997 and 1999 were average, both had above average local flow for the rest of the year, with 1997 particularly high. In contrast, 1998 had above average local flow in early spring but reduced local flow through late spring and summer which resulted in considerably reduced flow for the year. In 2000, local flow was close to average despite variation about the average from one season to the next. In 2001, local flow was considerably below average throughout the year.

Table 3.7.2 Mean seasonal local inflow (m^3/s).

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

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

3.8 Evaluation of the Local Flow

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

Comparison of hydrographs

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

September. However, on the first snowfall, the albedo of the glacier is increased and melting abruptly halts (Dr. Mindy Brugman, Columbia Mountain Institute, pers. comm.).

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

The winter component of the local flow can be divided into three parts:
1. the fraction of the winter flow that comes from tributary inflow,
2. the fraction of the winter flow that comes from known sources, namely direct precipitation to the water surface and flow from the Whatshan Reservoir, and
3. the remainder which will be considered error.

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

Error estimate for the local flow

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

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

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

[4] Local flows computed here were also compared to smoothed local flow data computed by B.C. Hydro based on the corrected Keenleyside discharges and obtained from K. Ketchum, B.C. Hydro, Burnaby. The hydrographs of both local flows follow each other in detail, and the difference between the two is flat point-alternating noise. The mean of the B.C. Hydro local flow for 1986-90,95-97 is 357 m^3/s. Differencing on a year by year basis and averaging gives the difference between these two local flows as 19 +/- 15 m^3/s or 5% of Qloc.

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

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

The four regions of the Arrow Reservoir

The local inflow was divided into four regions:

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

The drainage and water surface areas of these four regions are given in Table 3.9.1, and were determined from the 1:250,000 topographical maps using a digitizing tablet, computer and appropriate software, accurate to within 3%. The local drainage area determined in this way compares within 0.1% of that reported by WSC[5], and the water surface area compares within 2% of that determined from the storage-elevation curve.[6]

Table 3.9.1 Characteristics of the Arrow Reservoir regions

Name	Drainage Area km^2	Water Surface km^2	Estimated Yield m/yr	Flow m^3/s	Percentage
Revelstoke Reach	2,620	70	1.56	130	40%
Beaton Arm	1,270	31	1.50	60.4	19%
Main stem Upper A.	2,070	206	1.12	73.4	23%
Upper Arrow	5960	307		263.8	82%
Lower Arrow	3,650	191	0.49	56.7	18%
Total	9,610	498		320.5	

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

[5] The total drainage area for the Arrow Reservoir, which includes the water surface area, is 10,110 km^2. This compares well with the area of 10,100 km^2 estimated from drainage areas reported by WSC as shown in Table 3.7.1. (The extremely good agreement is considered fortuitous.)

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

Precipitation near the reservoir

A simple division of the local flow by drainage area assumes that the precipitation to all parts of the local drainage area is the same. This is not appropriate, however, as precipitation increases substantially from Castlegar to Revelstoke. As will be seen below, the near shore precipitation is also not an appropriate criteria for dividing the local flow as it does not reflect rainfall in the mountains. In the next subsection, stream yield will be used to divide the local flow.

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

Mean stream yield to each region

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

Table 3.9.2 Annual temperature and precipitation at five sites along Arrow[1]

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

1. Canadian Climate Normals, (1993).

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

1. Revelstoke Reach. The Illecillewaet (1.4 m/yr) accounts for nearly half of the drainage area to the Revelstoke Reach. The other half of the drainage area is taken to have an effective precipitation which is the mean of the Akolkolex (1.6 m/yr), Cranberry (1.5 m/yr) and Jordan (2.0 m/yr).
2. Beaton Arm. The Incomappleux (1.7 m/yr) accounts for 80% of the area draining into Beaton Arm. The remainder of the drainage area lies close to the arm and will be considered similar to Beaton Creek (0.78 m/yr).
3. Main stem Upper Arrow. Two thirds of the drainage area to the main stem of the Upper Arrow is considered similar to the Kuskanax (1.33 m/yr), which is the only large river into the main stem to have been metered by WSC. The remaining third is considered an average of Hill Creek at Mill Bridge Road (0.70 m/yr) and Brouse Creek (0.71 m/yr).
4. Lower Arrow. The arithmetic mean is taken of all streams into the Lower Arrow for which it was possible to determine an effective precipitation.

Recall that only half of the total local flow has been metered and a variety of assumptions are made in determining the effective precipitation to each drainage area. As a check, the effective precipitation was multiplied by the drainage area to give the effective streamflow for each region: these flows are given in Table 3.9.1. The sum of these streamflows is 320m^3/s, which is comparable to the mean local flow of 333 m^3/s found in section 3.7 for 1973-1990.

Allocation of local flows to basins

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

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

3.10 Flow through the narrows

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

$$\mathbf{Qnar + Qstorup = Qin + Qlocup}$$
$$\mathbf{Qout + Qstorlo = Qnar + Qloclo}$$

where;

Qnar	Flow through the Narrows	
Qin	Inflow from the Revelstoke Dam	
Qout	Outflow from the Keenleyside Dam	
Qstor	Storage Flow (rising water level corresponds to a positive Qstor)	
	Qstorup	Storage flow to the Upper Arrow
	Qstorlo	Storage flow to the Lower Arrow
Qloc	Local flow (all inflow other than that from the Revelstoke Dam)	
	Qlocup	Local inflow to the Upper Arrow
	Qloclo	Local inflow to the Lower Arrow

Method. Qin and Qout are used as described in Section 3.7. Qlocup and Qloclo were used as determined in Section 3.9, where the local flow was divided between the Upper and Lower Arrow based on stream yield to each. Qstorup and Qstorlo were determined using the storage-elevation curve discussed in Section 3.6 and detailed in Appendix 3.3. Note the storage-elevation curve includes the narrows with the Upper Arrow whereas the narrows is here included with the Lower Arrow. In this calculation of the narrows flow, the storage flows given by the storage-elevation curves are used without adjustment. Thus Qstorup is order (20 km^2/334 km^2)=6% higher than what would be observed at the north end of the narrows.

Results. The daily Narrows flow for 1973-2001 is shown in Figure 3.10.1(a) and the mean for 1973-1990 is shown in Figure 3.10.1(b). As expected, the Narrows flow is similar to the post-impoundment inflow and outflow with relatively steady flow through the year and showing a broad increase in flow during both late summer and winter. For comparison, the mean inflow and outflow are plotted with the mean Narrows flow, all averaged over the years 1986-1990, in Figure 3.10.1(c). As expected the Narrows flow generally lies between the inflow and outflow. The narrows flow most resembles the outflow as both local flow and storage in Lower Arrow is smaller than in Upper Arrow. The flow through the Narrows in 1997 to 2001 is shown in Figure 3.10.2. Mean seasonal and yearly flows are summarized in Table 3.10.1. The flows generally follow the mean hydrograph. Note the reduced flow during summer 2001.

Table 3.10.1 Mean seasonal narrows flow (m^3/s).

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

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

3.11 Annual stream flow as a climate gauge

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

Method. For convenience, means are here taken over each calendar year rather than from September 1 to August 31, as is more appropriate. Means over both periods should be similar as flow during the fall is relatively low.

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

3.12 Mean and total flow over the seasons

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

1. local flow (qloc097/8/9,),
2. Revelstoke project outflow (revpo97/8/9),
3. flow through the narrows (qnar097/8/9), and
4. Arrow reservoir outflow (arrro97/8/9).

Table 3.12.1 Average and total flows over the seasons, 1997

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc097	m^3/s	168	953	677	314	471
revpo97	m^3/s	733	697	1,166	1,097	901
qnar097	m^3/s	1,079	879	1,714	1,278	1,246
arrro97	m^3/s	1,234	695	1,829	1,296	1,306
qloc097	Mm^3	2047	5434	5732	1628	14853
revpo97	Mm^3	8930	3975	9873	5687	28414
qnar097	Mm^3	13145	5012	14513	6625	39294
arrro97	Mm^3	15033	3963	15487	6718	41186

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

Table 3.12.2 Average and total flows over the seasons, 1998

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc098	m^3/s	166	748	327	95	303
revpo98	m^3/s	853	690	1,022	839	866
qnar098	m^3/s	1,329	708	1,250	864	1,119
arrro98	m^3/s	1,556	486	1,285	852	1,174
qloc098	Mm^3	2022	4265	2769	492	9555
revpo98	Mm^3	10392	3935	8653	4349	27310
qnar098	Mm^3	16190	4037	10584	4479	35289
arrro98	Mm^3	18956	2771	10880	4417	37023

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

Table 3.12.3 Average and total flows over the seasons, 1999

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc099	m^3/s	142	680	728	244	413
revpo99	m^3/s	663	669	1198	1,053	872
qnar099	m^3/s	1,115	795	1,619	1,200	1,206
arrro99	m^3/s	1,336	651	1,649	1,215	1,277
qloc099	Mm^3	1,730	3,878	6,164	1,265	13,024
Revpo99	Mm^3	8,077	3,815	10,144	5,459	27,499
qnar099	Mm^3	13,583	4,533	13,708	6,221	38,032
arrro99	Mm^3	16,276	3,712	13,962	6,299	40,271

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

Table 3.12.4 Average and total flows over the seasons, 2000

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc000	m^3/s	174	710	594	152	380
revpo00	m^3/s	734	671	1105	873	845
qnar000	m^3/s	1,192	825	1,503	991	1,176
arrro00	m^3/s	1,404	694	1,558	1,014	1,253
qloc000	Mm^3	2,135	4,049	5,030	788	12,016
revpo00	Mm^3	9,005	3,826	9,356	4,526	26,672
qnar000	Mm^3	14,624	4,704	12,726	5,137	37,188
arrro00	Mm^3	17,225	3,957	13,192	5,257	39,515

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

Table 3.12.4 Average and total flows over the seasons, 2001

Flow	Units	Win*	Spr	Sum	Fal	Tot
qloc001	m^3/s	108	576	384	146	273
revpo01	m^3/s	734	555	694	627	673
qnar001	m^3/s	1,112	919	985	835	998
arrro01	m^3/s	1302	951	1037	916	1104
qloc001	Mm^3	1,316	3,285	3,251	757	8,609
revpo01	Mm^3	8,942	3,165	5,876	3,250	21,224
qnar001	Mm^3	13,547	5,241	8,340	4,329	31,473
arrro01	Mm^3	15,861	5,423	8,780	4,749	34,816

* Winter flow for 2001 is for Nov. 21, 2000 to Apr. 10, 2001. Values in Tables 3.12.1-5 should be shown to a maximum of 3 significant figures but all place values are given for computational checks.

3.13 Limnological Seasons

Limnological seasons demarcate major periods in the annual hydrologic input, stratification and mixing events within a lake or reservoir, and assist in better understanding and interpreting nutrient loading events and their associated biotic responses within the reservoir. The major limnological seasons selected for Arrow are given in Table 3.12.1.

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

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

For computing averages, the start and end of each limnological season is specified by a Julian day, chosen such that noon on January 1st is Julian day 1.5. A table for converting

between Julian day and calendar date is given in Appendix 3.1. Because the seasonal averages are defined by Julian day, in a leap year the calendar date of the start and end of the seasons will shift by one day. For example, in a leap year, the end of summer, at Julian day 264, will occur on September 20th rather than September 21st.

Table 3.12.1 Limnological seasons

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

Acknowledgements

Thanks to Dan Nixon and Stan Matthews, B.C. Hydro, Burnaby, for data, Kelvin Ketchum and Don Druce for discussion, data and reports on Hydro operations in the region, and Brent Tipple, Water Survey Canada, for information on WSC stations.

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Ashley, K.I., I. McGregor, B. Shepherd, D. Sebastian, S. Matthews, L. Vidmanic, P. Ward, H. Yassien, L. McEachern, H. Andrusak, D. Lasenby, J. Quirt, J. Whall, E. Taylor, A. Kuiper, P.M. Troffe, C. Wong, G. Scholten, M. Zimmerman, P. Epp, V. Jensen and R. Finnegan. 1999. Okanagan Lake Action Plan Year 3 (1998) Report.

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

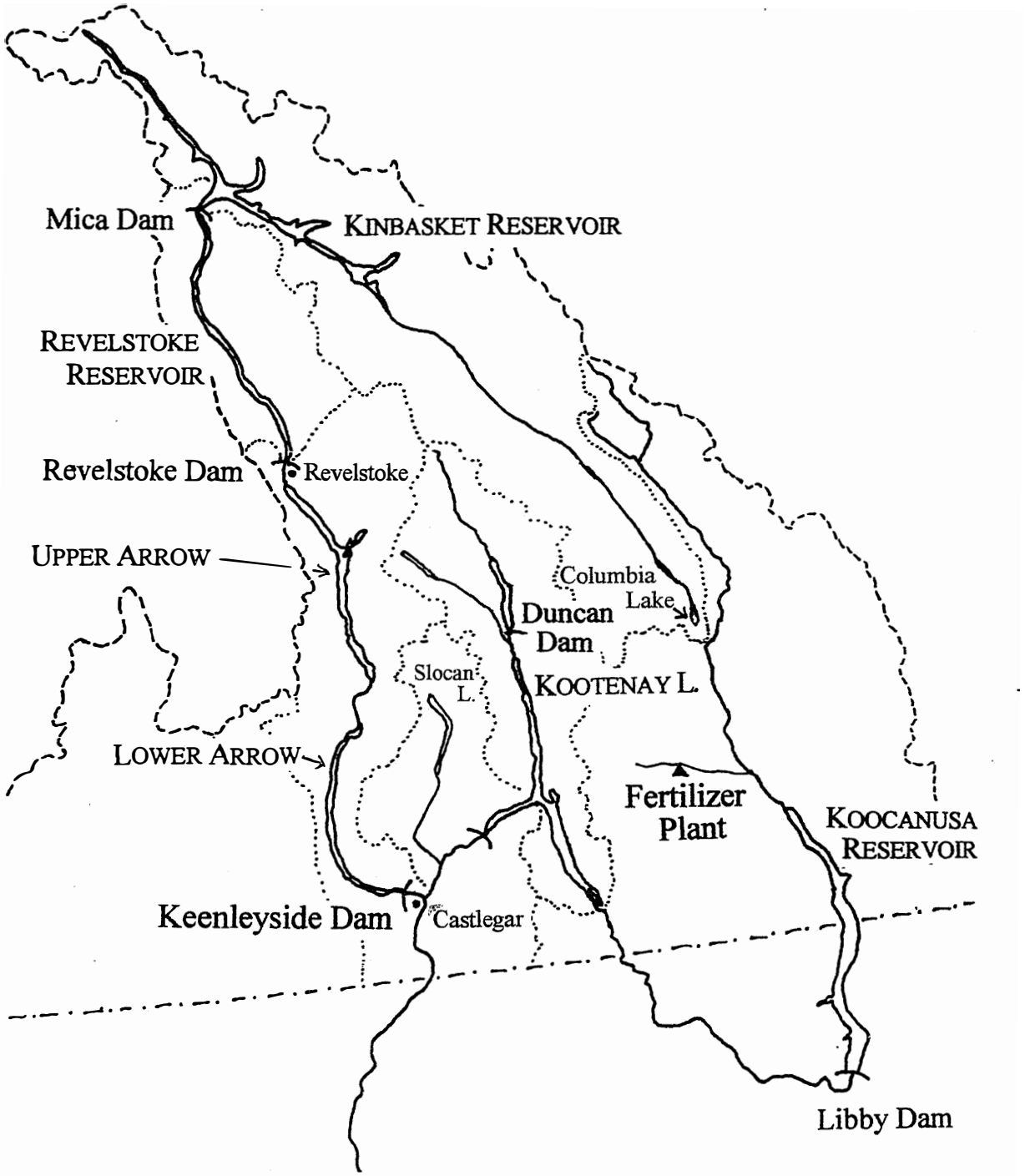


Figure 3.1.2 Upper Columbia River basin. Adapted from Inland Waters Directorate (1977).

Figure 3.2.1 Main Inflow: Columbia River near/at the Revelstoke Dam site

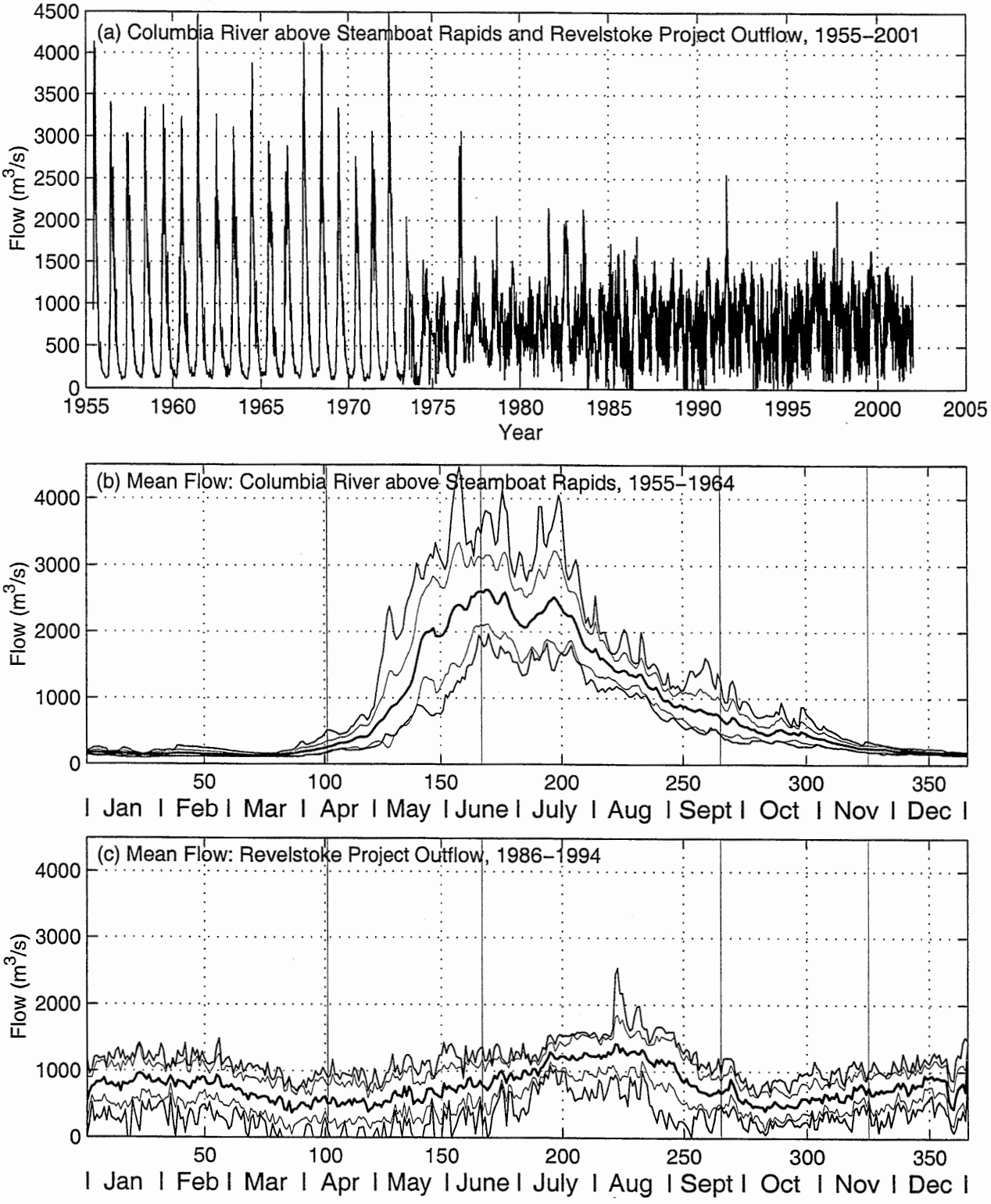


Figure 3.2.1 Main inflow. **(a)** The Columbia River from WSC station 08ND011 "Columbia River above Steamboat Rapids", 1955-1986 and WSC station 08ND025 "Revelstoke Project Outflow", 1986-2001. Mean pre **(b)** and post **(c)** impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.2.2 Main Inflow: Columbia River at the Revelstoke Dam, 1997–2001

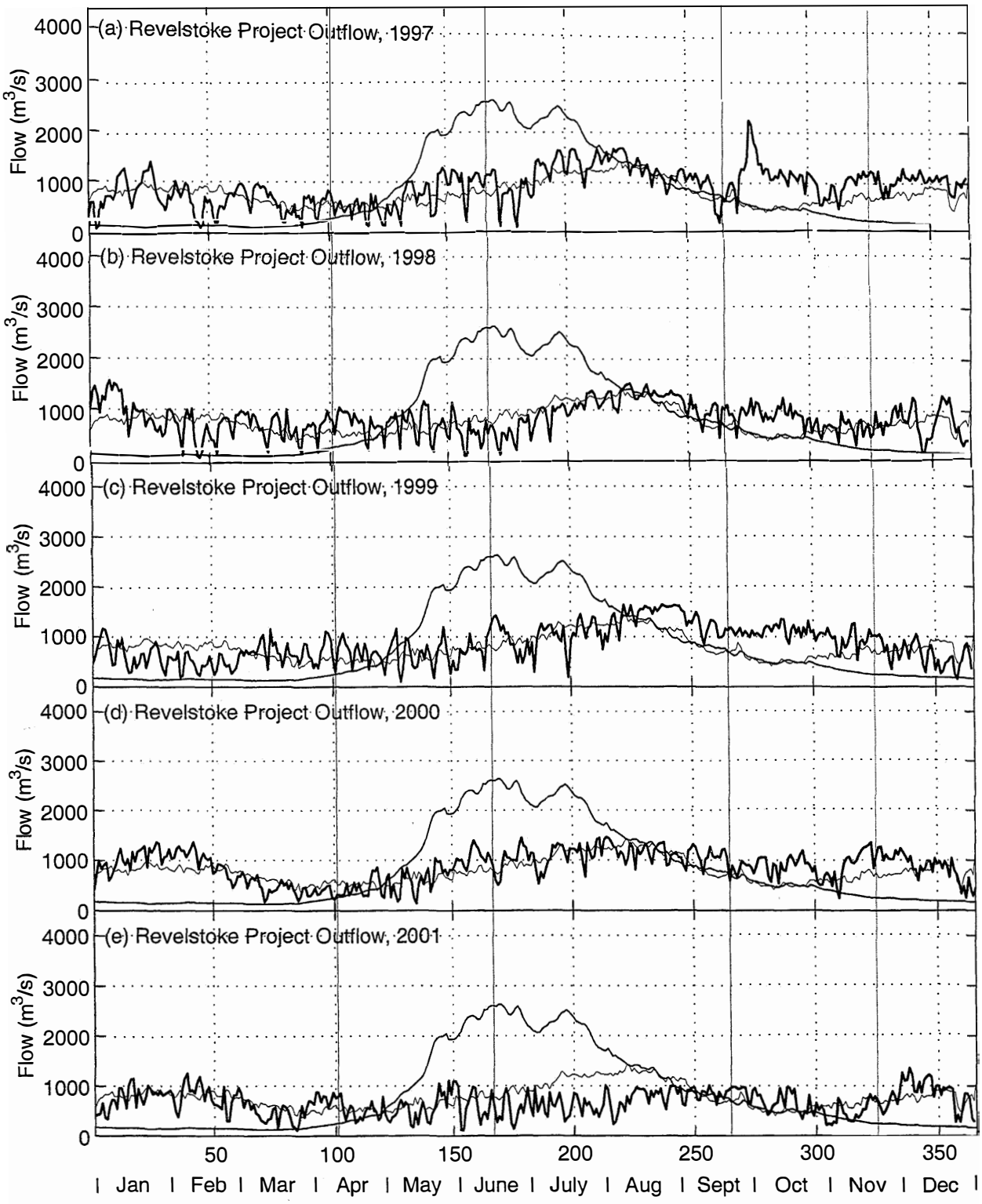


Figure 3.2.2 Main inflow, from WSC station 08ND025, "Revelstoke Project Outflow", **(a)** 1997, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **e)** 2001(heavy line). Mean pre-impoundment flow for 1955-1964 (medium line) and mean post-impoundment flow for 1986-1994 (light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

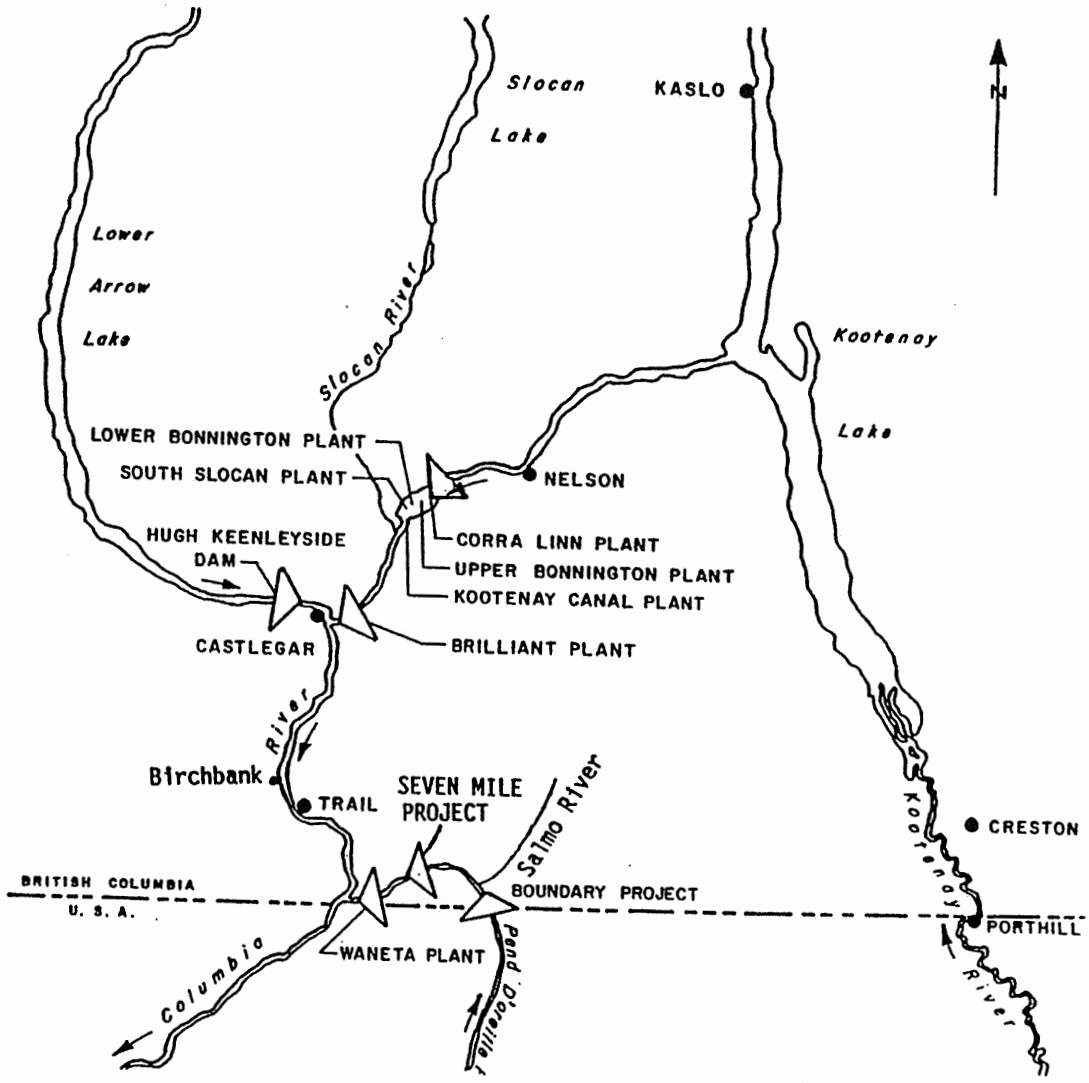


Figure 3.3.1 Map of Columbia Basin around Castlegar. Adapted from Ketchum (1990).

Figure 3.3.2 Outflow: Columbia River near/at Hugh Keenleside Dam site

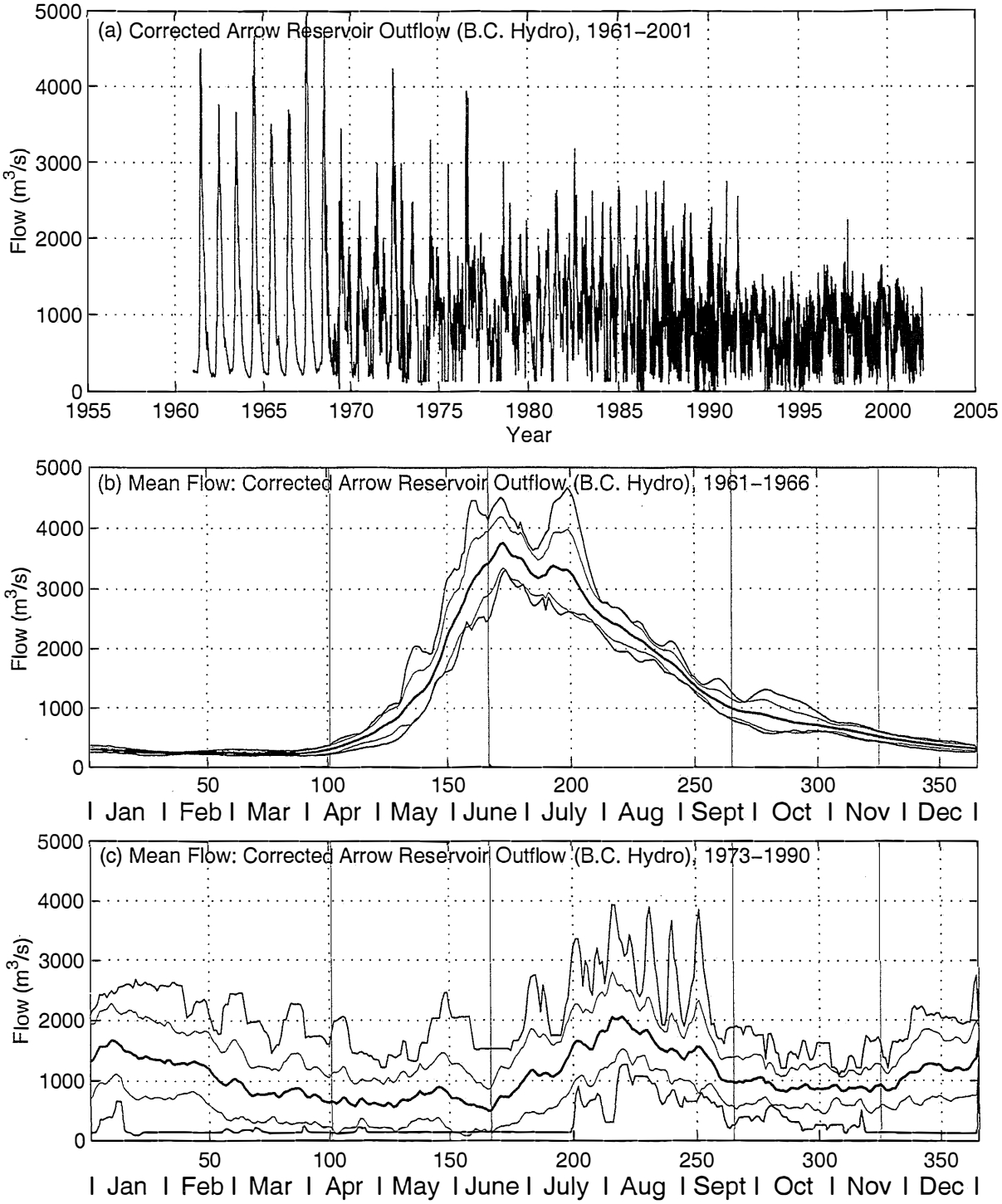


Figure 3.3.2 Outflow. **(a)** WSC station 08NE002, "Columbia River at Castlegar", 1961-1972 and WSC station 08NE126 "Arrow Reservoir Outflow", 1973-2001. Both data sets corrected to 1990 by K. Ketchum as described in the text. Mean pre **(b)** and post **(c)** impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.3.3 Outflow: Columbia River at the Hugh Keenleyside Dam, 1997–2001

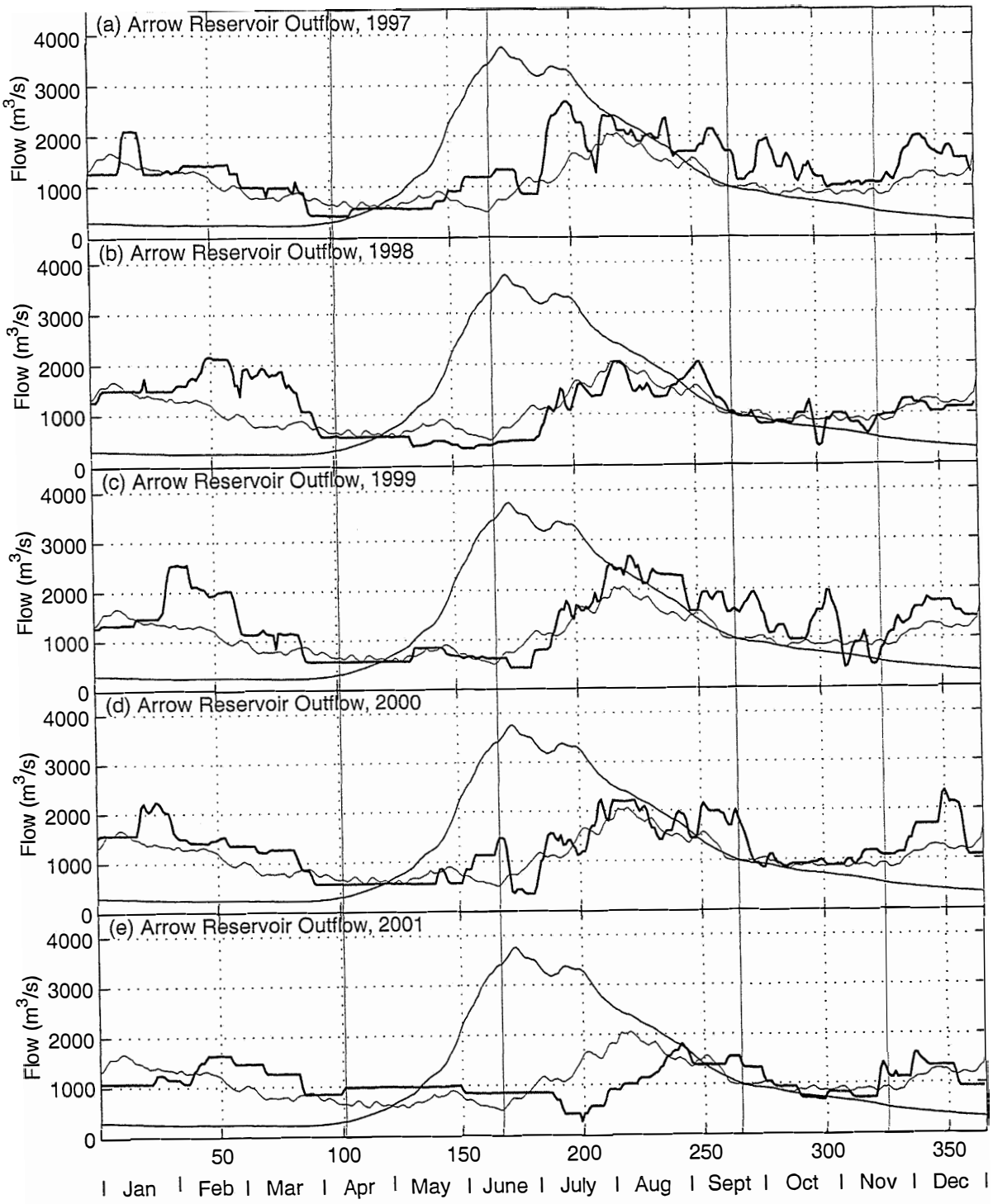


Figure 3.3.3 Outflow from WSC station 08NE126 "Arrow Reservoir Outflow", **(a)** 1997, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **e)** 2001 (heavy line). Mean pre-impoundment flow for 1961-1966 (medium line) and mean post-impoundment flow for 1973-1990 (light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.4.1 Illecillewaet River at Greeley

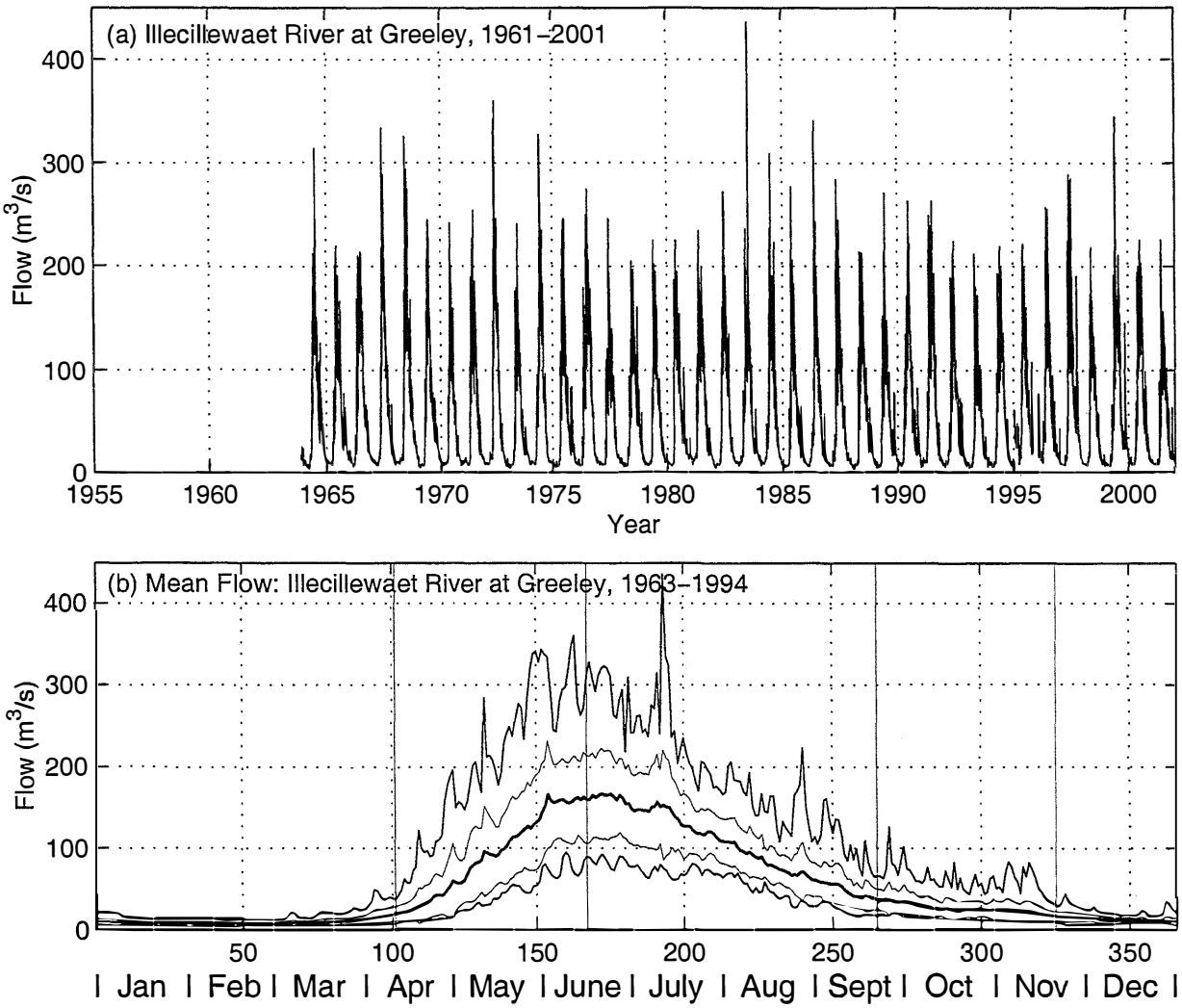


Figure 3.4.1 **(a)** WSC station 08NE013, "Illecillewaet at Greeley", 1961-2001. **(b)** Mean flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.4.2 Illecillewaet River at Greeley, 1997–2001

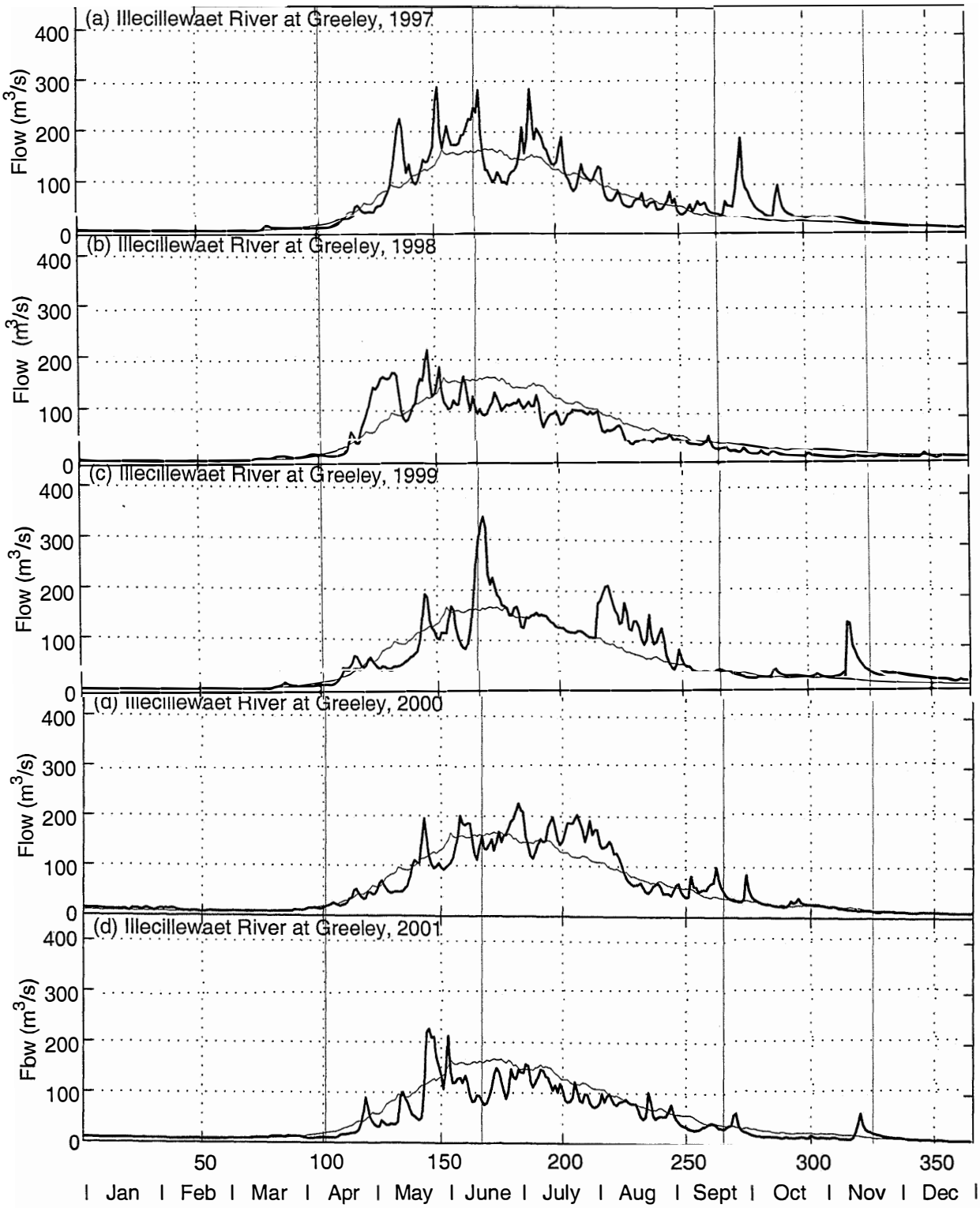


Figure 3.4.2 WSC station 08NE013, "Illecillewaet at Greeley" for **(a)** 1977, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **(e)** 2001 (heavy line). Mean flow for 1963-1994 (light line) is shown for comparison. See methods for interpolation and replacement of missing data and for replacement of anomalous winter flow: note the replacement of missing data for July 5-August 8, 1999 with the mean flow. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.5.1 Water Level: Lower Arrow

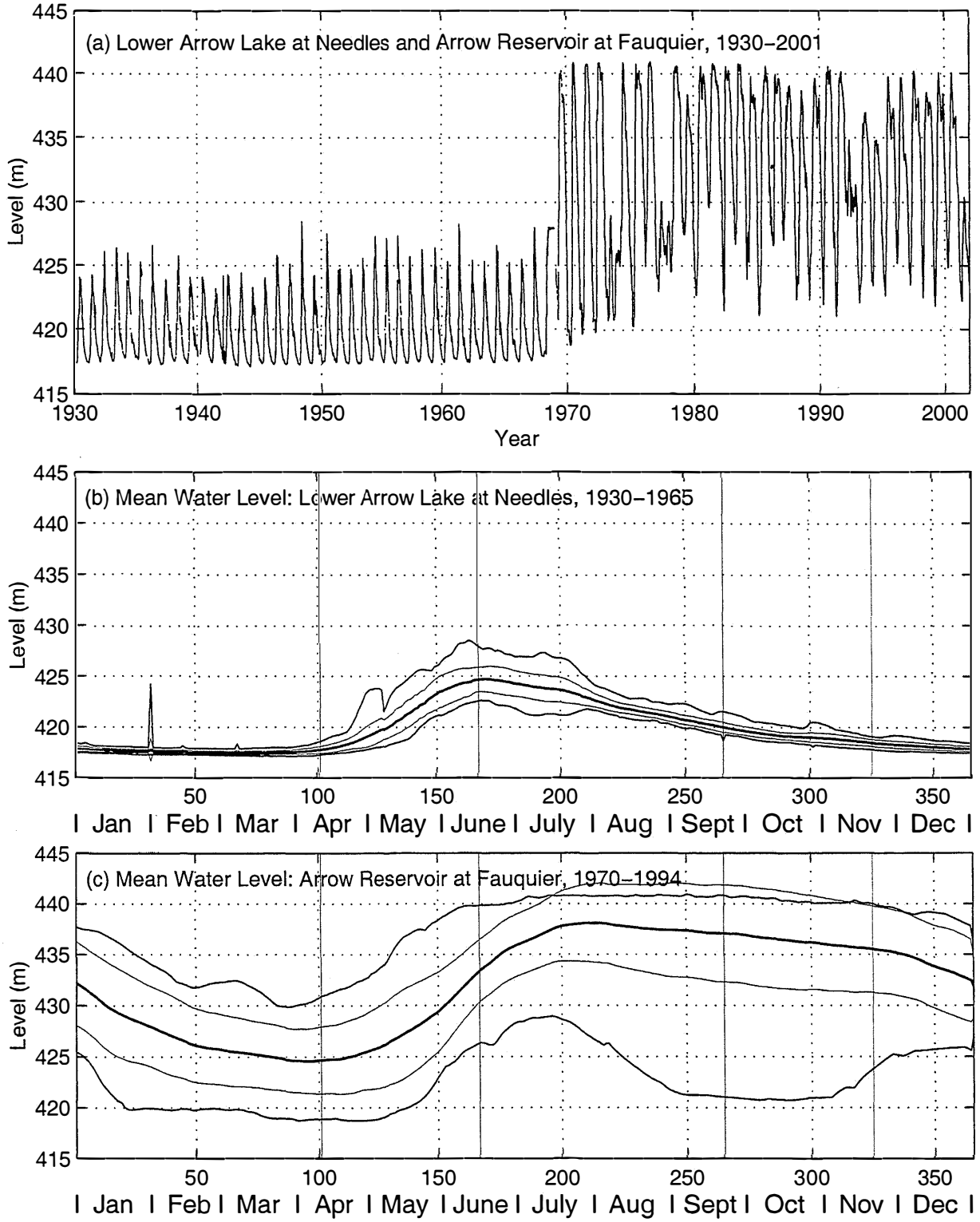


Figure 3.5.1 Water level. **(a)** WSC station 08NE046, "Lower Arrow Lake at Needles" for 1930-1968 and WSC station 08NE102, "Arrow Reservoir at Fauquier" for 1969-2001. Mean pre **(b)** and post **(c)** impoundment flow for years indicated. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.5.2 Water levels: Lower Arrow at Fauquier, 1997–2001

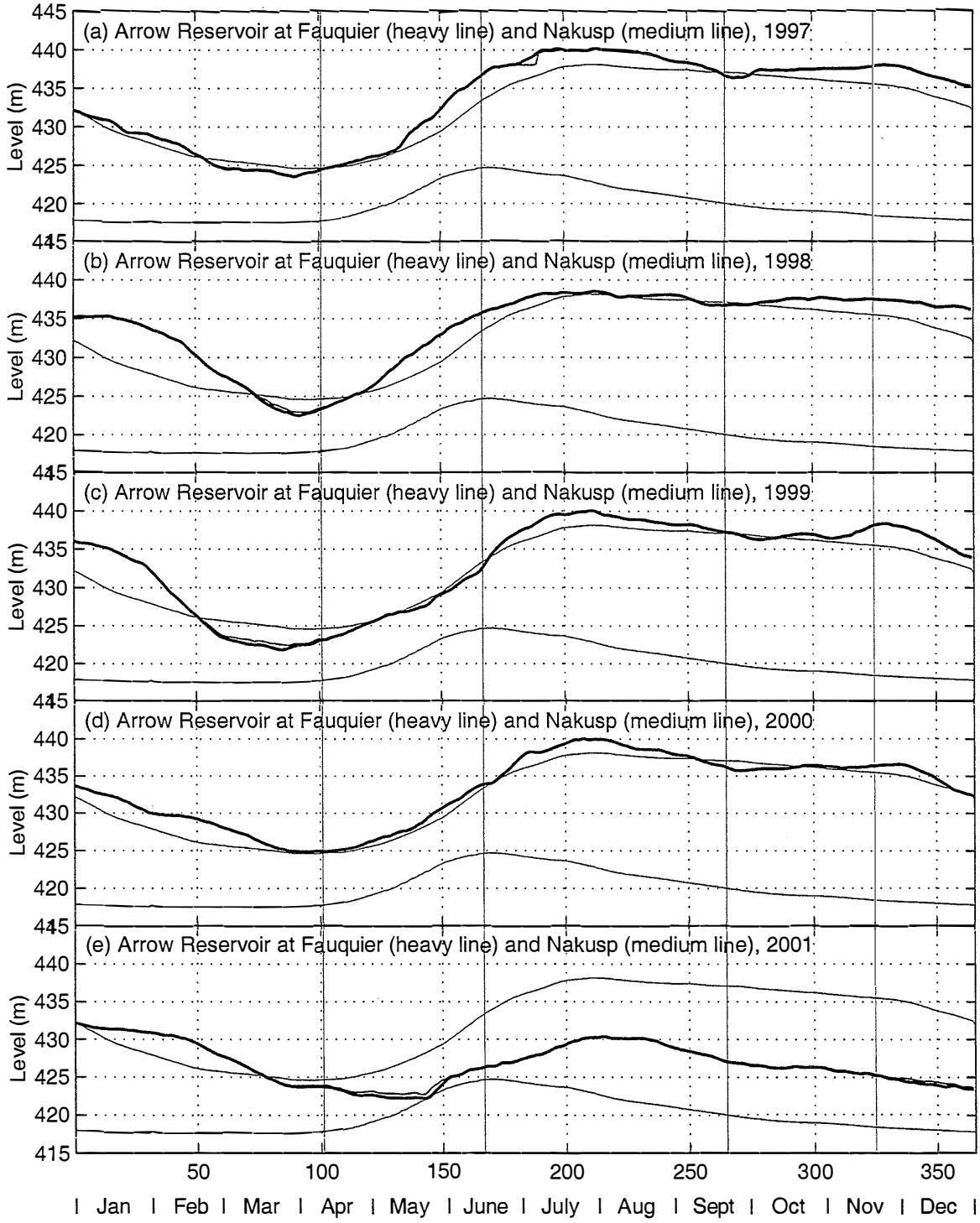


Figure 3.5.2 Water levels for WSC station 08NE102 "Lower Arrow at Fauquier" (heavy line) and WSC station 08NE104 "Upper Arrow at Nakusp" (medium line) for **(a)** 1997, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **(e)** 2001. Note the two curves are generally coincident except near day 180 in 1997 when Nakusp data is erroneous and around day 90 in 1998 and 1999 when water levels in Upper Arrow are higher as discussed in the text. Mean pre-impoundment water level for 1930-1965 (lower light line) and mean post-impoundment water level for 1970-1994 (upper light line) are shown for comparison. Vertical lines mark limnological seasons (Section 3.13).

Figure 3.5.3 Upper and Lower Lake Level, 1991

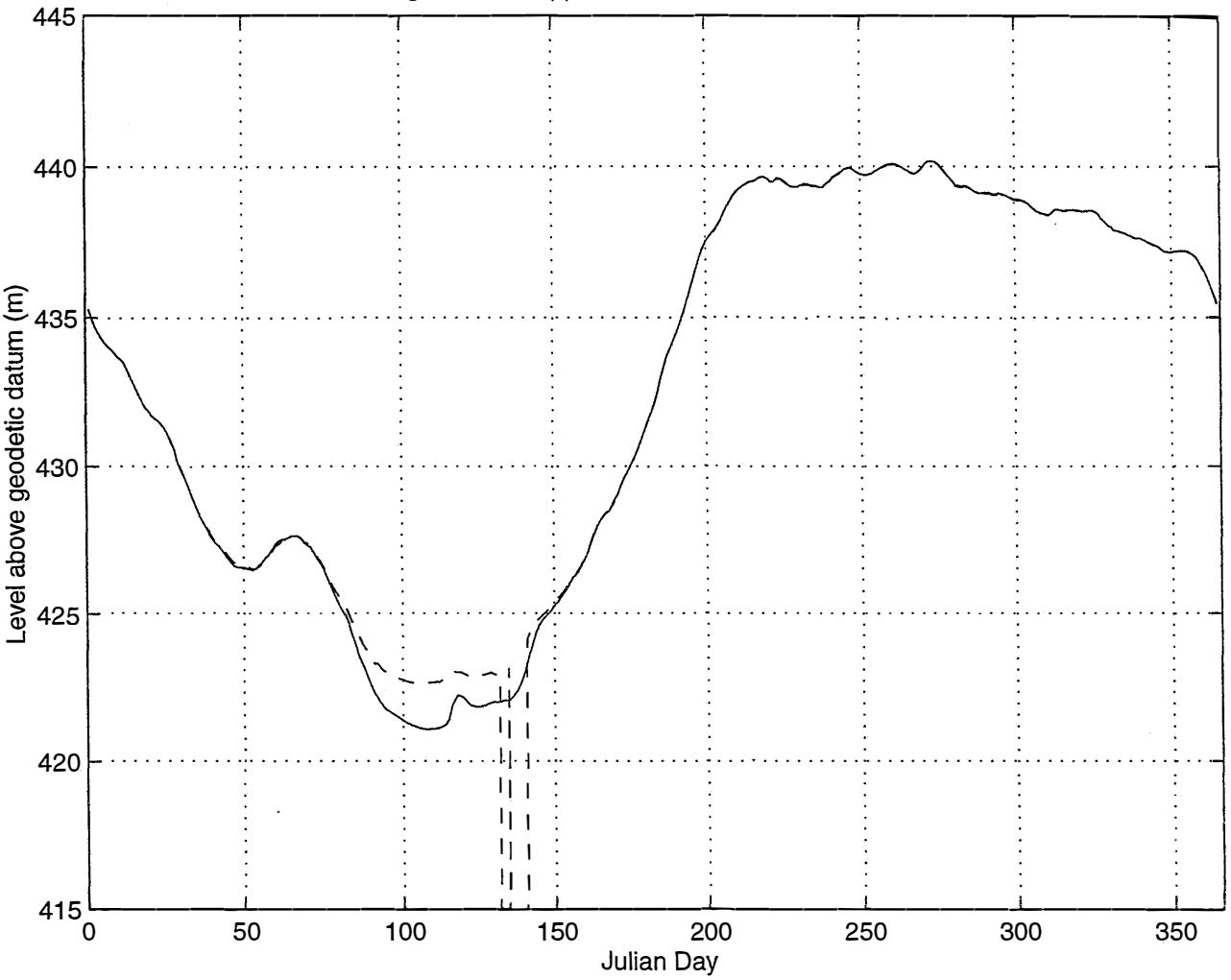


Figure 3.5.3 1991 water level for the Lower Arrow at Fauquier (08NE102) and the Upper Arrow at Nakusp (08NE104). The two curves are almost coincident except from day 75 to 150 when Upper and Lower Arrow water levels are different and flow through the narrows is riverine. The vertical lines in the Nakusp level near day 140 indicate missing data. See Appendix 3.1 for conversion between date and Julian day.

Figure 3.6.1 Storage Flow

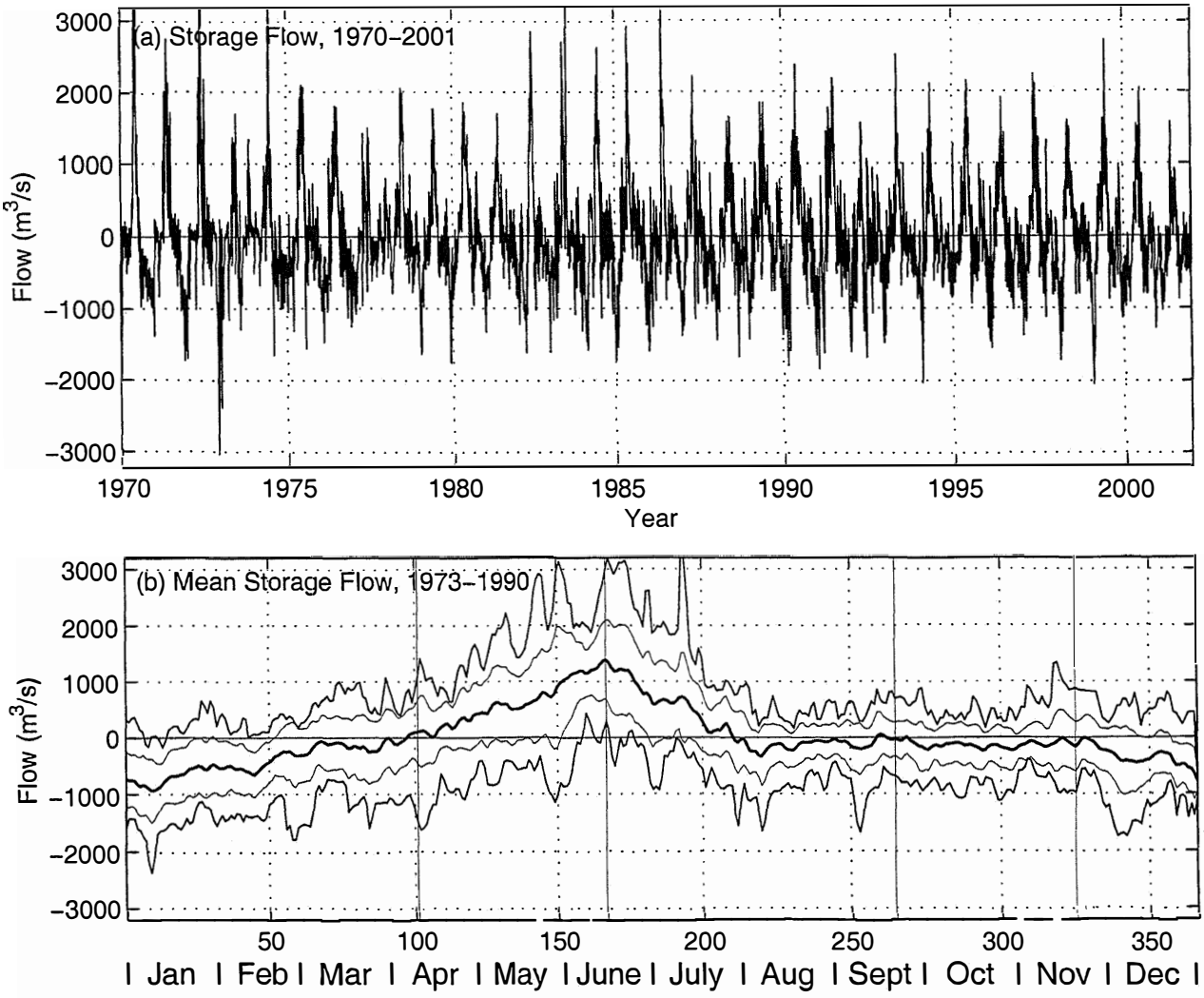


Figure 3.6.1 Storage flow. **(a)** Storage flow for 1970-2001. **(b)** Mean storage flow for 1973-1990. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.6.2 Storage Flow, 1997–2001

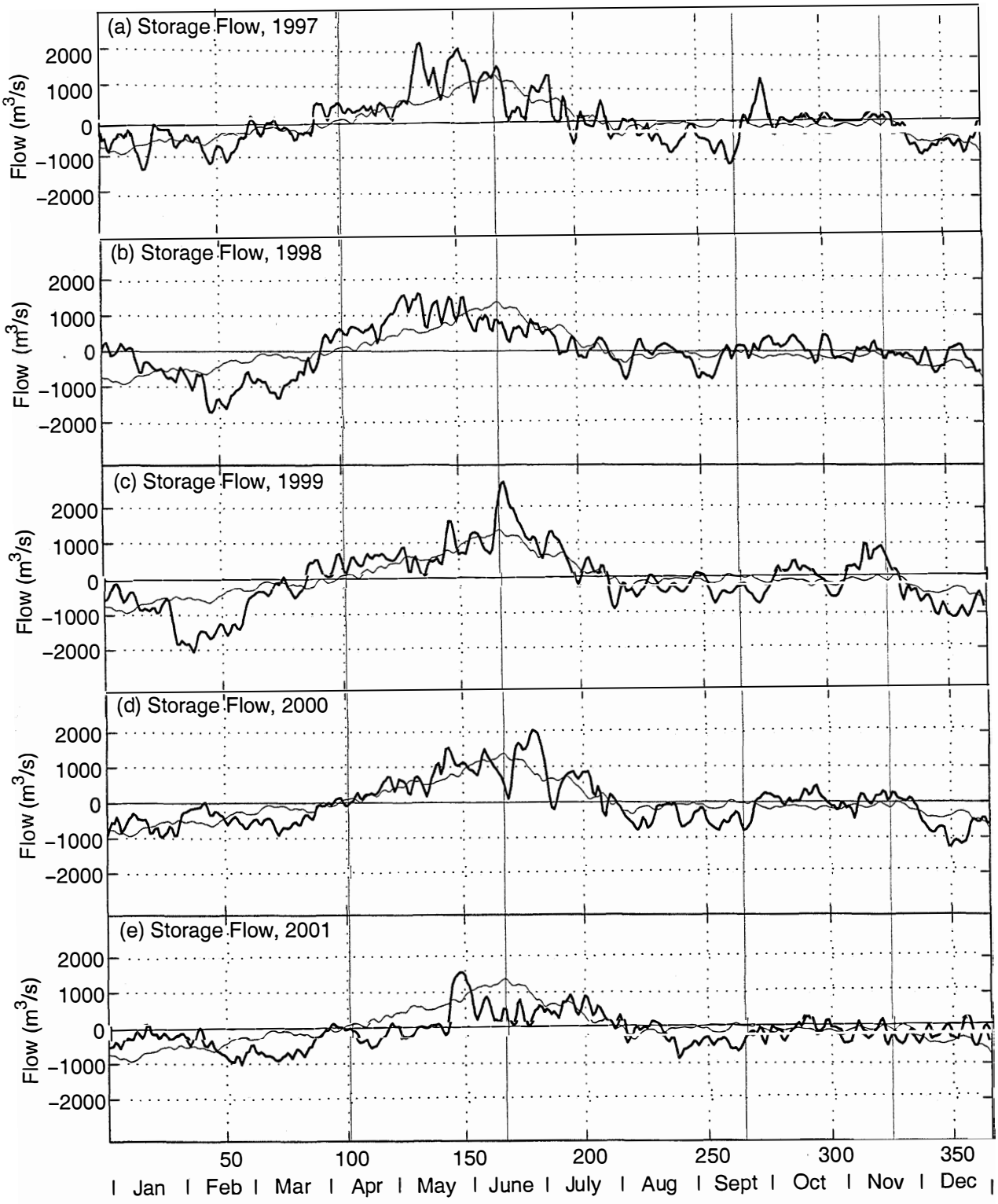


Figure 3.6.2 Storage flow for **(a)** 1997, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **(e)** 2001 (heavy line). Also shown is the mean storage flow for 1973-1990 (light line). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.7.1 Local Flow

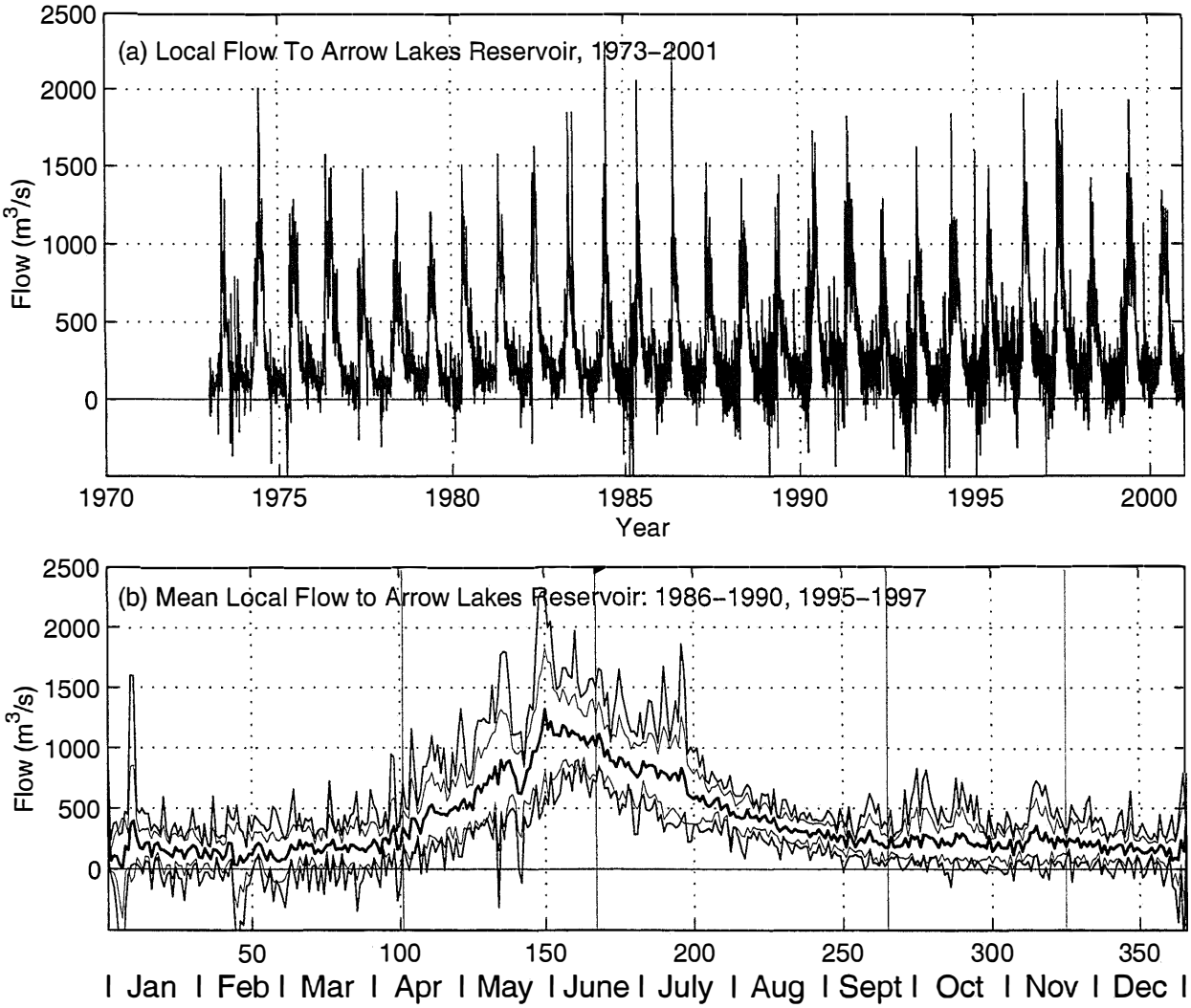


Figure 3.7.1 Local flow. **(a)** Local flow for 1973-2001. **(b)** Mean local flow for 1986-1990, 1995-1997. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). Local flows below zero are erroneous: see discussion in the text. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.7.2 Local Flow, 1997–2001

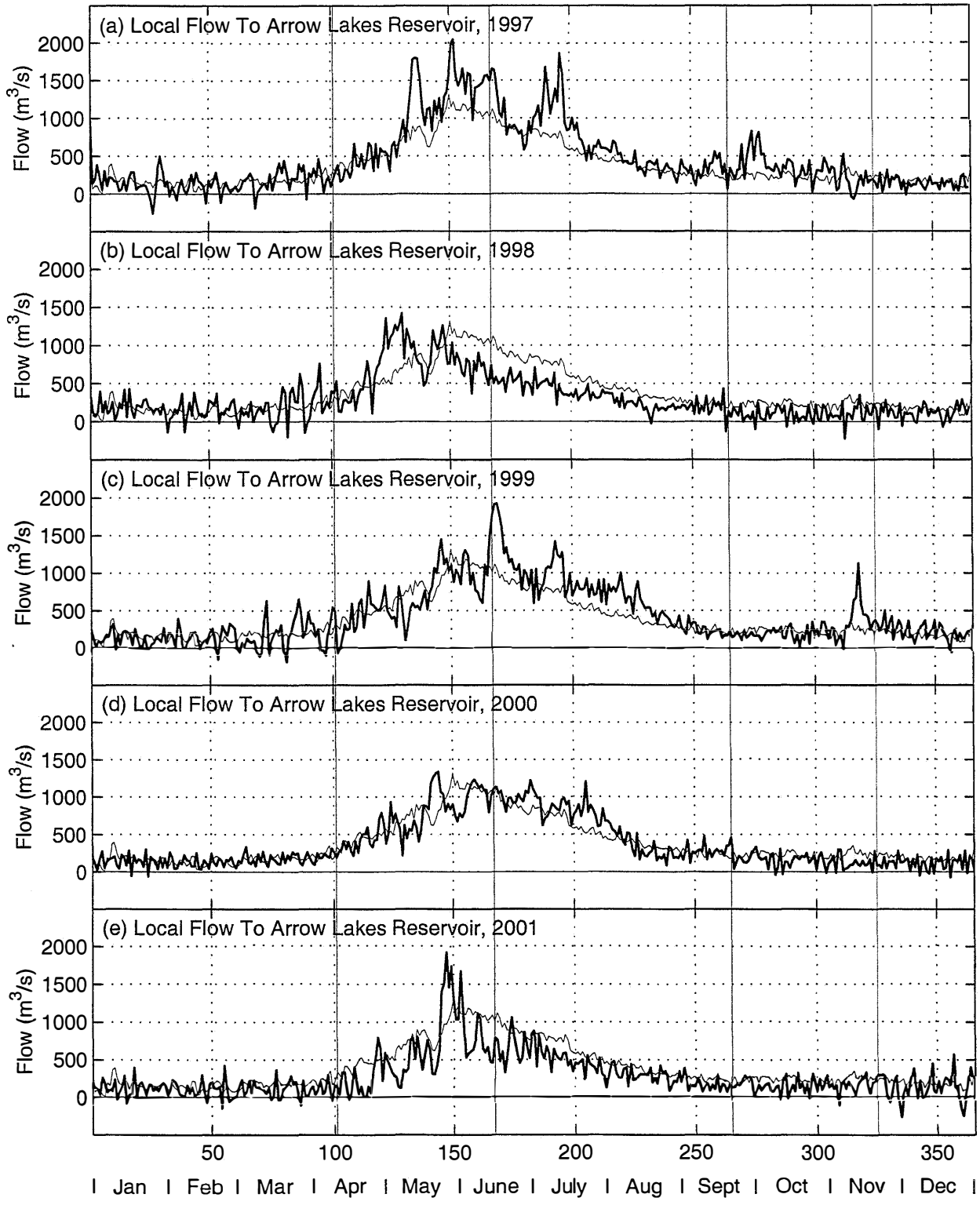


Figure 3.7.2 Local flow for **(a)** 1997, **(b)** 1998, **(c)** 1999 **(d)** 2000 and **(e)** 2001 (heavy lines). Also shown in the mean local flow for 1986-1990, 1995-1997 (light lines). Local flows below zero are erroneous: see discussion in the text. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

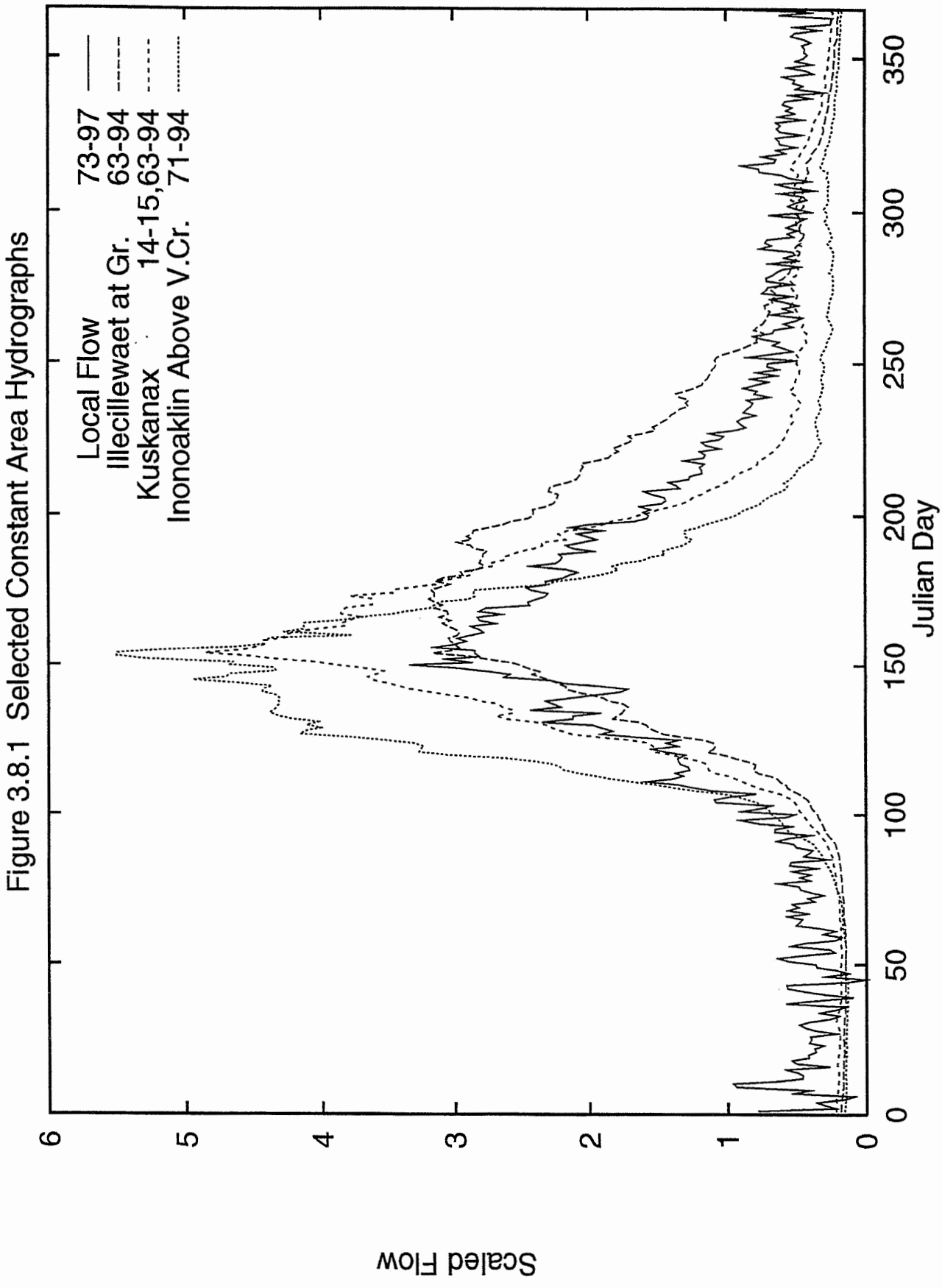


Figure 3.8.1 Selected hydrographs of local inflow plotted with constant area. The area under each curve is 365.25 and the resulting mean flow is 1 m3/s.

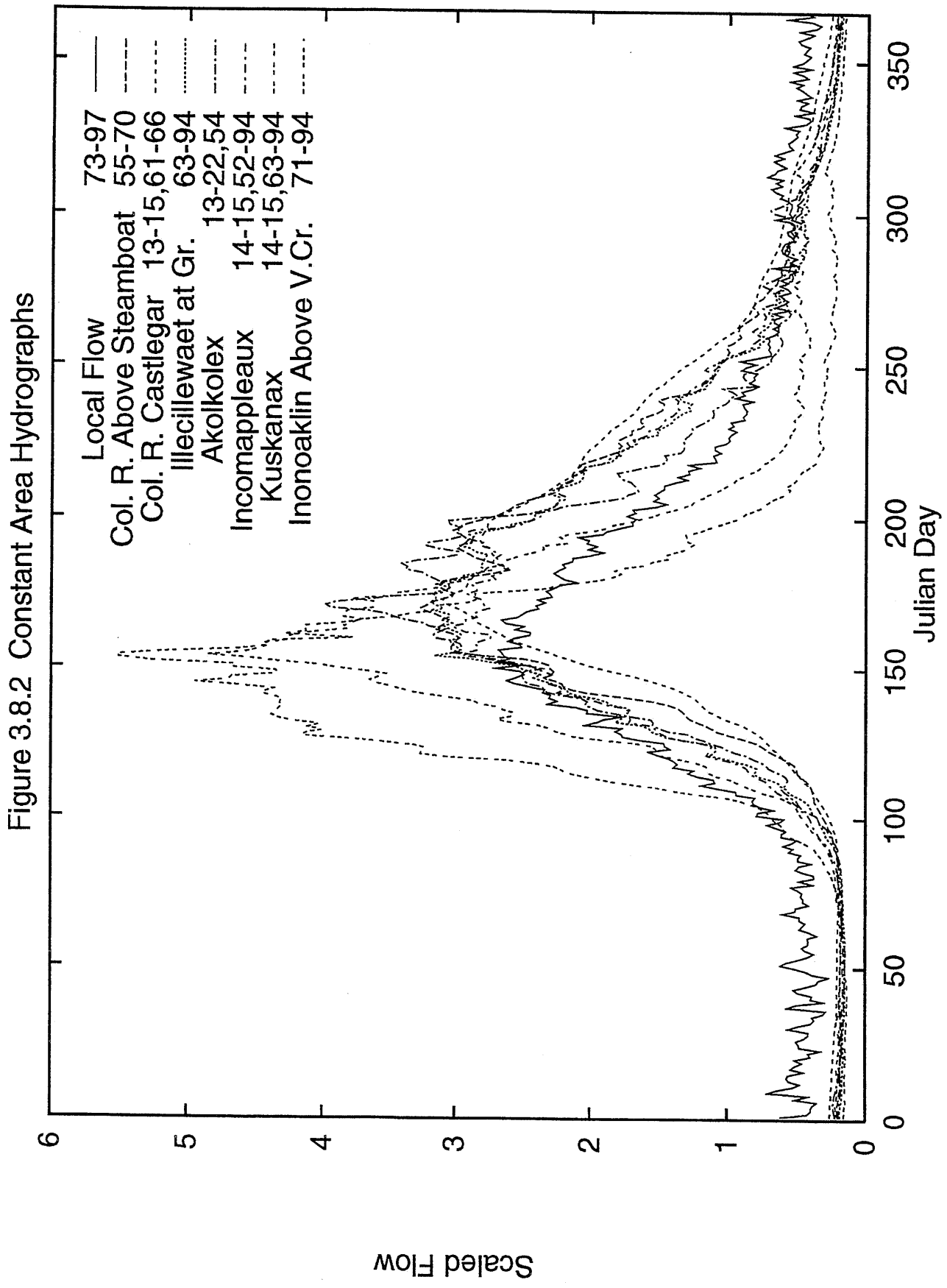


Figure 3.8.2 Hydrographs of local inflow plotted with constant area. The area under each curve is 365.25 and the resulting mean flow is 1 m3/s.

Figure 3.10.1 Narrows Flow

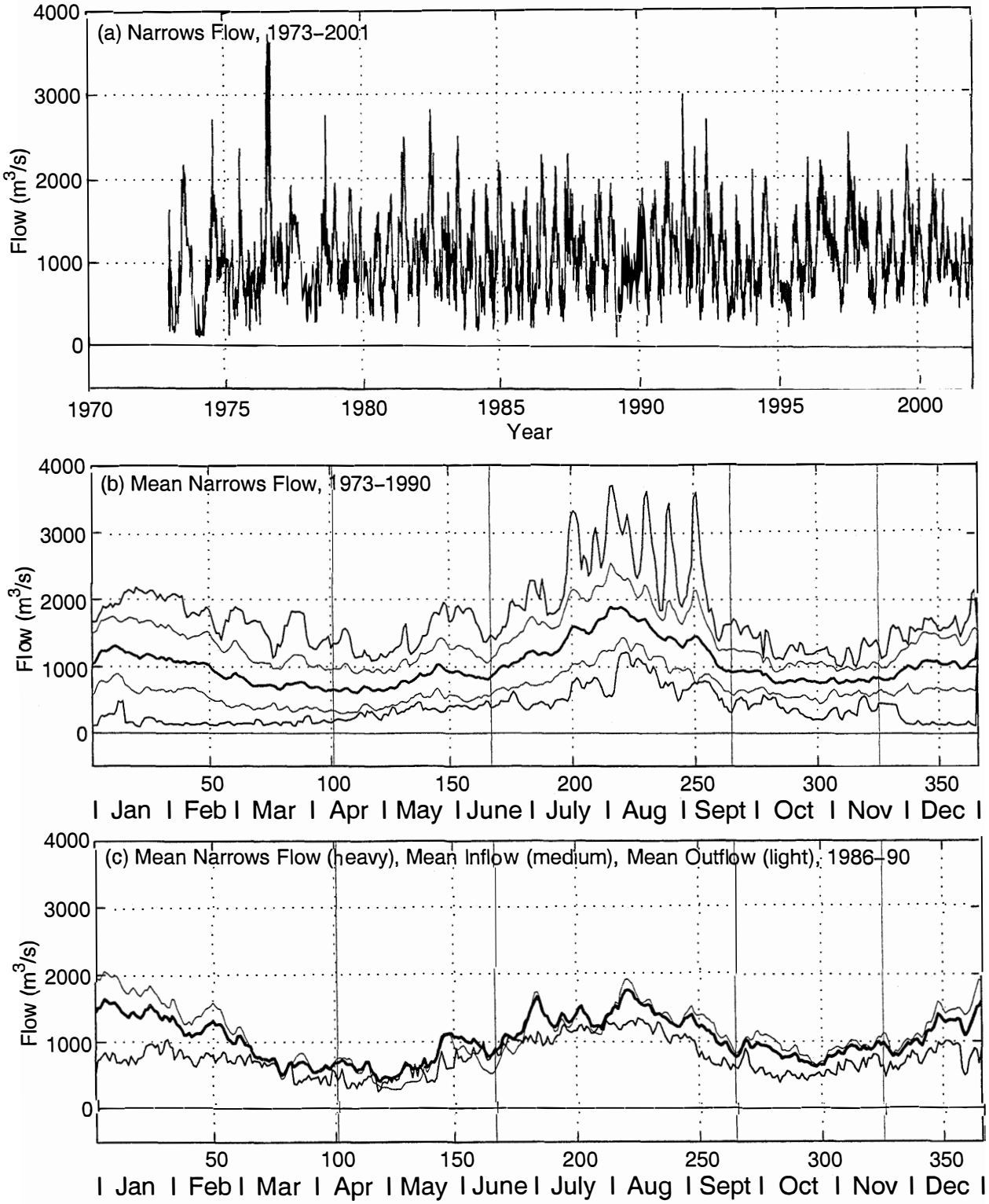


Figure 3.10.1 Narrows flow. **(a)** Narrows flow for 1973-2001. **(b)** Mean narrows flow for 1973-1990. Mean (heavy line), maximum and minimum (medium lines) and mean ± one standard deviation (light lines). **(c)** Comparison of mean Narrows flow (heavy line) mean inflow (medium line) and mean outflow (light line) for 1986-1990. Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.10.2 Narrows Flow, 1997–2001

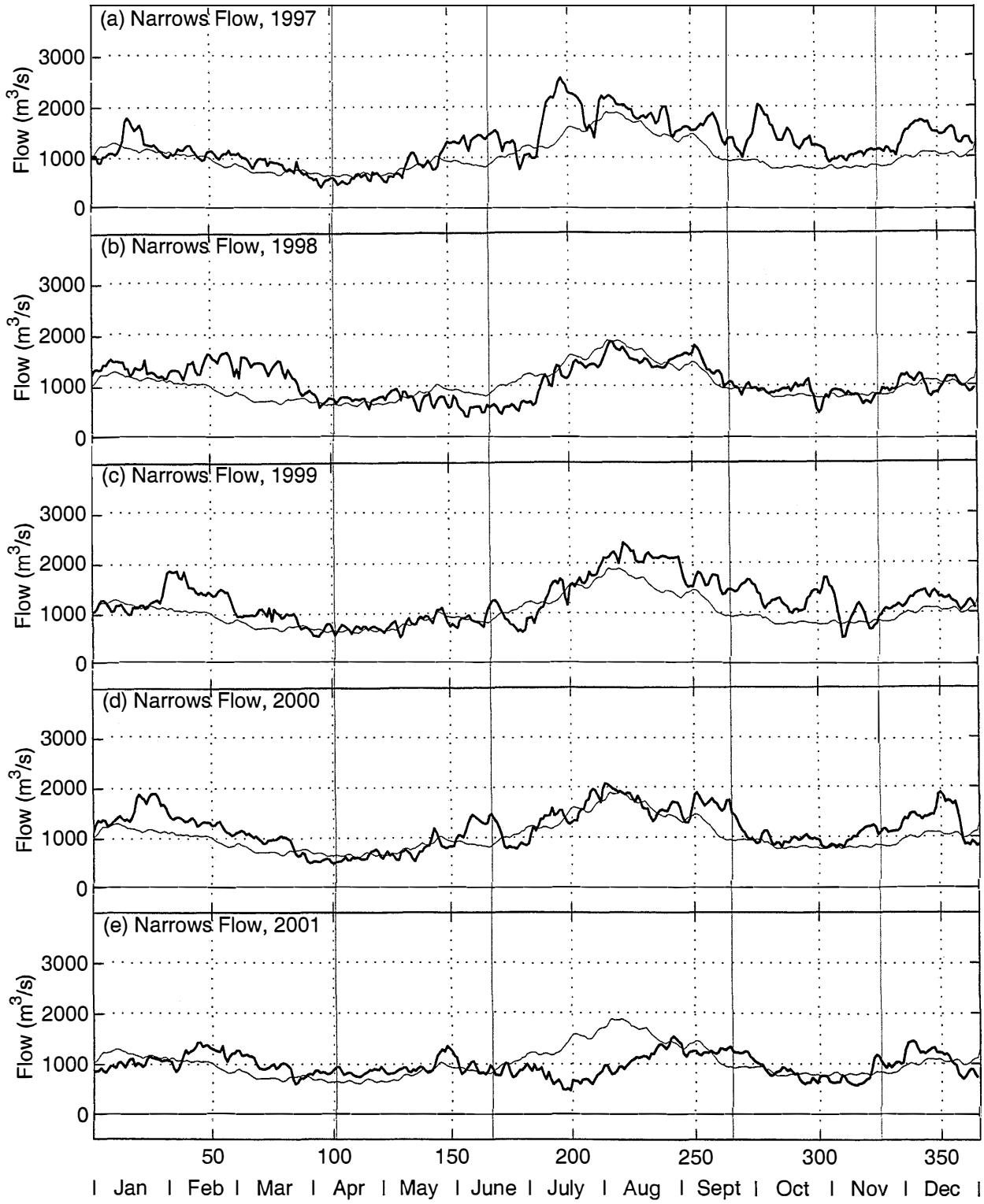


Figure 3.10.2 Narrows flow for **(a)** 1997, **(b)** 1998, **(c)** 1999, **(d)** 2000 and **(e)** 2001 (heavy line). Also shown in the mean local flow for 1973-1990 (light line). Vertical lines mark limnological seasons (Section 3.13). See Appendix 3.1 for conversion between date and Julian day.

Figure 3.11.1a Mean Annual Local Flow

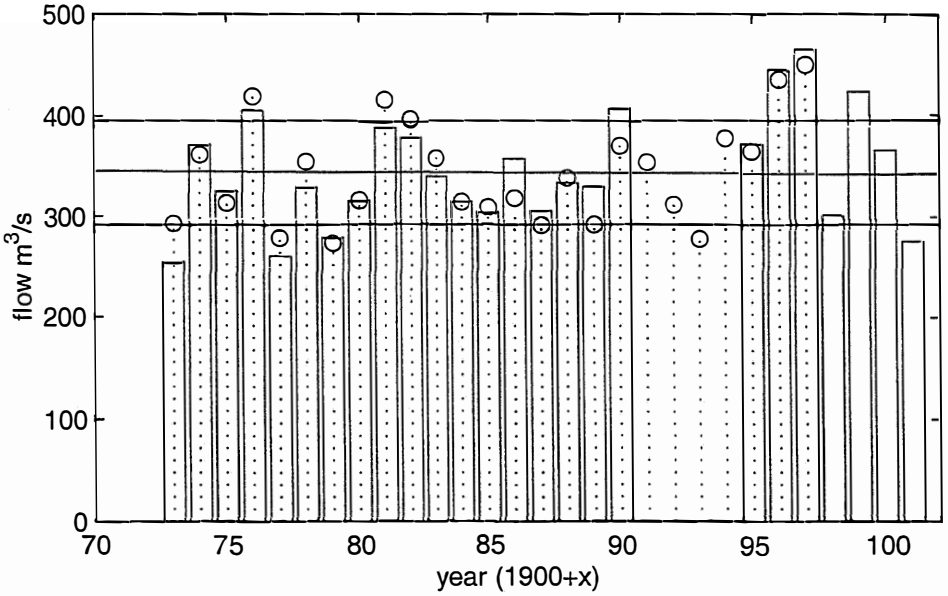


Figure 3.11.1b Mean Annual Flow of the Illecillewaet River

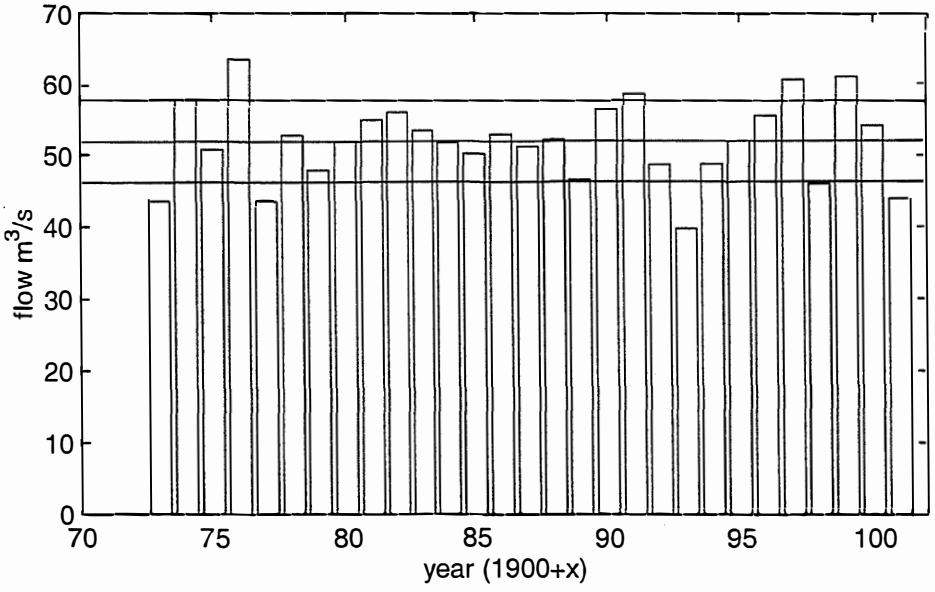


Figure 3.11.1 **(a)** Mean annual local flow from 1973 to 2001. Bars represent the mean annual local flow computed in Section 3.7. Circles represent the mean annual flow computed from the smoothed local flow from B.C. Hydro. Horizontal lines mark the mean, the mean plus one standard deviation and the mean minus one standard deviation. **(b)** Mean annual flow for the Illecillewaet. Horizontal lines mark the mean, the mean plus one standard deviation and the mean minus one standard deviation.

APPENDIX 3.1
CONVERSION BETWEEN DATE AND JULIAN DAY

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

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

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

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

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

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

APPENDIX 3.2
WATER SURVEY CANADA STATIONS, FLOWS, DRAINAGE AREAS AND EFFECTIVE PRECIPITATION

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

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

Notes to Table A3.2.1

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

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

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

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

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

Table A3.2.3 One letter abbreviation used to indicate month

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

Table A3.2.4 Drainage areas and estimated flows for rivers and streams sampled in Chapter 7 but not gauged by WSC.

	Drainage Area*	Flow	Yield	Comment
	Km^2	m^3/s	m/y	
Halfway River	327	13.5	1.3	Assume Yield
St.Leon's Cr.	109	4.5	1.3	Assume Yield
Cape Horn Cr.	39	1.6	1.3	Assume Yield
Slewiskin Cr.	96	3	1	Assume Yield
Mosquito Cr.	410	13	1	Assume Yield
Burton&Caribou Cr.	531	17	1	Assume Yield
Barnes Cr.	201	4	0.63	WSC Flow
Whatshan Discharge	390	7	0.57	WSC Flow
Eagle Cr.	112	1.4	0.4	Assume Yield
Dear Cr.	79	0.85	0.33	WSC Flow
Little Cayuse Cr.	32	0.19	0.24	WSC Flow
Syringa Cr.	22	0.21	0.31	WSC Flow

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

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

Station	Station Name	Year	L	Drainage Area km^2	Mean Flow m^3/s	Effective Precip. m/yr	M	Q
	Columbia River Input							
BC08ND025	Revelstoke Project Outflow	1986-1994		NA	779	NA	M	Q
BC08ND011	Columbia River Above Steamboat Rapids.	1955-1986		26,400	796	0.95		
BC08ND002	Columbia River At Revelstoke[7]	1912-1950		26,700	854	1.01		
BC08ND006	Columbia River At Twelve Mile Ferry[8]	1948-1968		28,500	929	1.03		
	Local Flow							
BC08ND014	Jordan River Above Kirkup Creek	1963-1988	L	272	17.3	2.01		
BC08ND004	Jordan River Near Revelstoke	1946-1947 1956-1957		350	N1	NA		
BC08ND022	Dolan Creek Above Diversions [9]	1985-1989 Apr-Sept		NA	0.041	NA		
	Revelstoke							
BC08ND003	Illecillewaet River Near Revelstoke[10]	1911-1916 Mar-Dec	L	1230	E 52	1.3		Q
BC08ND013	Illecillewaet River At Greeley	1963-1994		1170	52.6	1.42	M	
BC08ND001	Akolkolex River Near Revelstoke	1913-1922 part 1954	L	394	19.9	1.59		Q
BC08NE123	Cranberry Cr. Above B.C. Hydro Intake[11]	1980-1986		99.6	4.84	1.53		
	Beaton							
BC08NE001	Incomappleux River Near Beaton	1914-1915 1952-1994	L	1020	55.8	1.73		Q
BC08NE008	Beaton Creek Near Beaton	1952-1994	L	99.5	2.46	0.78		
	Shelter Bay-Galena							
BC08NE124	Hill Creek Above Spawning Channel	1982-1984		15.1	0.691	1.44		

See notes to this table on Page 3-49.

[7] Includes Jordan River
[8] Includes Jordan And Illecillewaet Rivers
[9] Enters the Columbia from west just before the Illecillewaet, near Revelstoke townsite; A 0.095, Y 0.233, U 0.047, L 0.016, G 0.01, S 0.016.
[10] Assume Jan and Feb Flows equal that in March
[11] Into Columbia between Revelstoke and Upper Arrow

BC08NE120	Hill Creek At Mill Road Bridge	1977-1980	L	28.2	0.623	0.70		
BC08NE121	Hill Creek Near 820 M Contour	1977-1981		17.1	0.471	0.87		
BC08NE035	Strauss Creek Near Nakusp -Not On Chart	1928-1929 May-Sept		NA	-	NA		
BC08NE006	Kuskanax Creek Near Nakusp	1914-1915 1963-1994	L	337	14.2	1.33	M	Q
BC08NE117	Kuskanax Creek At 1040 m Contour	1973-1994		113	5.34	1.49		
BC08NE007	Nakusp Creek Near Nakusp[12]	1914-1914 Apr-Dec	L	104	E 0.95	0.29		
BC08NE021	Brouse Creek Above Diversions	1924-1929 1975-1986		1.01	0.023	0.71		
BC08NE022	Brouse Creek Near Nakusp (Lower Stn)[13]	1924-1925 May-Sept		6.22	E 0.01	0.05 Note2		
BC08NE026	Brouse Creek (West Fork) Near Nakusp[14]	1925-1929 May-Sept		4.66	E 0.0038	0.03 Note2		
BC08NE101	Halfway Cr. (West Fork Of Wensley Cr.) Near Nakusp	1968-1975 May-Sept	L	2.07	E 0.043	0.66		
	Boundary Between Upper And Lower Arrow							
BC08NE023	Mauchline Creek Near Arrow Park [15]	1923-1926 Jun-Aug		0.34	Note1	NA		
BC08NE034	Reinecker Creek Near Burton	1928-1929 Apr-Sept	L	3.63	E 0.023	0.19		
	Burton							
BC08NE005	Caribou Creek Near Burton City[16]	1914-1914 Aug-Dec.		531	Note1	NA		Q
BC08NE050	Pin Creek Near Fauquier	38,39,42 May-Sept	L	0.85	E 0.024	0.89		
	Fauquier-Needles							
BC08NE052	Fauquier Creek Near Fauquier[17]	1938-1939 1942-1944 Apr-Sept	L	9.84	E 0.22	0.71		
BC08NE063	Whatshan River At Needles	1944-1951	L	609	11.2	0.58		
BC08NE078	Whatshan River Near Needles [18]	1950-1965		396	4.22	0.34		

[12] Assume flows For Jan, Feb, March and Dec are equal
[13] Y 0.039, U 0.031, L 0.009, G 0.009, S 0.011
[14] Y 0.012, U 0.012, L 0.007, G 0.003, S 0.003
[15] Near Mosquito in Narrows
[16] G 5.75, S 3.36, O 4.59, N 9.11, D 10.9
[17] Use 80% (From Kuskanax) to scale to full year flow; A 0.073, Y 0.642, U 1.12, L 0.365, G 0.076, S 0.047

BC08NE077	Barnes Creek Near Needles	1950-1994	L	201	4.01	0.63	M	
BC08NE051	Heart Creek Near Fauquier [19]	1938-1939 May-Sept	L	23.8	E 0.36	0.48		
BC08NE127	Inonoaklin Creek Near The Mouth	1987-1990 Jul-Nov		377	Note1	NA		Q
BC08NE110	Inonoaklin Creek Above Valley Creek	1971-1982 1987-1994		298	3.80	0.40	M	
BC08NE009	Inonoaklin Creek Near Edgewood	1915-1920	L	401	5.00	0.39		
	Edgewood-Applegrove							
BC08NE122	Mackenzie Creek Near 520 M Contour	1977-1981	L	20.7	0.502	0.76		
BC08NE125	Mackenzie Creek Above Fish And Wildlife Diversion	1982-1984		NA	0.533	NA		
BC08NE027	Ferguson Creek Near Edgewood[20]	1925-1927 1958-1959 Jun-Sept	L	1.92	E 0.038	0.62		
BC08NE030	Mclean Creek Near Edgewood (Not On Chart)	1927-1929 April-Sept		6.99	E 0.016	0.07 Note2		
BC08NE028	Renata Creek Near Renata	1930-1930 Aug-Sept		195	Note1	NA		
	Renata, Deer Park							
BC08NE087	Deer Creek At Deer Park	1958-1994	L	80.5	0.840	0.33	M	
BC08NE082	Cayuse Creek Near Deer Park[21]	1955-1958 Apr-Sept	L	51.3	0.85	0.52		
BC08NE083	Little Cayuse Creek Near Deer Park	1955-1958 Apr-Sept	L	24.6	0.19	0.24		
	Sryinga Creek Park							
BC08NE085	Syringa Creek Near Syringa Creek	1958-1960 Jun-Sept	L	21.5	0.21	0.305		
	Sum Of Known Local Drainage Area And Flow For Stream Records Marked "L"			4936	186.8			
	Outflow							
BC08NE126	Arrow Reservoir Outflow	1973-1994		NA	1170		M	Q
	Arrow Local Flow	73-90		10114	333	1.1		
BC08NE002	Columbia River At Castlegar	1913-1915 1961-1972		36,500	1210	1.05		

[18] Spot values only for 1957-1965
[19] Use 78% (from Deer Cr.) to scale to full year flow.
[20] Not on chart; U 0.111, L 0.045
[21] A 0.669, Y 4.05, U 3.13, L 0.750, G 0.179, S 0.057

APPENDIX 3.3
STORAGE-ELEVATION CURVE FOR ARROW RESERVOIR

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

Table A3.3.1 Storage-elevation curves for Arrow Reservoir

Volume = c(1) * (El-c(2)) ** c(3) + c(4) * El + c(5)
Area = c(1)*c(3)*(El-c(2))**(c(3)-1) + c(4)
NB: El in ft, Volume in cfs-days, Area in cfs-days/ft
Equations taken from BCH FLOCAL database

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

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

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

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

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

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

* These values were extrapolated from the given data.

** Elevations rounded to the nearest foot.

A3.3.1 Location of boundary between Upper and Lower Arrow

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

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

Next, consider the boundary between Upper and Lower Arrow. The area for Upper and Lower Arrow, as determined from the storage-elevation curve, are 27 km^2 larger and 15 km^2 smaller, respectively. Thus the storage-elevation curve has the Upper Arrow being larger by a mean difference of 21 km^2. As the reservoir is approximately 1 km wide at this point, the boundary between the Upper and Lower Arrow is about 20 km downstream, near Burton at the south end of the narrows. Thus the storage elevation curve includes the narrows with the Upper Arrow.

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

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

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

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

Discussion	Report Section	Narrows included with:
Surface areas and volumes from the digitized bathymetric charts.	Section 2.2, Tables 2.2 and 2.3	Upper Arrow
Area of the drawdown zone.	Section 2.3	Upper Arrow
Summary of Upper Columbia lakes and reservoirs; area, volume.	Table 3.1	Lower Arrow
Storage-elevation curve.	Section 3.6, Appendix 3.3	Upper Arrow
Division of local flow into four regions.	Section 3.9	Lower Arrow
Nutrient budget.	Chapter 9	Lower Arrow

APPENDIX 3.4
EVALUATION OF LOCAL FLOW BY EXAMINATION OF MEAN WINTER FLOWS OF TRIBUTARY HYDROGRAPHS

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

The winter component of the local flow can be divided into three parts:
1. the fraction of the winter flow that comes from tributary inflow,
2. the fraction of the winter flow that comes from known sources other than tributary flow, namely direct precipitation to the reservoir surface and flow from Whatshan Reservoir, and
3. the remainder which will be considered error.

Section A3.4.1 will show that approximately 40 m^3/s of the winter flow can be accounted for by direct precipitation to the reservoir surface and flow from Whatshan Reservoir.

A3.4.1 Known sources of additional local flow during winter

The first source of additional winter flow to the reservoir is direct precipitation to the reservoir surface. Using a mean precipitation of 0.9 m/yr on 500 km^2 gives 14 m^3/s. Rain gauge data (Sect. 3.9) and data for 1997 show similar levels of precipitation.[22] Also contributing to the local flow in winter is precipitation on near shore regions, either as rain or as snow which melts within a few weeks. Assuming a near shore region of area comparable to that of the reservoir would give a total flow from direct precipitation of 28 m^3/s.

A second source of winter flow is the Whatshan reservoir. The annual mean outflow for Whatshan is 9.3 m^3/s. The mean flow from Whatshan in 1997 was 13.3 m^3/s and the mean flow for day 1-75 was 12.2 m^3/s.

In conclusion, direct precipitation and Whatshan flow contribute approximately 40 m^3/s to the local flow.

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

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

[22] A similar value is obtained by using mean winter precipitation data from four meteorological stations along the reservoir, described in Table 3.9.2. Also the 1997 rainfall for day 1-100 at Greeley, near Revelstoke, applied to the entire water surface gives 17 m^3/s, which is also roughly comparable to the mean flow.

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

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

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

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

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

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

4

Meteorological Measurements

CHAPTER 4
METEOROLOGICAL MEASUREMENTS

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4.1 Methods

Observations of wind speed and direction, air temperature, relative humidity and solar radiation were continued in 2001 at one shore station near Fauquier on the Lower Arrow. The shore station at Nakusp on the Upper Arrow had been discontinued in November 1999. In 2001, solar radiation was also measured from mid-April to mid-November at Hill Creek on the Upper Arrow, see Chapter 15.

The Handar meteorological station was located approximately 3 km south of Fauquier at 49° 51.500' N and 118° 05.274' W, reasonably well exposed to conditions on the reservoir. An R.M. Young propeller vane anemometer was used for wind speed and direction. The direction for which the vane reading changes from 0 to 360° was set to be at right angles to the axis of the reservoir so that readings in the small "dead band" of about 1 degree would be unlikely. Vaisala temperature and relative humidity sensors were mounted in a R.M. Young radiation shield. A Rimco SP440 silicon photodiode pyranometer was used for measuring solar radiation.

The anemometer was overhauled by the supplier before deployment in July 1997. Rotation of the propellor generates pulses that are counted continuously and the wind speed should be accurate to 2%. Including the uncertainty of setting the vane zero point, the direction should be good to 5 degrees. The air temperature and relative humidity sensor was calibrated by the supplier before deployment; the specified accuracies are 0.2 °C and 3 %, respectively. The Handar and pyranometer was set-up on the roof of a building at UBC and compared to the readings of a calibrated pyranometer. The Handar was found to be low by ~5.7% low in May 1997 and ~6.2% low in June 2002. Data shown here was corrected by 6%. The Handar and pyranometer were also checked in the field when a Kipp and Zonen CM5 pyranometer and Campbell CR21 logger were setup next to the Handar at Fauquier and data was collected for two (sunny) days during which the Handar was low by ~7.2%. The variation among these calibrations suggests an uncertainty in the calibration of about ± 1.5%. The specified accuracy of the sensor is 5%.

All variables other than wind speed were sampled once per minute and the average values were recorded every 15 minutes. Although less subject to error than a buoy station, the direction readings can be quite noisy due to the turbulent nature of wind. The air

temperature and humidity is also turbulent. All variables were averaged to hourly values. Due to a software error, an arithmetic average was applied to the wind direction, rather than a vector average. Fortunately, the dead band and 0° of the wind monitor faced east, which can result in winds from the east being reported as from the west, while the winds of interest are north-south (along-lake). Wind speed is unaffected by this error.

The station was deployed on 2 July 1997. Data was down loaded on 29 August, and 1 December 1997; 26 April, 4 August and 26 October 1998; 17 March, 22 May, 31 July, and 19 November 1999; and 13 April, 18 June, 17 & 19 July and 10 November 2000; April 6, July 08 and December 1, 2001; and May 1, 2002. The Handar clock ran slow (1.6s/day) and time of the data was adjusted to reflect this drift. When the Handar memory is full new data is over written. Data was lost from December 1-2, 1997, July 8-9, 2002 and 1- 24 December 1-24, 2002. Data was also lost from early January to mid April in 2000 due to battery failure.

4.2 Results

Temperature, humidity, solar radiation and the along and cross channel components of the wind are given in Figures 4.1-7. Air temperature, relative humidity and solar radiation are similar at Fauquier and Nakusp (Chapter 4, Pieters et al. 1999).

In 1997, mean monthly air temperatures were average throughout the year except for July (slightly below average) and November and December (slightly above average). The fall of 1997 and most of 1998 was dominated by an ENSO (El Niño/Southern Oscillation) event. In 1998 mean monthly air temperatures were above average throughout the year, most notably in July, August and September. The weather in 1999 returned to generally average conditions except for an especially protracted period of low solar radiation and low air temperatures from the middle of June to the middle of July. In 2000, air temperature and solar radiation were close to average. Like 1999, June 2000 was again cloudy though not as severe and persistent as the June/July period in 1999. Solar radiation in April 2001 was lower than in 1998 and 1999 (the only other years for which a complete April record was available). On April 12, 2001, surface ice was encountered around Nakusp during primary productivity sampling. Water surface temperatures on April 18, 2001 (4.5 °C at AR2, Chapter 6) were a couple of degrees colder than usual but this difference may not be significant. May 2001 had typical air temperature and sunlight while June 2001 showed below average air temperature and sunlight. Both July and August 2001 were fine with above average sunlight and air temperatures.

References

Canadian Climate Normals, British Columbia. 1993. Canadian Climate Program, Atmospheric Environment Service, Environment Canada, Ottawa, Volume 1, 134pp.

Pieters, R., L.C. Thompson, L. Vidmanic, M. Roushorne, J. Stockner, K. Hall, M. Young, S. Pond, M. Derham, K. Ashley, B. Lindsay, G. Lawrence, D. Sebastian, G. Scholten, F. McLaughlin, A. Wüest, A. Matzinger and E. Carmack. 1999. Arrow Reservoir limnology and trophic status, year 2 (1998/99) report. RD 72, Fisheries Branch, Ministry of Environment, Lands and Parks, Province of British Columbia.

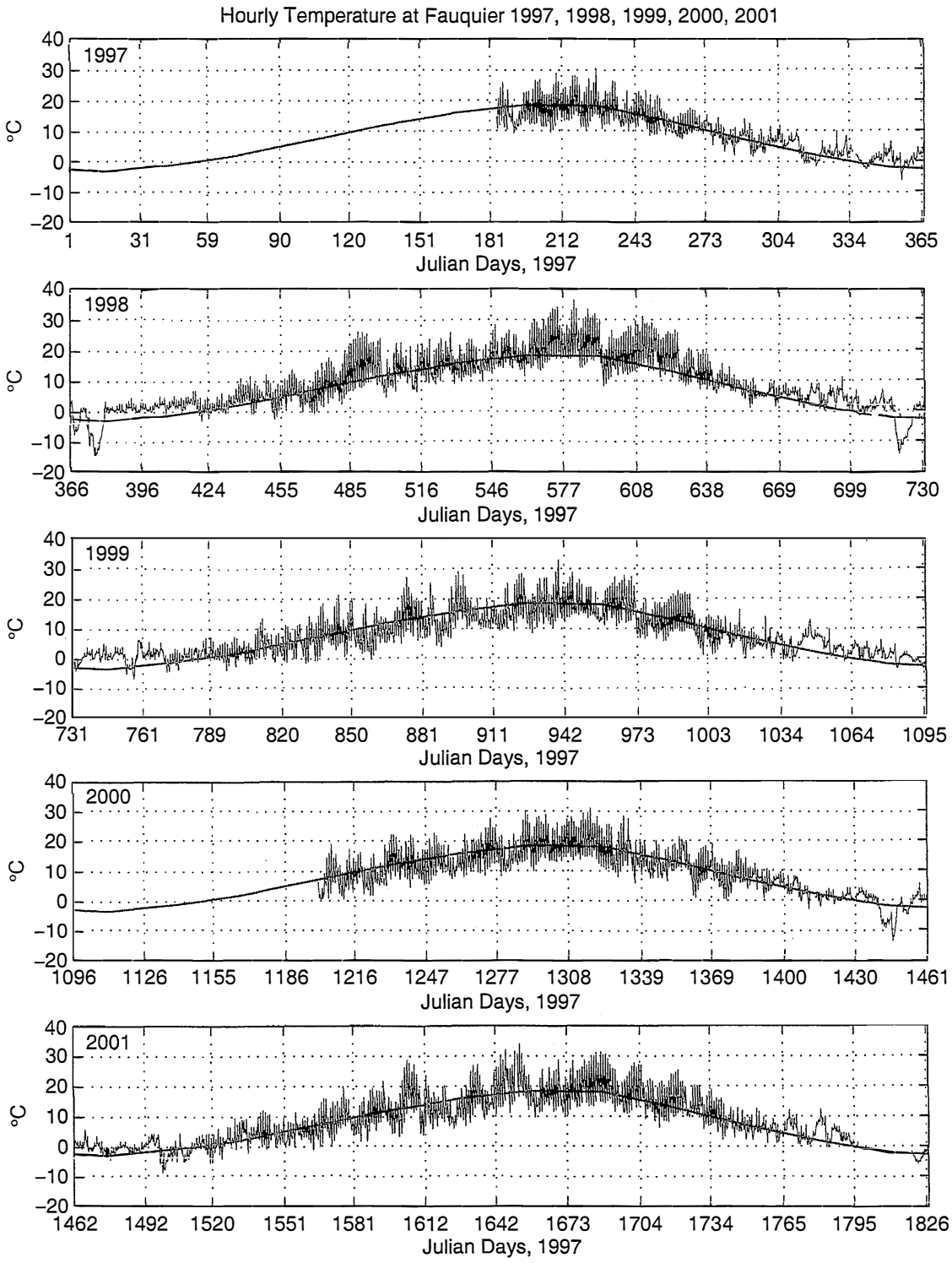


Figure 4.1 Hourly air temperature at Fauquier, 1997-2001. Thick line shows mean monthly air temperatures from 1961-1990 at Fauquier (Canadian Climate Normals 1993).

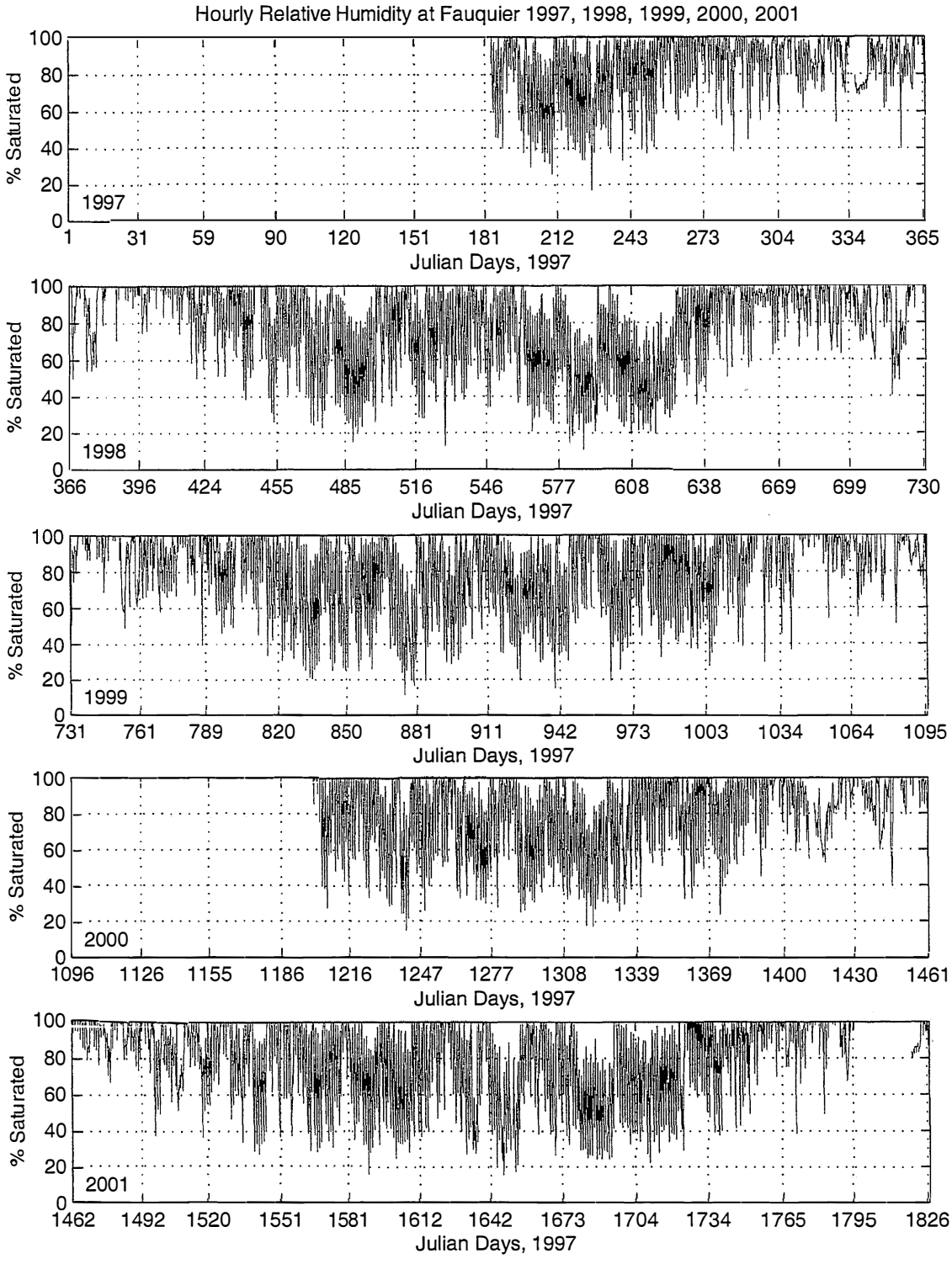


Figure 4.2 Hourly relative humidity at Fauquier, 1997-2001.

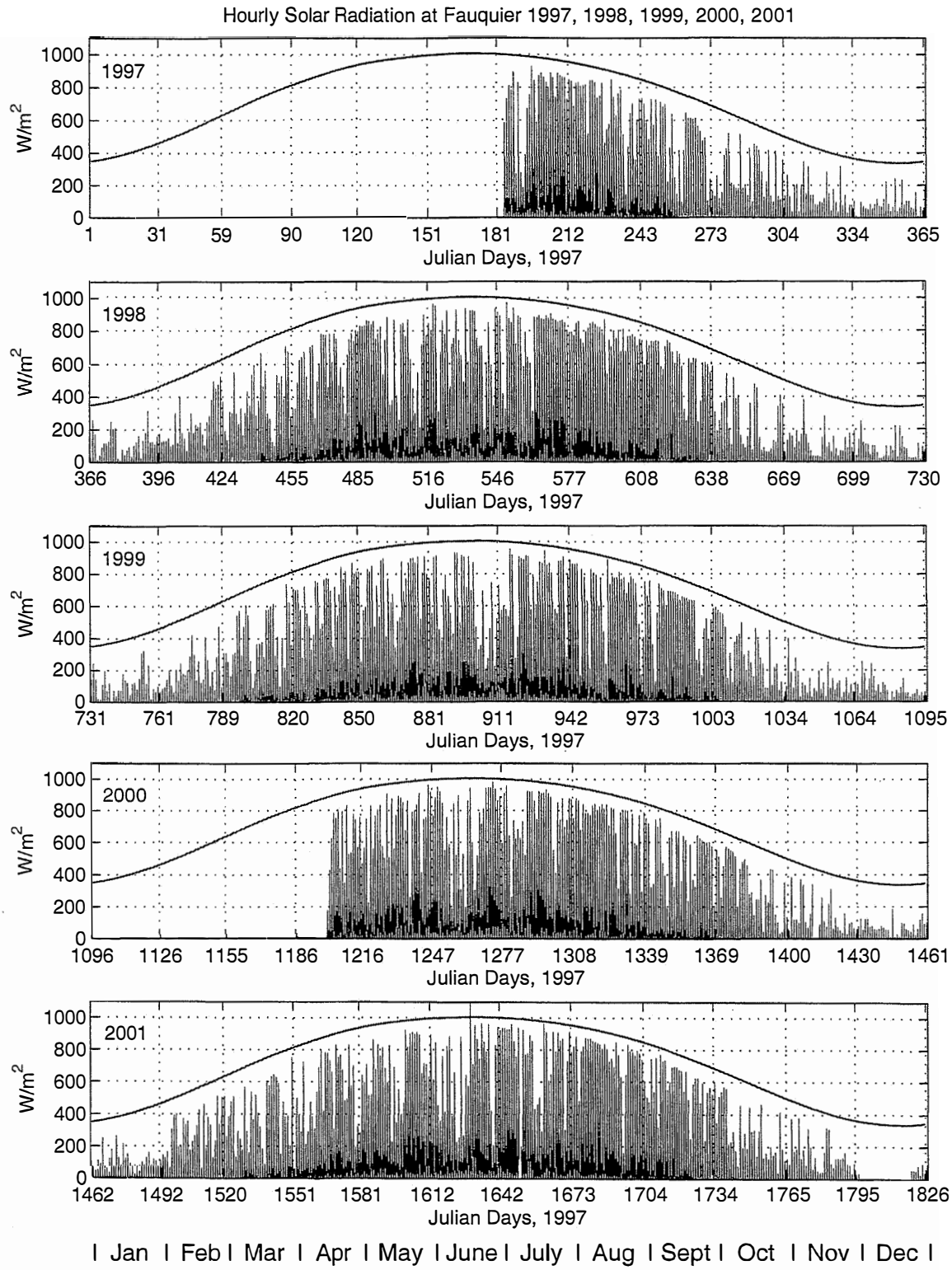


Figure 4.3 Hourly solar radiation at Fauquier, 1997-2001. Heavy line gives daily maximum incident shortwave solar radiation at a given latitude with no atmosphere. See also Figure 15.4.

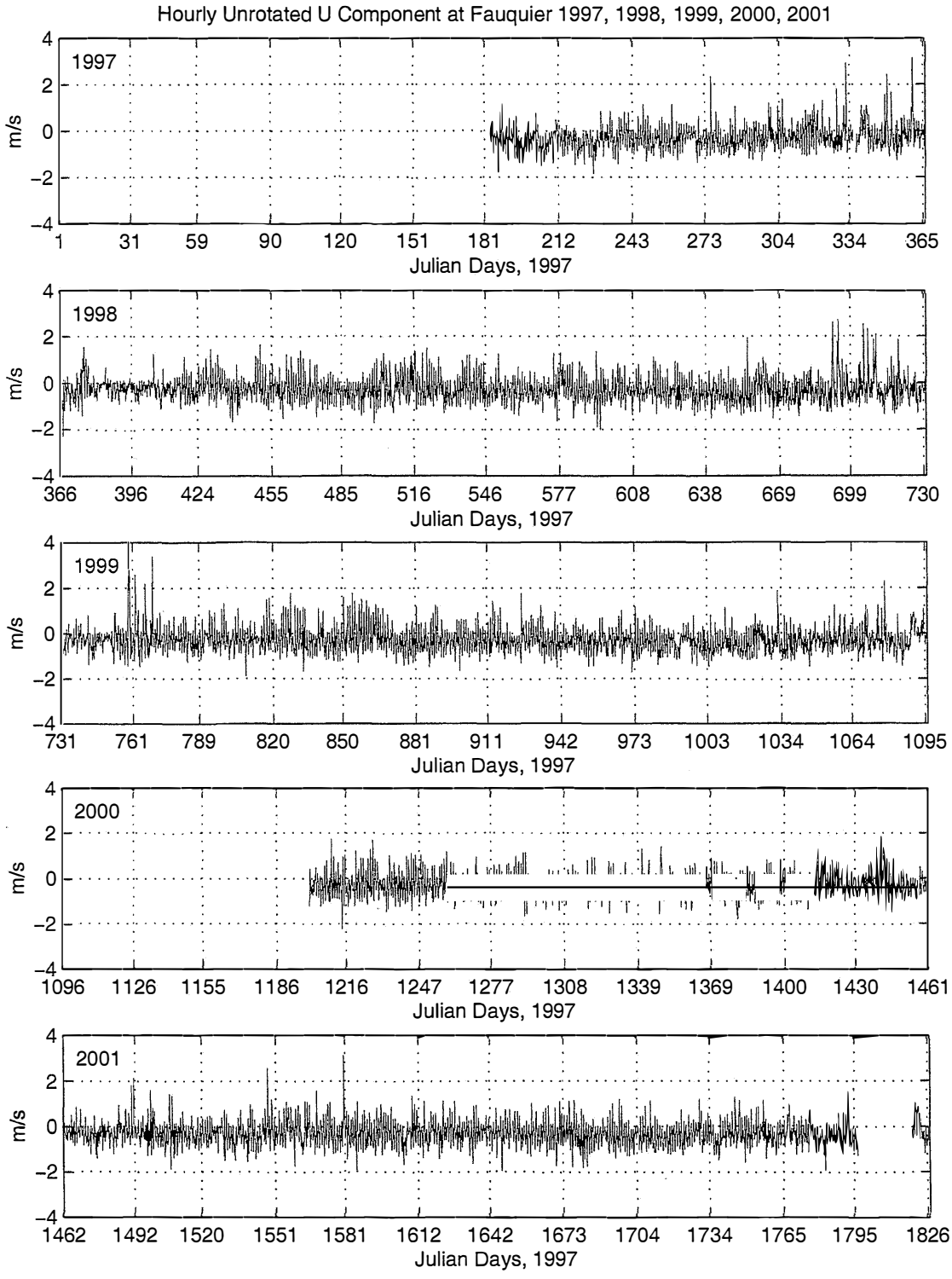


Figure 4.4 Hourly cross channel U component of the wind at Fauquier, 1997-2001. U is positive to the east.

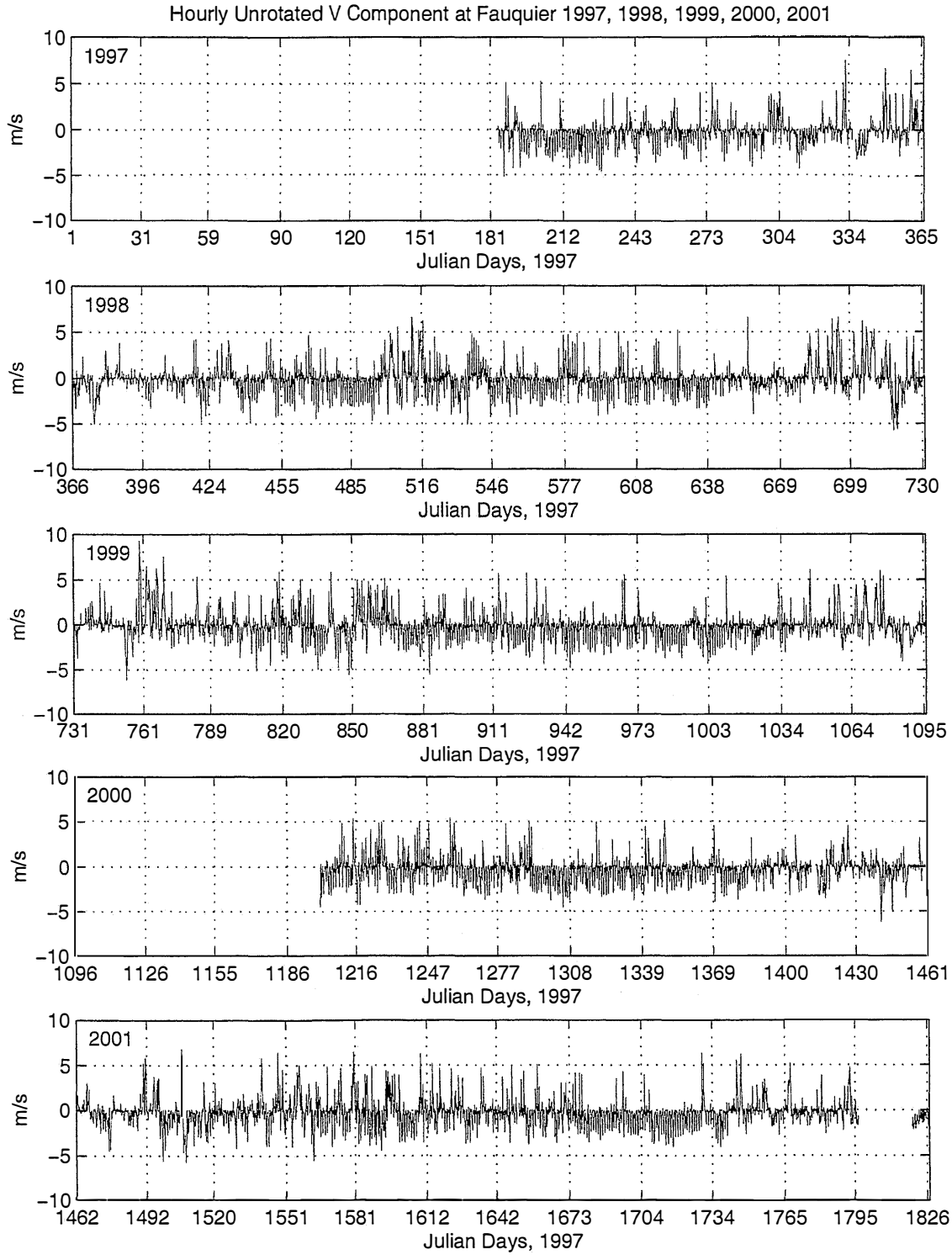


Figure 4.5 Hourly along channel V component of the wind at Fauquier, 1997-2001. V is positive to the north.

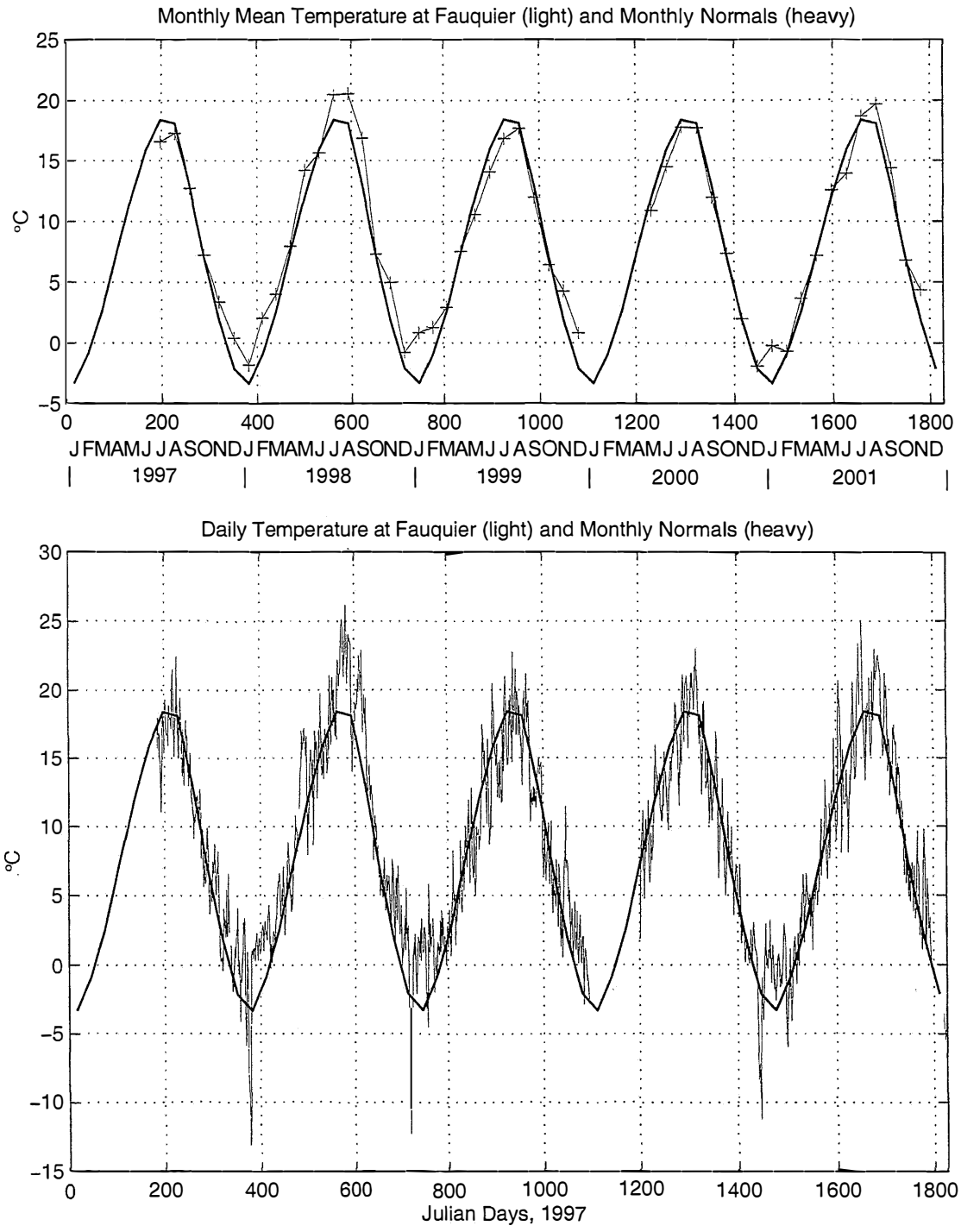


Figure 4.6 Monthly and daily mean air temperature at Fauquier, 1997-2001.

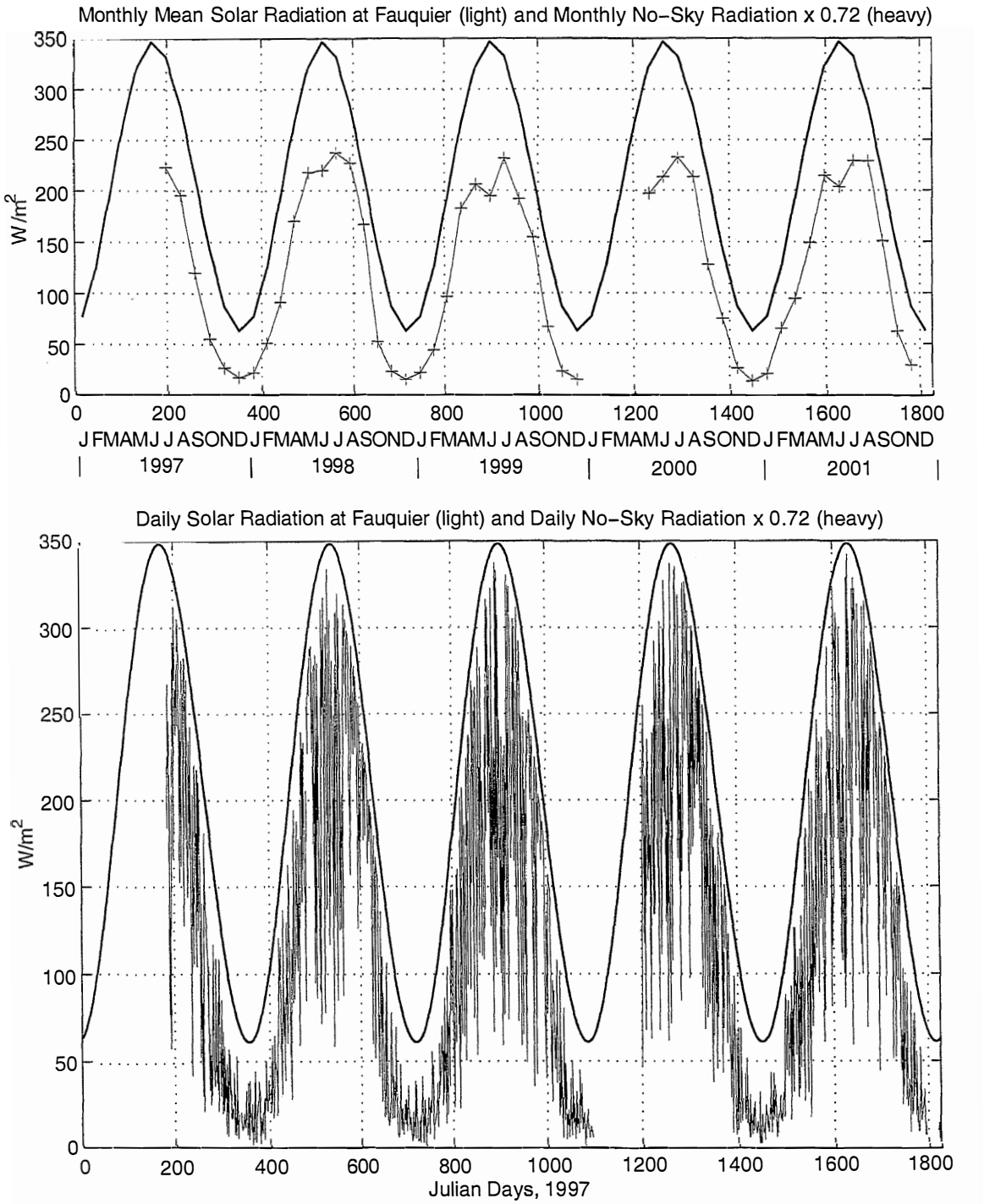


Figure 4.7 Monthly and daily mean solar radiation at Fauquier, 1997-2001.

5

Summer Circulation

CHAPTER 5
SUMMER CIRCULATION

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5.1 Introduction

This chapter will examine aspects of summer circulation as it relates to the delivery of nutrients to the euphotic zone. Summer here refers broadly to the productivity period from late spring to early fall. There are three ways in which nutrients become available for phytoplankton growth:

1. nutrients are present in the lake once stratification begins in the spring,
2. nutrients are contributed by river flow through the summer and
3. nutrients are mixed from below into the surface layer as the surface layer cools and deepens in the fall.

The historic work on productivity in lakes has focussed on the first. Vollenweider (1976) correlated the phosphorus present in the water column during spring overturn with productivity represented by chlorophyll biomass in summer.

However, the Arrow Lakes Reservoir is a riverine lake with medium residence time. The large riverine flow can contribute nutrients in two ways during summer. First, strong wind can mix the surface layer deep enough to entrain water from the river based interflow. Second, as river water plunges, it must lift the surface waters, including a proportion of older river water, up and out.

5.2 Aspects of Summer Circulation

River density determines how the river will flow through the Upper Arrow. In summer, density is primarily controlled by temperature. Incoming rivers are generally cooler than the lake surface but warmer than 4°C, the deep temperature of the lake. As a result, rivers plunge to an intermediate depth, typically 10-20 m.

Mixing of the river with ambient water from the lake will tend to increase the temperature of the inflow and reduce the depth to which it plunges. This mixing will be most intense near the plunge zone, but will continue as the flow intrudes. The extent of mixing in the plunge zone is difficult to estimate. The initial density (temperature) of the river will provide the maximum depth to which the river can intrude. Observation of the

intrusion of the Kootenai River into the south arm of Kootenay Lake suggests the intrusion depth is close to this maximum (Carmack and Grey, 1982).

The temperature of the primary flow into Upper Arrow, the Columbia River, is shown in Figure 5.1a. The temperature of the Columbia River was measured at three locations:

1. in a penstock of the Revelstoke Dam (daily),
2. at the Highway 1 bridge in Revelstoke during monthly river chemistry sampling and
3. at station HL2 near Arrowhead (Figure 1.1) where the old riverbed enters Upper Arrow (monthly).

While the first two of these are approximately 40 km upstream of Arrowhead, the temperatures generally agree to within a degree or so.

Other rivers and streams, such as the Illecillewaet, join the Columbia River between the Revelstoke Dam and Arrowhead. In fact, about 40% of the local flow to the Arrow Lakes enters this reach between Arrowhead and Revelstoke (Section 3.9) of which the Illecillewaet represents nearly half the drainage. The temperature of the Illecillewaet and Akolkolex Rivers (Figure 5.1b) generally follow that of the Columbia during spring, when the contribution of the local flow is greatest (Figure 5.2). During summer these rivers can be cooler than the Columbia River (e.g. 1999 and 2000) and in all years they cool faster than the Columbia River in fall. (The outflow from Beaton Arm will be warmer and will likely enter Upper Arrow at a shallower depth than the Columbia River.)

The depth to which rivers will plunge into the lake is determined by the temperature-dominated stratification in the lake. Large river inflows can carry significant quantities of heat that can, in turn, modify the temperature profile. The temperature in Upper Arrow in July shows similar general structure for 1961-2 and 1997-2001 (Figure 5.3). Note that windstorms can mix the surface and internal waves can distort the profiles at depth.

The conductivity of river water varies considerably through the year (Chapter 8). In summer the river conductivity drops and reduced conductivity can indicate river inflow (Figure 5.4). Conductivity data was not collected in 1961. While conductivity data in 1962 is of low vertical resolution, conductivity is reduced in the top 20 m with some reduction at 30 m also. From 1997-2001, the conductivity is typically lowest from 5 to 15 m, with the exception of 1999 when the reduction extended to almost 30 m.

To examine the maximum plunge depth over the summer, the temperature of the Columbia River is plotted with the temperature of the Upper Arrow at 1.5, 10, 20 and 30m (Figure 5.5). For most years the temperature of the Columbia River lies between the temperature of the lake at 10m and 20m. In early summer the Columbia River is cooler with a maximum plunge depth between 20 and 30m and in late summer it warms, but rarely intrudes shallower than 10m. The exception is mid-June to mid-July, 1999 a period of very low sunshine, with low air and water temperatures. The Columbia River remains a few degrees colder and its maximum plunge depth lies between 20 and 30 m, consistent with the reduced conductivity at greater depth seen in 1999 (Figure 5.4).

Residence time

The bulk residence time of Upper Arrow is total volume (30 km^3) divided by total inflow (1,000 m^3/s), approximately 1 year. However, this estimate is only meaningful if the reservoir is continuously stirred. Instead the near surface provides a short circuit for the summer inflow, reducing its residence time while increasing the residence time of the deep water.

Estimates of the residence time for the surface are given in Table 5.1. These assume that the basin walls are vertical and while Upper Arrow is steep sided the reduction in surface layer volume with low water levels (1961, 1962, 2001), has not been accounted for. However, this error is small compared to the error inherent in choosing the depth of the surface layer, to which the residence time is very sensitive. Here the depth of the surface layer is chosen to be the maximum depth of the Columbia River inflow (Figure 5.5).

The residence time of the surface layer has increased after construction of Mica Dam as summer inflow is reduced. The current surface residence time is relatively uniform except for 1997. Low inflow in 2001 is balanced by reduced surface layer depth. Phytoplankton production is controlled by flushing if the surface layer residence time is less than a week. Peak flow in 1961 and 1962 is almost double the mean summer flow, which would reduce the surface residence time to the order of a week for the 10-20 days of peak flow observed in these years.

Table 5.1 Surface residence time

Year	Mean Summer Flow	Estimated Mean Summer Epilimnion Depth	Upper Arrow Surface Residence Time
	m^3/s	m	days
1961	2522	20	18
1962	2545	20	17
1997	1714	15	19
1998	1250	20	36
1999	1619	25	34
2000	1503	20	30
2001	985	15	34

* Using an Upper Arrow surface area of 192 km^2

Summer mixing events

Winds of sufficient intensity can mix the surface layer to the depth of the river inflow, and this occurred around day 208 in 1997 (Figure 5.6). The Columbia River inflow is expected to slot into the lake between 10 and 20 m. Note that the euphotic zone extends to that depth in 1997.

This data from 1997, suggests that for most years there are only a few storms each summer with sufficient intensity and duration to result in mixing to the riverine layer (Figure 5.7).

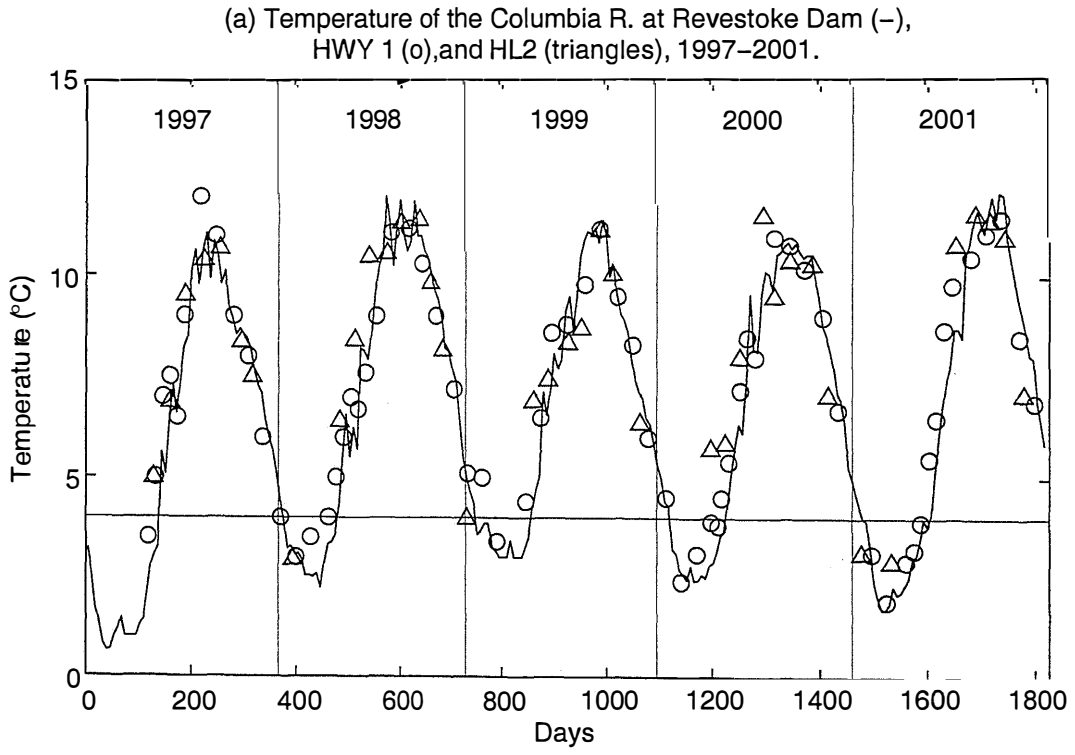
Conclusions

The Columbia River inflow typically plunges into Upper Arrow at depth of 10-20 m. The euphotic zone (1% light level) can extend to this depth. Episodic mixing events occur a few times each summer which mix riverine waters to the surface. The surface layer is replaced every 20-30 days also bringing riverine nutrients to the euphotic zone.

References

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Vollenweider, RA, 1976. Advances in defining critical loading levels of phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol., 33: 53-83.



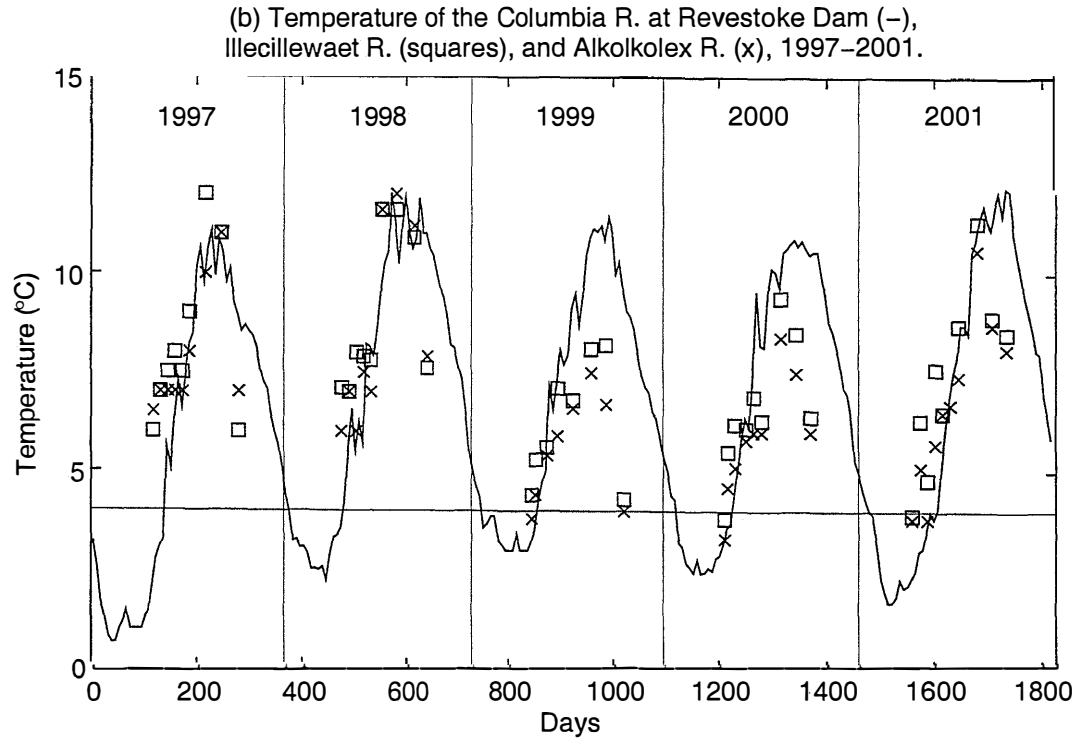


Figure 5.1 Temperature of the Columbia, Illecillewaet and Akolkolex Rivers.

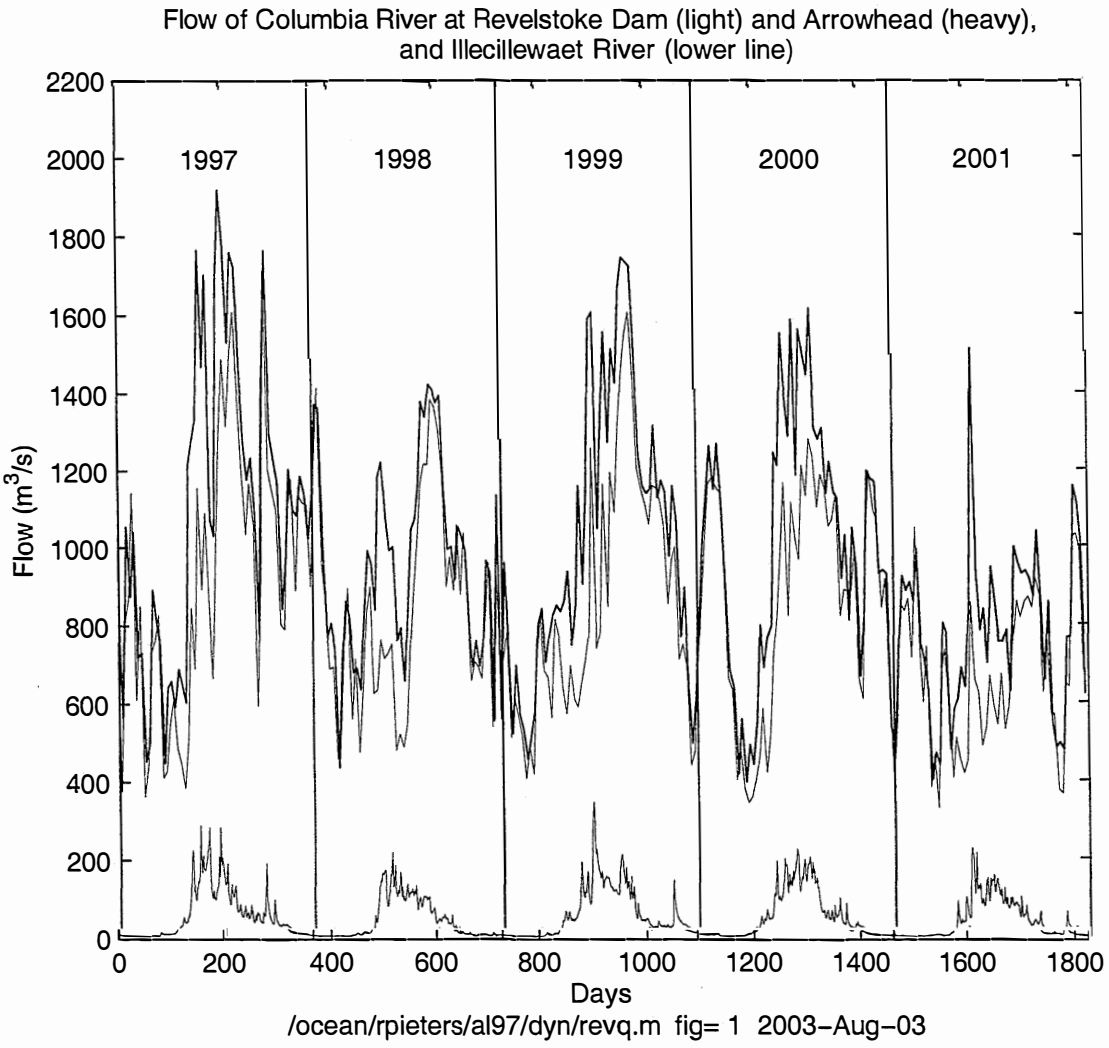


Figure 5.2 Flow of the Columbia River.

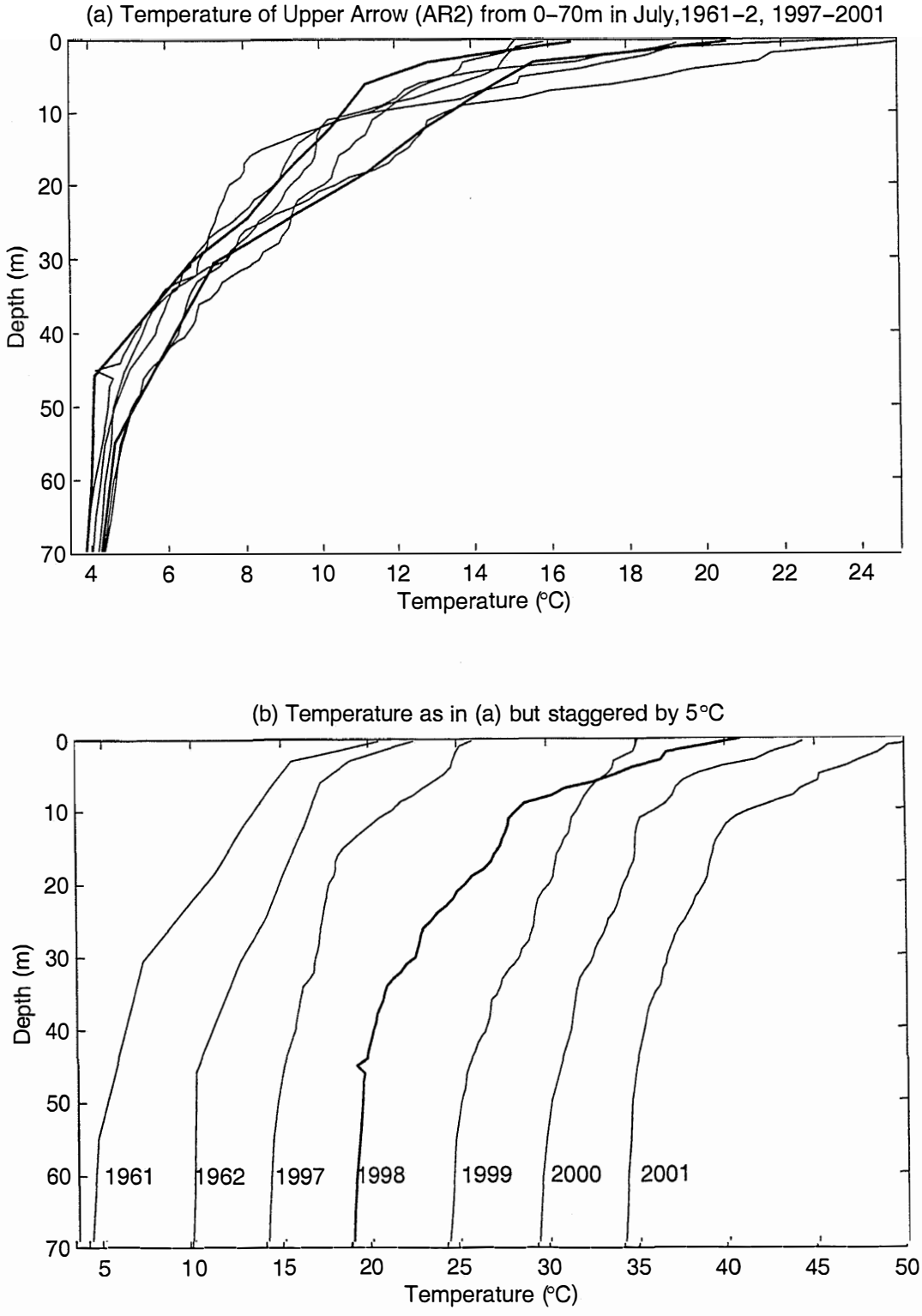


Figure 5.3 Temperature of Upper Arrow (AR2) from 0-70m in July 1961-62, 1997-2001.

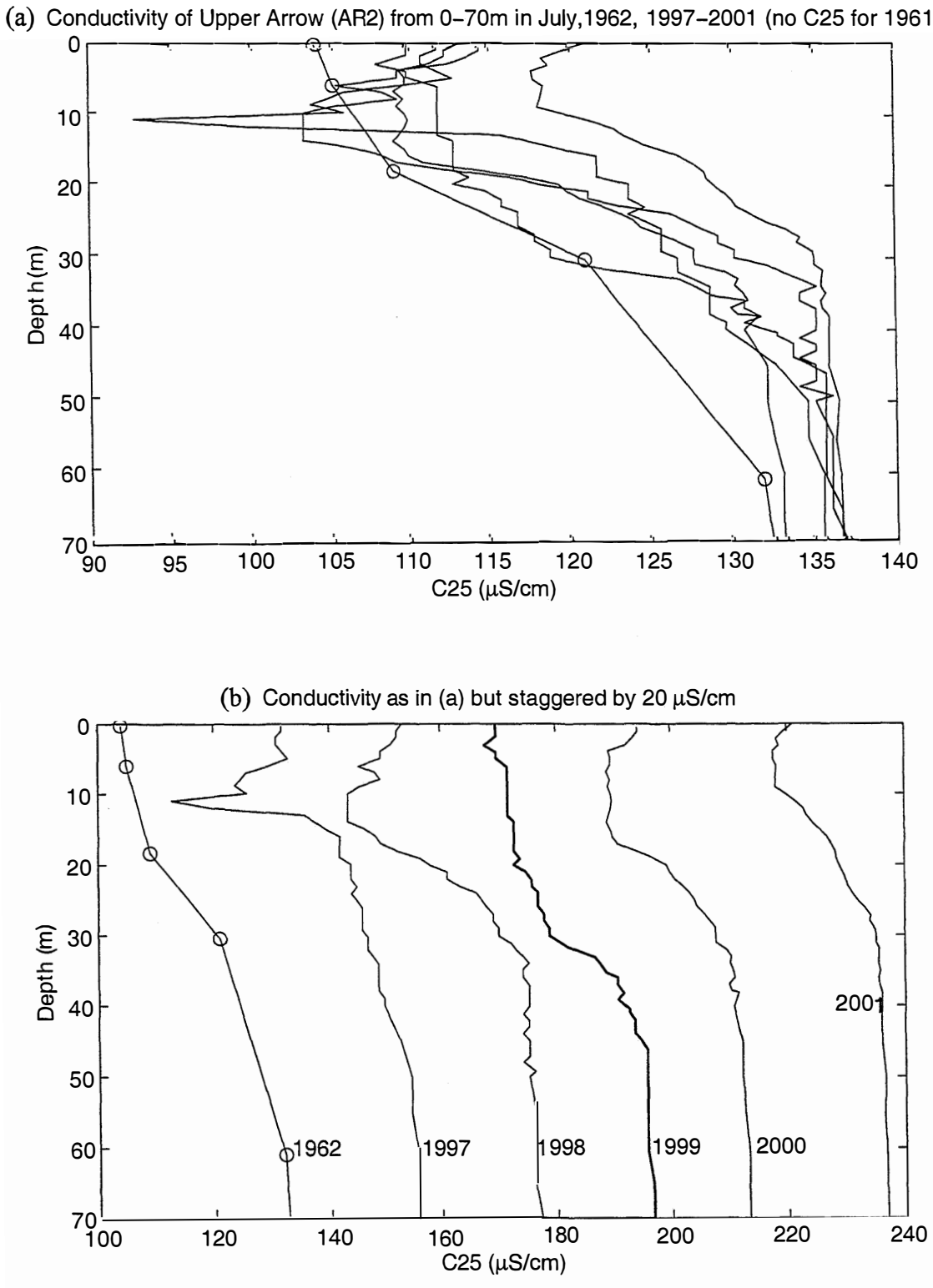


Figure 5.4 Conductivity of Upper Arrow (AR2) from 0-70m in July 1961-62, 1997-2001.

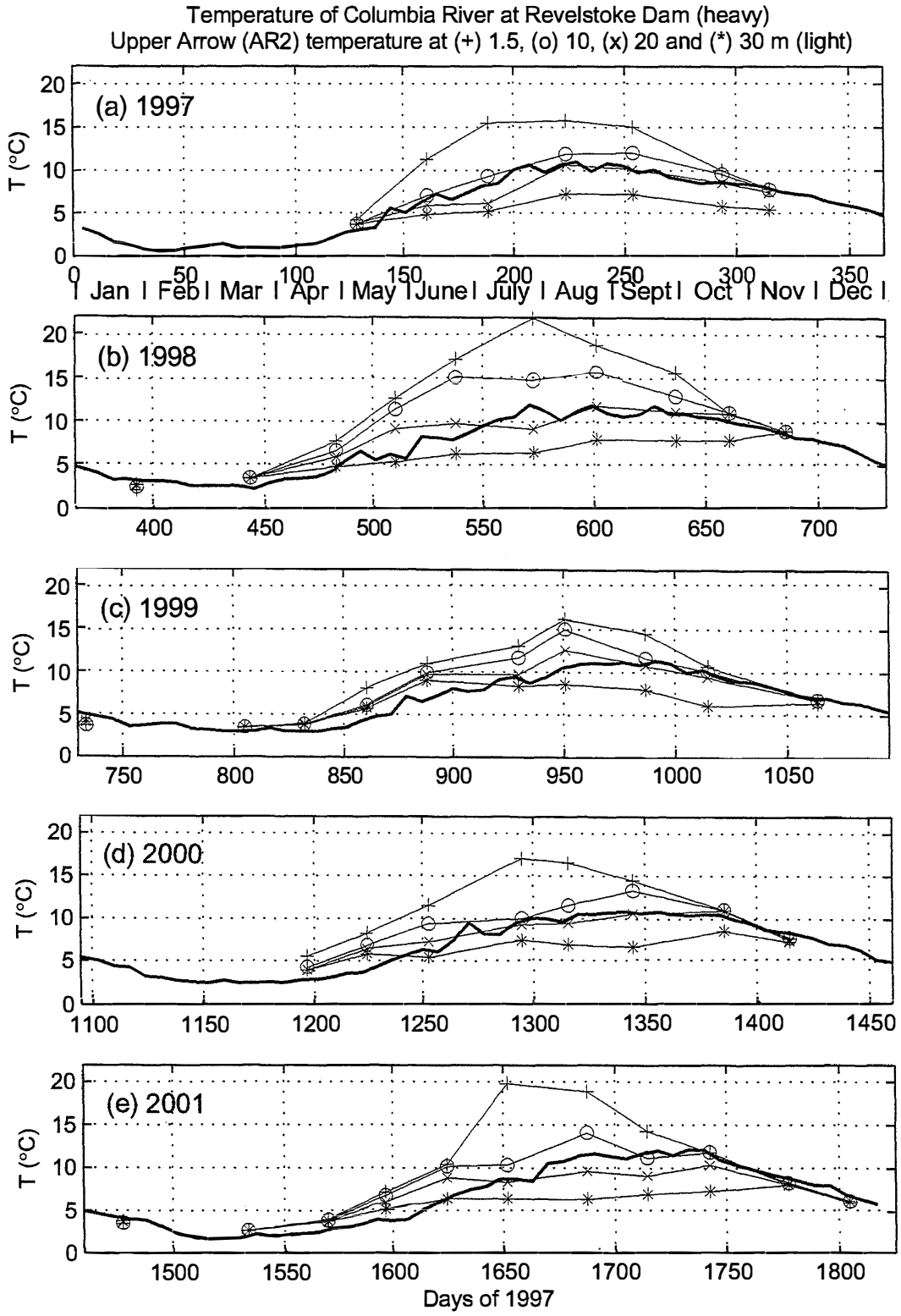


Figure 5.5 Temperature of the Columbia River relative to that in Upper Arrow (AR2), 1997-2001.

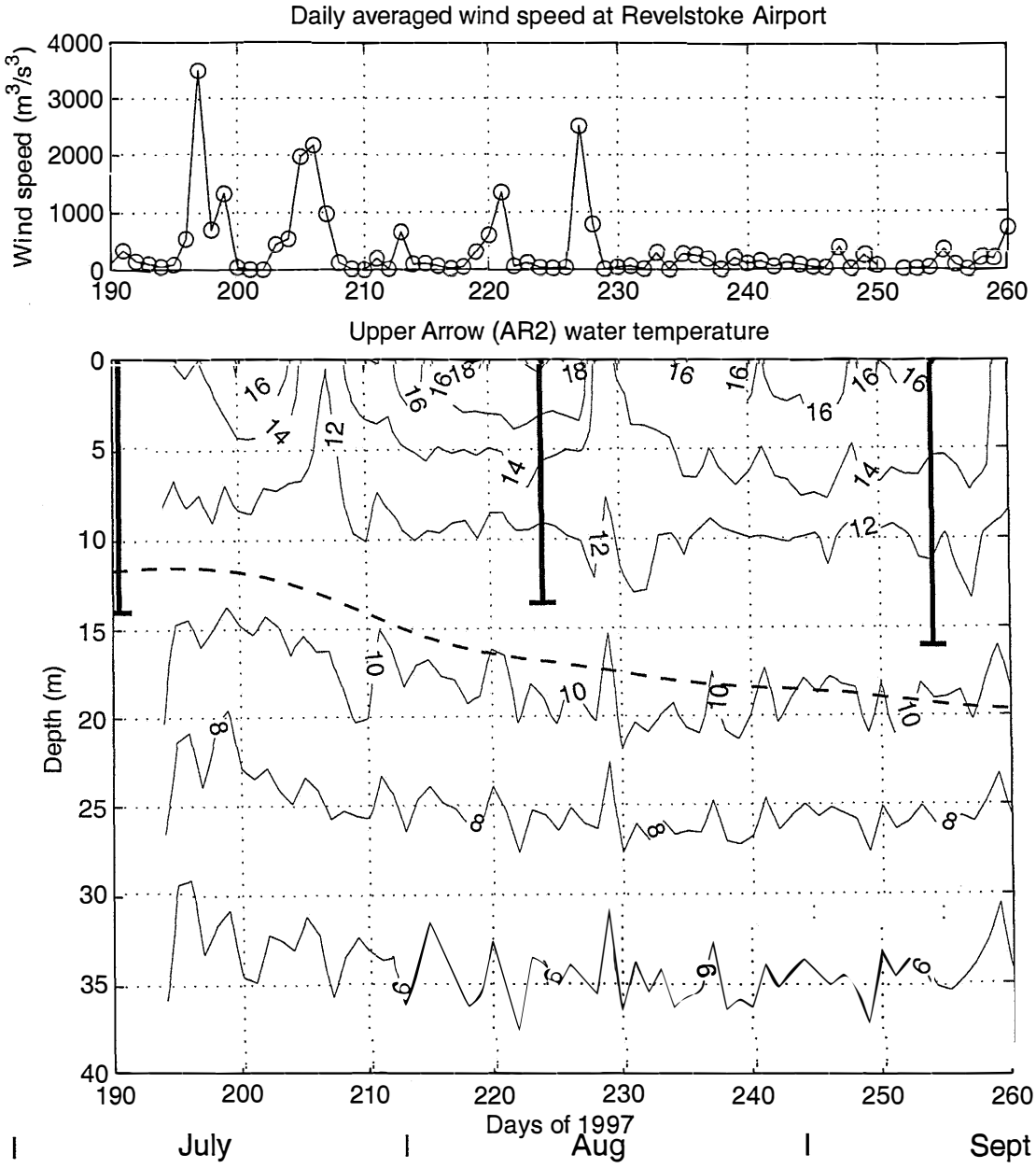


Figure 5.6 Wind and water temperature in Upper Arrow, summer 1997. Bars mark estimated depth of the 1% light level determined from Secchi disk data. Dashed line indicates the maximum plunge depth for the Columbia River, actual plunge will be shallower due to plunge mixing.

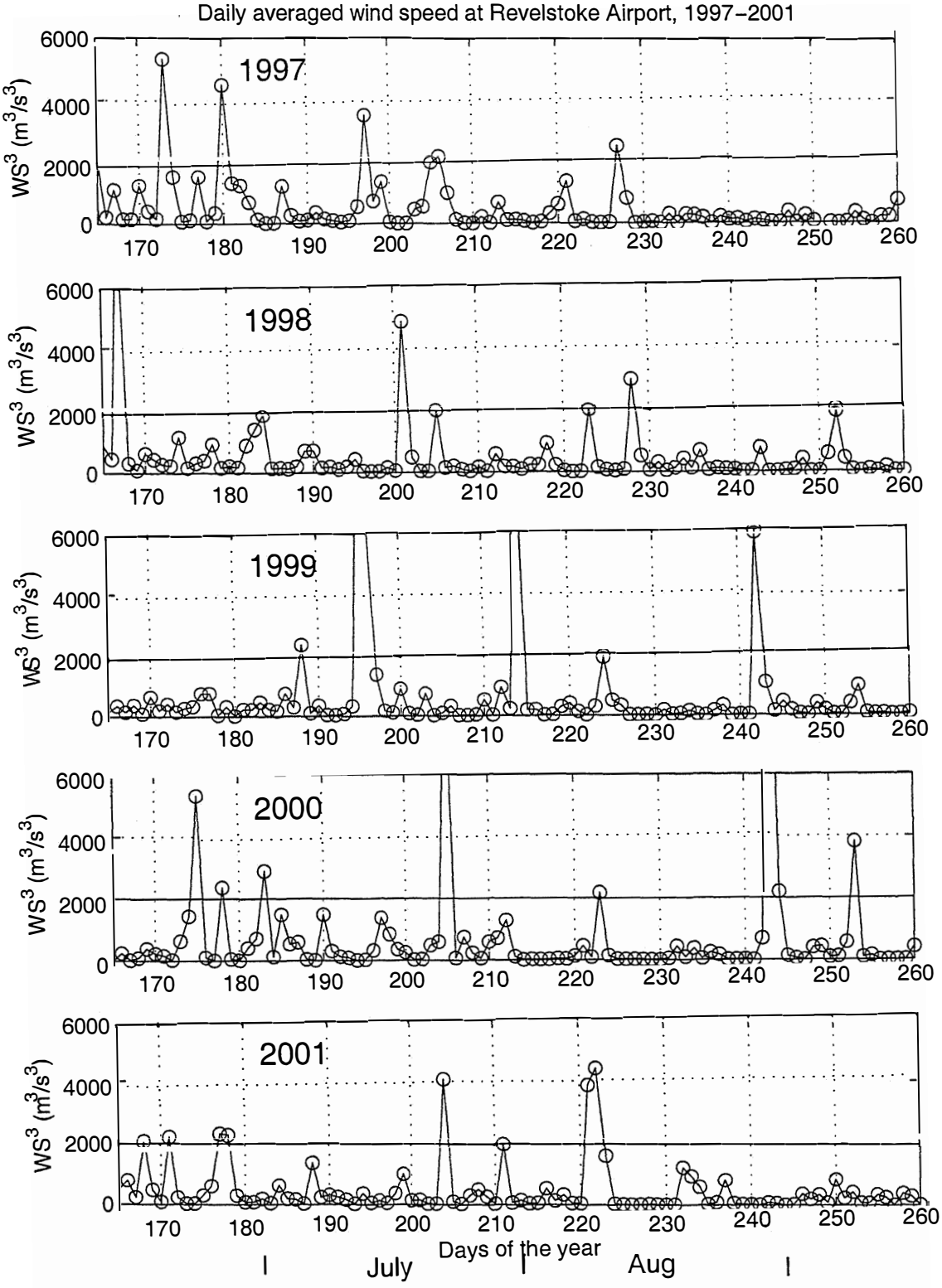


Figure 5.7 Wind during summer in 1997-2001.

6

Hydrolab and CTD Surveys

CHAPTER 6
HYDROLAB AND CTD SURVEYS

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6.1 Hydrolab Surveys

Methods

Hydrolab surveys were conducted in January and monthly from March to December, 2001. Vertical casts were taken at eight primary stations (AR1-8) and 4 secondary stations (HL1-4)[1]; see Figure 1.1. The Hydrolab (Surveyor III) measured depth, temperature, specific conductance, pH, dissolved oxygen, ORP or redox (oxidation-reduction potential) and turbidity. Casts were limited by cable length to 100 m depth. Measurement of temperature and conductivity below 100 m using a Seabird CTD is discussed in Section 6.2.

Stations HL1 and HL2 were inaccessible from the main lake from April to June due to very low water levels.

Calibration

The hydrolab was calibrated in April 1997, early April 1998, early May 1999 and early October, 1999.[2] Comparison of Hydrolab data from the field to water samples (Chapter 7) indicates that the Hydrolab was likely calibrated in February 2000.

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[1] The secondary stations (labeled 'HL') were renamed after July 1997. See Appendix 6.1 for detail.

[2] Hydrolab specifies the accuracy (resolution) for the Surveyor III as ±0.15 (0.01)°C for temperature, ±15 (1) µS/cm for specific conductivity within the 1500 µS/cm range, ± 0.2 (0.01) pH units for pH, ±0.2 (0.01) mg/l for dissolved oxygen [1 month], ±20 (1) mV for redox and ±0.3 m for the 0-100m depth sensor. Sensor stability is rated three years for temperature, six months for specific conductance and one month for all other sensors.

Temperature. The Hydrolab and Seabird were lashed together and cast at stations in the Arrow Lakes Reservoir (AR2 and AR4) in August 1999 and Slocan Lake (SL1) in November 2000. Comparison of temperature indicated that the Hydrolab was low by 0.25 ± 0.08 °C from 4-16 °C with no apparent trend. The hydrolab data shown here has been corrected by adding 0.25 °C.

Specific Conductance. The Hydrolab gives conductivity data converted to specific conductance (conductivity at 25 °C) using an equation for the temperature dependence of potassium chloride (with an internal instrument setting of 'fresh' rather than 'salt'). Hydrolab specific conductance was averaged from 0-20 m and 0-30 m and compared to the laboratory values (Chapter 7) of the integrated water samples from AR1-8 on the Arrow Lakes Reservoir and from SL1 on Slocan Lake. With the wider range of specific conductance data afforded by both Arrow and Slocan it is apparent that the Hydrolab values are low by 20%. The specific conductance shown is raw data multiplied by 1.2. The standard deviation of the difference between the lab and corrected hydrolab data was 5.7 µS/cm.

pH. As with conductivity, the pH of the hydrolab (pH_{HLAB}) was integrated from 0-20 m and 0-30 m and was compared to the pH of the 0-20 m and 0-30 m integrated water samples (pH_{PESC}) for Stations AR1-8 on the Arrow Lakes Reservoir and for Station SL1 on Slocan Lake. The mean monthly difference $<pH_{PESC} - pH_{HLAB}>$ was found to drift with jumps when the Hydrolab was calibrated. Differences varied from –0.2 to –0.9 pH units for 2000. These were larger than the hydrolab specified accuracy of ±0.2 pH units. The variation about the mean value for each sampling trip was on the order of ±0.2 pH units. The pH for 2000 was corrected by adding the mean value of the pH difference $<pH_{PESC} - pH_{HLAB}>$ for each monthly sampling trip to the Hydrolab data for that trip. However, as seen in the figures, calibration to the surface waters introduces some variation in the deep water pH which would generally be expected to vary little over the stratified period. The source of this variation in calibration between deep and surface waters is not known but suggests erroneous temperature or conductivity compensation. Note that the pH calibration stability for the Hydrolab is only rated as 1 month and that the accuracy of the standard pH probe is specified for water with specific conductance > 200 µS/cm.

Dissolved Oxygen. Oxygen sensors typically require calibration for each sampling trip. Calibration is done against in-situ bottle samples from which oxygen is determined by Winkler titration. This involved and time consuming process was beyond the scope of the present work. Raw data shown here provide a rough indication of oxygen levels as discussed below.

Redox. Oxidation-reduction potential, (ORP or redox) is the voltage measured between an inert platinum electrode and a reference electrode in ionic contact with the water. Values which are positive are associated with oxidising conditions, and negative values are associated with reducing (i.e. zero oxygen conditions). It is used primarily for determining the favoured oxidation state of chemical species (e.g. Fe and P) in low oxygen conditions (Wetzel 1975).

In well oxygenated waters, such as the Arrow Reservoir, the redox potential is expected to be +300 to +500 mV. The redox potential given by the Hydrolab was in the range of 60-140 mV in 2000 with the lowest values occurring near the surface in August. These values are typical of very low oxygen water (e.g. hydrogen sulphide is favoured over sulphate below +100mV). These low values are erroneous and likely result from a sensor or calibration problem. As redox is primarily of interest in low oxygen conditions not encountered in the Arrow Reservoir, it will not be discussed further.

Results

Contour Plots. Contour plots of temperature, specific conductance as a function of Julian day[3] are shown in Figure 6.1 and 6.2. The figures are arranged from north to south, namely HL1 (Beaton Arm), HL2 (old Columbia River inflow), AR1-4 (Upper Arrow), AR5 (Narrows) and HL3, AR6-8 and HL4 (Lower Arrow); see Figure 1.1. Contour plots of pH and dissolved oxygen are shown in Figure 6.2 and 6.3 for stations AR2 and AR7 only. A heavy solid line along the bottom of the contour plot indicates the bottom depth of the hydrolab casts. For stations whose water depth is less than 100 m, the maximum depth of a cast can vary substantially with slight variations from station position, as bottom bathymetry is typically steep.[4] For deep stations, cast depth may also be reduced by extreme weather conditions. All contours show the water surface as zero depth: variations in water level can also affect cast depth. Survey dates are marked by the cast file name[5] on the top of the contour plot. Any contour plot reflects a tradeoff between smoothing and accuracy. In order to represent accurately the data at the cast dates, no smoothing has been done to the contours shown. To facilitate comparison between stations, all plots are shown with the same depth, time and contour scales.

Temperature. Temperature is shown at all 12 stations in Figure 6.1a-l. The Upper Arrow basin (AR1-4) was nearly isothermal at 3-4 °C from 0-100 m in January to March 2001. A thermocline gradually developed over the summer between 0 and 40 m as the basin warmed. Maximum summer surface temperatures were as high as 25 °C, comparable to the peak temperatures of 26 °C seen in 1998, and significantly higher than the peak temperatures of 16-20 °C seen in 1997, 1999 and 2000. Temperatures at 60-100 m ranged from 4-5 °C throughout the summer and fall months similar to 1998, 1999 and 2000 but almost 1 °C higher than in 1997. The basin began to cool in September, with a deepening thermocline, but remained stratified into December. Temperature profiles in Beaton Arm (HL1) were similar, however the water at 100 m is a degree warmer while the base of the thermocline is roughly 10 m shallower (e.g. 7 °C contour).

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[3] Julian day defined such that noon, Jan 1st is day 1.5. Conversion between date and Julian day is given in Appendix 3.1.

[4] The small deep hole at HL4 is difficult to locate and contributes to the depth variation at that station.

[5] File name convention: e.g. ar211g97 is station AR2 at the 11th of auG, 1997. Months are indicated by the first unique letter in the name of each month, i.e.: Jan-J, Feb-F, March-M, April-A, maY-Y, jUne-U, juLy-L, auG-G, Sept-S, Oct-O, Nov-N and Dec-D.

Temperature isopleths at HL2 (old Columbia River inflow) were markedly different from the main basin conditions, and reflected the shallow riverine nature of this station (Figure 1.1). Data for April, May and June are missing because low water levels made it difficult to navigate to this location. Temperature profiles were near isothermal from surface to bottom (0-20 m) except in August when a 0-5 m layer of warmer (up to 22.5 °C) lake water lies over the river water flowing into the lake at depth.

Temperature profiles in the narrows (AR5) were more riverine in nature than the upper basin profiles with near isothermal conditions except in July, August and September when some stratification developed.

Temperature profiles in the Lower Arrow basin (HL3, AR6-8, HL4) were similar to the upper basin, except for the 5 °C isotherm which was slightly (10 m) deeper. Comparison of AR2 and AR7 indicate that during the stratified period the lower basin is a few degrees warmer than the upper basin in the top 20 m, especially in August when 18 °C water extended to 15m. Maximum summer surface temperatures were around 23 °C, similar to the highs of over 24 °C seen in 1998 but significantly higher that seen in 1997, 1999 and 2000. HL4 was similar to the stations in the main basin and did not exhibit a slightly broader thermocline which in 1997 and 1998 may have been related to the withdrawal from the Keenleyside Dam.

Specific Conductance. Conductivity corrected to 25 °C is shown for all 12 stations in Figure 6.2a-l. Specific conductance is a measure of the capacity for water to conduct an electrical current and is related to the total concentration of dissolved ionic matter in the water (Lind 1979).[6]

Specific conductance in the Upper Arrow basin (AR1-4) was unstratified at the start of the sampling period. Specific conductance became weakly stratified over the summer and surface values reached a seasonal minimum of just under 100 µS/cm in midsummer. Specific conductance then increased slightly during fall and remained weakly stratified.

Specific conductance in the near surface of Beaton Arm (HL1) was similar to Upper Arrow at the start of the sampling period and decreased to a slightly (10 µS/cm) lower value during midsummer.

Specific conductance isopleths at HL2 were quite different from the main basin conditions, reflecting the shallow riverine nature of this station (Columbia River inflow). Specific conductance was generally mixed from surface to bottom (0-20m) even during a period in August when temperatures suggest a 0-5 m surface layer of warm lake water. The seasonal trend was similar to the main basin with higher values in the spring decreasing to the lowest values in midsummer before increasing again in the fall. This variation is also reflected in the specific conductance of the Columbia River at Revelstoke (Appendix 8.2).

[6] Specific conductance refers to the conductivity of the sample as it would be at a specific temperature, in this case 25 °C. All values discussed are converted to specific conductance.

Specific conductance profiles in the narrows (AR5) were more riverine than the lake profiles. The profiles in 2001 were similar to those in 1999 when almost no conductivity stratification developed during summer, in contrast to those in 1997, 1998 and 2000 when significant stratification occurred. Generally, at AR5, stratification in specific conductance taks longer to develop and is weaker than in the main basins.

Conductance profiles in the Lower Arrow basin (HL3, AR6-8, HL4) were similar to the upper basin with similar vertical and seasonal trends of smaller amplitude. In 2001, stratification in conductivity took longer to develop. In 2001, stratification at HL4 was almost absent.

Occasional values of very low specific conductance (2 to 30 µS/cm) were recorded at the shallowest measured depth (0.1 to 0.3 m) throughout the year. These low values result in bunched contour lines on the respective figures. In all cases, the conductivity returns to 100 to 150 µS/cm for the second reading of the cast around 1.0 m. For the most part, readings from the other sensors seem reasonable. Bubbles may have been present on the conductivity sensor at the start of the cast.

pH. The pH is shown for Beaton Arm (HL1) and representative Upper Arrow (AR2) and Lower Arrow (AR7) stations, Figure 6.3a-c. As noted from the water samples in Section 7.4, the pH in Arrow Reservoir is weakly alkaline. Here the absolute value of pH shows minimal vertical and seasonal stratification at all stations.

Dissolved Oxygen. Dissolved oxygen is shown for Beaton Arm (HL1) and representative Upper Arrow (AR2) and Lower Arrow (AR7) stations, Figure 6.4a-c. Raw dissolved oxygen concentrations in Arrow Lake Reservoir were uniformly high and exhibited minimal vertical stratification and seasonal variation at all stations. This indicates that the Arrow Reservoir is well oxygenated throughout, consistent with an oligotrophic system. Reduced concentrations near the surface in summer are a result of lower oxygen solubility with increased water temperature.

6.2 CTD Surveys

Methods

In order to measure water temperature and conductivity below 100 m a Seabird Electronics SBE-19 internally recording CTD profiler[7] was used at Stations AR1-8 and Beaton Arm (HL1) monthly from January to December, 2001. Seabird data was not collected on Beaton Arm in April, May and June due to low water levels and in December, likely as a result of weather conditions. In addition, data is missing from Lower Arrow in October.

The Seabird CTD was fitted with a pump (SBE 5T) to flush the conductivity cell and allow a slower cast rate needed to resolve near surface features. The conductivity cell and associated electronics are designed so that the zero conductivity of a dry cell results in a stable and low noise raw reading. As a result the Seabird is suitable for low conductivity applications such as found in Arrow Reservoir. In addition, the SBE-19 was fitted with a fluorometer and transmissometer.

Another feature of the Seabird is ease of use: a sliding magnet on the outside closes a reed switch inside the housing which starts the Seabird and opens a new file in memory. The switch is slid the other way to end the cast. As a result multiple casts can be done without access to a computer.

The Seabird was deployed upside down to prevent breakage of the glass conductivity cell near the bottom. Underneath the Seabird was a 10kg weight on approximately 1 m of line. The cast was stopped when the cannonball touched bottom but, for the most part, before the Seabird would touch bottom. Under extreme weather conditions the cast depth may have been reduced. Down and up cast rates were about 0.5 m/s. The data collection rate was 2 Hz. Data shown (Figure 6.5) are from both the upcast and downcast (downcast given for reference). No adjustments have been made for pump path: the fluorometer is ≈1.5s behind, as a result fluoresence features appear 0.75 m shallower than true depth on the upcast. The transmissometer is lashed to the side of the SBE-19 and transmissometer features would appear ~0.5m shallower on the upcast.

Conductivity was converted to specific conductance (conductivity at 25 °C) using an equation described in Chapter 5 of Pieters et al. (1999). Salinity was computed using the following: S [PSU]=0.75 * C25 [µS/cm] / 1000 (Pieters et al. 1999). Equivalent density at the surface (pressure set to zero) was computed from temperature and salinity using Chen and Millero (1986). This neglects pressure effects which may come into play below ~150 m.

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[7] Seabird Electronics specifies the resolution (and accuracy) of the SBE-19 as 0.001 °C (0.01 °C/6 months) for temperature, 0.15 µS/cm (1 µS/cm/month) for conductivity in the low conductivity range and 0.1 m (1.7m) for the 1000 psia (680m) pressure sensor.

Calibration

Temperature. The SBE-19 temperature was factory calibrated in April, 1998 and was good to ±0.002 °C. Subsequent checks and calibrations were done in a 200 liter insulated plastic tank, with vigorous stirring by a 5 cm diameter plastic propeller. The temperature sensor was checked in October 1998, September 1999 and April 2000 against a Guildline 9540 Digital Platinum Resistance Thermometer (T_G). The Guildline was considered to have an accuracy of at least 0.02 °C, as described in Pieters et al (1998). In these checks, the temperature difference (T_G-T_{SBE}) was found to be within –0.002 to 0.007 °C and as a result the Seabird was confirmed to be accurate to about 0.03 °C. In 2001 the SBE-19 was checked against a factory calibrated Seabird SBE-38 thermometer (SN 0106, with accuracy 0.001 °C and resolution 0.0001 °C). The Seabird was found to agree within 0.004 °C. The Seabird data is shown without adjustment.

Conductivity. The conductivity sensor was calibrated using dilute solutions of potassium chloride and a WTW LF340 conductivity meter which indicates that the conductivity of the Seabird has remained within a few µS/cm from October 1998 to April 6, 2000. The Seabird data was converted to C25 and compared to the C25 from both the integrated and discrete laboratory[5] samples for both the Arrow Reservoir and Slocan Lake. While considerable scatter results from comparison of field data, the Seabird data was on average 2.4 ± 2 µS/cm lower than the laboratory samples. Seabird data is shown without adjustment.

Fluorometer. A fluorometer is used to measure the fluorescence of the chlorophyll *a* pigment of phytoplankton. The instrument emits a blue light (460 nm). Chlorophyll *a* pigment absorbs the blue light and re-emits the energy as red light (685 nm). The instrument detects this red light. The fluorometer was not calibrated for the phytoplankton of Arrow Reservoir but does give an indication of relative abundance.

Different species of phytoplankton have different chlorophyll *a* response and the fluorometer should be calibrated to in situ chlorophyll *a* measurements. The factory calibration used here is based on the response of the instrument to the fluorescent compound coproporphyrin methyl ester and assumes that 0.5 mg/l of this compound corresponds to 50 µg/l of chlorophyll *a*. This assumption is reflected in the units which are marked in the figures as 'copro µg/l'.

Trasmissometer. The transmissometer measures the transmission of 660 nm (red) light through a 25 cm path. The source is modulated at 1 KHz to improve rejection of ambient light. Losses result primarily from scattering and absorption. 100% transmission is that for pure water. The transmissometer provides a measure of the concentration of material in the water and of water clarity. Drift in the transmissometer is tracked by checking the transmission through air after careful cleaning of the transmissometer windows. This varied by at most 1.5% over the study period. The transmissometer is particularly sensitive to moisture inside the instrument which can condense on the windows in cold water. Unfortunately these droplets, which may not be visible to the eye, result in a

dramatic but erroneous reduction of light transmission (e.g. Figure 6.5n). The manufacturer has improved its drying of the transmissometer (evacuating and filling with dry gas).

Results

Temperature and conductivity are shown in Figure 6.5 for station AR2 in Upper Arrow and for station AR7 in Lower Arrow for January to December 2001[8].

Consider Figure 6.5g for AR2 in July 2001. Throughout the figure, the heavy lines mark the upcasts and light lines mark the downcasts. The **upper plot** shows temperature, specific conductance (C25), fluorescence (F copro µg/L), percent transmission and density through the water column. The depth is given on two scales: an expanded scale shows variations over 0-50 m and a compressed scale shows from 50 m to the bottom. In the temperature panels, straight lines near 4 °C show the temperature of maximum density (TMD) as calculated from Chen and Millero (1986) for a salinity of 0 and 0.1 PSU.[9] The **middle panels** give property-property plots (provided for reference) and the **lower plot** gives temperature and specific conductance below 50 m on an expanded scale (temperature is marked with T and specific conductance is unmarked).

In January 2001 both the upper and lower basins show little sign of the residual stratification as observed in 1999 and 2000. This indicates that water has penetrated to the bottom (as confirmed by a drop in deep conductivity and rise in temperature, Figure 6.6). The temperature is very close to the temperature of maximum density and stability remains slightly salt stratified. In February and March both basins show slight reverse stratification with temperatures slightly less than 4 °C in the top 50 m. Between March and April water penetrated to the bottom in both basins as indicated by the jump in conductivity and temperature (Figure 6.6) which is the largest observed in the 3 year record of SBE-19 data. April surface waters remained comparatively cold, near 4 °C in Lower Arrow on April 10 and slightly above 4 °C in Upper Arrow on April 18.

By May the surface water temperatures are higher than the 4 °C, particularly in Lower Arrow and summer stratification begins. Surface temperatures peak in July just above 20 °C. In August, sections of uniform temperature in the top 15 m in Lower Arrow gives evidence of recent wind mixing. In fall a mixed surface layer develops and deepens as surface waters cool. In Upper Arrow through October, November and December, surface mixed layer temperatures cool to 12, 5 and 5.5 °C as the surface layer is mixed down to 12, 30 and 50 m, respectively. In December, temperature and conductivity remain slightly stratified to 50 m in both basins.

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[8] The file names at the top of each plot give the date for each cast: see footnote 5 for filename convention.

[9] Conductivity in the water column varies from 100 to 150 uS/cm at 25C (Appendix 7.3). This corresponds to a salinity range of 0.075 to 0.112 g/kg; see also Appendix 5.1, Pieters et al. (1999).

During summer the deep waters of both the Upper and Lower Arrow show temperatures that vary around the temperature of maximum density (TMD). Conductivity increases steadily into the deep waters indicating salinity stratification.

Fluorescence. Fluorescence is a process by which light of one wavelength is absorbed by chlorophyll *a* and re-emitted as light at another wavelength. The emitted light is then detected, and the signal strength is proportional to the concentration of chlorophyll *a* present in the sample.

In Upper Arrow a clear peak in fluorescence is first seen in June. The peak occurs around 10 m, is largest in July and August, corresponding to high rates of primary production and high chlorophyll *a* (Chapter 15). Upper Arrow remained relatively stratified in September (in contrast to Lower Arrow) with a large peak in fluorescence. This is decreased in October as the surface layer begins to mix down.

In Lower Arrow a broad peak in fluorescence occurs in May, a month earlier than on Upper Arrow. The May peak is relatively deep, from 10-18 m. From June to July a shallower peak is seen, around 10 m, and is generally less that that observed in Upper Arrow. In September, uniform temperature and conductivity to 20 m indicate a recent mixing event. While this increases the nutrients available, the phytoplankton are also mixed deeper where they can experience light limitation. However, in this case the Secchi depth of 8m suggests the photic zone extends to about 16 m. Data for Lower Arrow is not available for October, and by November, the surface layer is mixed to 30 m.

When the surface layer is mixed in the fall, the temperature and conductivity are typically uniform from the surface to the bottom of the mixed layer. However, the fluorescence is not as uniform and can be slightly higher below the surface suggesting, in that case, phytoplankton growth since the last mixing event. Fluorescence levels decrease through the fall of 2001 as the surface mixed layer deepens.

Transmissivity. The transmissometer shines a beam through a 25 cm path in the water and the fraction of the beam detected determines the % transmission. The relatively long path length is ideal for identifying water masses in very clear lakes such as the Arrow Reservoir.

In July and August, when the transmission data on the down cast differs significantly from that on the upcast, the data is erroneous as it is affected by moisture condensation on the interior of the instrument windows. If the instrument touches bottom (e.g. AR7 in March 2001) the transmissivity also drops (and fluorescence at times rises).

Transmissivity values are high, generally above 90%. In the deep water, transmissivity is particularly high generally above 95%. Transmission in the surface waters decreases both due to stream and river inflow during freshet and phytoplankton growth. An example would be AR7 in June when the peak in fluorescence occurs with a marked reduction in transmission.

Acknowledgements

Many thanks to Mark Young of Kootenay Wildlife Services for tireless deployment of these instruments and for extra Seabird casts (February and December) done during mysid sampling.

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Pieters, R., L.C. Thompson, L. Vidmanic, M. Roushorne, J. Stockner, K. Hall, M. Young, S. Pond, M. Derham, K. Ashley, B. Lindsay, G. Lawrence, D. Sebastian, G. Scholten, F. McLaughlin, A. Wüest, A. Matzinger and E. Carmack. 1999. Arrow Reservoir limnology and trophic status report, year 2 (1998/99). RD 72, Fisheries Branch, Ministry of Environment, Lands and Parks, Province of British Columbia.

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APPENDIX 6.1
NAMING OF HYDROLAB SECONDARY STATIONS (HL1-4)

At the four secondary stations (HL 1-4) only hydrolab data is collected. These stations are shown in Table A6.1.

Table A6.1 Hydrolab stations.

Station Name: (as used in all reports and in data after July, 1997)	Location (See Figure 1.1.)	Previous Station Name: (before Aug, 1997)
HL 1*	Beaton Arm	HL 1
HL 2	Near Arrowhead	HL 2
HL 3	Between Fauquier and Edgewood	HL 4
HL 4	~ 2 km downstream of Syringa Creek, at the small 59 m hole (see Chart 3056).	HL 5

The original field plans, early versions of Figure 1.1, and hydrolab data collected from May-July, 1997 reflected *five* secondary stations HL1-5, with an additional station (old HL3) near AR5 in the narrows. (No data were collected at the narrows secondary station, old HL3). After July 1997 the secondary stations were renamed to reflect the usage of Table A6.1

* For Seabird data, the Beaton Arm casts are labelled ARB which is the same as HL1.

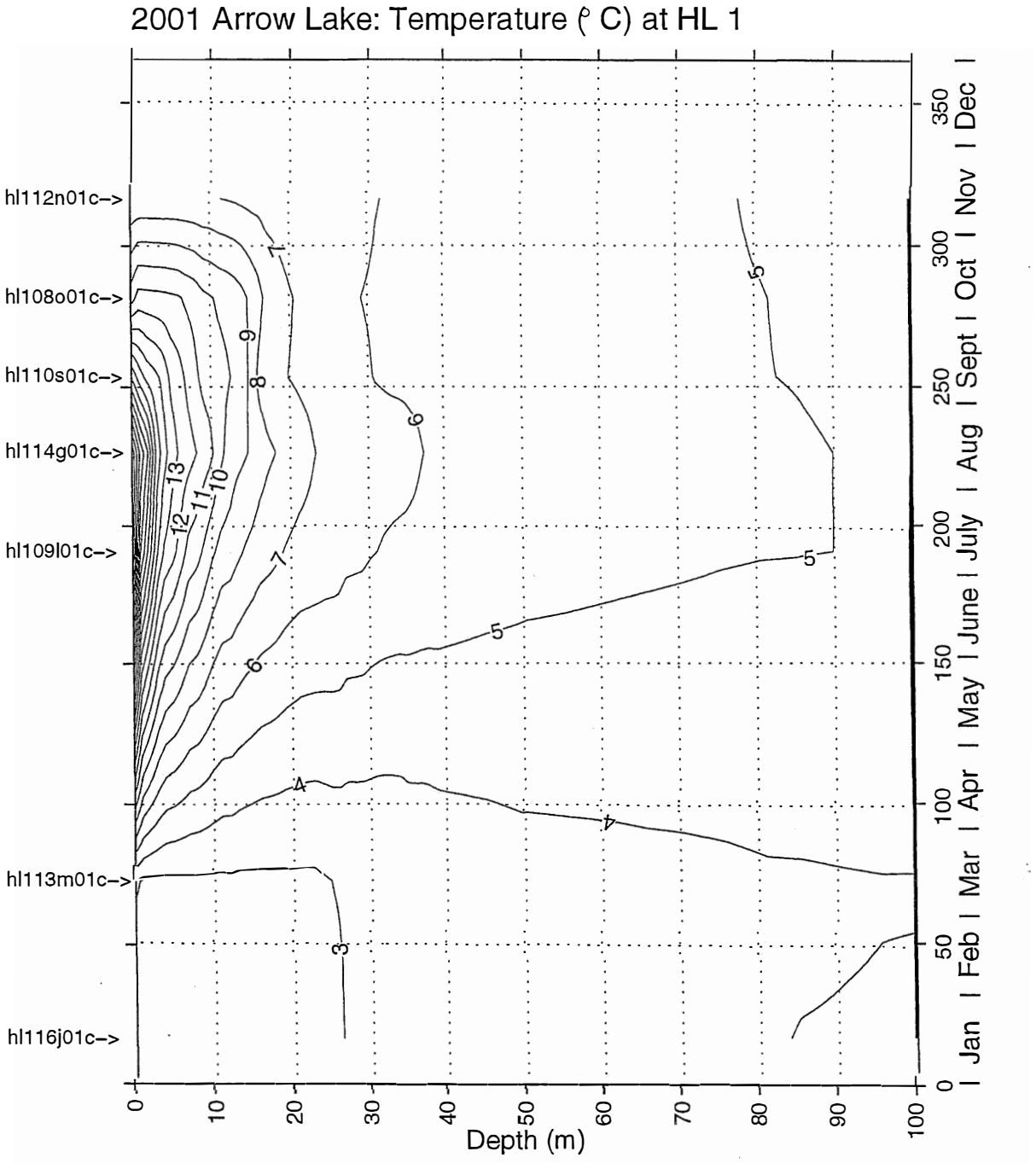


Figure 6.1a 2001 Hydrolab temperature contours at station **HL1**. Interpolation for missing April, May and June data is not accurate, c.f. AR2. Surface temperature 25.2 and 23.6 °C in July and August, respectively.

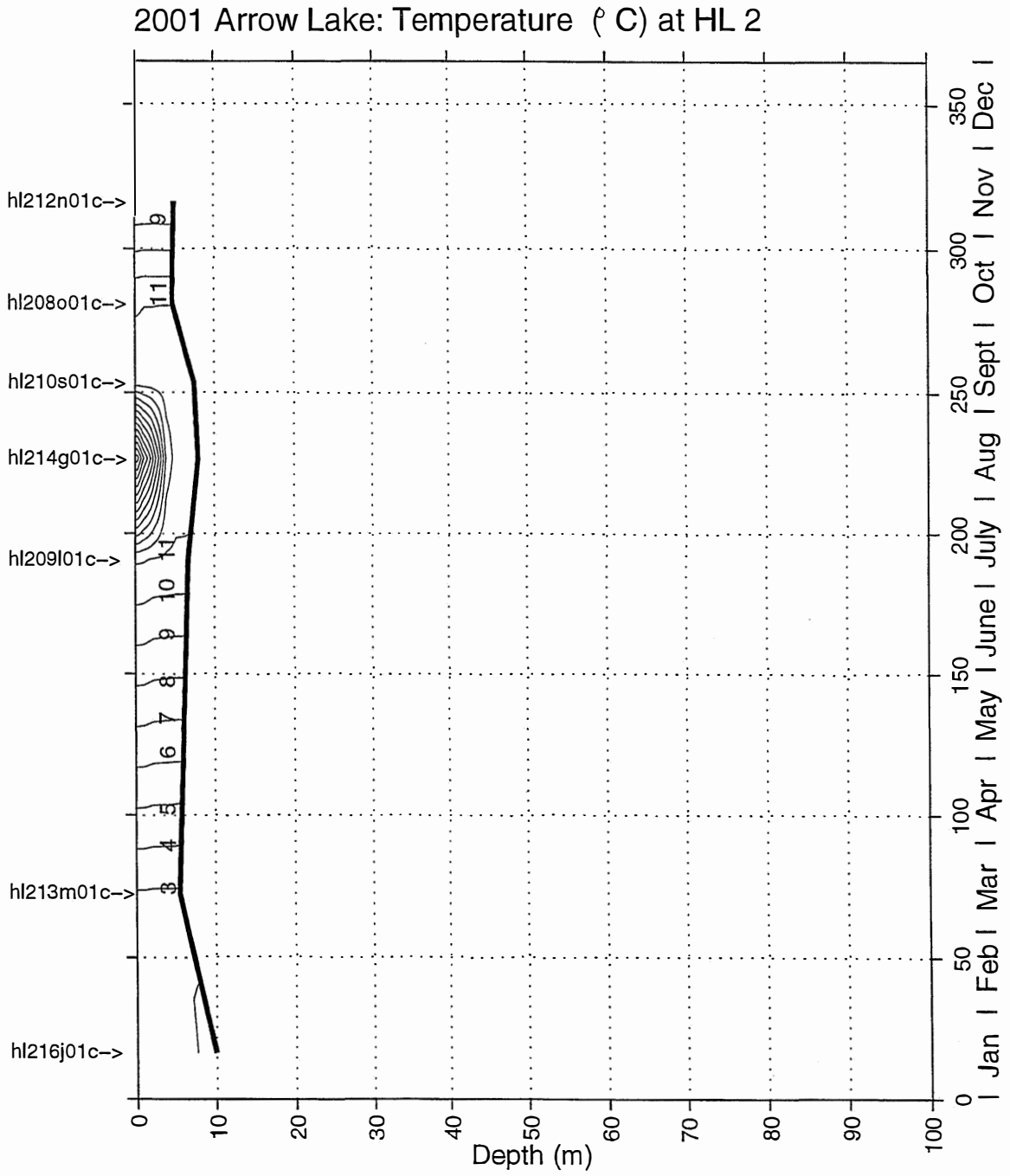


Figure 6.1b 2001 Hydrolab temperature contours at station **HL2**. . Interpolation for missing April, May and June data is not likely accurate. Surface temperature 22.5 °C in August when warm lake water likely present near the surface.

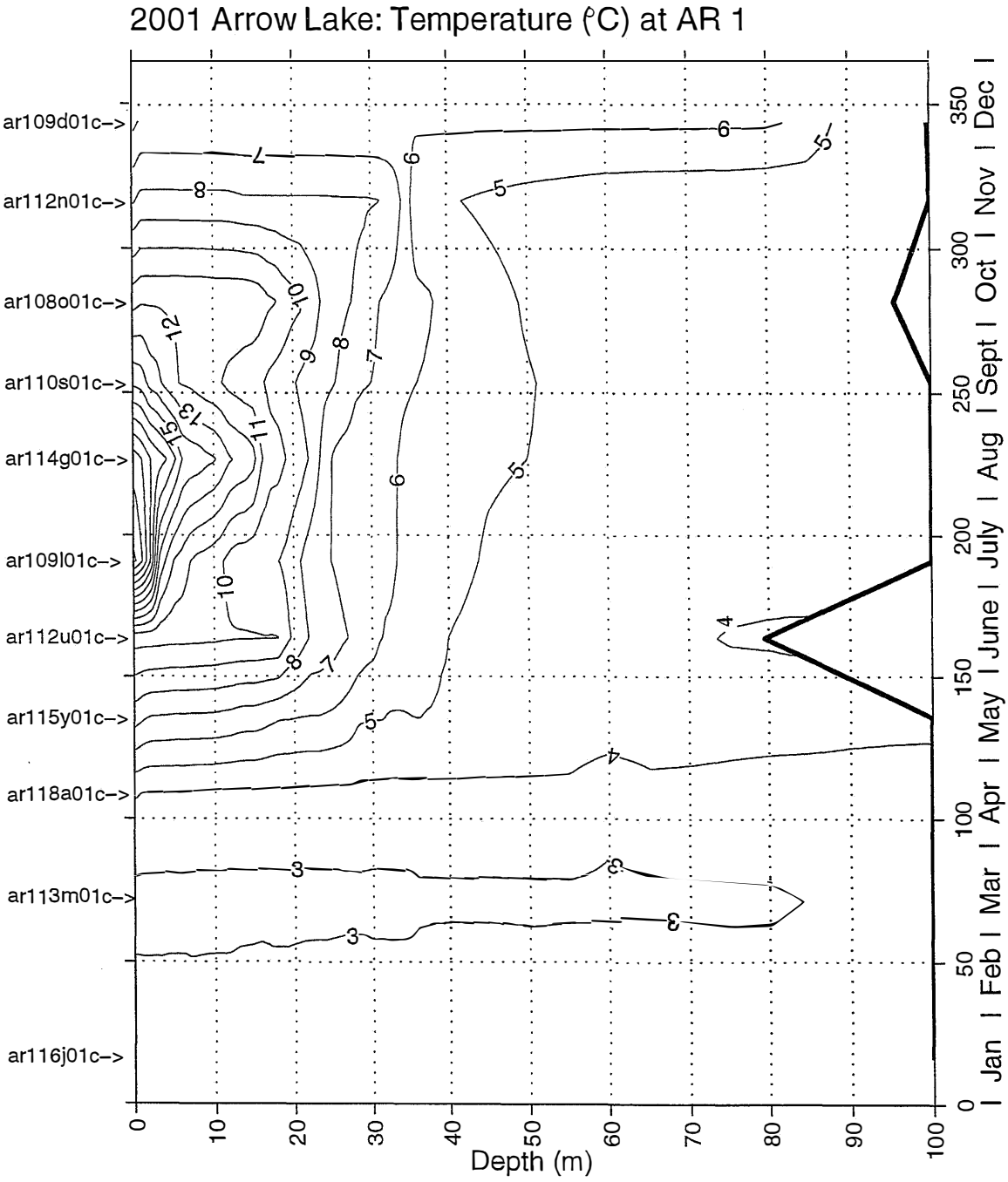


Figure 6.1c 2001 Hydrolab temperature contours at station **AR1**. Surface temperature 21.2 and 19.5 °C in July and August, respectively.

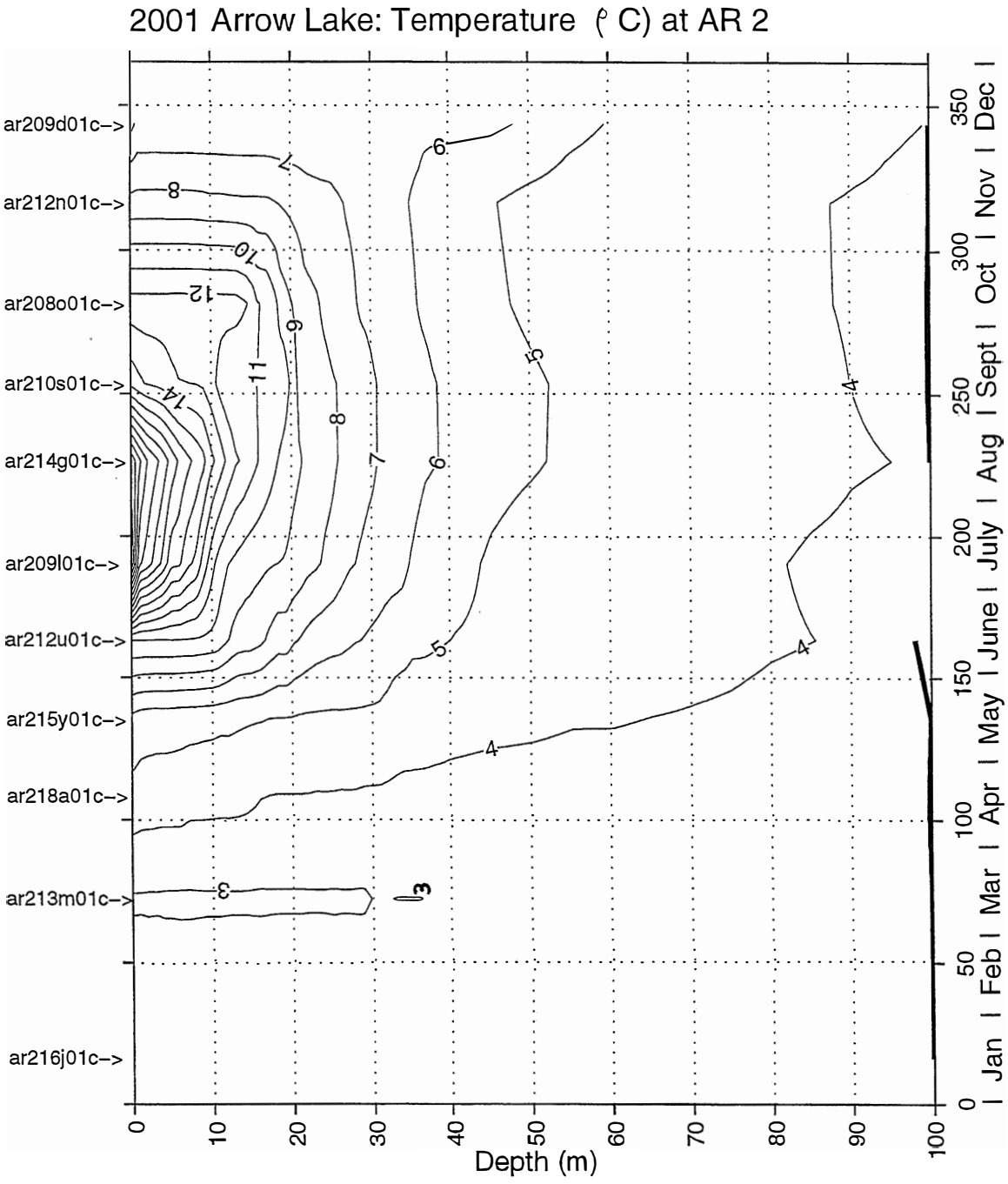


Figure 6.1d 2001 Hydrolab temperature contours at station **AR2**. Surface temperature 24.2 and 22.7 °C in July and August, respectively.

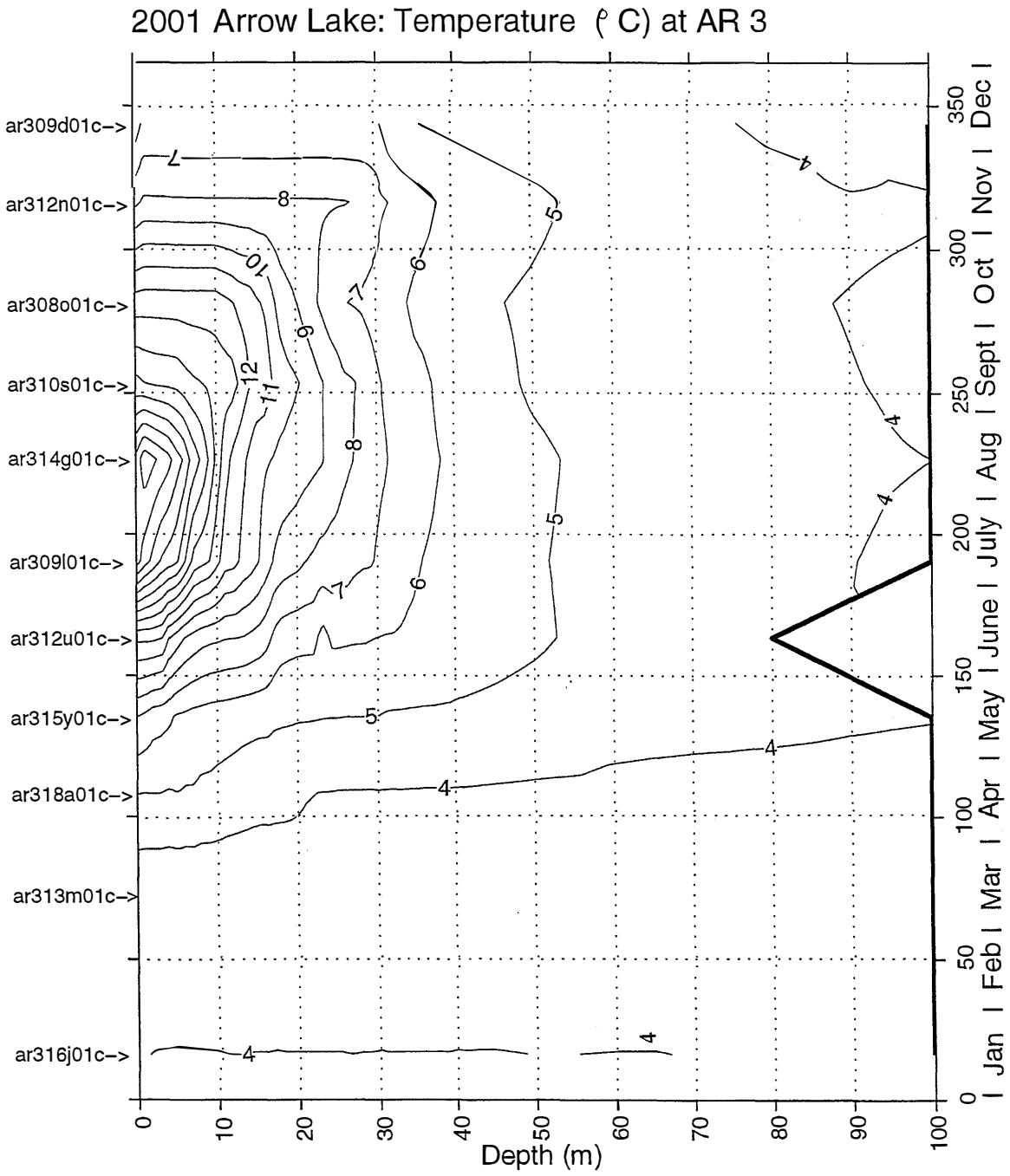


Figure 6.1e 2001 Hydrolab temperature contours at station **AR3.** Surface temperature 19.5, 20.7 and 15.3 °C in July, August and September, respectively. The temperature inversion above 1.1 m in August is likely the result of instrument not being at equilibrium when the 0 m reading was taken.

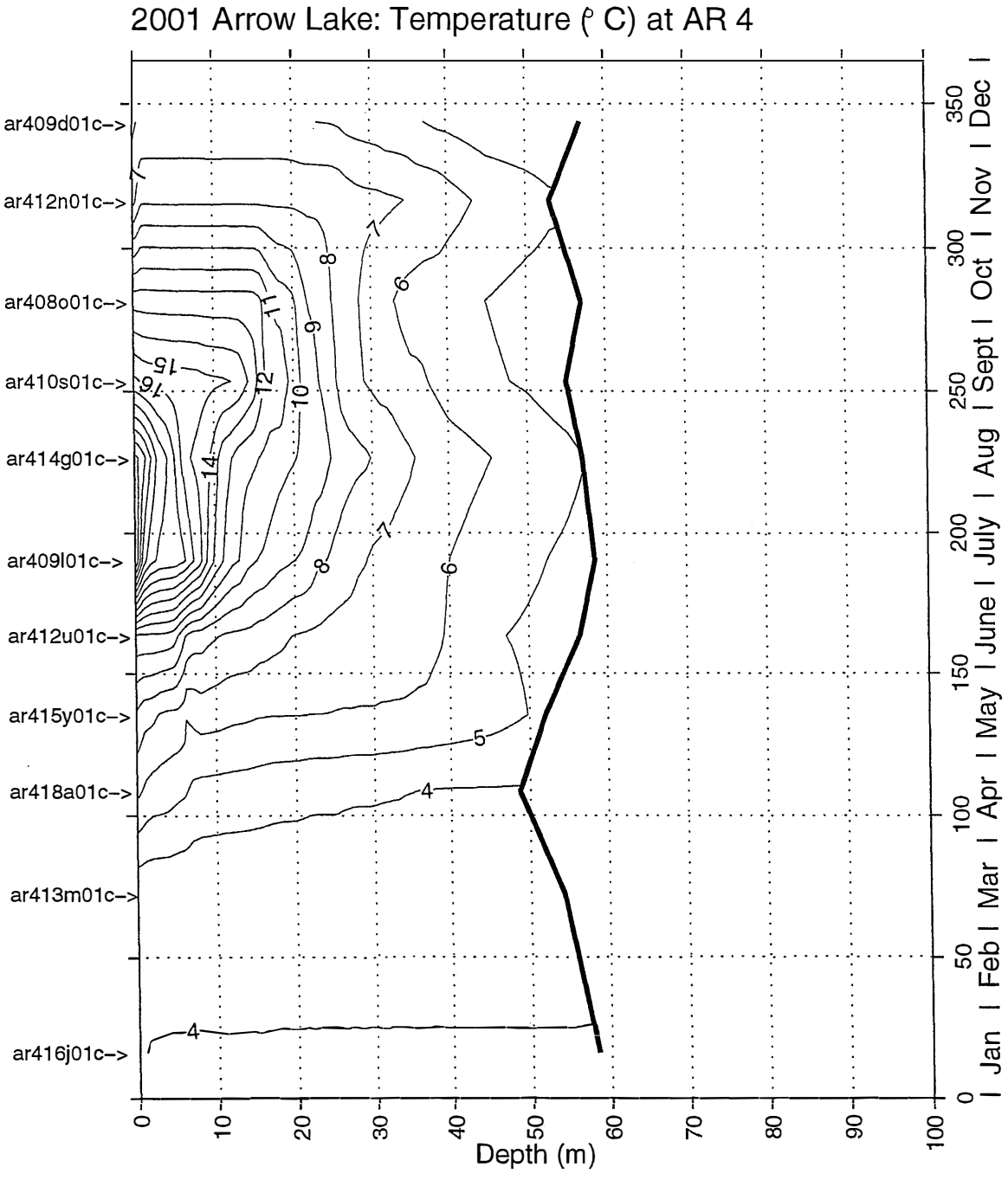


Figure 6.1f 2001 Hydrolab temperature contours at station **AR4**. Surface temperature 23.1, 22.2 and 16.3 °C in July, August and September, respectively.

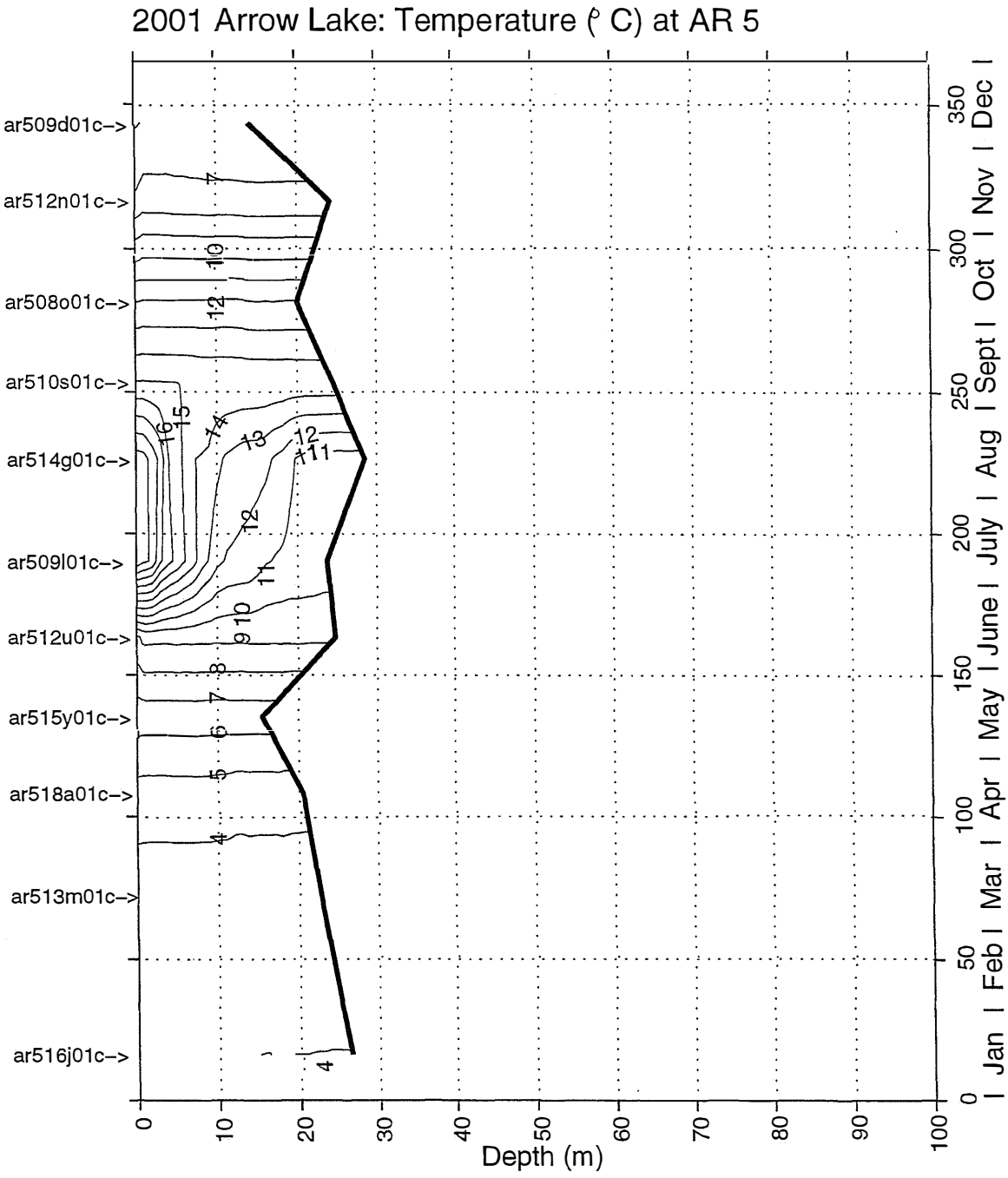


Figure 6.1g 2001 Hydrolab temperature contours at station **AR5**, Narrows. Surface temperature 19.8 and 19.5 °C in July and August, respectively.

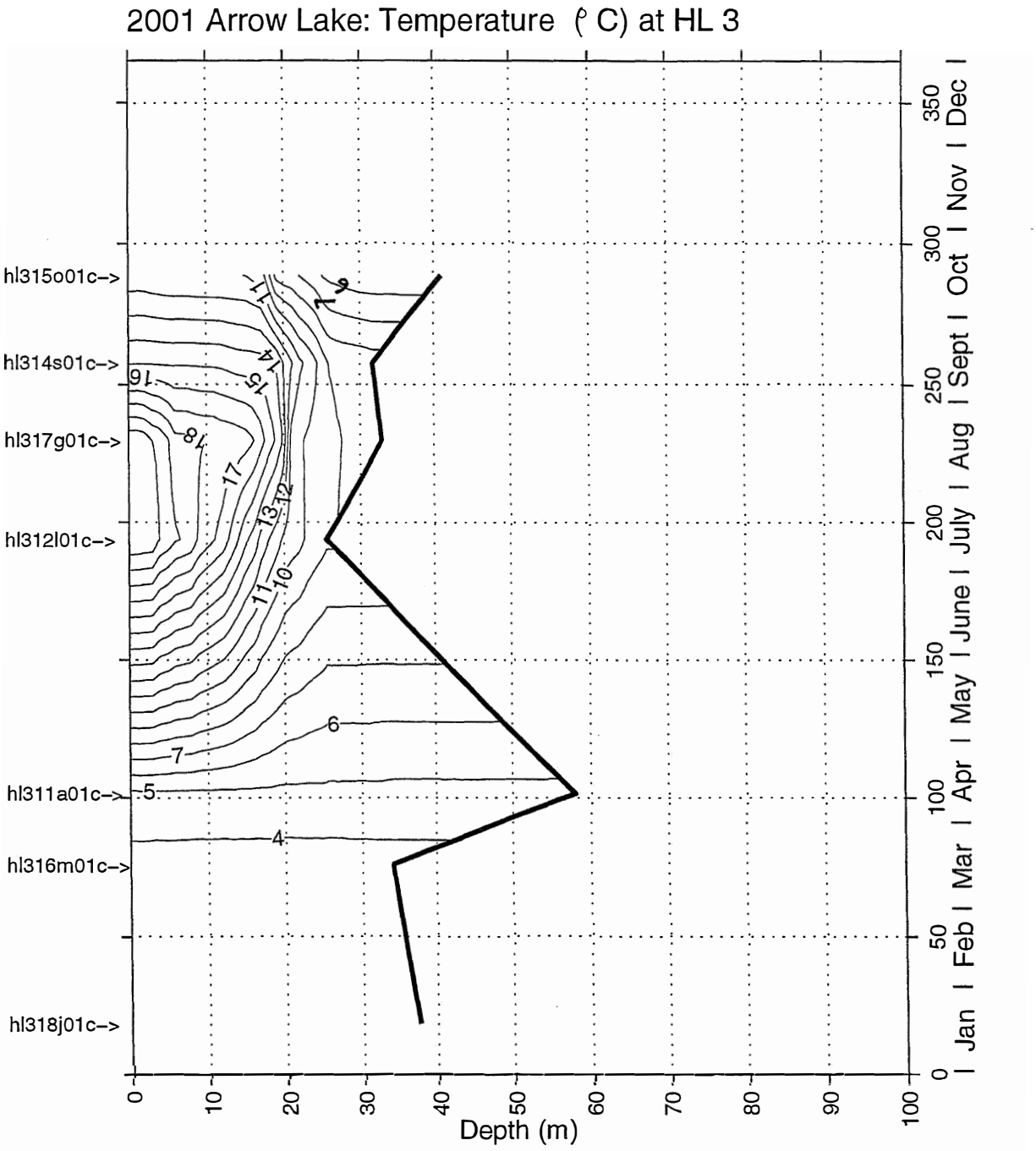


Figure 6.1h 2001 Hydrolab temperature contours at station **HL3**. Surface temperature 20.9 and 20.8 °C in July and August, respectively. Note May and June data missing.

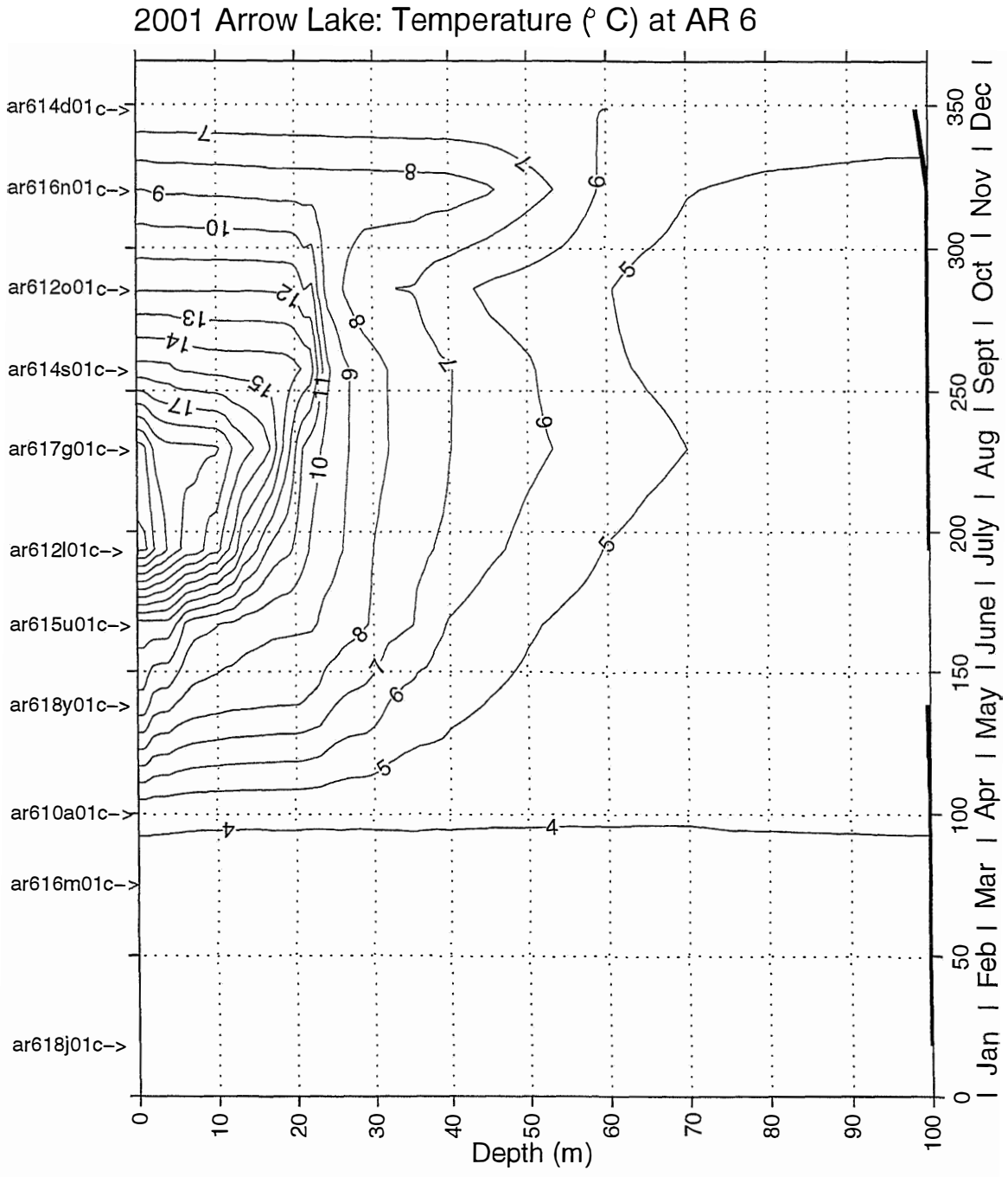


Figure 6.1i 2001 Hydrolab temperature contours at station **AR6**. Surface temperature 22.2 and 21.5 °C in July and August, respectively.

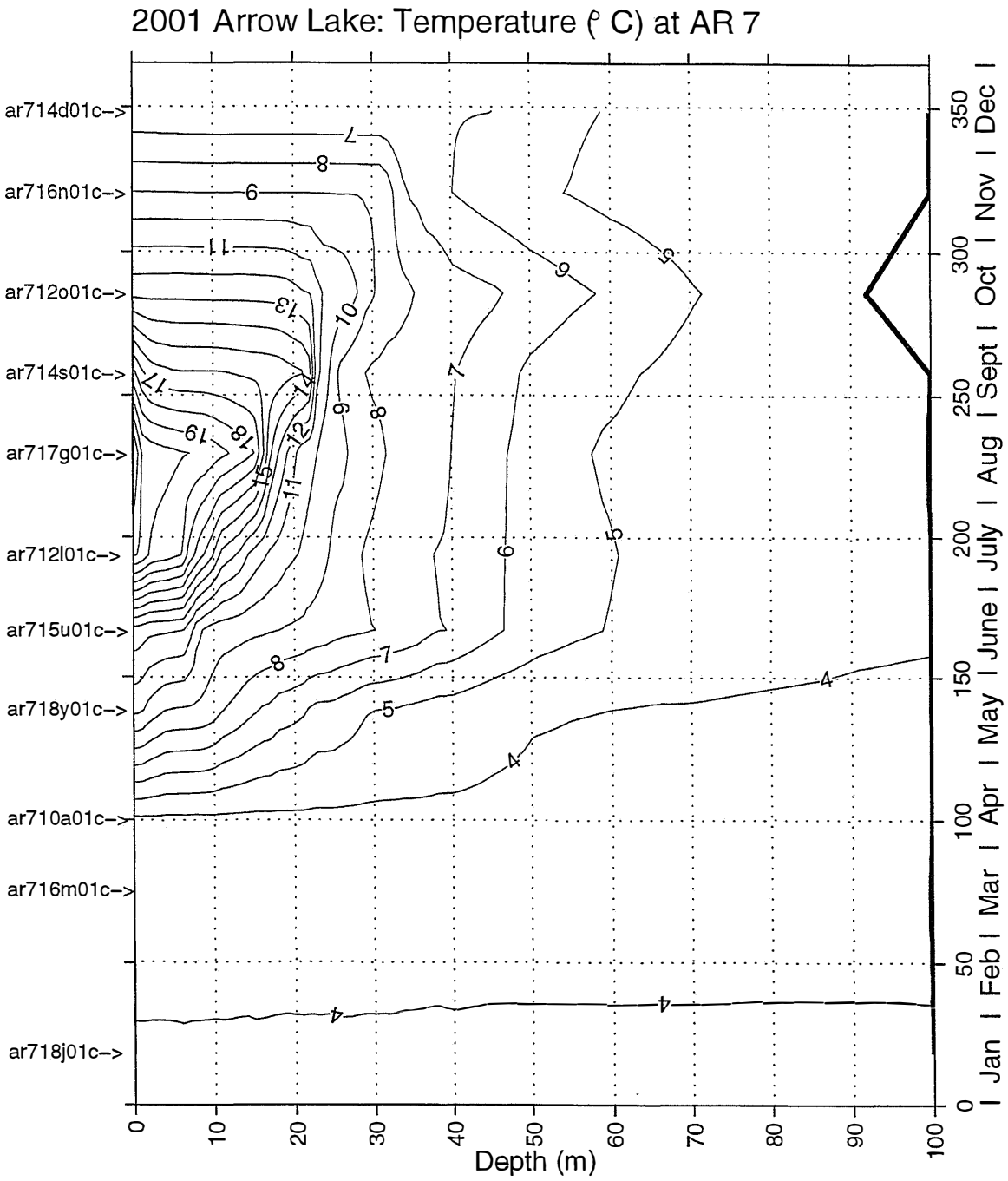


Figure 6.1j 2001 Hydrolab temperature contours at station **AR7**. Surface temperature 21.1 and 23.1 °C in July and August, respectively.

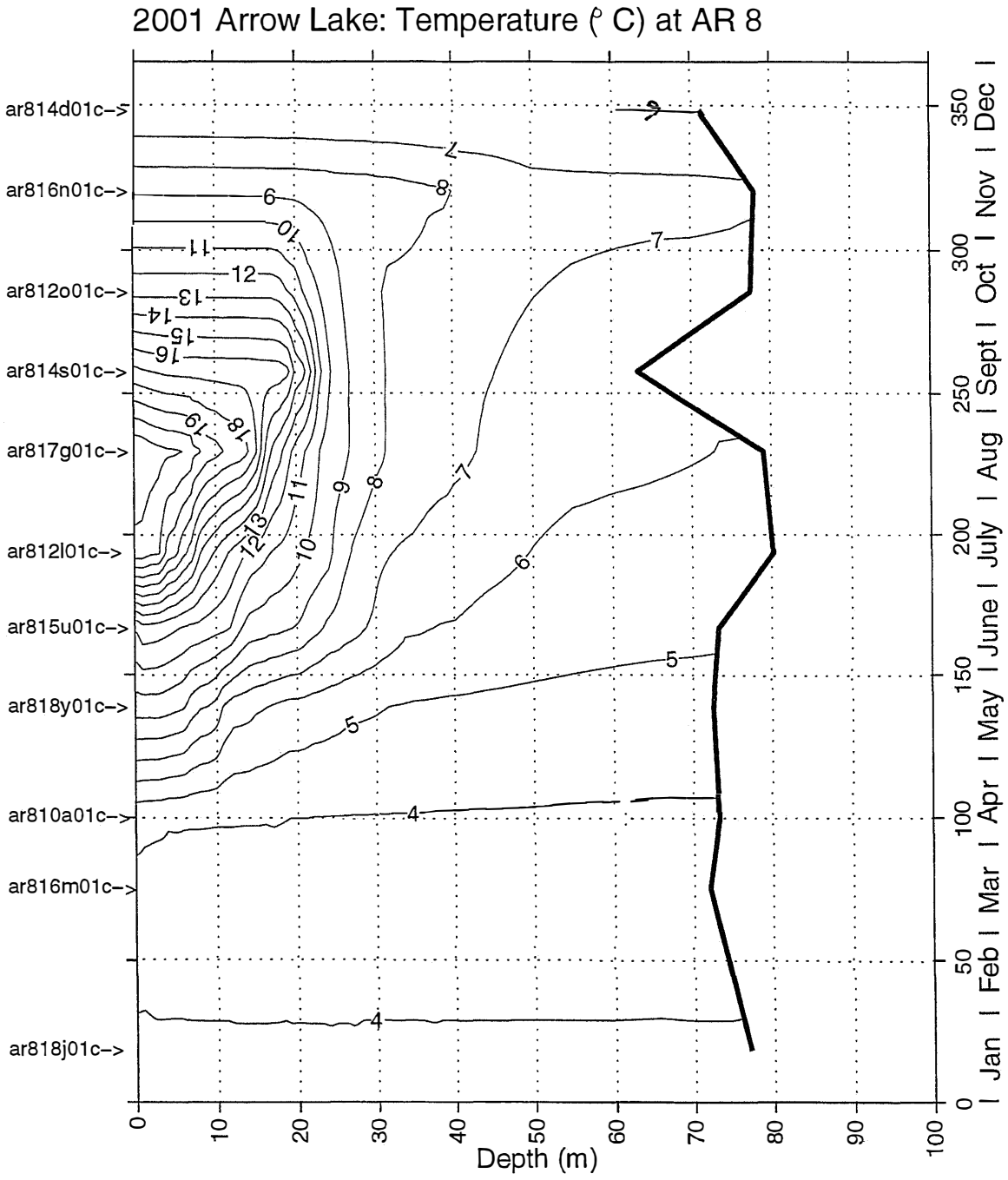


Figure 6.1k 2001Hydrolab temperature contours at station **AR8**. Surface temperature 20.6 and 21.9 °C in July and August, respectively.

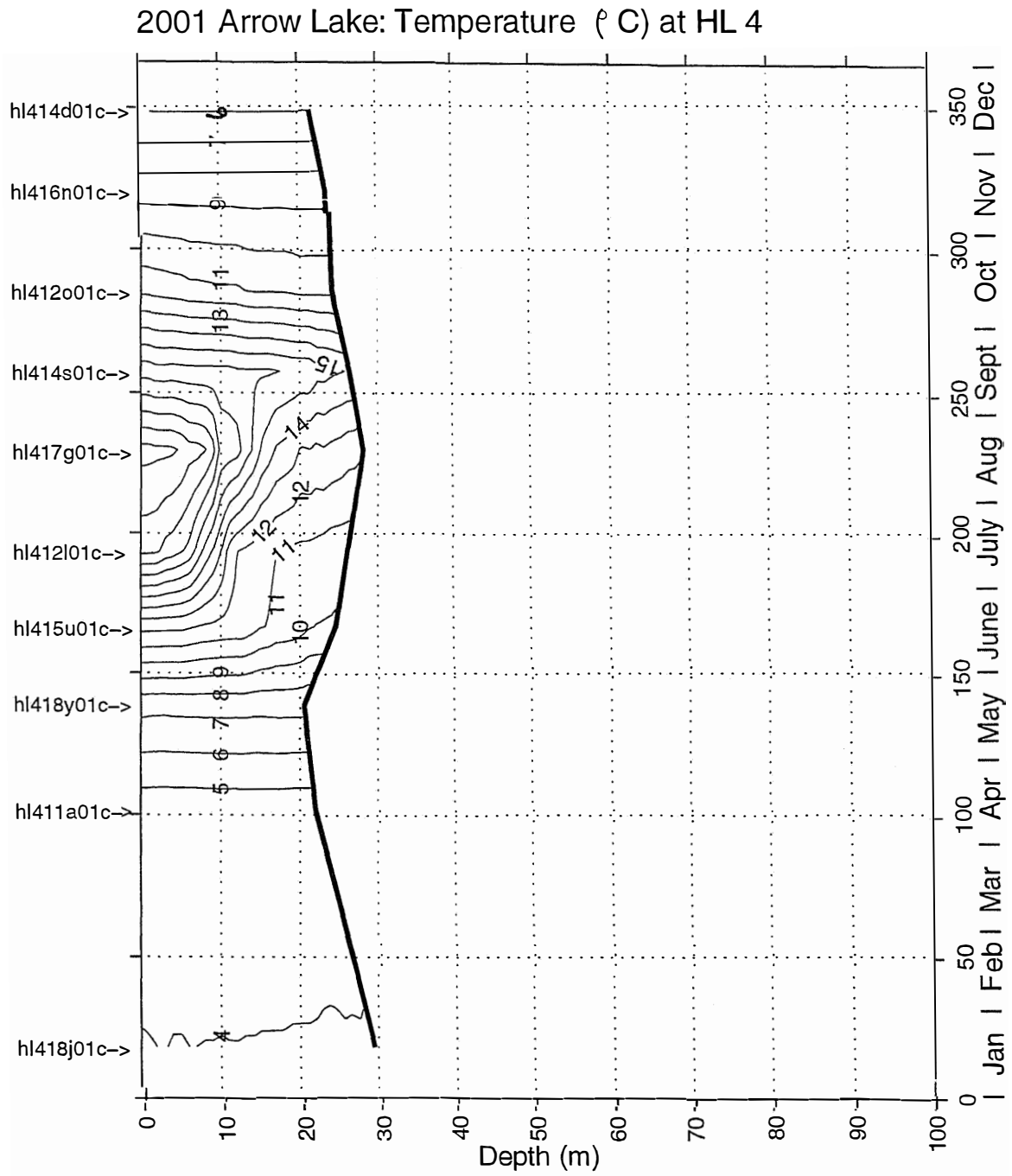


Figure 6.11 2001 Hydrolab temperature contours at station **HL4**. Surface temperature 21.3 °C in August.

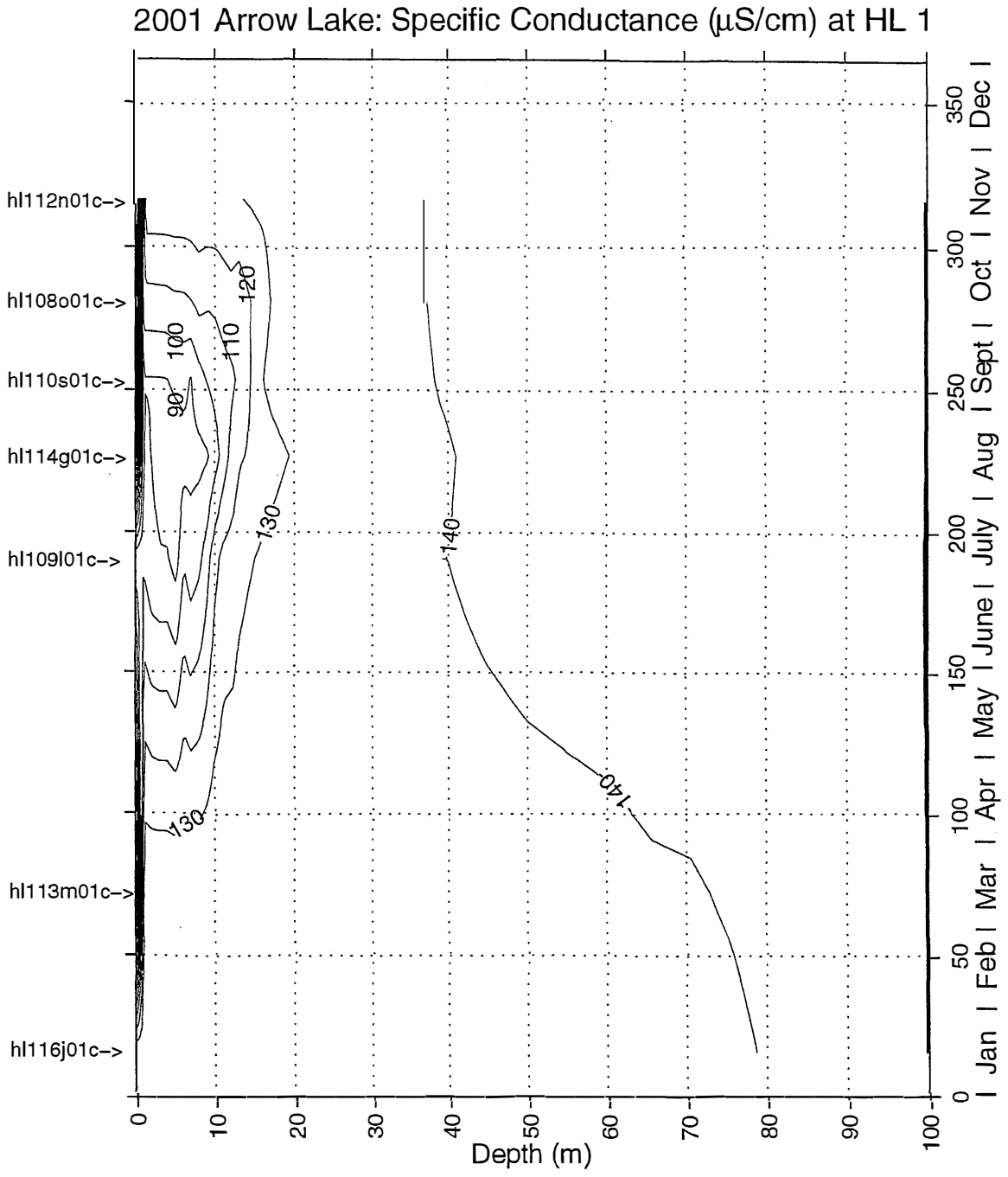


Figure 6.2a 2001 Hydrolab specific conductance contours at station **HL1**, Beaton Arm. Bunched contours near the surface result from a single low surface reading at the start of the cast. Note missing data for April, May, June and December.

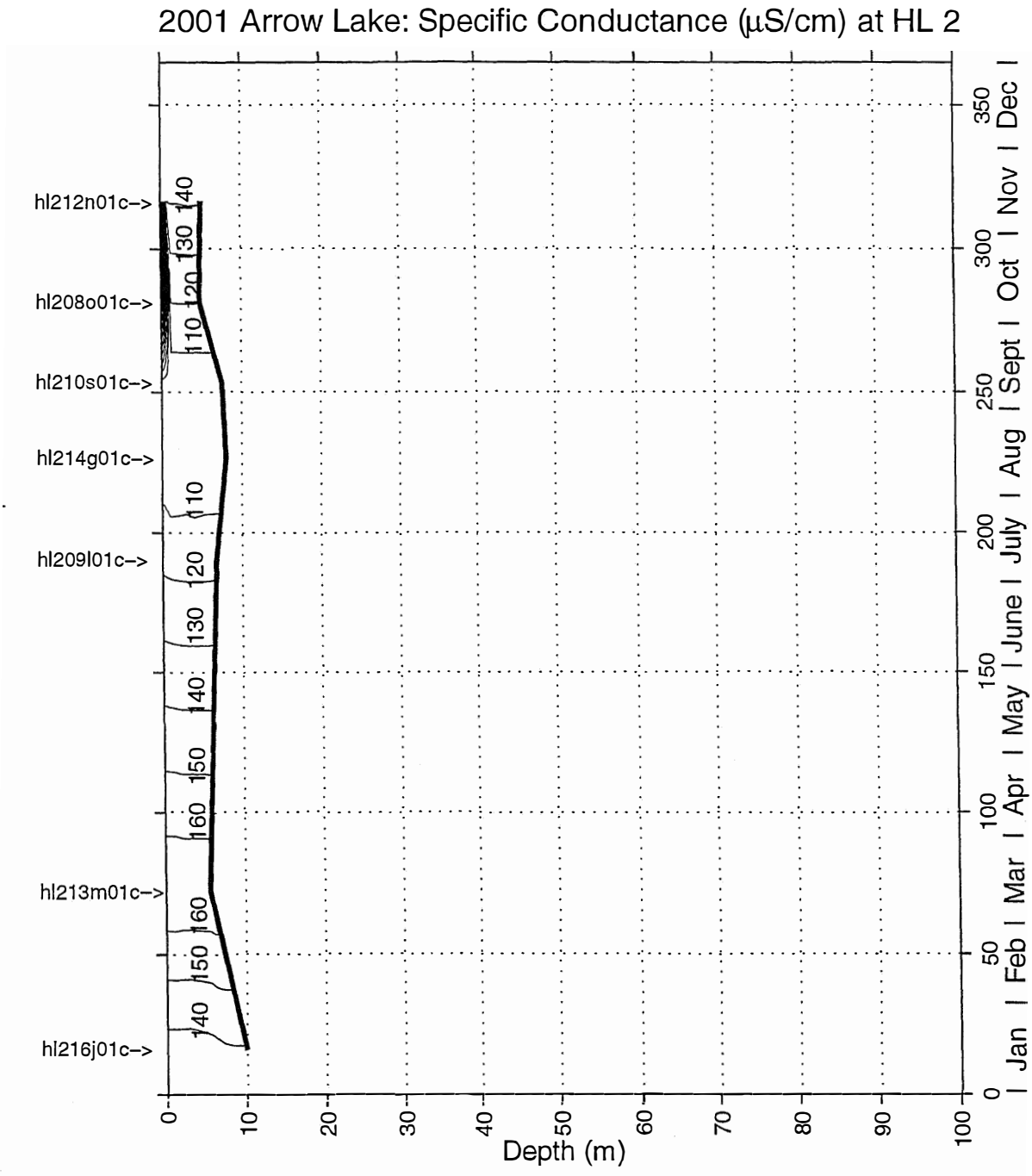


Figure 6.2b 2001 Hydrolab specific conductance contours at station **HL2**. Bunched contours at the surface result from a single low reading at the surface of the cast. Note missing data for April, May, June and December.

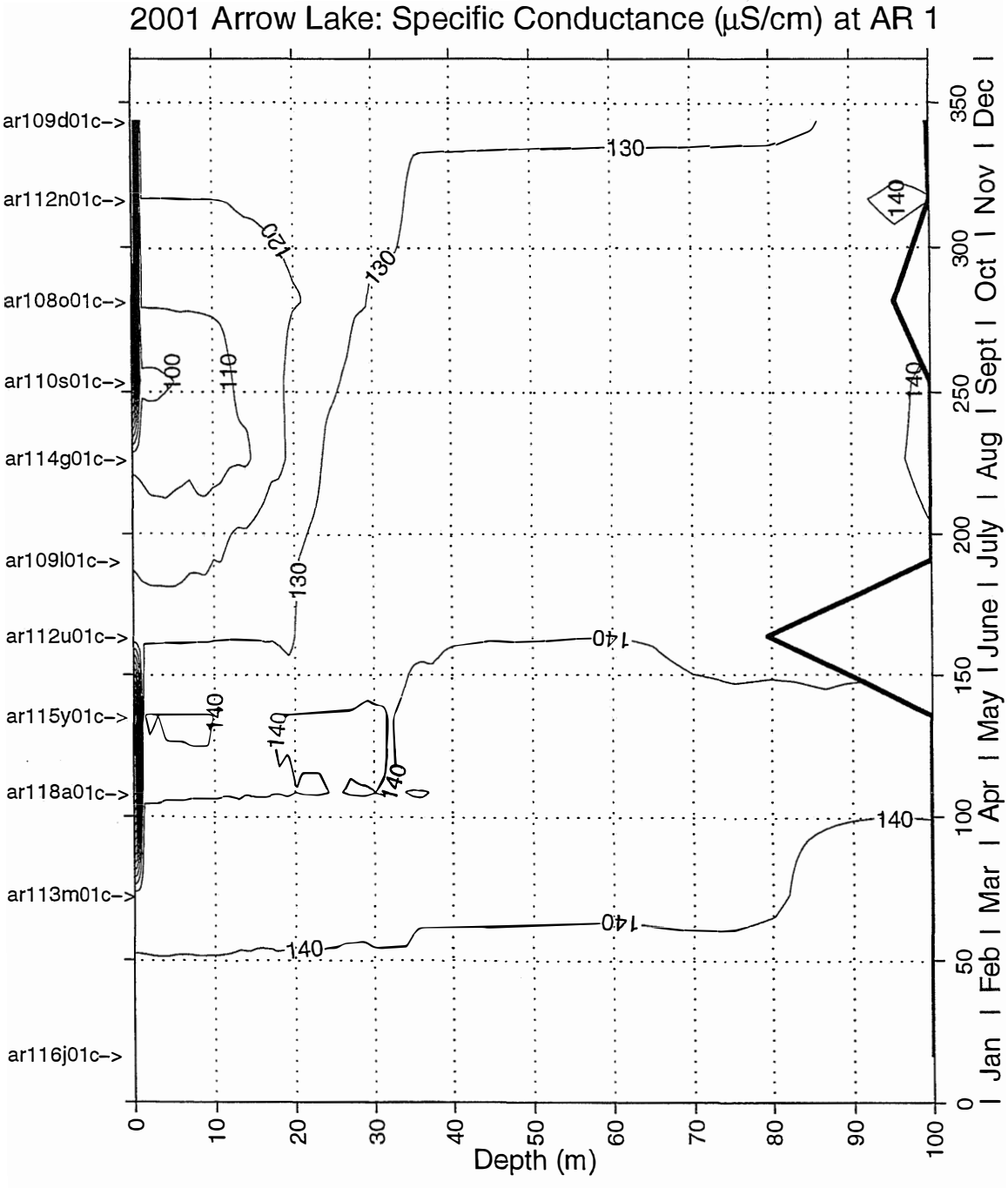


Figure 6.2c 2001 Hydrolab specific conductance contours at station **AR1**. Bunched contours at the surface result from a single low surface reading at the start of the cast.

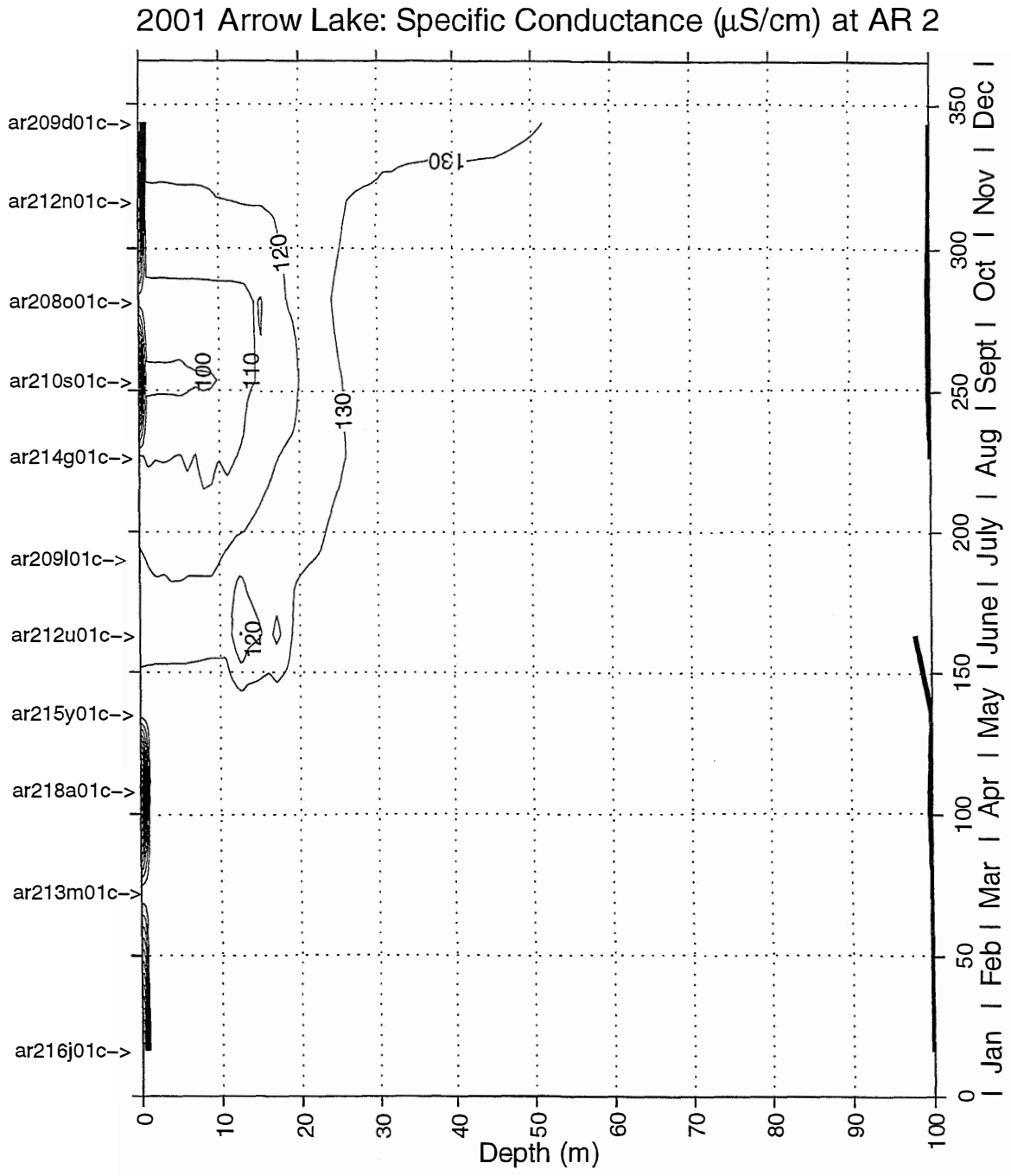


Figure 6.2d 2001 Hydrolab specific conductance contours at station **AR2**. Bunched contours at the surface result from a single low surface reading at the start of the cast.

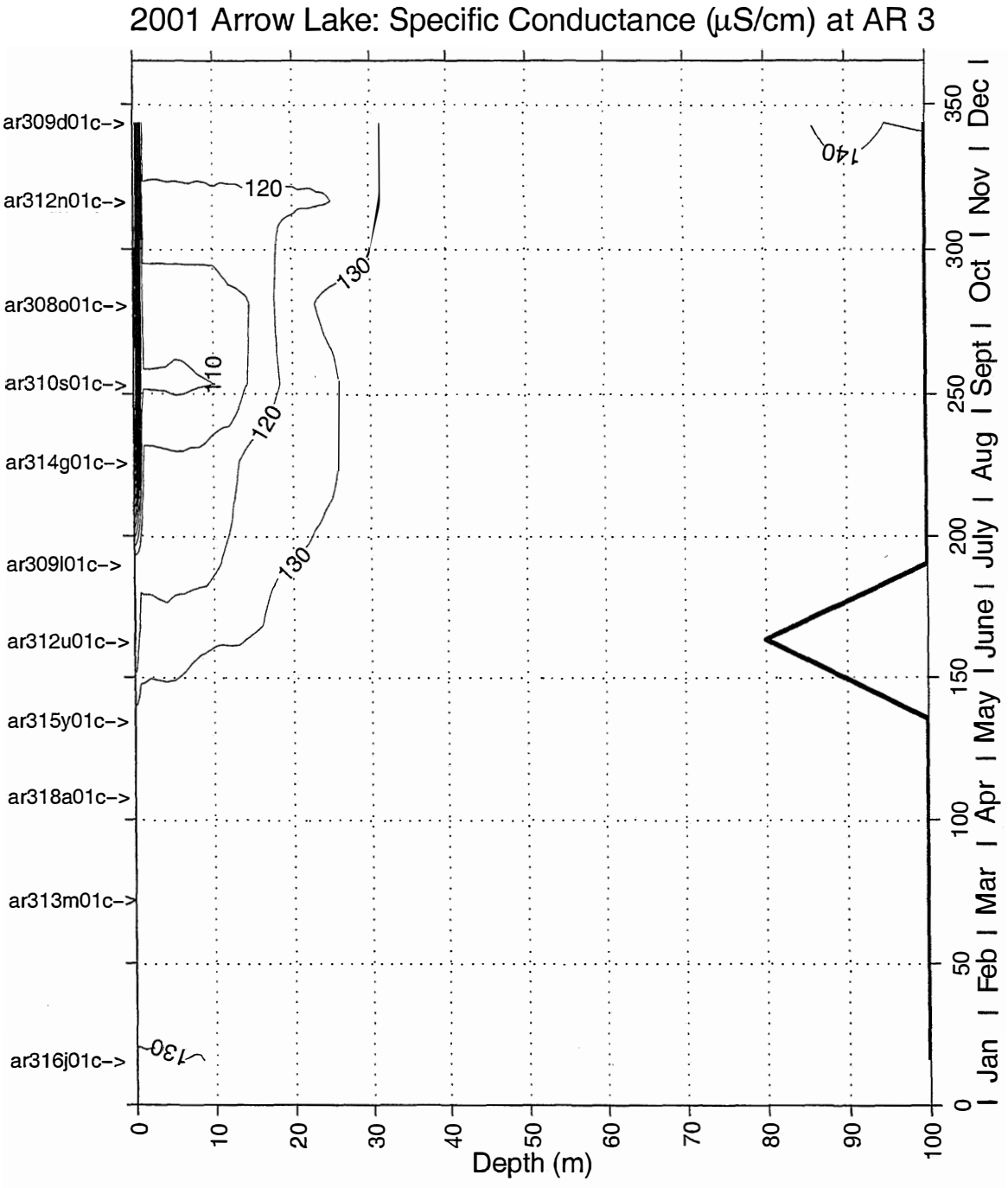


Figure 6.2e 2001 Hydrolab specific conductance contours at station **AR3**. Bunched contours at the surface result from a single low surface reading at the start of the cast.

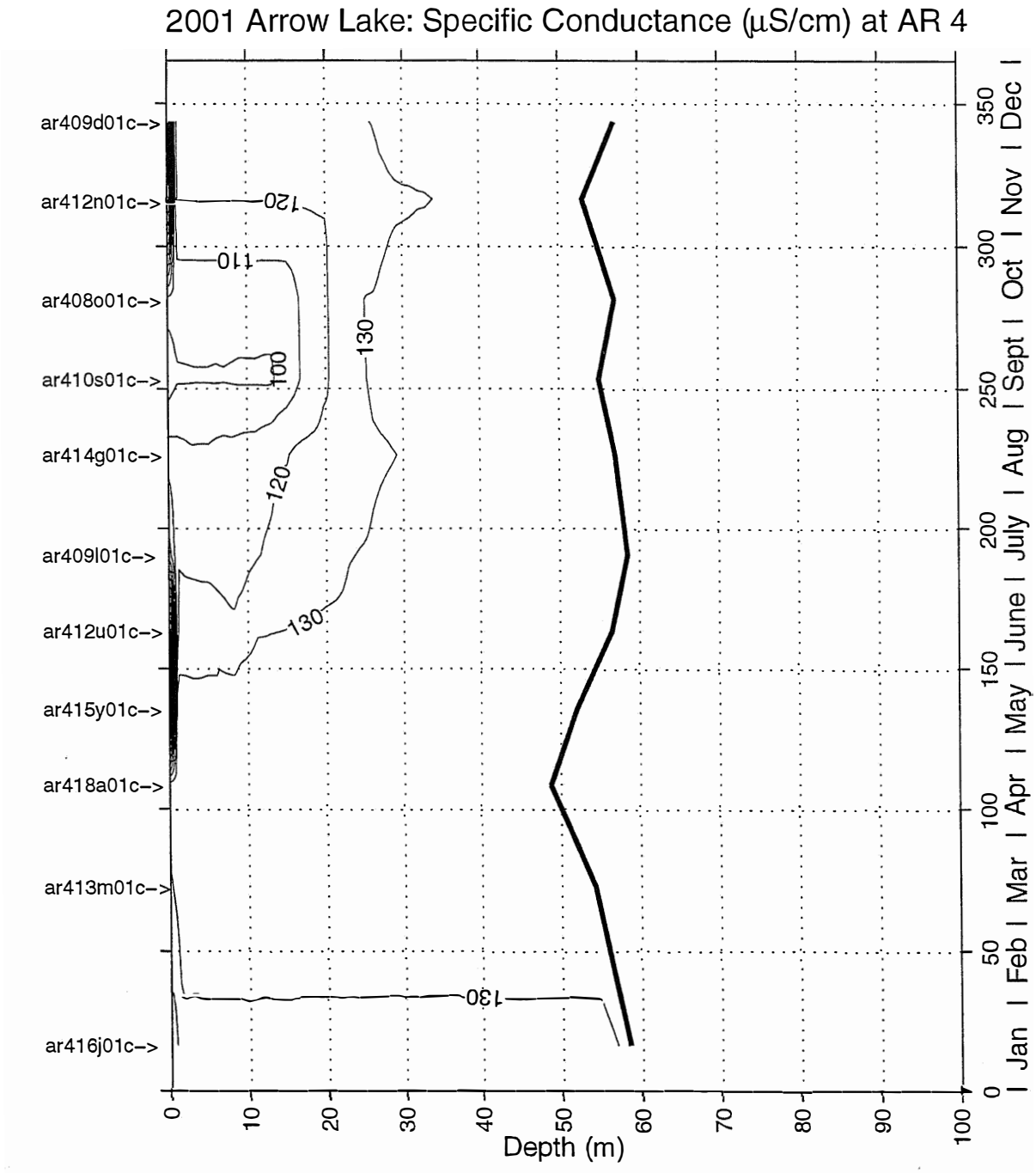


Figure 6.2f 2001 Hydrolab specific conductance contours at station **AR4**. Bunched contours at the surface result from a single low surface reading at the start of the cast.

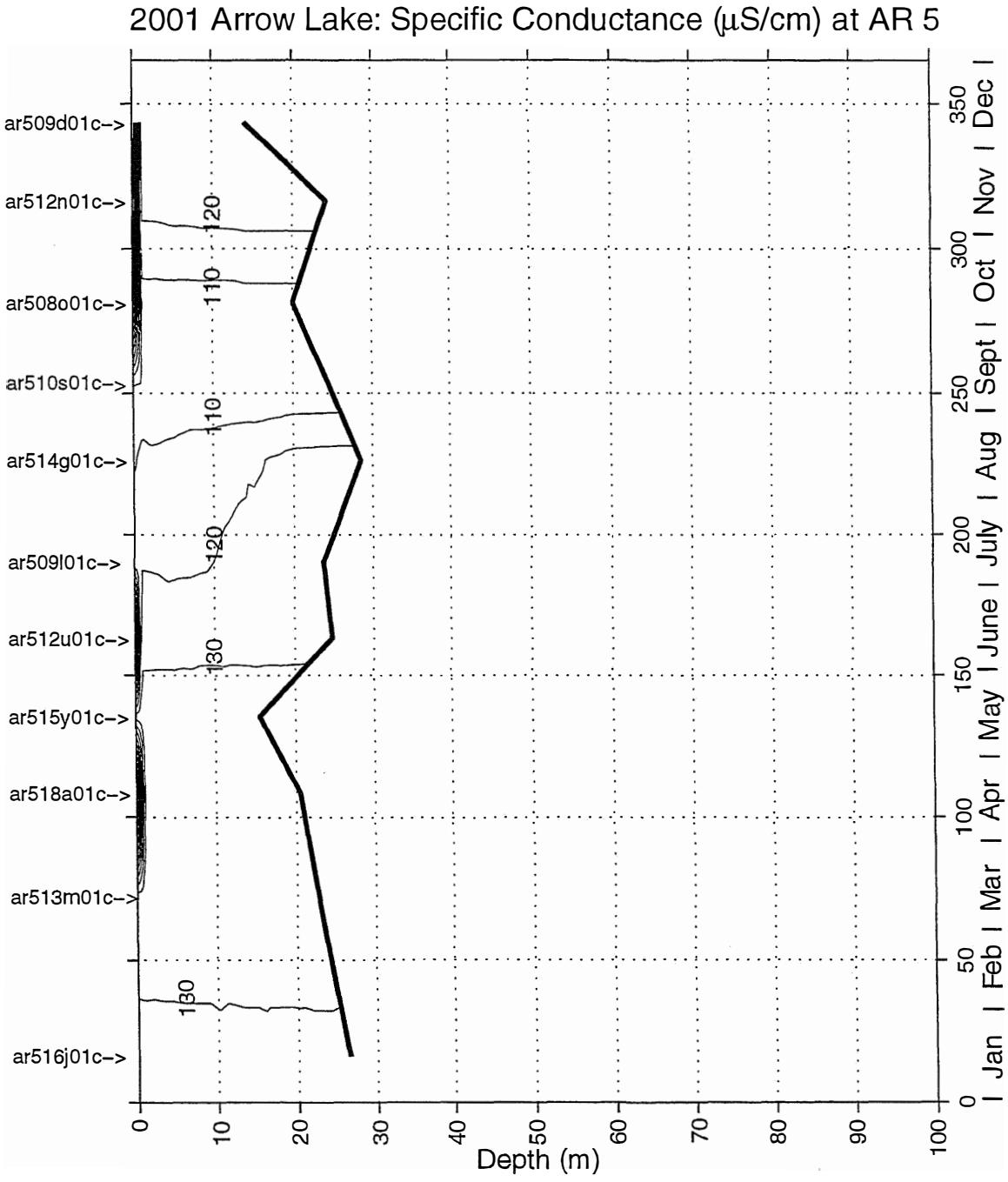


Figure 6.2g 2001 Hydrolab specific conductance contours at **AR5**, Narrows. Bunched contours at the surface result from a single low surface reading at the start of the cast.

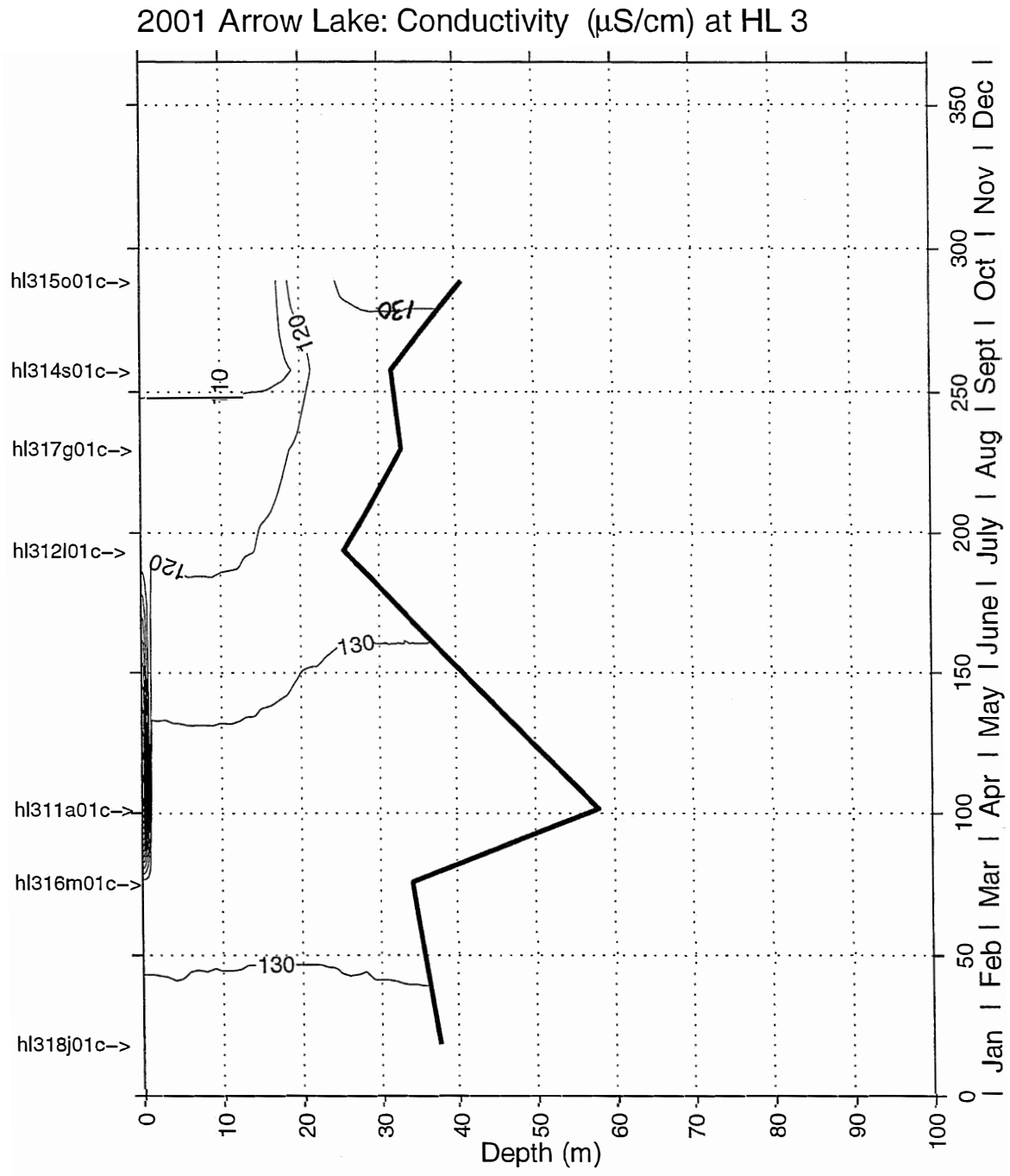


Figure 6.2h 2001 Hydrolab specific conductance contours at station **HL3.** Bunched contours at the surface result from a single low surface reading at the start of the cast. Note missing data May, June, November and December.

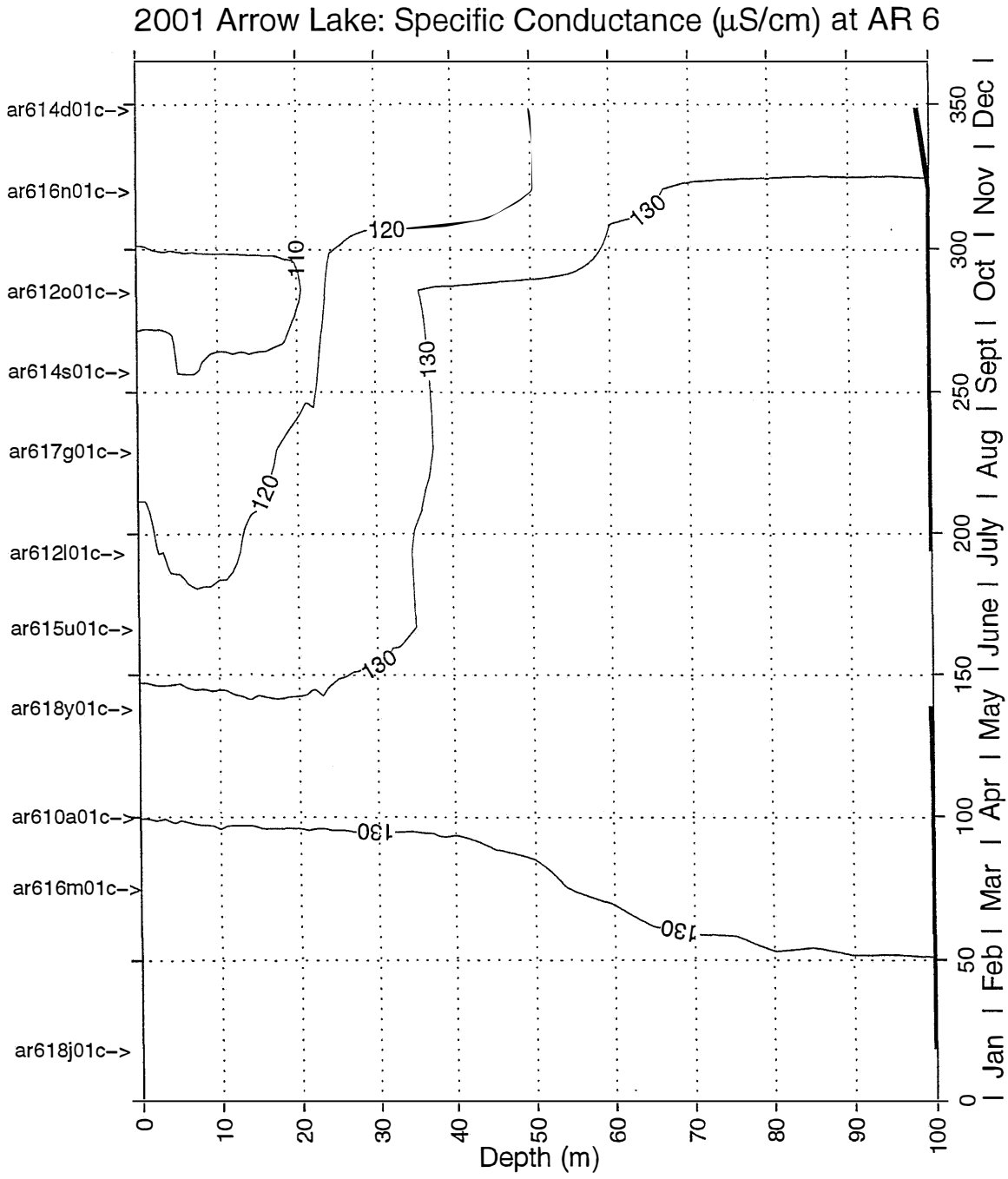


Figure 6.2i 2001 Hydrolab specific conductance contours at station **AR6**.

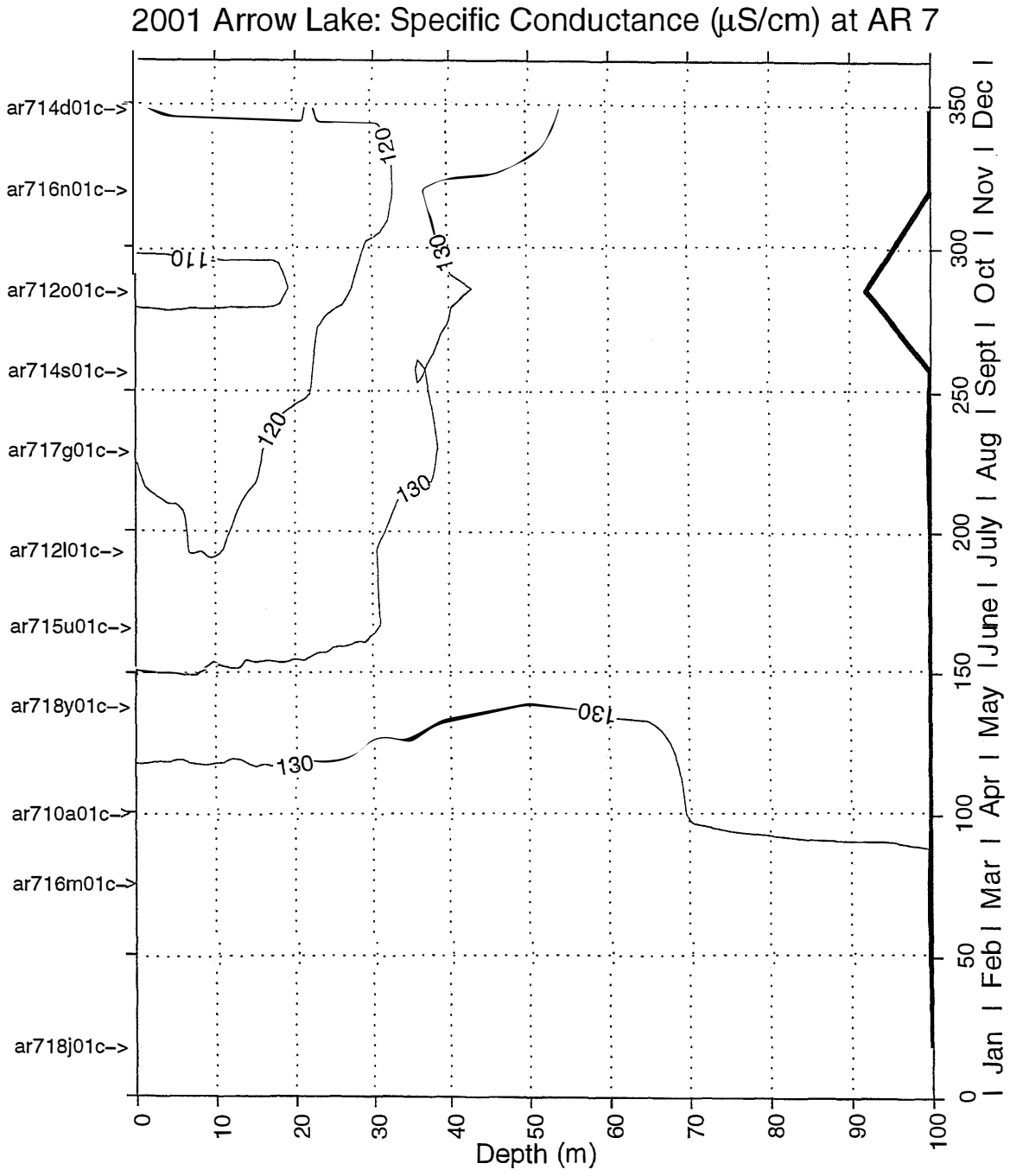


Figure 6.2j 2001 Hydrolab specific conductance contours at station **AR7**.

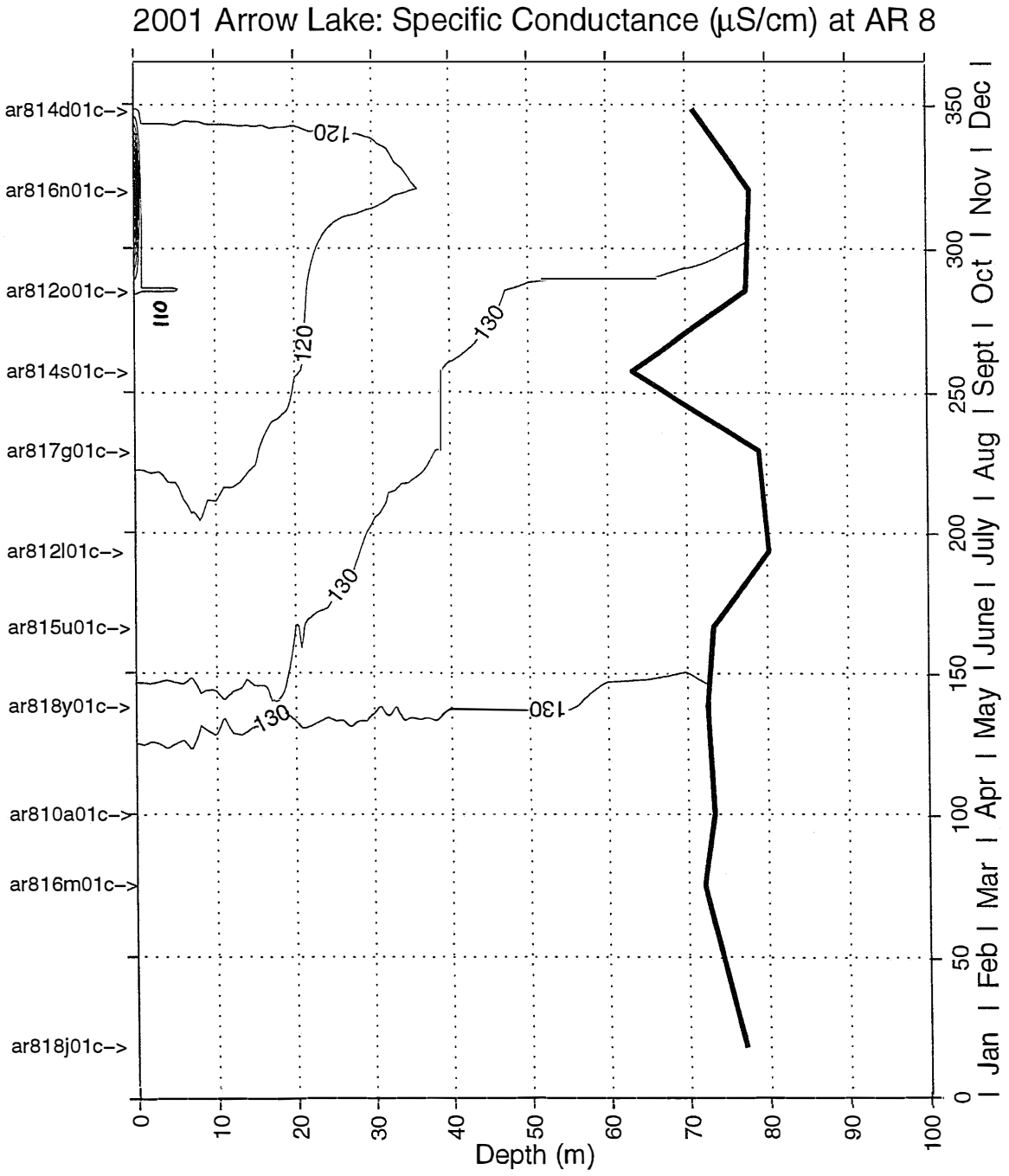


Figure 6.2k 2001 Hydrolab specific conductance contours at station **AR8**. Bunched contours at the surface result from a single low surface reading at the start of the cast.

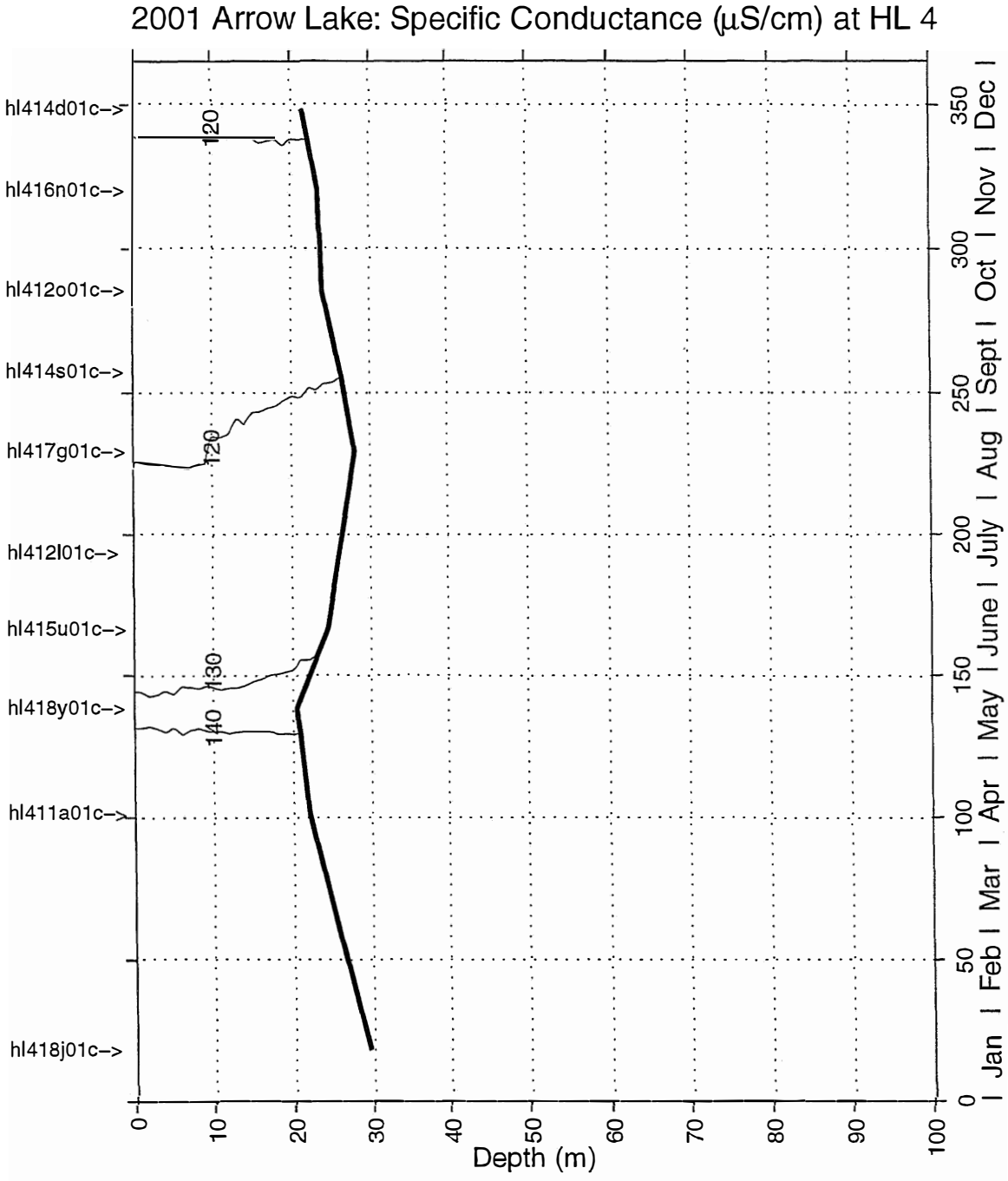


Figure 6.21 2001 Hydrolab specific conductance contours at station **HL4**.

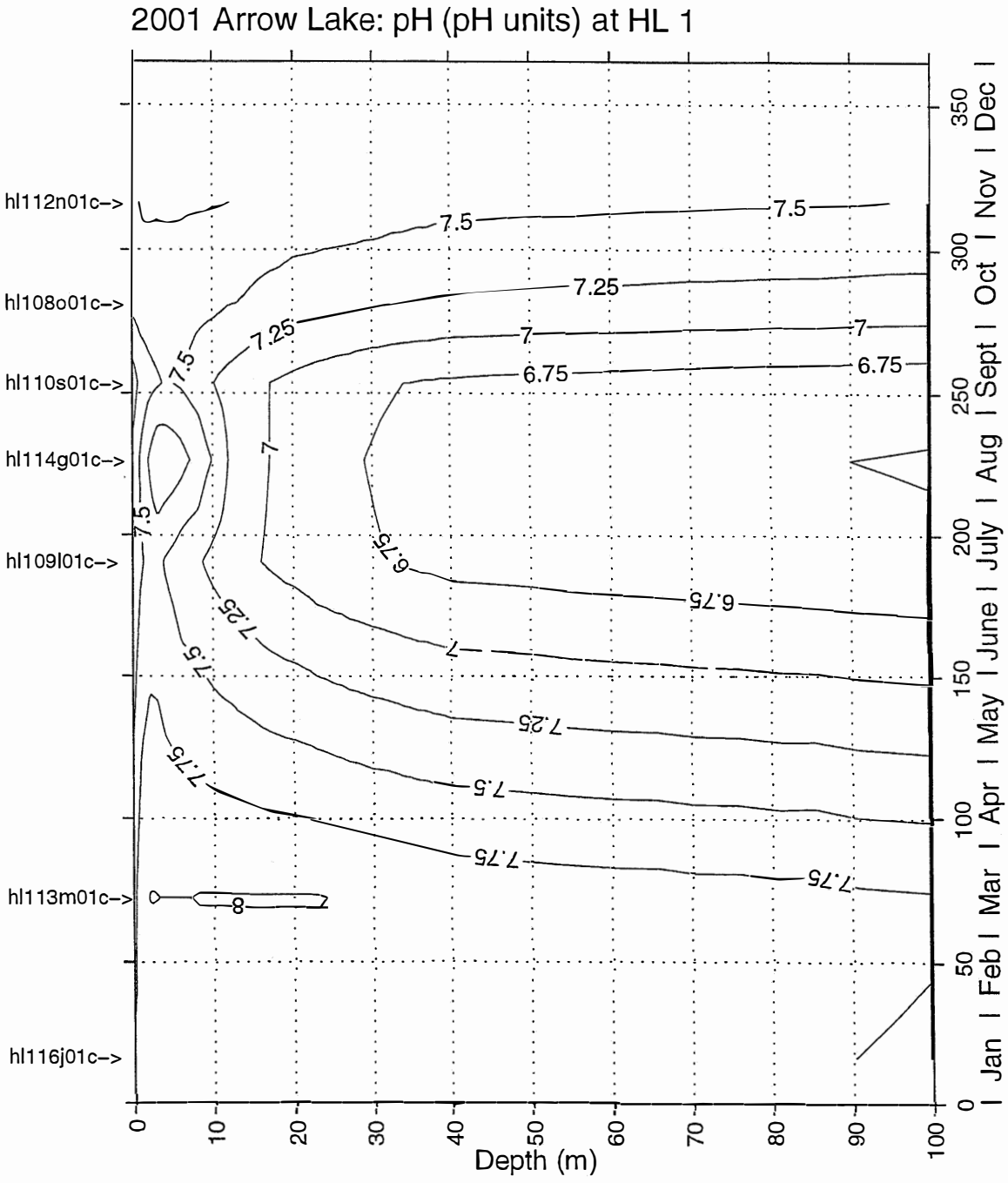


Figure 6.3a 2001 Hydrolab pH contours at station **HL1**, Beaton Arm.

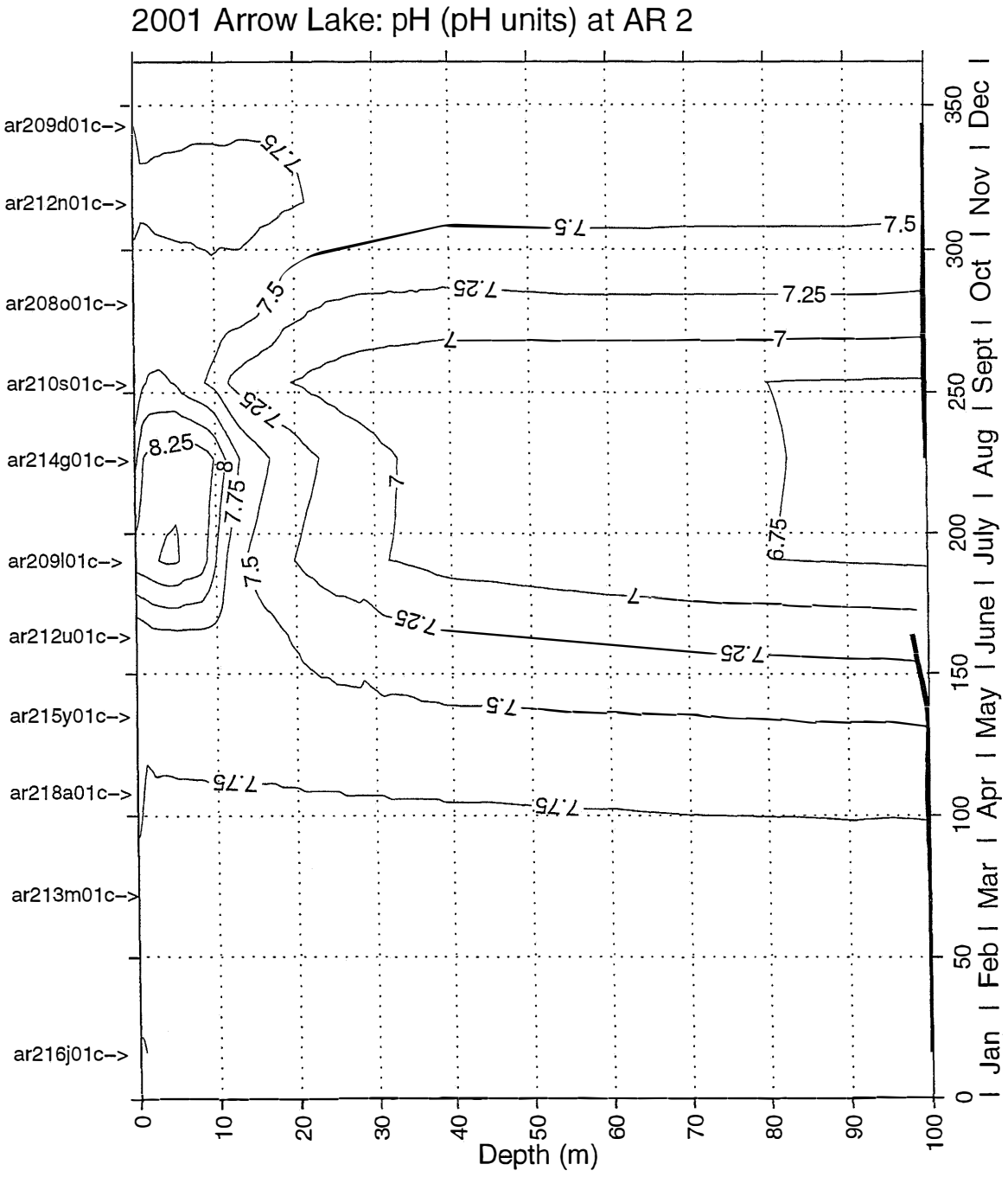


Figure 6.3b 2001 Hydrolab pH contours at station **AR2**, Upper Arrow.

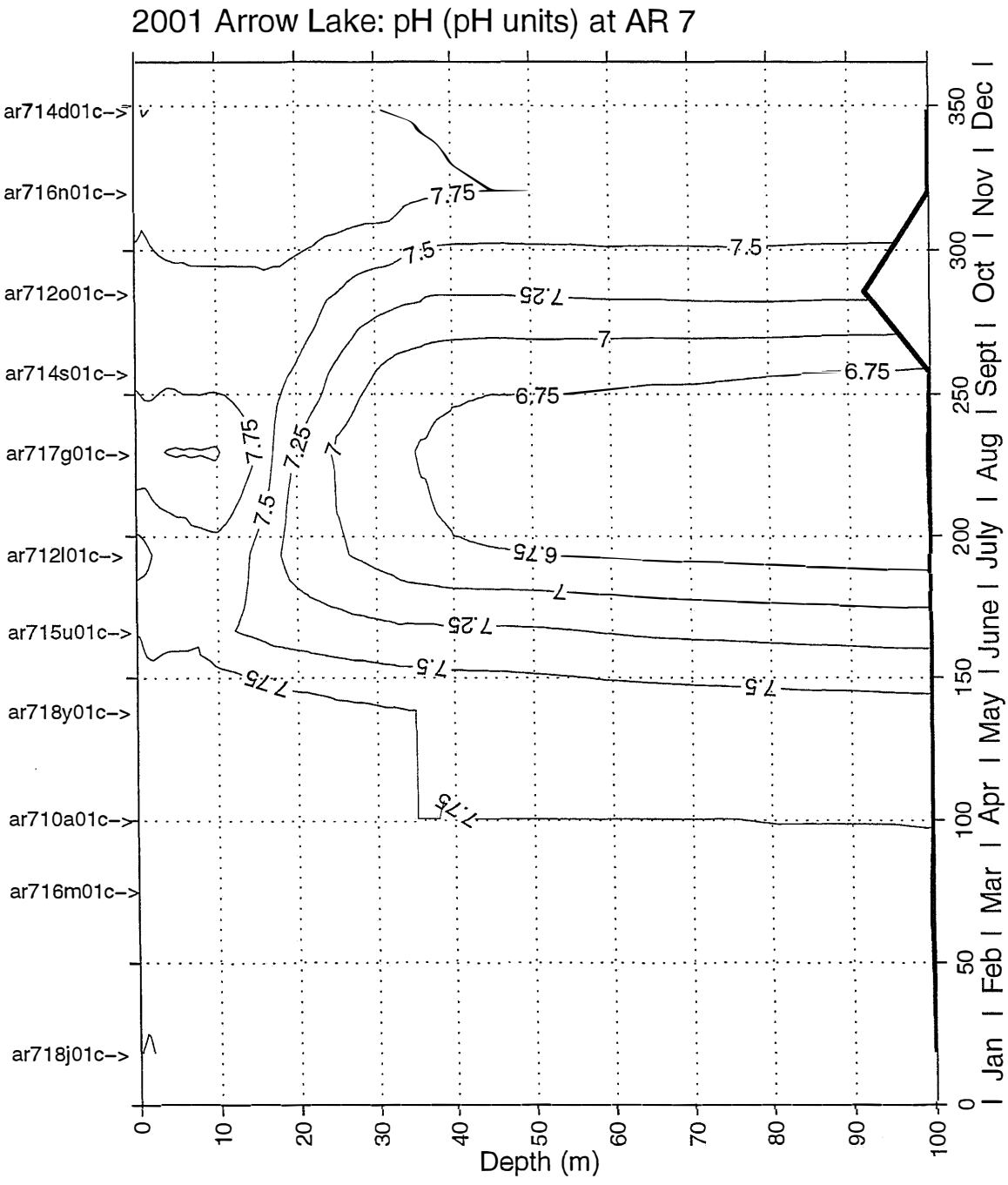


Figure 6.3c 2001 Hydrolab pH contours at station **AR7**, Lower Arrow.

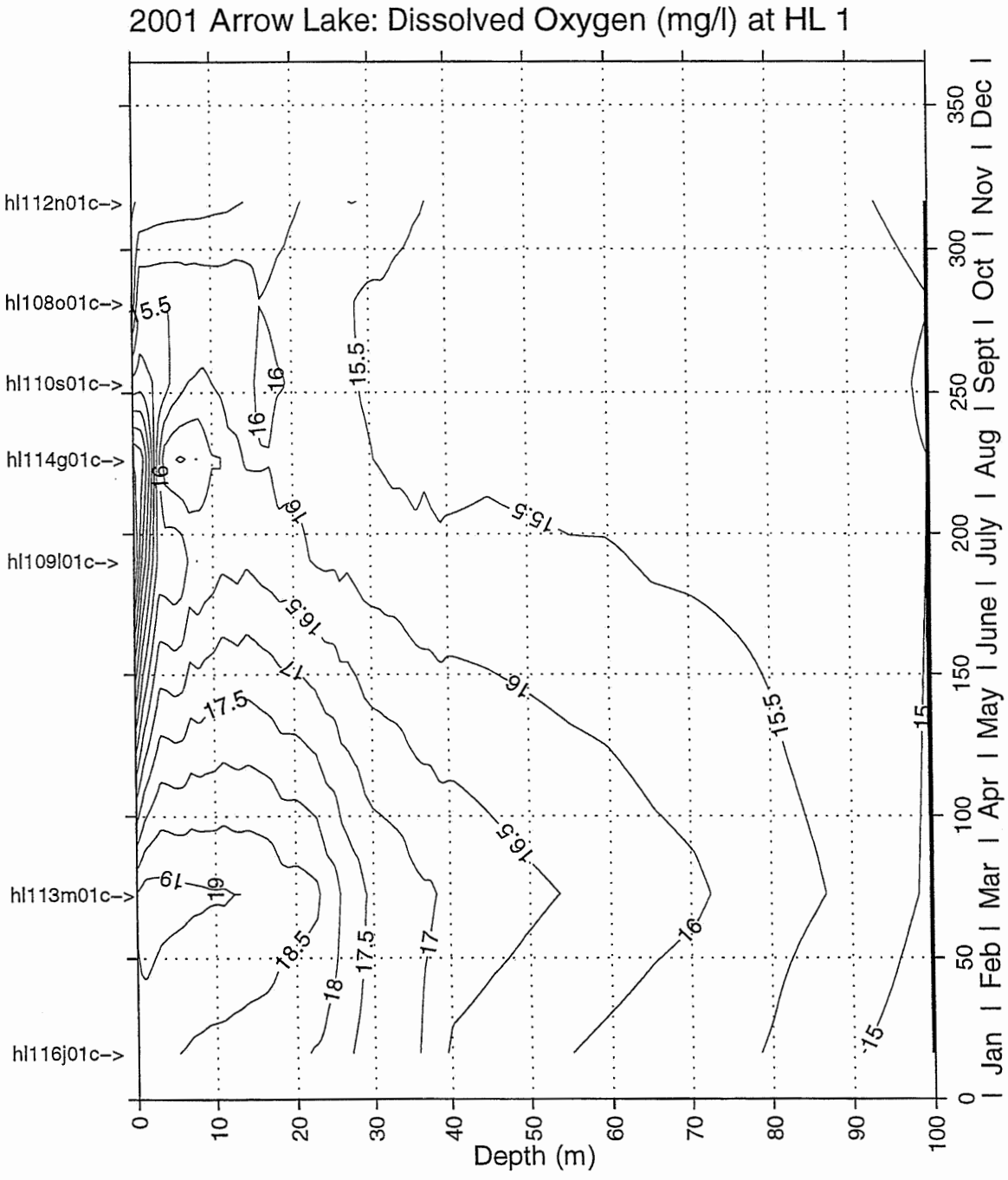


Figure 6.4a 2001 Hydrolab dissolved oxygen contours at station **HL1**, Beaton Arm.

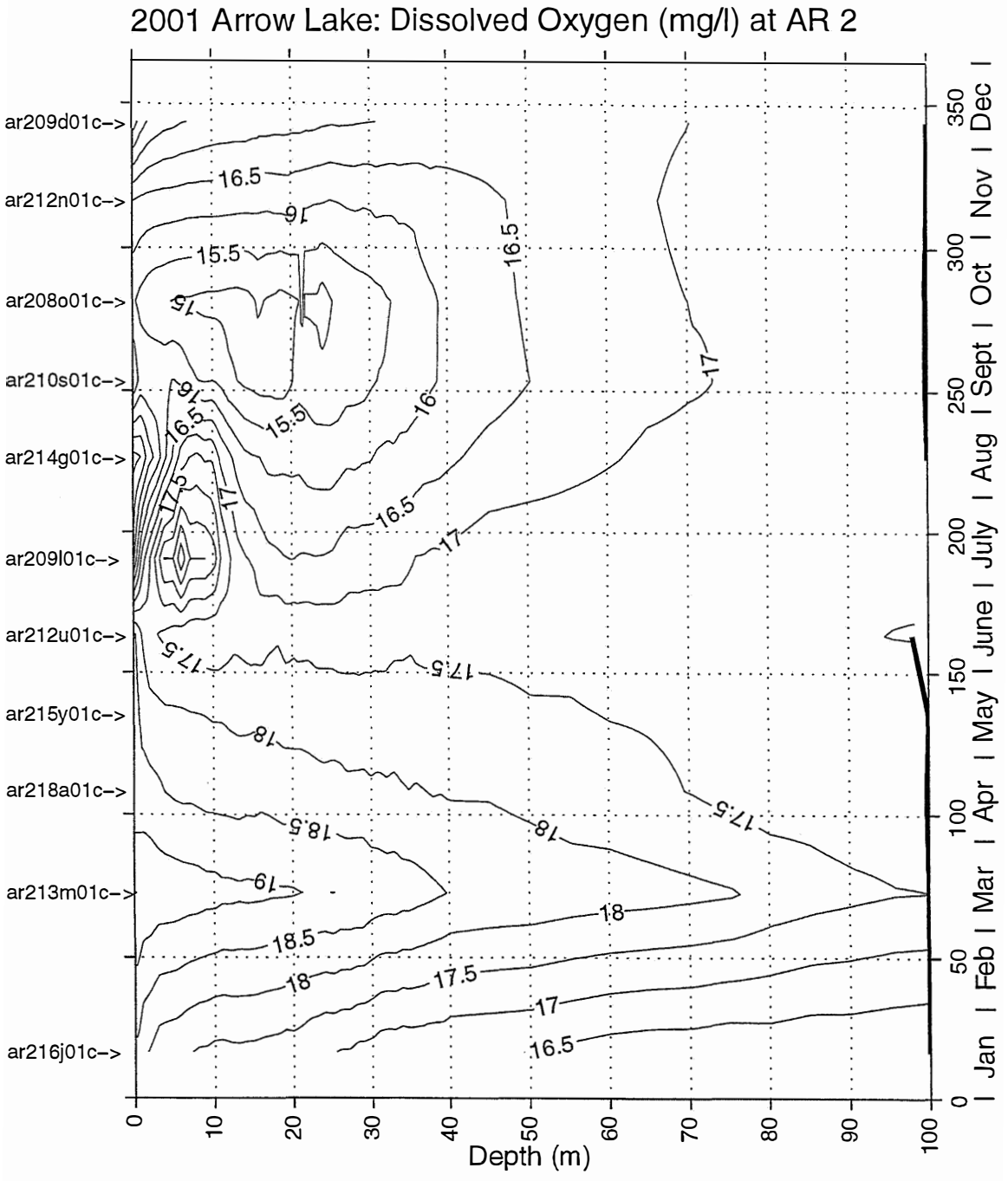


Figure 6.4b 2001 Hydrolab dissolved oxygen contours at station **AR2**, Upper Arrow.

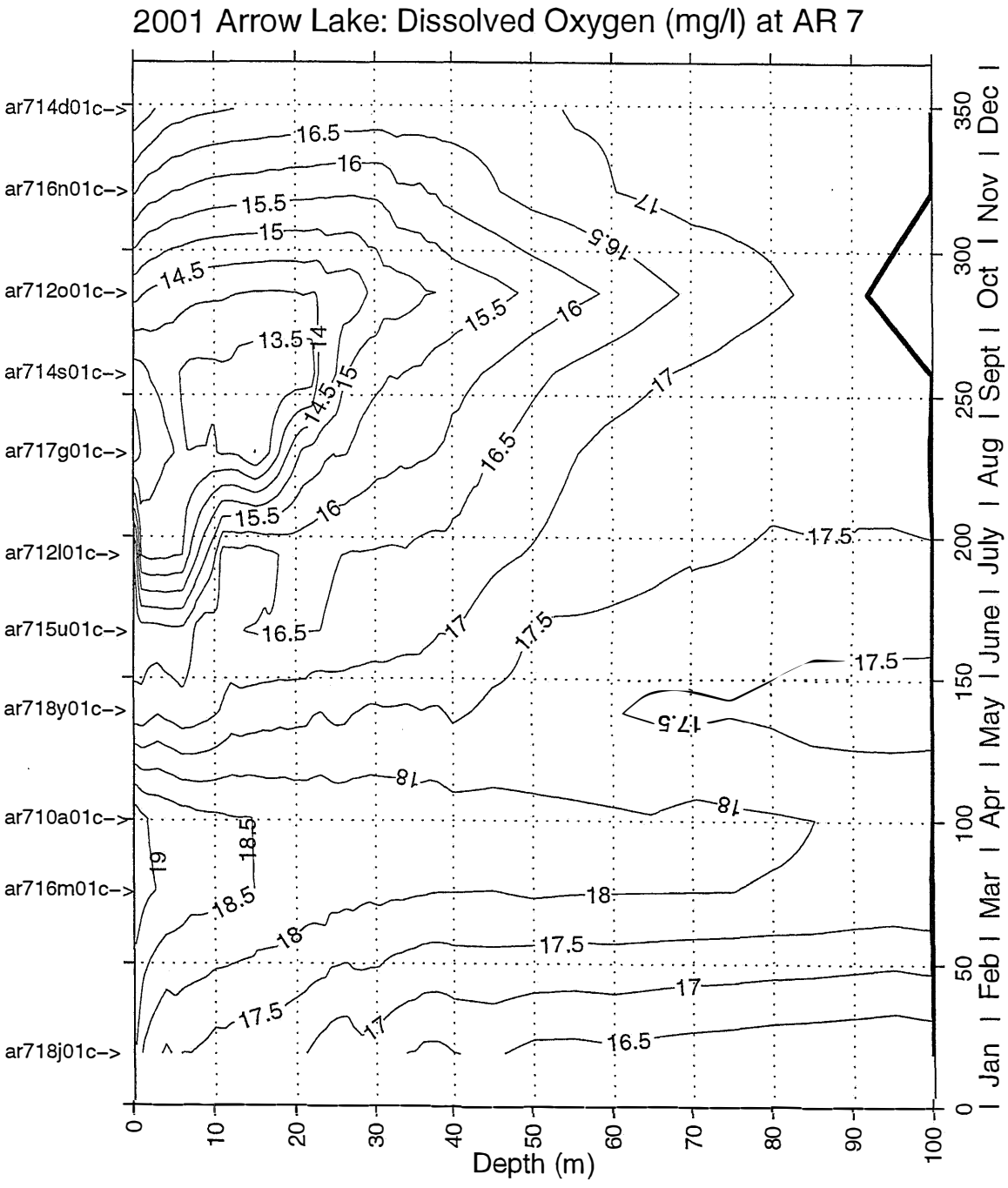


Figure 6.4c 2001 Hydrolab dissolved oxygen contours at station **AR7**. Lower Arrow.

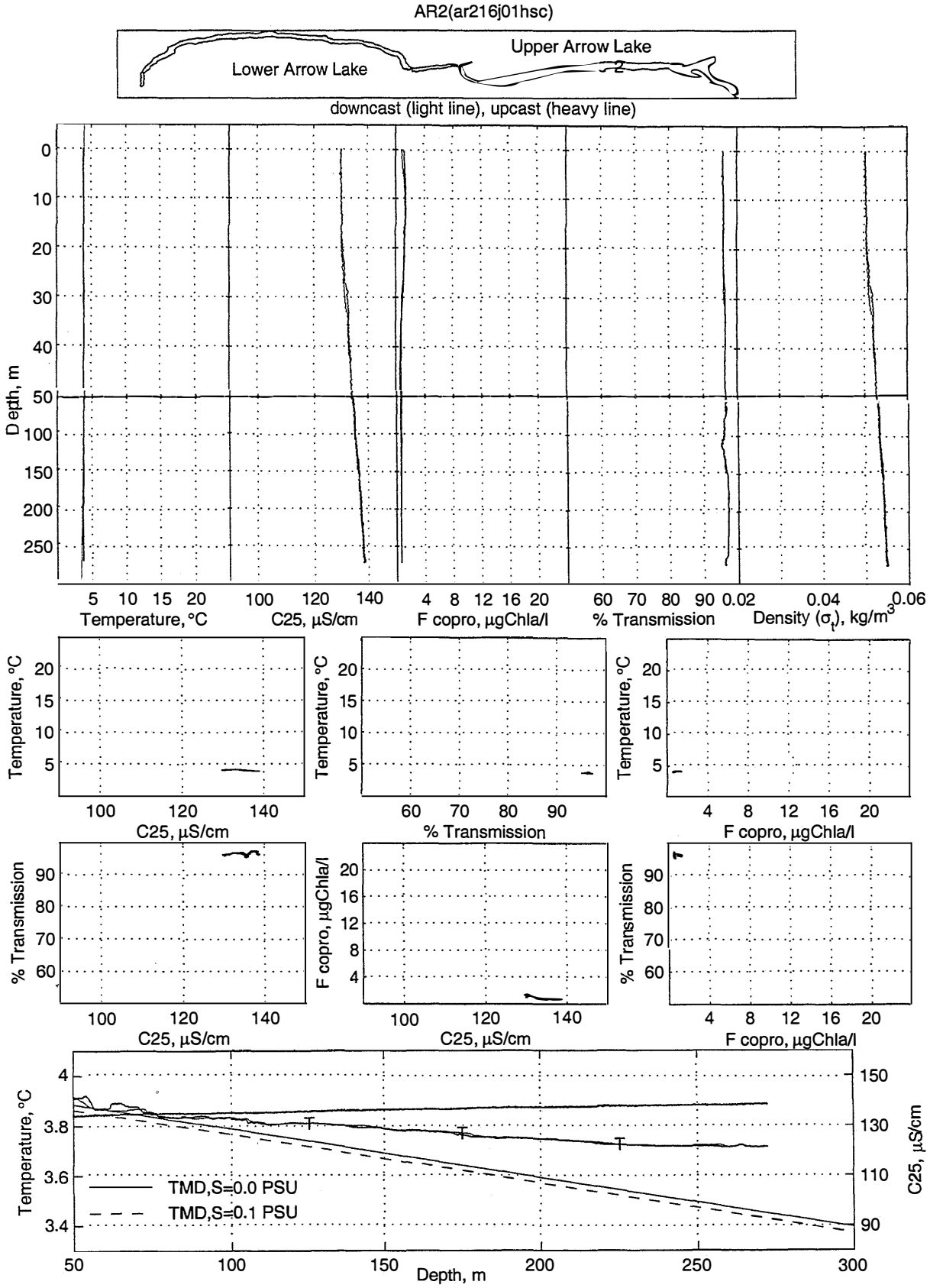


Figure 6.5a Seabird, Upper Arrow, AR2, **January** 2001.

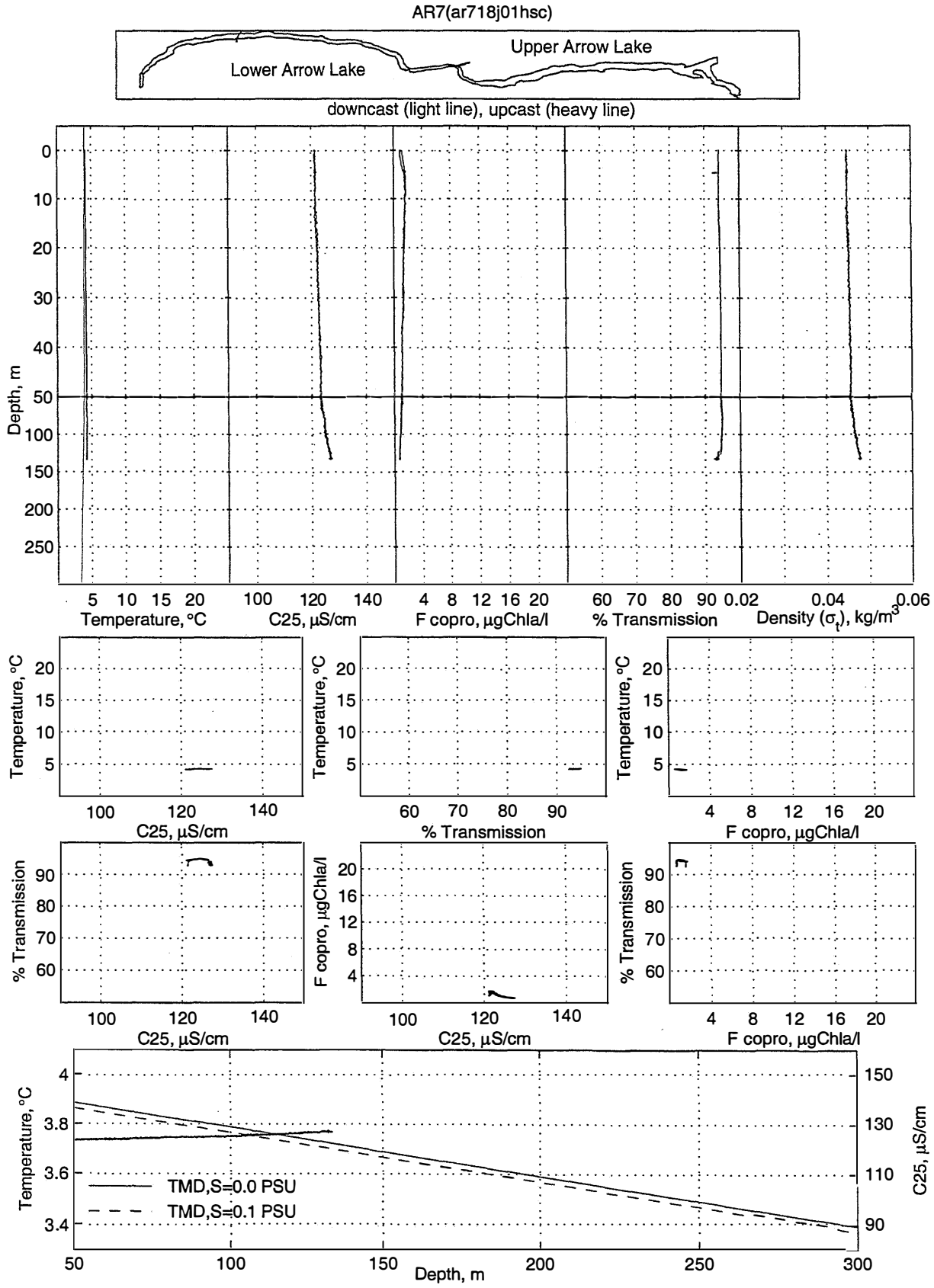


Figure 6.5b Seabird, Lower Arrow, AR7, **January** 2001.

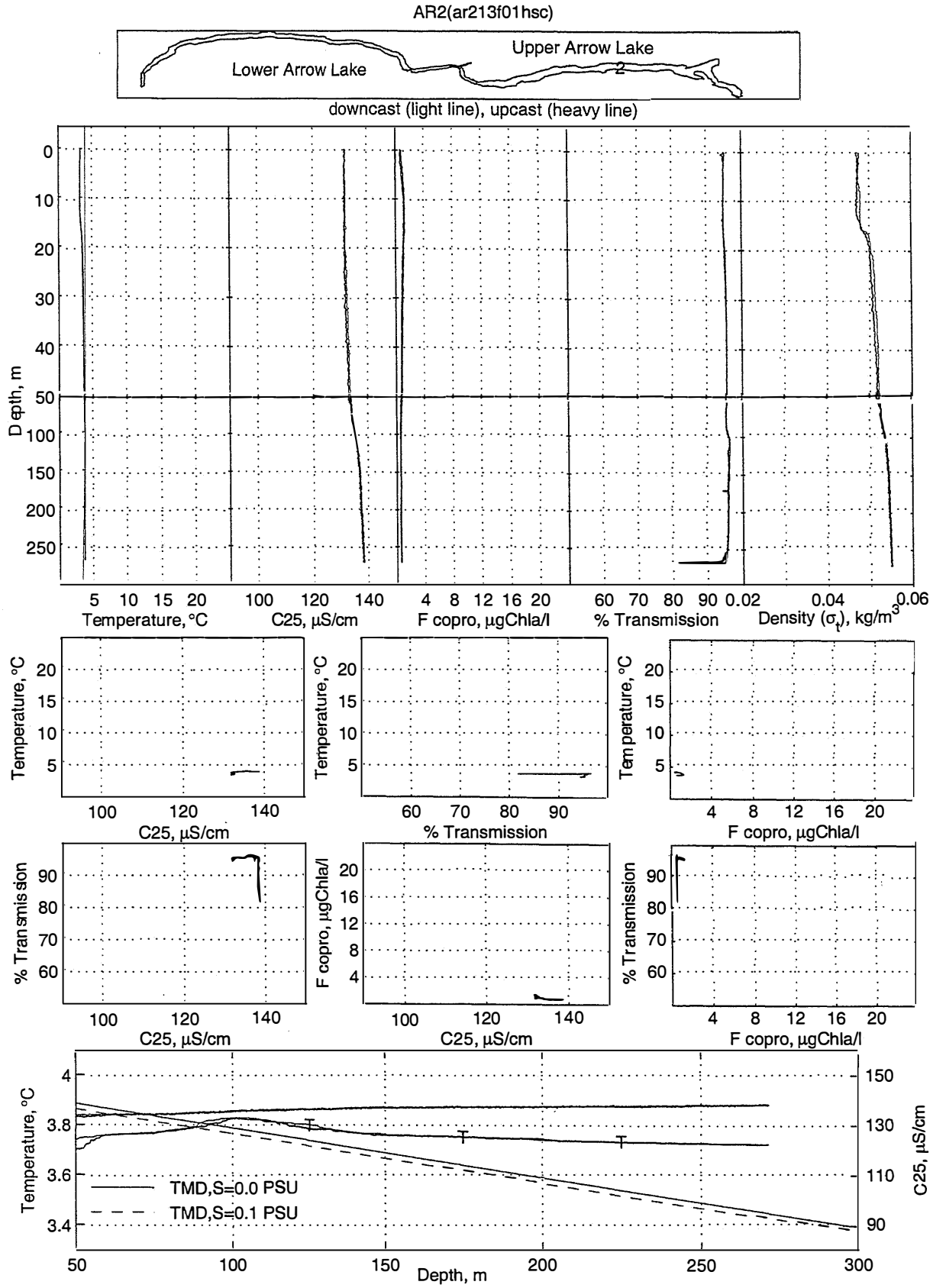


Figure 6.5c Seabird, Upper Arrow, AR2, **February** 2001.

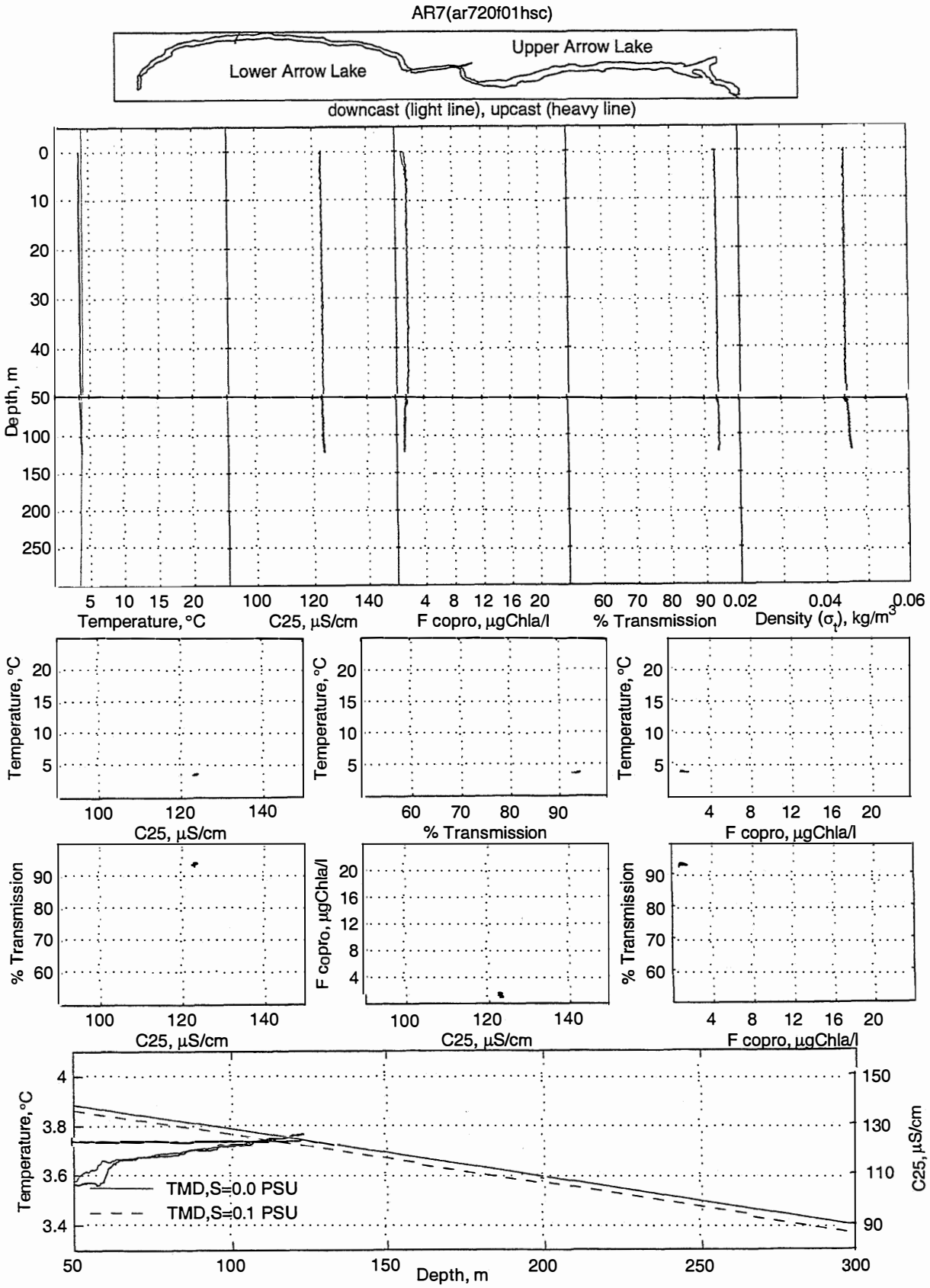


Figure 6.5d Seabird, Lower Arrow, AR7, **February** 2001.

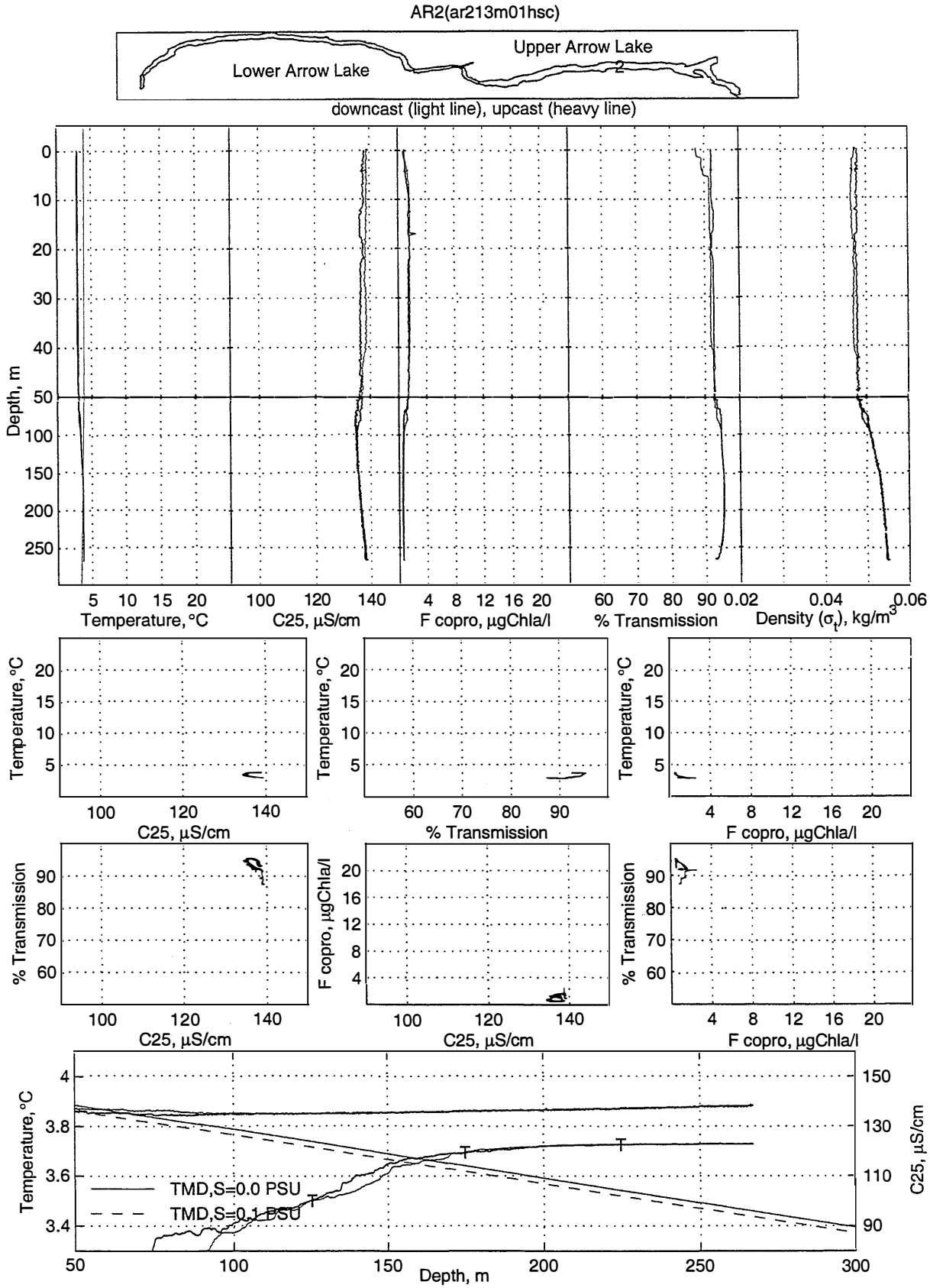


Figure 6.5e Seabird, Upper Arrow, AR2, **March** 2001.

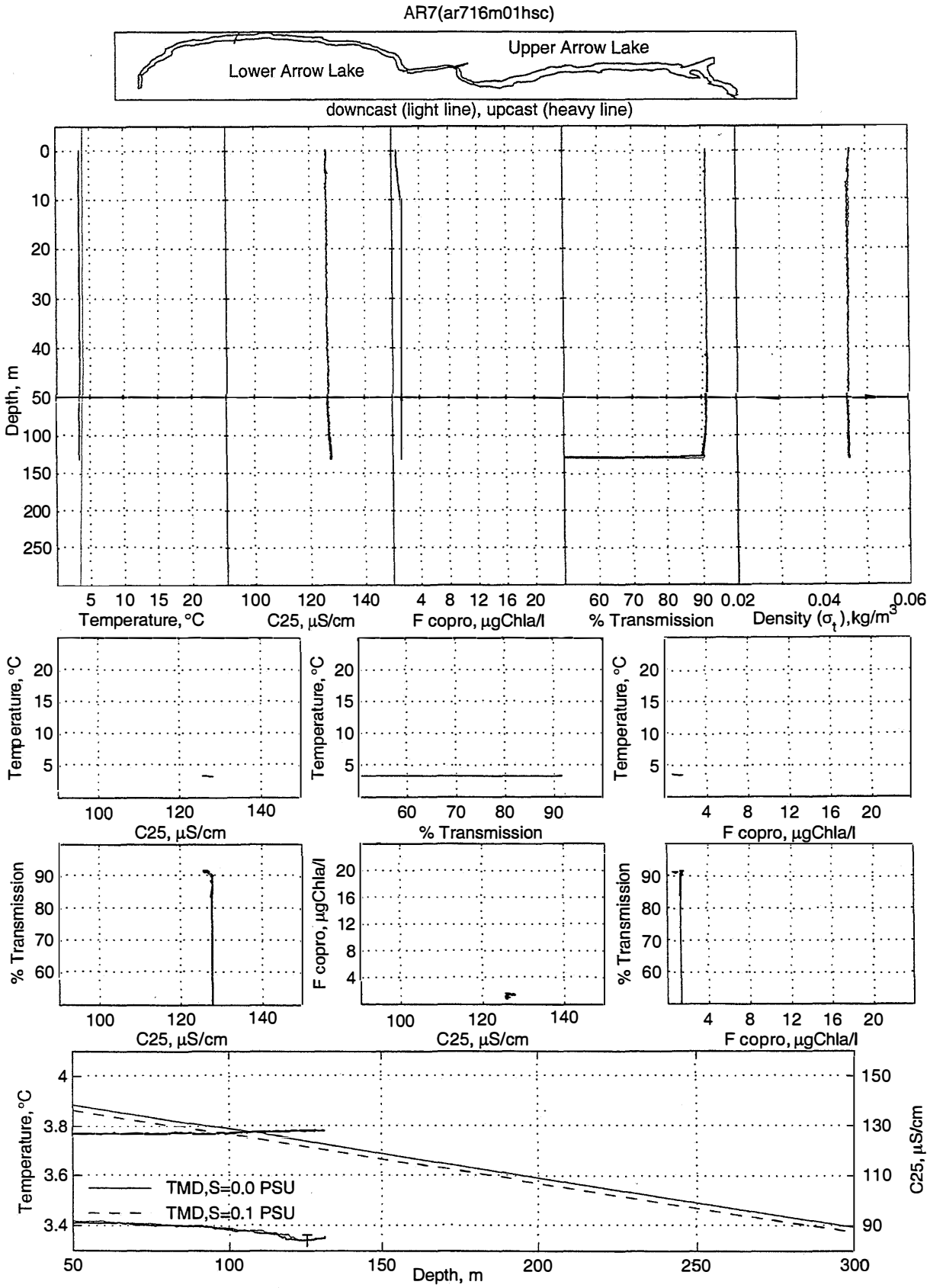


Figure 6.5f Seabird, Lower Arrow, AR7, **March** 2001.

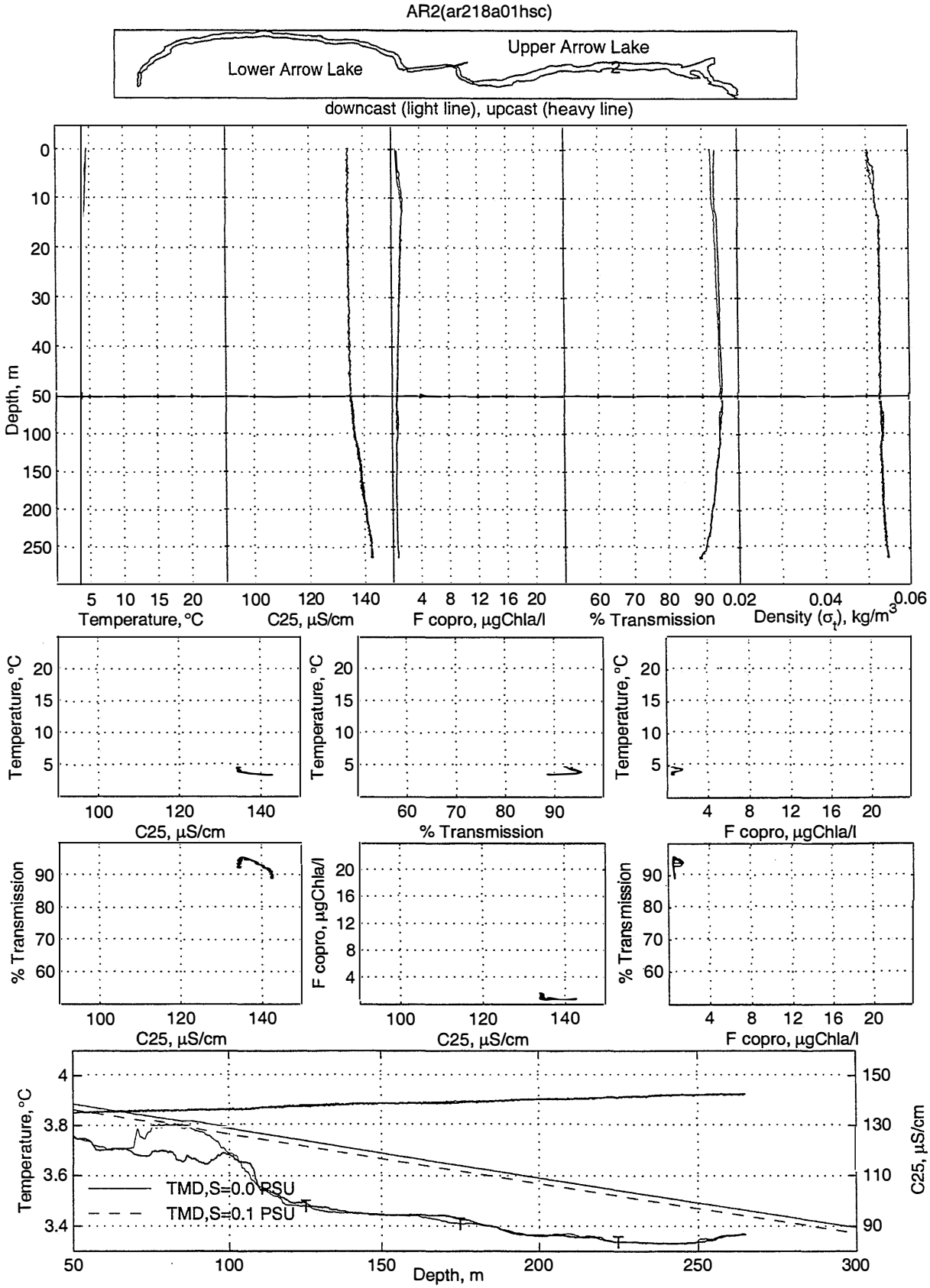


Figure 6.5g Seabird, Upper Arrow, AR2, **April** 2001.

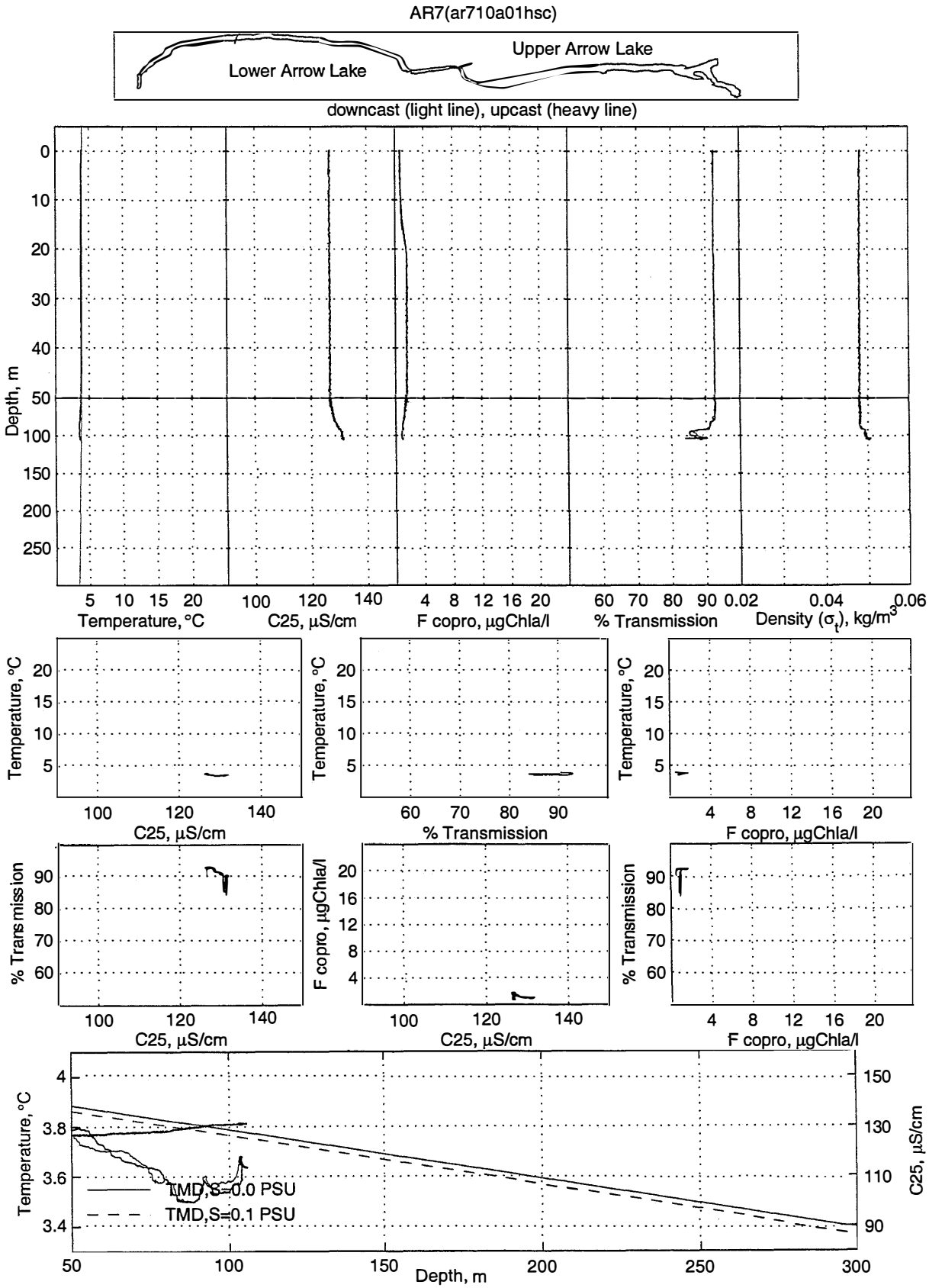


Figure 6.5h Seabird, Lower Arrow, AR7, **April** 2001.

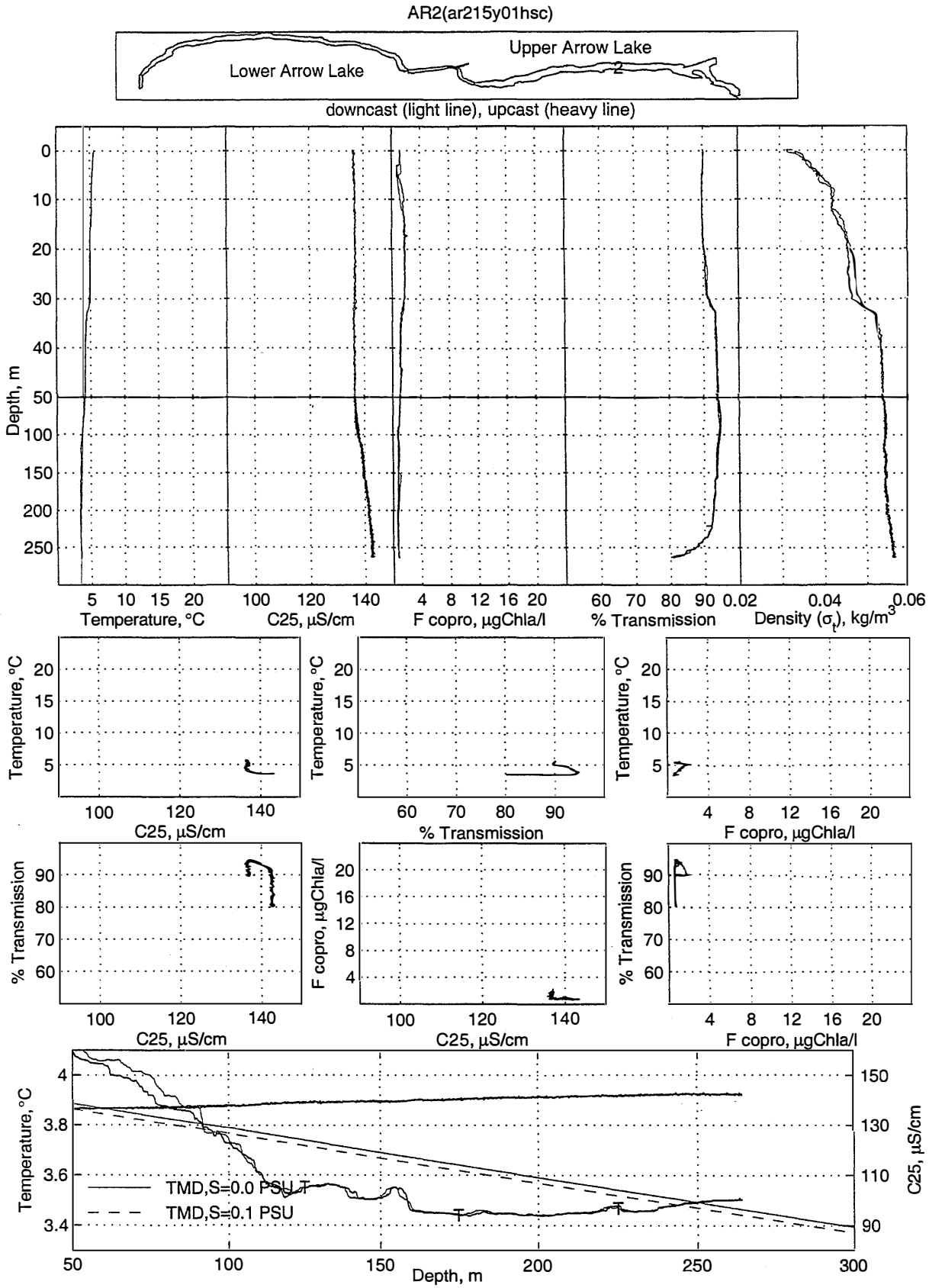


Figure 6.5i Seabird, Upper Arrow, AR2, **May** 2001.

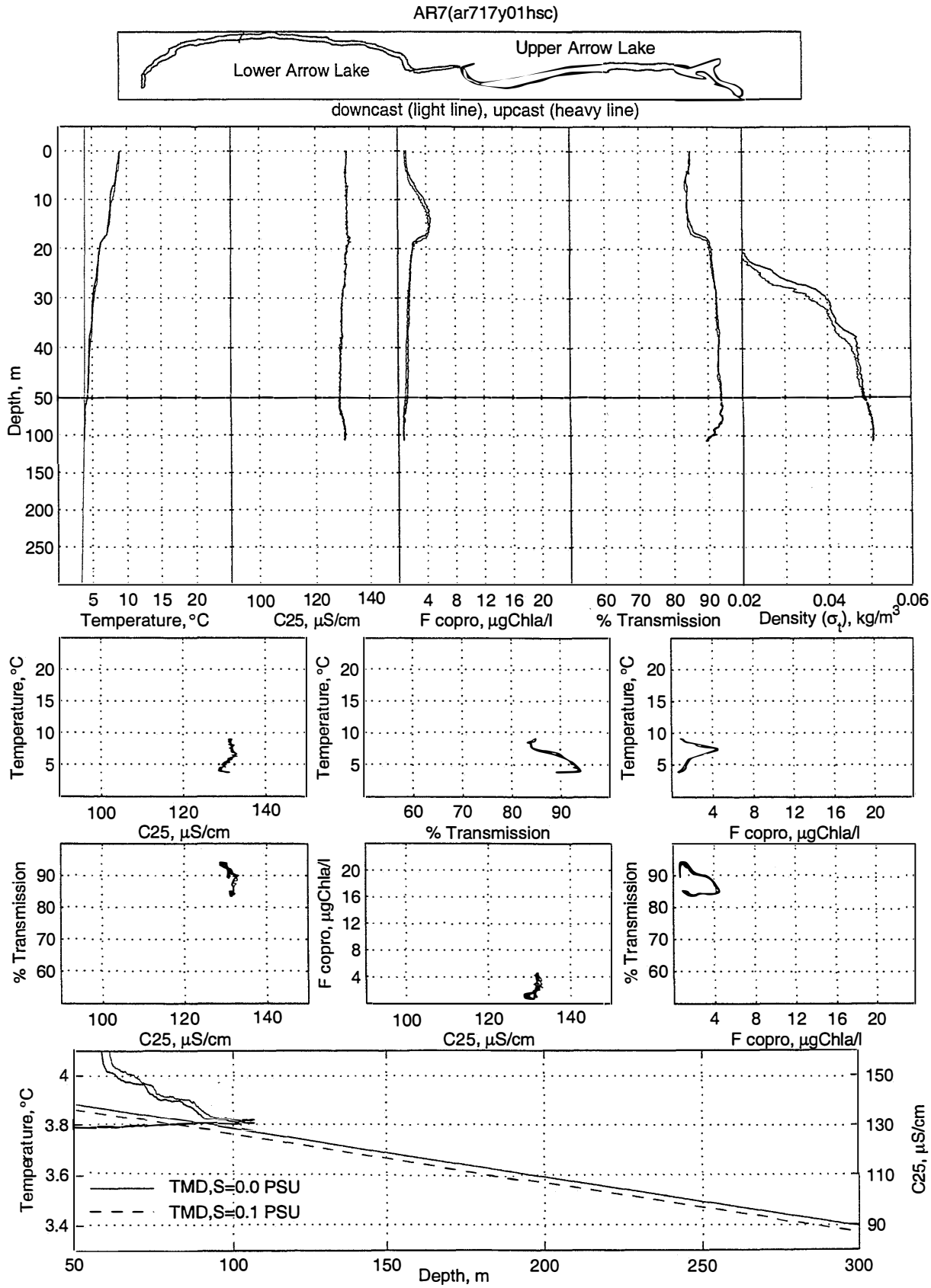


Figure 6.5j Seabird, Lower Arrow, AR7, **May** 2001.

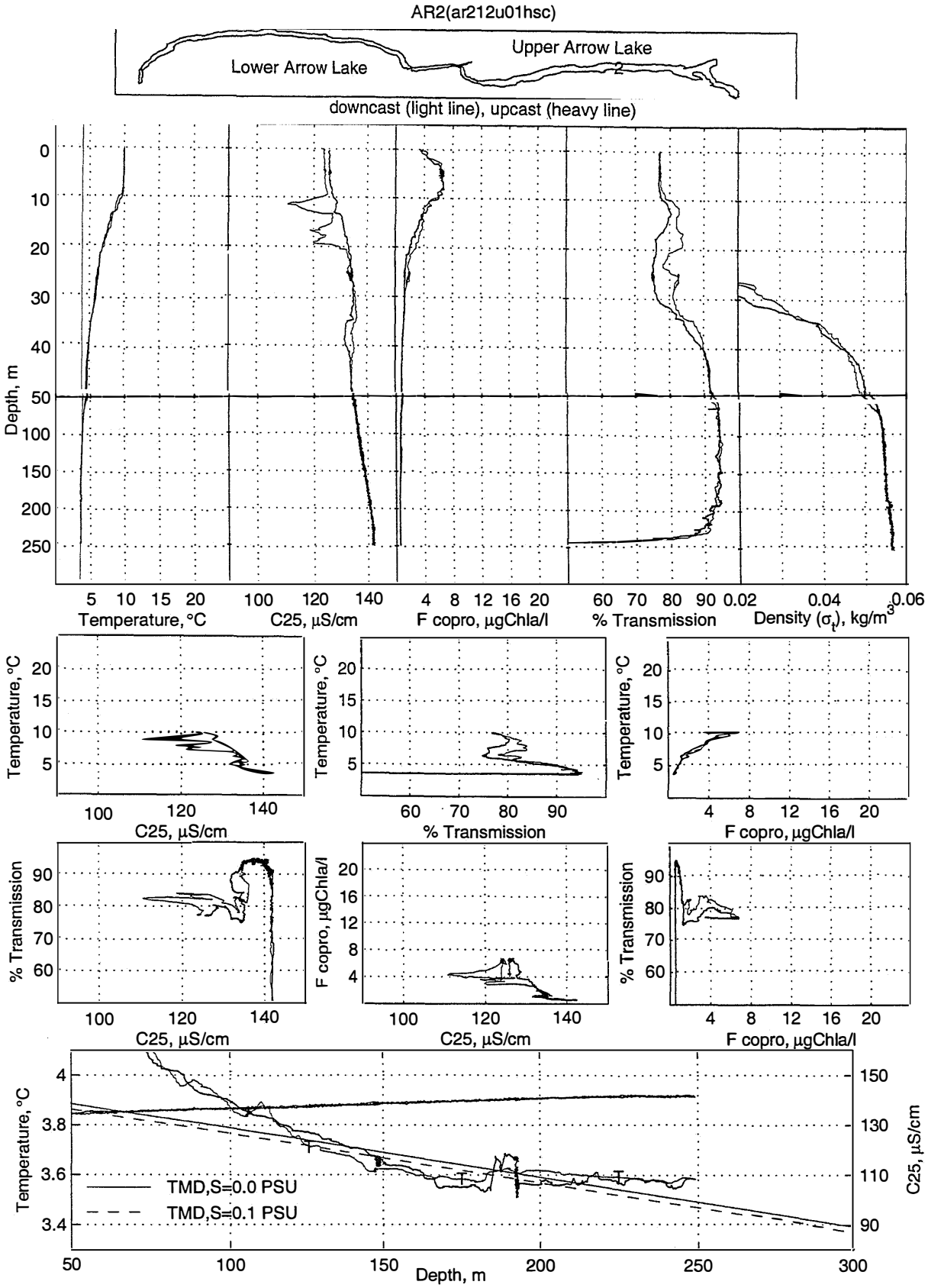


Figure 6.5k Seabird, Upper Arrow, AR2, **June** 2001.

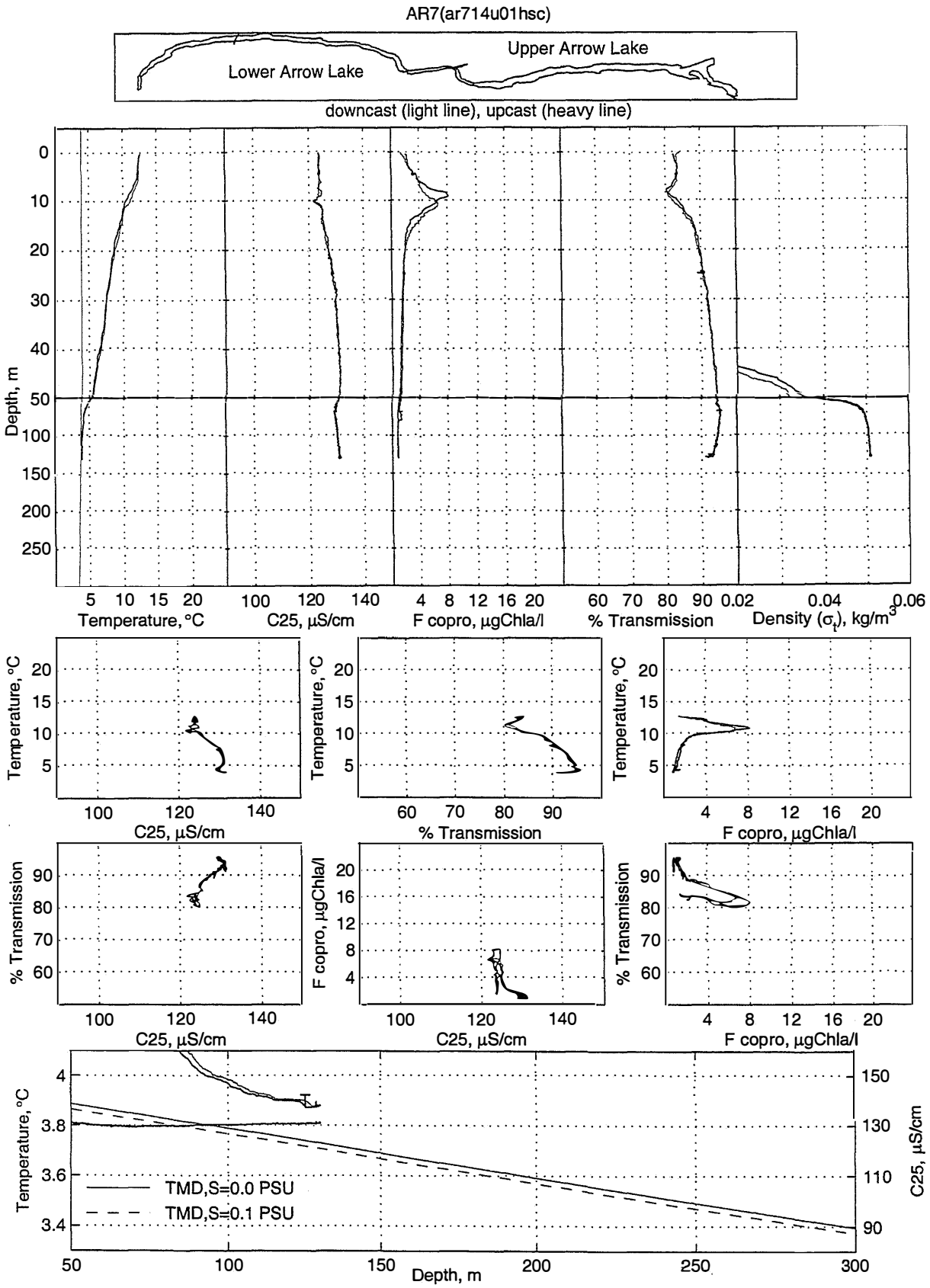


Figure 6.5l Seabird, Lower Arrow, AR7, **June** 2001.

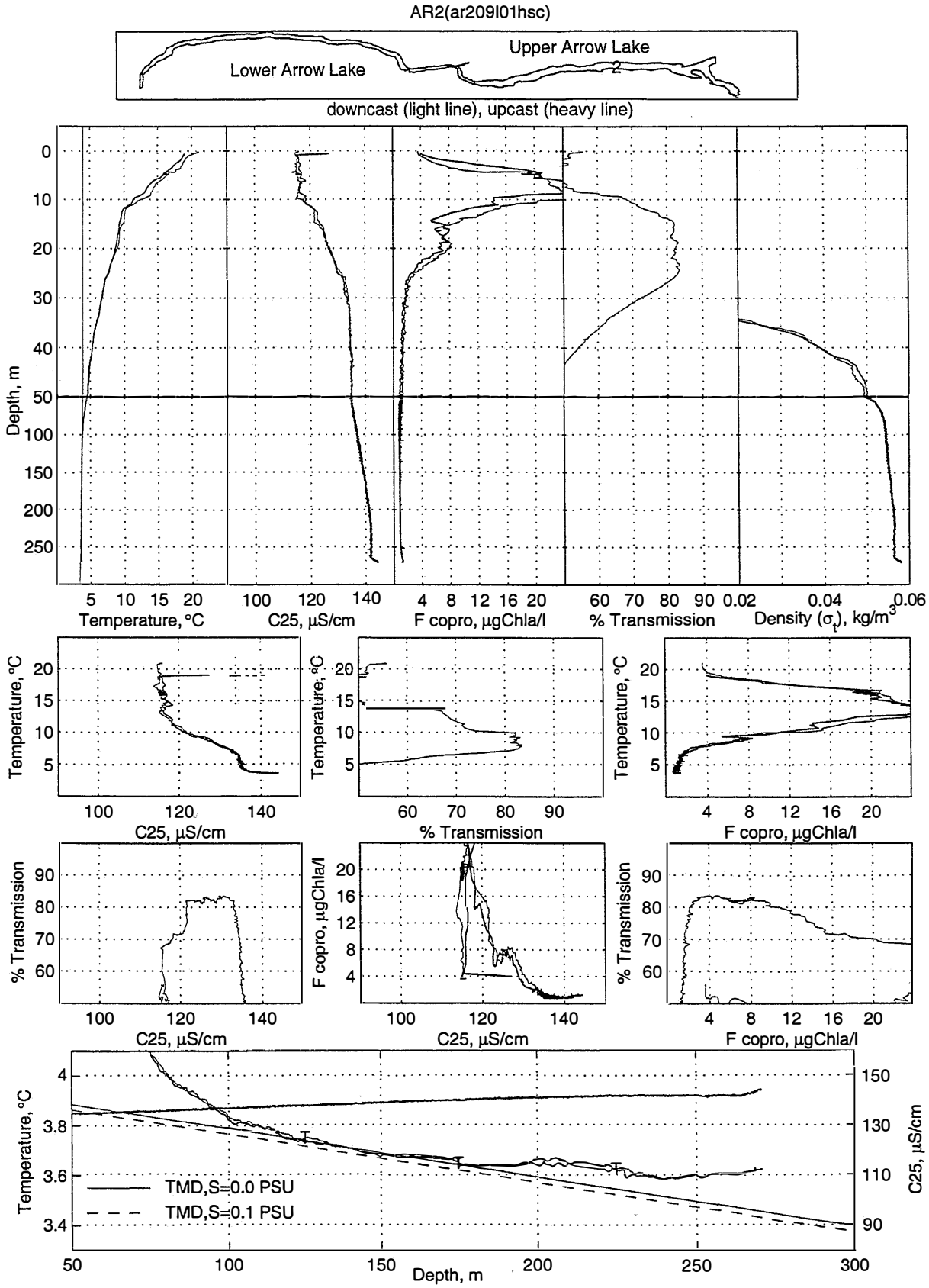


Figure 6.5m Seabird, Upper Arrow, AR2, **July** 2001.

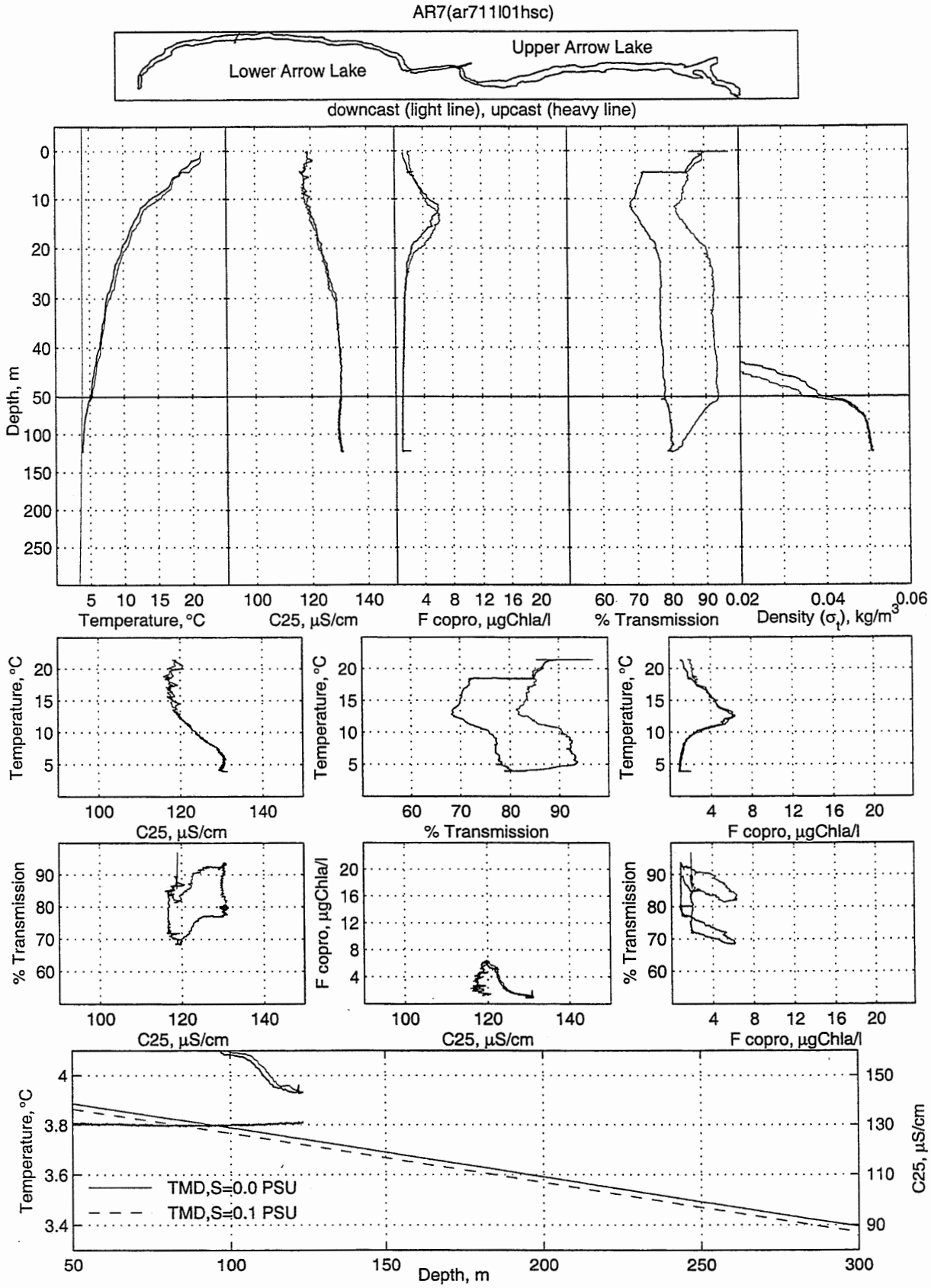


Figure 6.5n Seabird, Lower Arrow, AR7, **July** 2001.

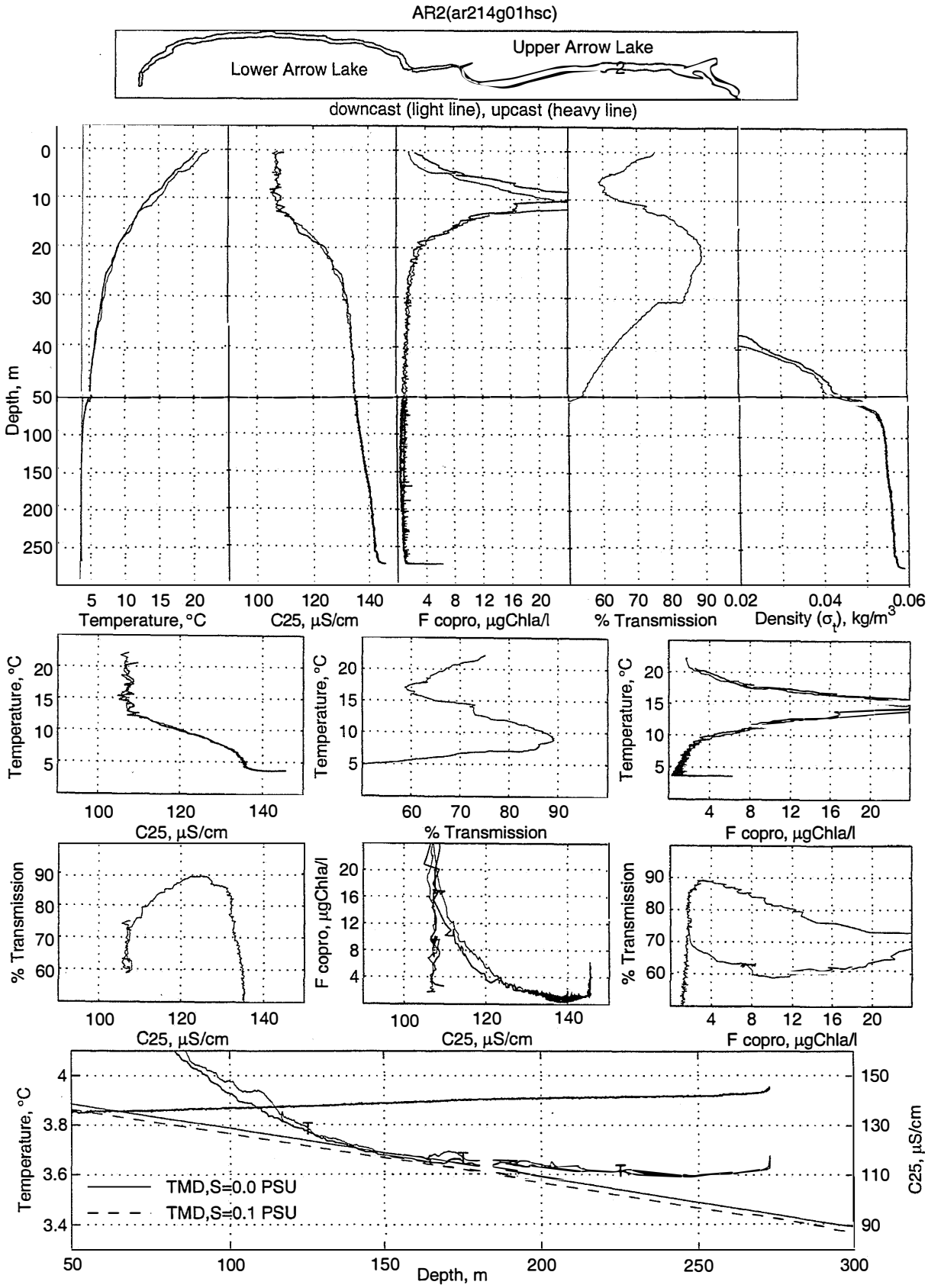


Figure 6.5o Seabird, Upper Arrow, AR2, **August** 2001.

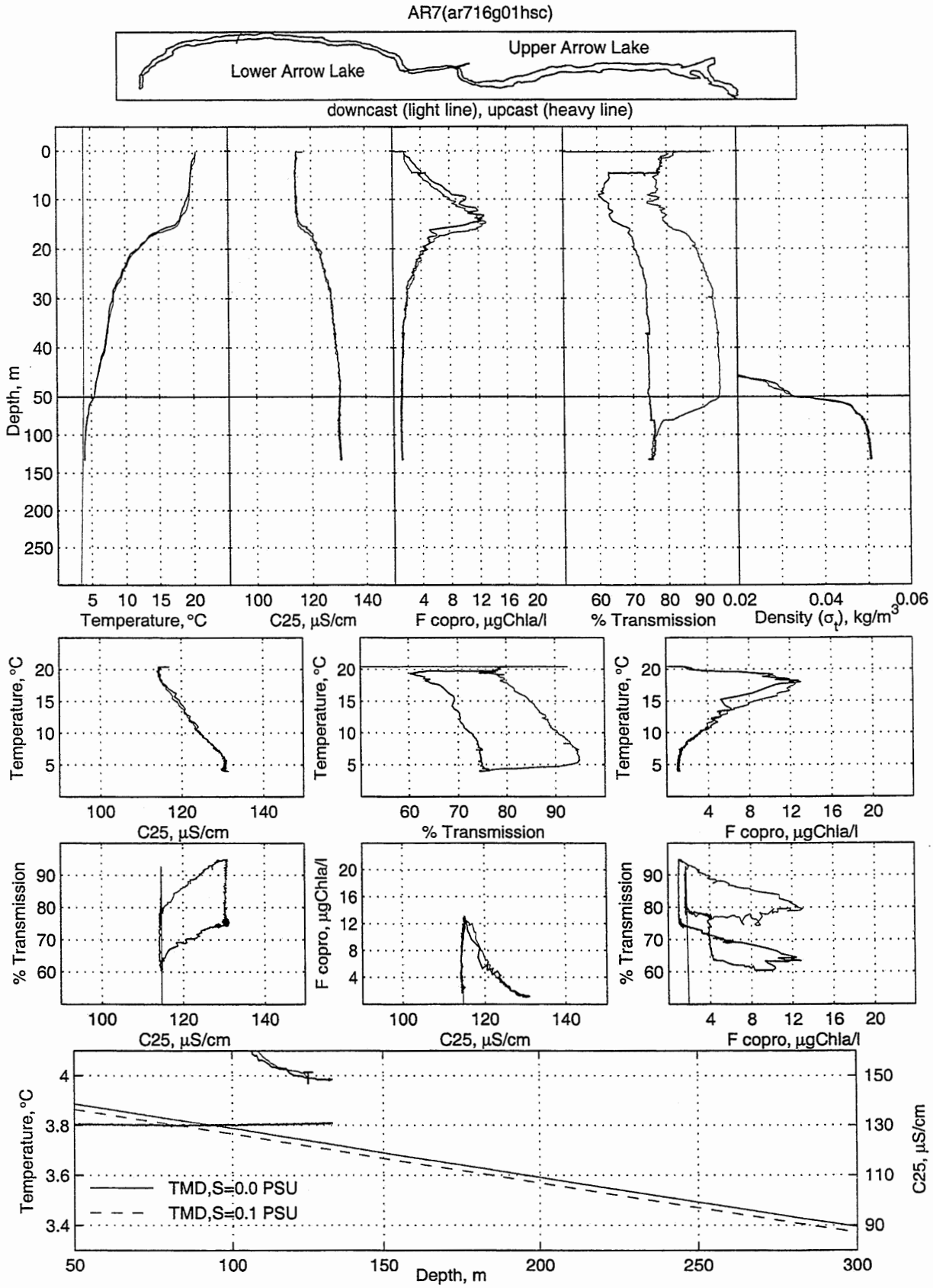


Figure 6.5p Seabird, Lower Arrow, AR7, **August** 2001.

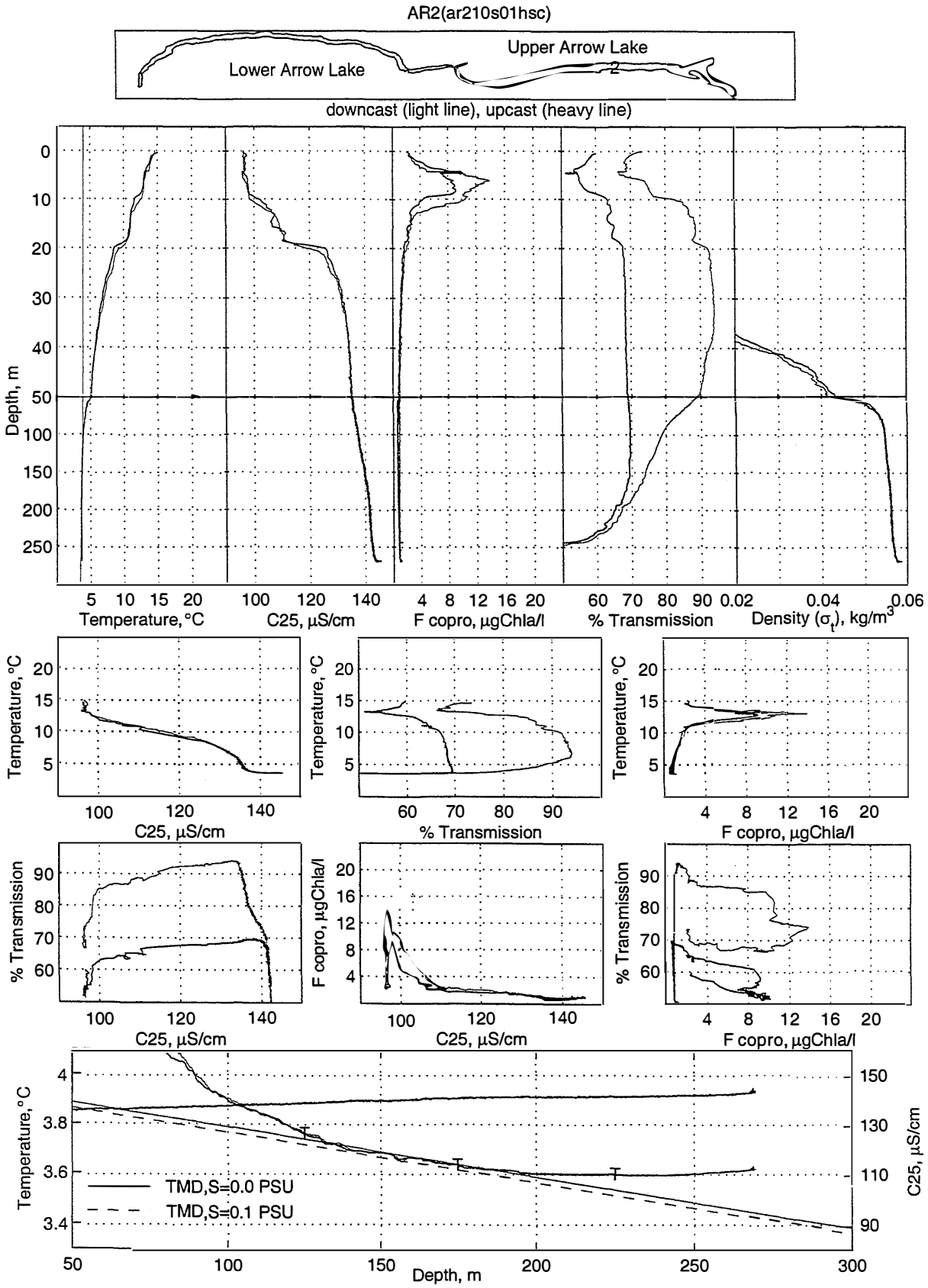


Figure 6.5q Seabird, Upper Arrow, AR2, **September** 2001.

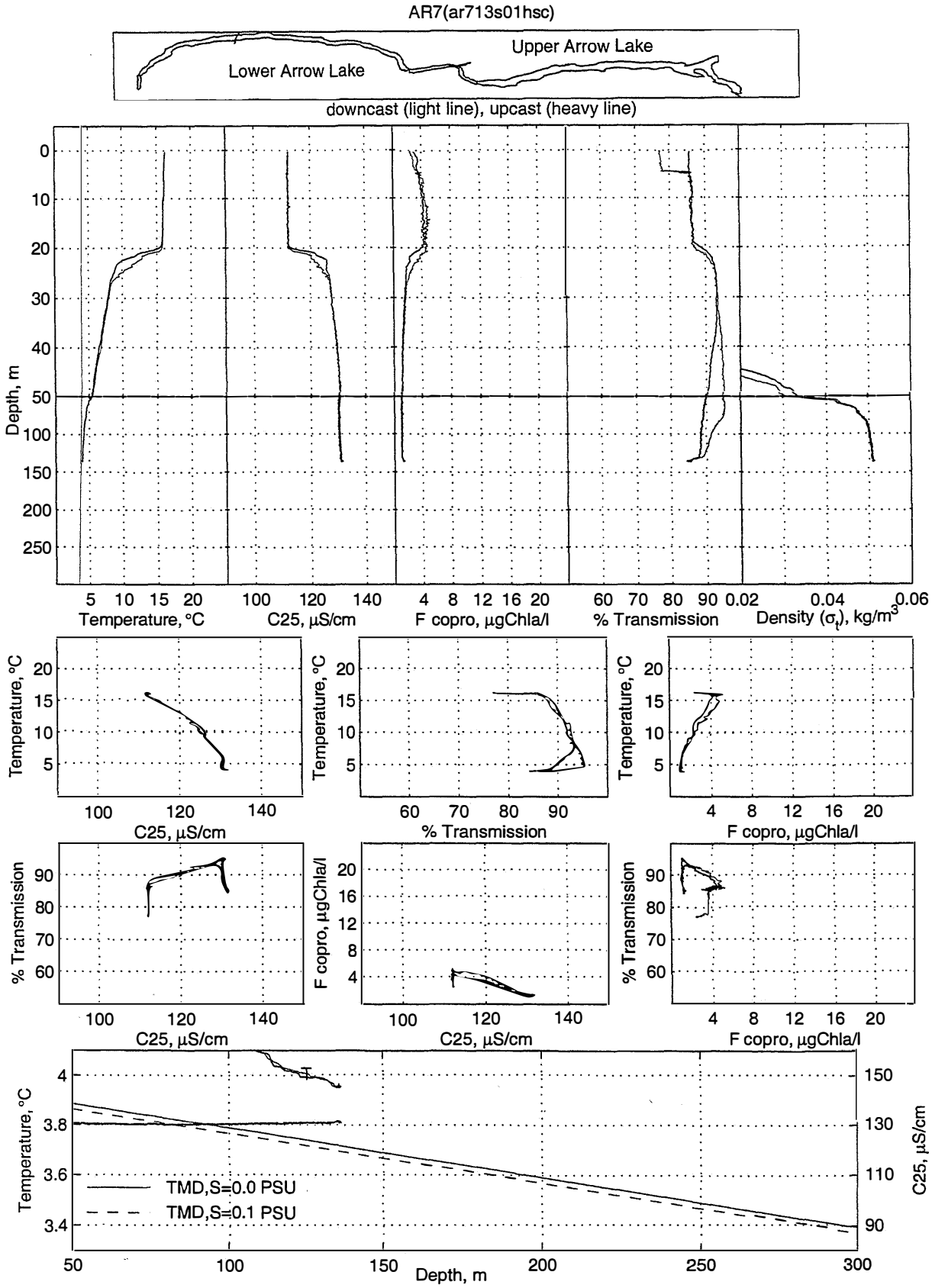


Figure 6.5r Seabird, Lower Arrow, AR7, **September** 2001.

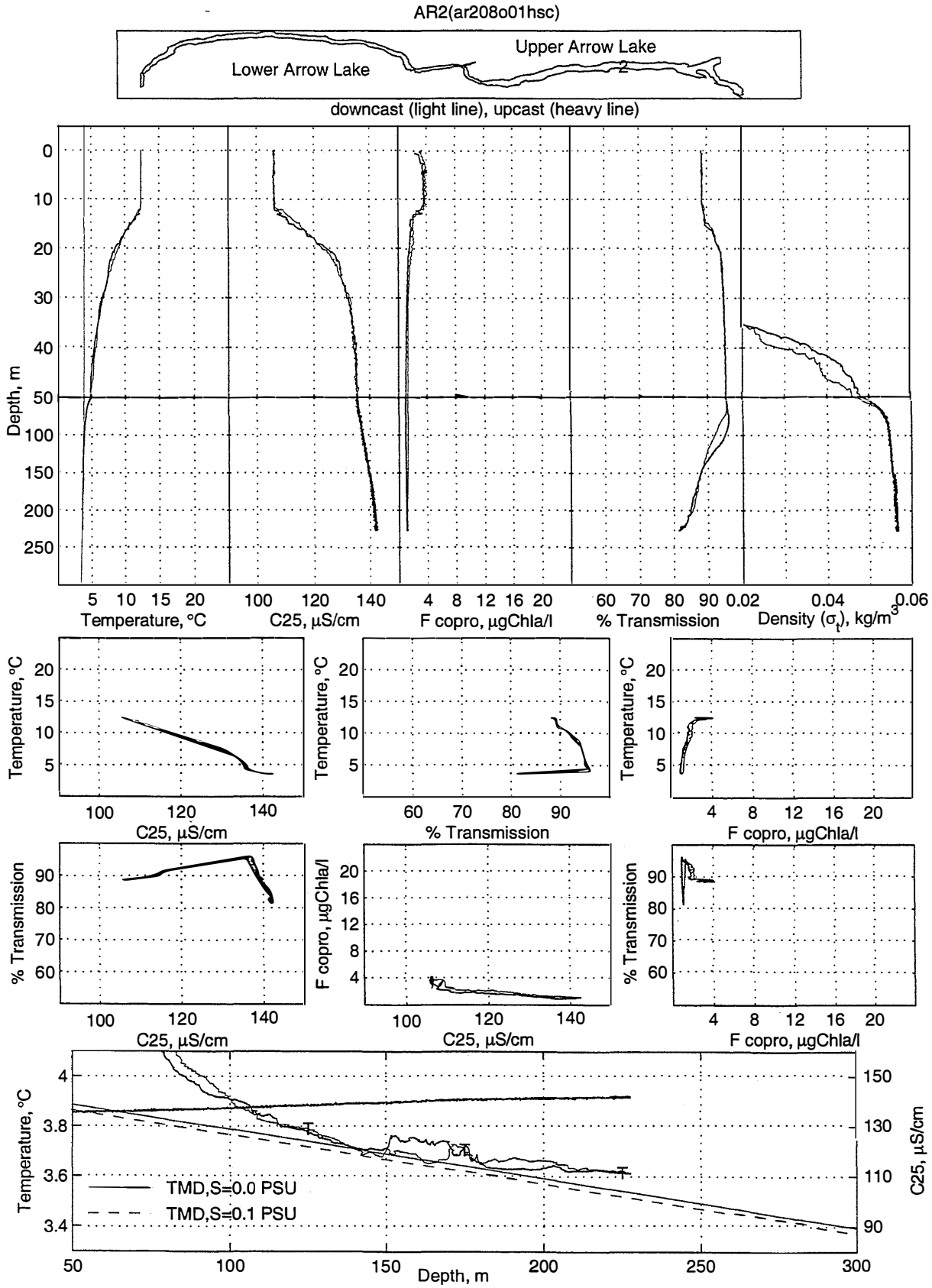


Figure 6.5s Seabird, Upper Arrow, AR2, **October** 2001. (No Oct. AR7 cast; Fig. 6.5t)

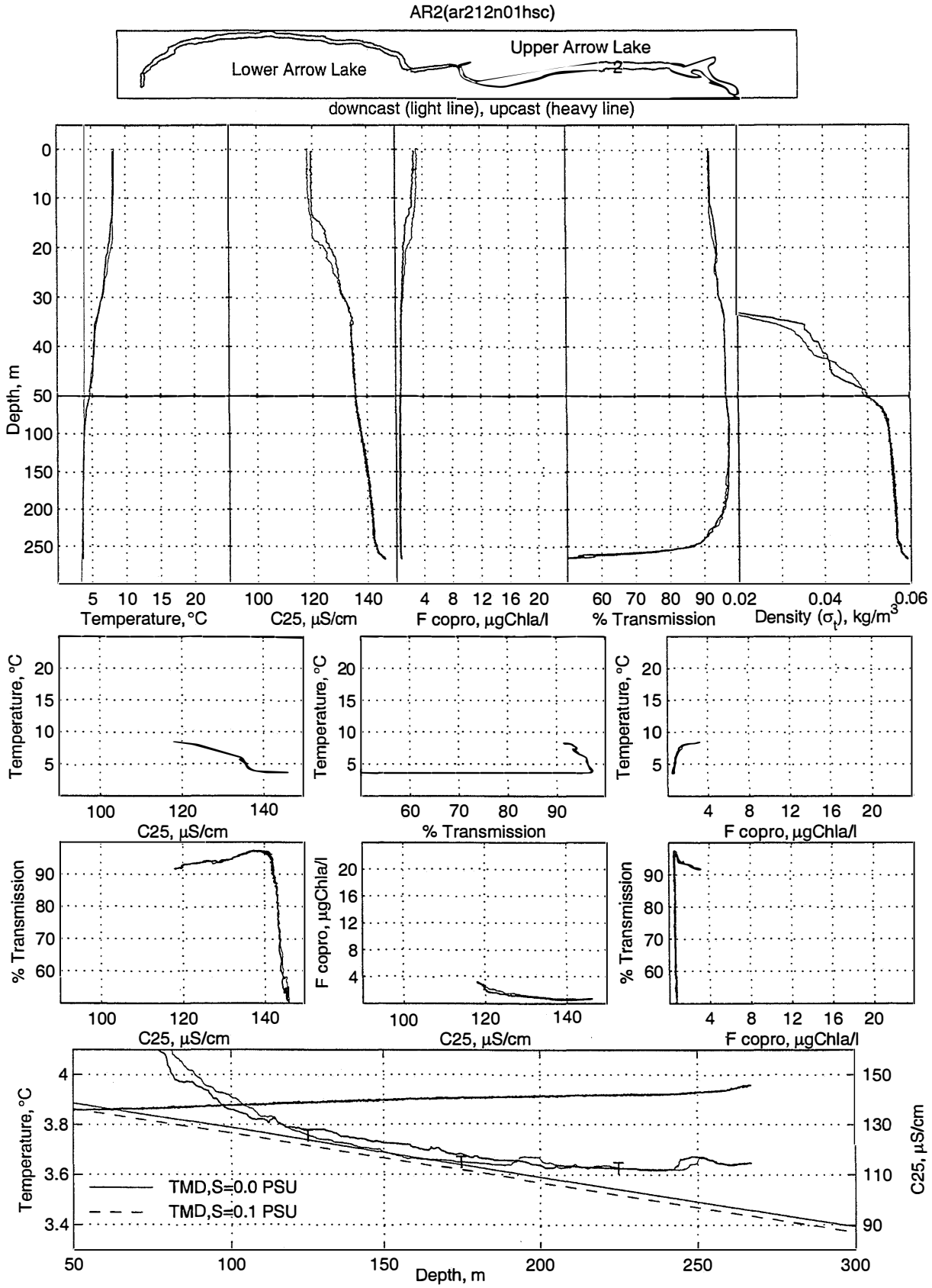


Figure 6.5u Seabird, Upper Arrow, AR2, **November** 2001.

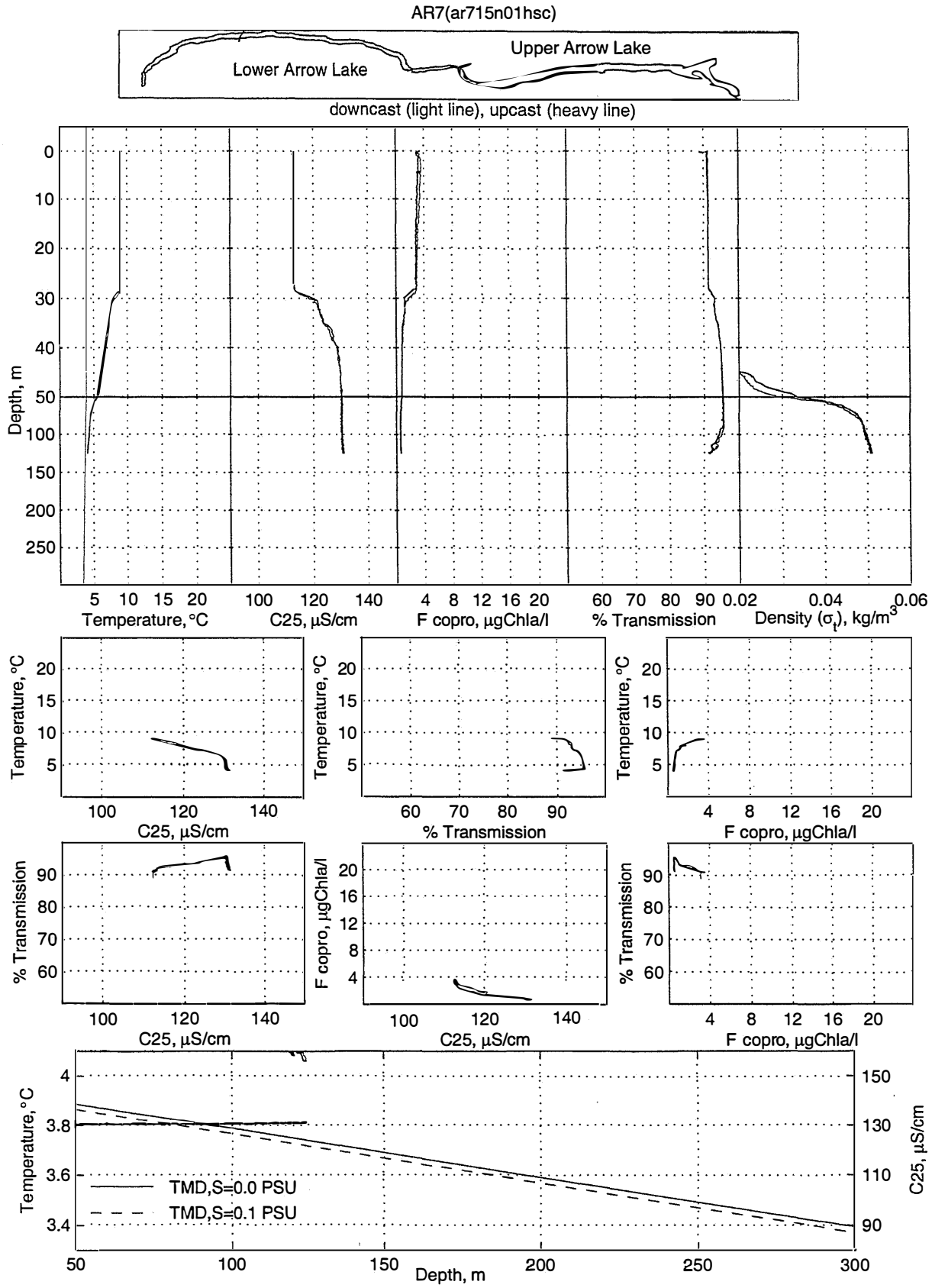


Figure 6.5v Seabird, Lower Arrow, AR7, **November** 2001.

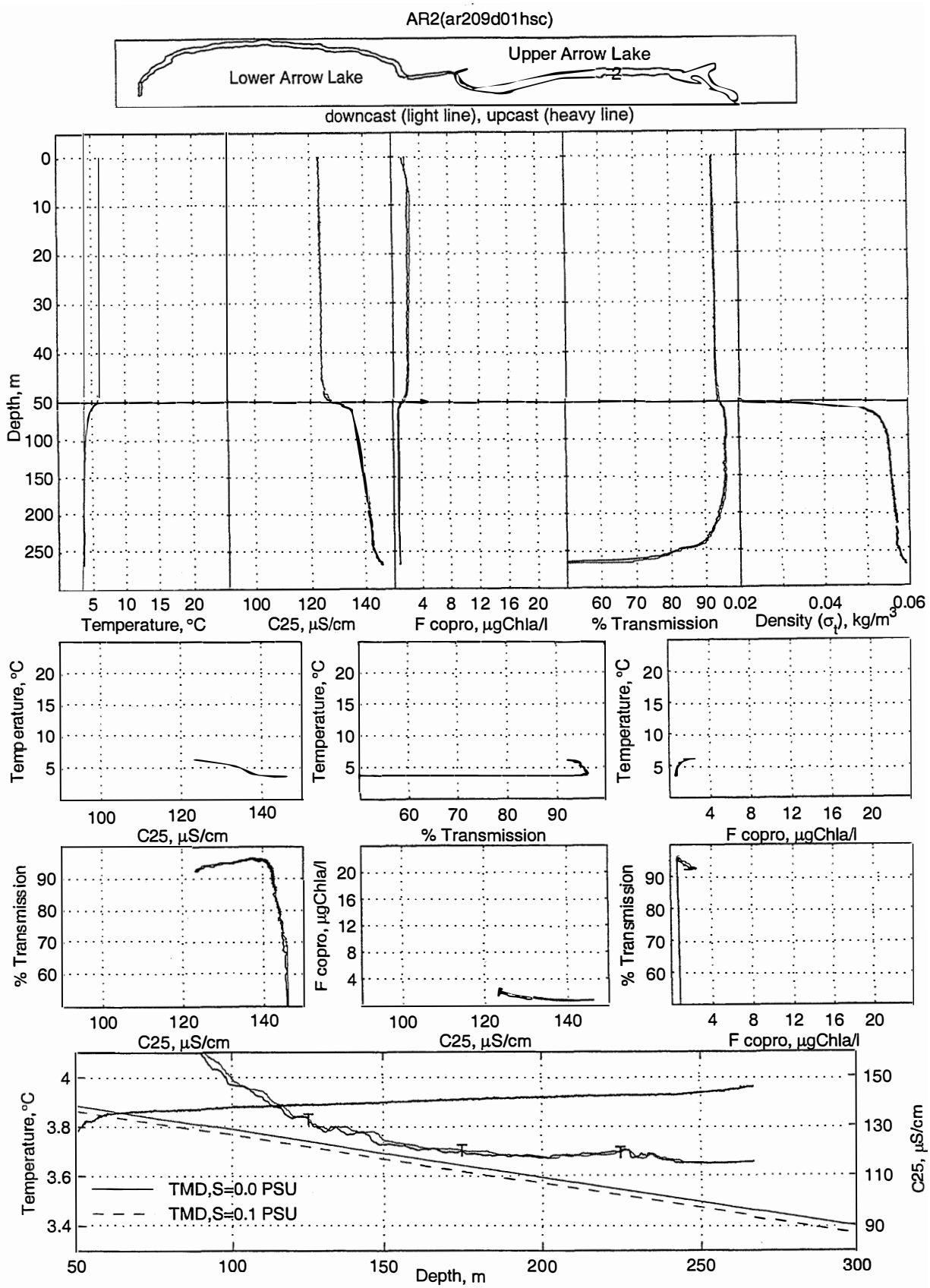


Figure 6.5w Seabird, Upper Arrow, AR2, **December** 2001.

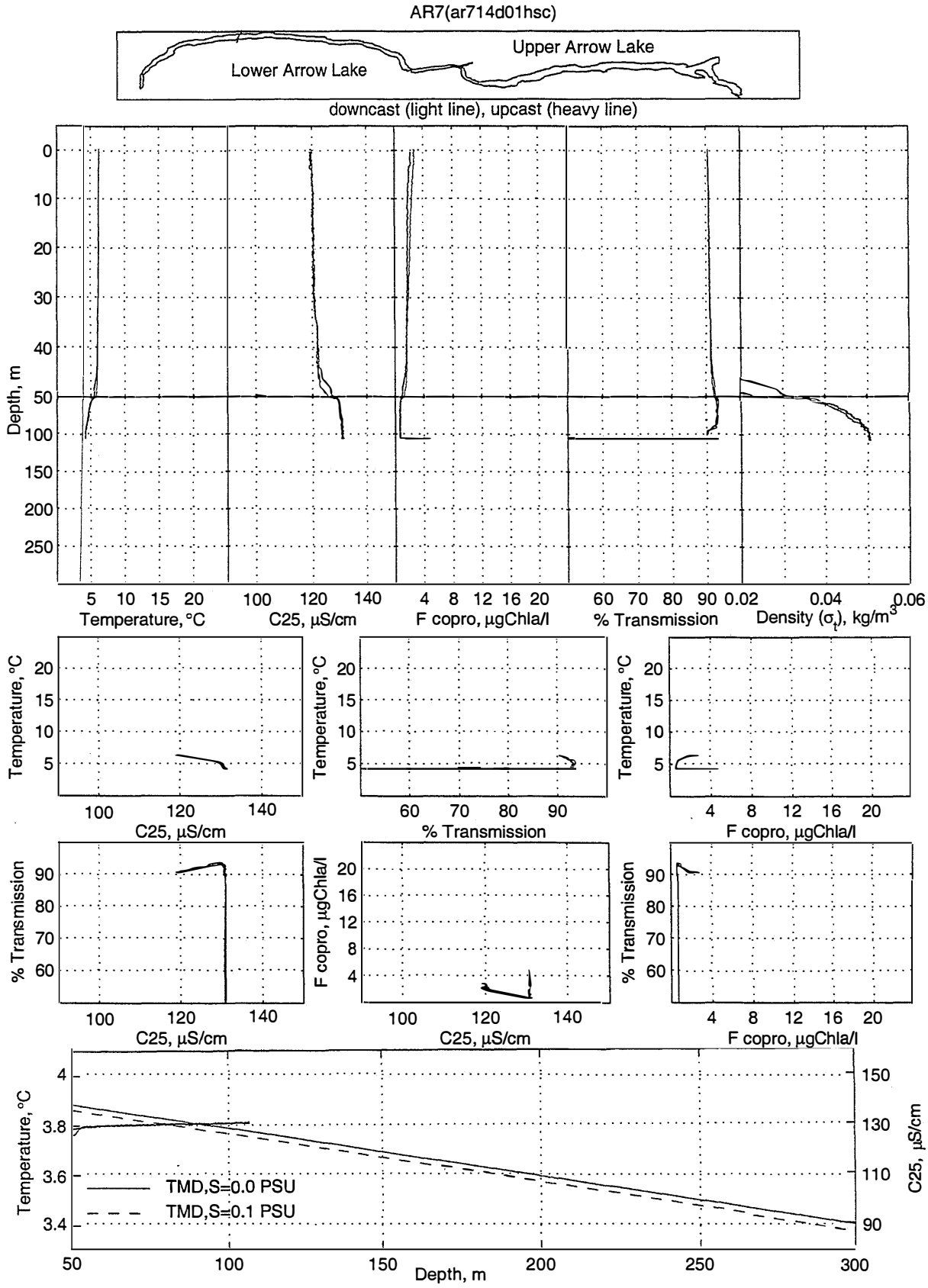


Figure 6.5x Seabird, Lower Arrow, AR7, **December** 2001.

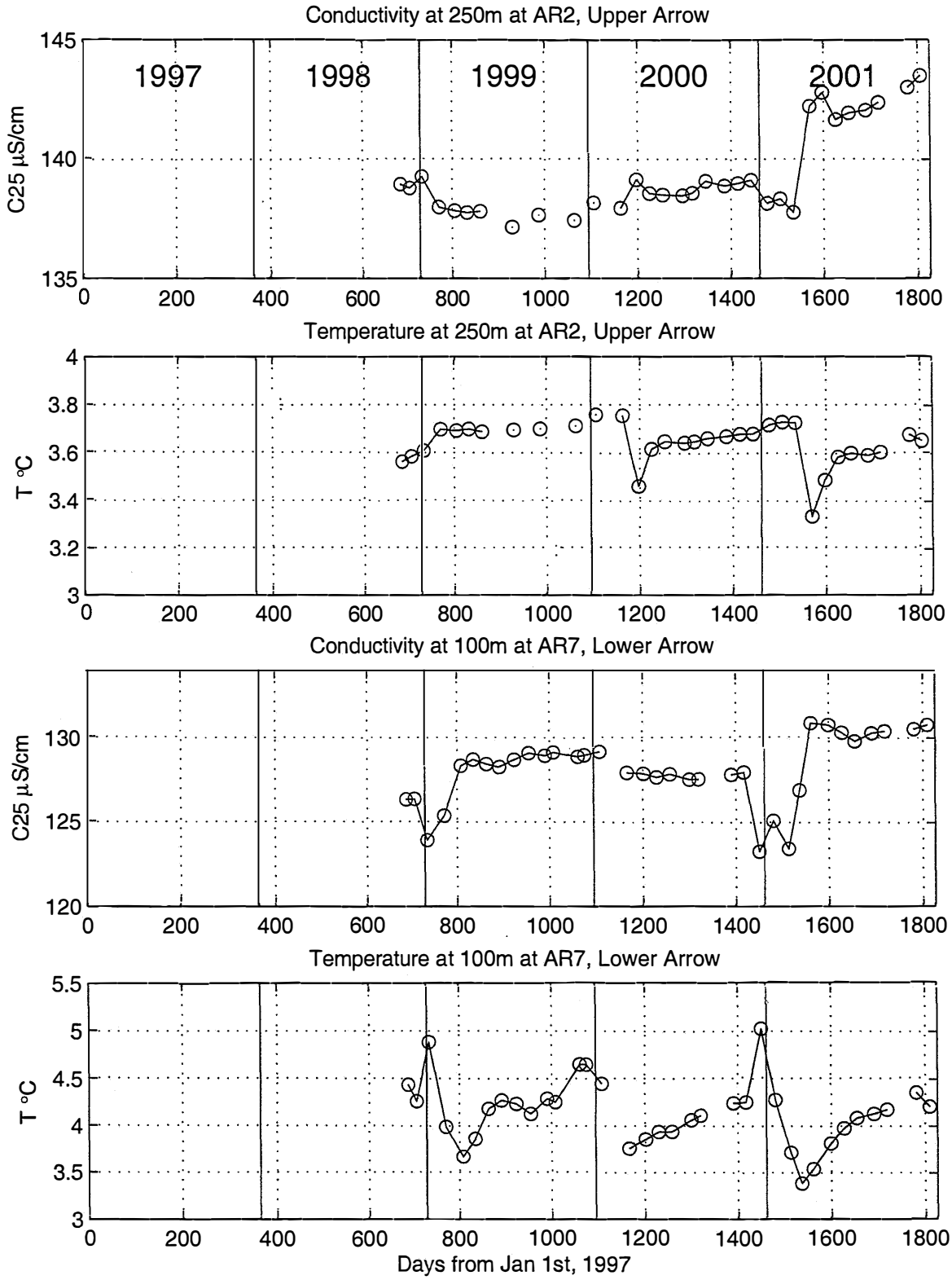


Figure 6.6 Deep temperature and conductivity in Upper and Lower Arrow.