Colonization and Community Development of Salmonids and Benthic Macroinvertebrates in a New Stream Within Kenai Fjords National Park, Alaska

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Draft Report to the National Park Service
Cooperative Agreement No. CA9-700-2-9021

August 1996

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Executive Summary

Delusion Creek in McCarty Fjord, Alaska, was studied intensively over three field seasons from 1992 to 1994 to investigate the colonization by salmonids and macroinvertebrates of a new stream system formed by glacial ice recession within the last 40 years. Although remnant ice remains within the watershed, the stream is principally fed by snow melt and by two lakes formed since recession. The stream was typically clear water at base flow, but high runoff events caused marked increases in stream and lake turbidities. Stream discharge was extremely variable during the summer months and in 1995 increased from a base flow of under 5 m^3s^{-1} to over 25 m^3s^{-1} after less than 48 hours of sustained rainfall. Discharge and prior rainfall records indicate that episodic spates (freshets) of this nature may occur 3 to 4 times annually. These relatively frequent spate events are a major factor in maintaining an unstable channel and increased turbidity levels, which restrict the abundance and diversity of invertebrates in the main stream channel even though water temperatures reach 9°C. The benthic community was dominated by chironomids and a low density of stoneflies. An unusually late rainy season in 1993, which resulted in stable flows through June and July, was a significant factor in increasing invertebrate density in the main channel, particularly among the chironomids. Diamesinae and Orthocladiinae were the principal chironomid families found. First-order feeder streams above the upper lake were found to support greater invertebrate diversity.

In less than 40 years, Delusion Creek has been colonized by sockeye, coho, and pink salmon. Two chinook salmon were also observed in 1994. Over 1000 sockeye salmon spawned in the upper lake in 1993. Ninety-three percent of these juveniles remain in the system two years to reach smolting

size. The kettle ponds south of the upper lake were found to be important rearing areas for juvenile coho salmon. In the main stream channel, Dolly Varden char were the dominant salmonid. Water chemistry of the lakes indicate that nitrogen is likely limiting primary productivity within the Delusion system. Experiments with artificial channels showed that enrichment with nitrogen and phosphorus increased chlorophyll-*a* levels and significantly reduced numbers of invertebrates drifting from the channels. We suggest that primary productivity and invertebrate abundance are (have been) enhanced by the colonization of the (a) system by anadromous salmon. Salmon spawners may, thus, act as a positive feedback to the productivity of these new stream systems.

Introduction

This report marks the completion of a cooperative agreement between the National Park Service (NPS) and the University of Alaska Anchorage's Environment and Natural Resources Institute (ENRI). This study examined the colonization and community development of macroinvertebrates and salmonids within the Delusion Creek watershed in McCarty Fjord, Kenai Fjords National Park. The park was set aside, in part, to protect the environmental integrity of fjord ecosystems of which aquatic invertebrates and anadromous fish provide an integral biological component and linkage to the sea. Salmon runs have colonized drainages within McCarty Fjord that have developed due to glacial recession this century. Two drainages (Delight Lake and Desire Lake) and their associated streams that have been deglaciated since the 1930s support commercial fishing for sockeye salmon in McCarty Fjord. A third drainage, Delusion Creek (unofficial name), lying north of Delight and Desire Creeks, was progressively deglaciated between 1950 and 1978 (Post, 1980). This report will introduce the concept of succession and disturbance in streams and examine the data from this study with particular reference to a proposed model for glacial stream development (Milner and Petts, 1994).

Site Description

Kenai Fjords National Park

Located in southcentral Alaska, Kenai Fjords National Park caps the southern tip of the Kenai Peninsula. The park overlays an area of approximately 2630 km^2 in the Kenai Mountains bordering the Gulf of Alaska. It is dominated by the massive Harding Icefield and

Grewingk-Yalik Ice Complex, which are interspersed with peaks greater than 2000 m and drained by 38 distinct outlet glaciers (Wiles and Calkin, 1989). Predominant vegetation in the park (areas either not glaciated or deglaciated for more than 150 years) consists of a mixed Sitka spruce (*Picea sitchensis*) and Mountain Hemlock (*Tsuga mertensiana*) forest (Helms and Allen, 1995). A coastal temperate forest, precipitation ranges from 30 to 100 cm/yr with a mean annual temperature of 2.7°C (Rice, 1987).

Study Area

The Delusion Creek Drainage lies in upper McCarty Fjord (Figure 1) in Kenai Fjords National Park, 96 km southwest of Seward. The fjord is approximately 30 km long terminating to the north at McCarty Glacier. McCarty Glacier is an active tidewater glacier that reached its Neoglacial maxima in 1860 (Figure 1) and has since undergone a catastrophic retreat exposing three stream systems (Delight, Desire, and Delusion) along its eastern shore (Post, 1980).

The Delusion Creek system, the youngest of the three, was progressively deglaciated between 1942 and 1980. Figure 2 is an aerial photograph taken in 1952 (scale 1:40,000) showing that a remnant ice sheet still covered the majority of the watershed. The present-day lakes have yet to form and the existing stream runs along the west side of the valley. An aerial photograph (scale 1:63,000) taken in 1978 (Figure 3) shows the remnant sheet having receded to the upper end of the watershed. Lower Delusion Lake is emergent, while Upper Delusion Lake remains partially covered by a remnant ice sheet. In comparing the two aerial photos, it is of particular interest that the three tributary glaciers along the east side of the watershed appear to have retreated more rapidly than the main valley

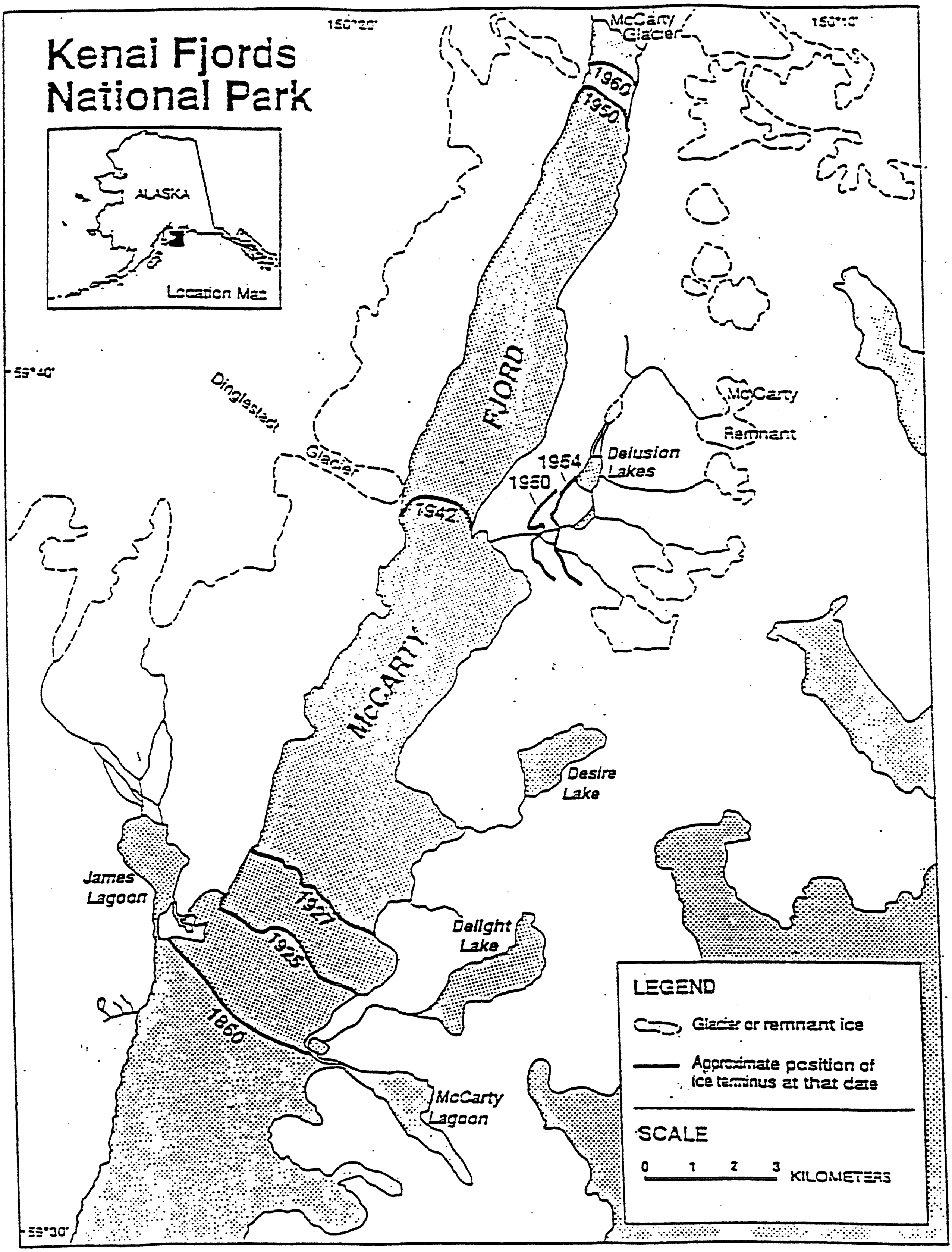


Figure 1. Study area, McCarty Fjord in Kenai Fjords National Park.

Figure 2: Delusion Creek Drainage 1952 (Aerial Photo, USAF).

Figure 3: Delusion Creek Drainage 1978 (Aerial Photo, USGS).

glacier. This suggests the possibility of differential deglaciation within the Delusion Creek watershed. Figure 4 is a conglomerate of aerial photos taken during summer 1993 (scale approximately 1:25,000). In this photo, Delusion Creek runs along the east side of the valley and both lakes are completely formed (Lower Delusion Lake has an area of approximately 0.15 km^2, while Upper Delusion Lake is approximately 0.50 km^2). Two small cirque glaciers remain in the watershed draining into the lower lake and the midportion of the stream, respectively.

Delusion Creek is a large second-order stream approximately 2.5 km in length. A clear-water stream, Delusion flows over unconsolidated glacial till into McCarty Fjord. Observed peak flows occur during summer storm events, and it is assumed that spring snow melt generates significant though lesser peaks.

Unlike its famous sibling to the south, Glacier Bay National Park, Kenai Fjords National Park, which was created in 1978, has received scant scientific attention. However, Helms and Allen (1995) suggest the McCarty Fjord area demonstrates a unique pattern of vegetation succession when compared to their study area of Exit Glacier, near Seward, or the classic studies in Glacier Bay. The dominant early colonizing species in McCarty Fjord was *Alnus sinuata* in contrast to *Populus balsamifera* at Exit Glacier or *Epilobium latifolium* and *Dryas drummondii* in Glacier Bay (Helms and Allen, 1995). Vegetation in McCarty Fjord may, however, be similar to sites in Prince William Sound described by Cooper (1942). The majority of the Delusion Creek watershed lacks a well-developed soil, and the landscape is characteristic of glaciated terrain.

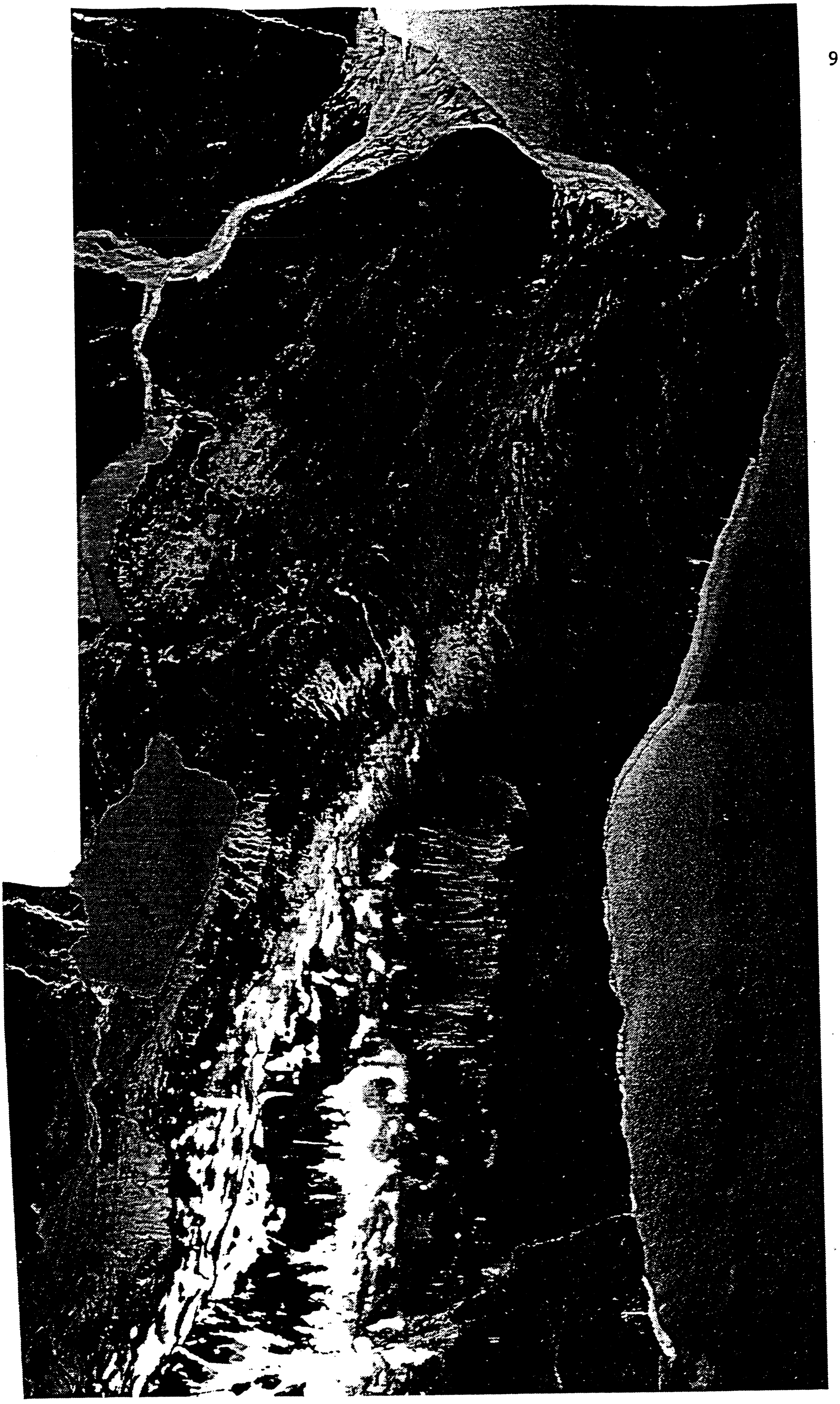


Figure 4: A composite aerial photo of Delusion Creek (scale 1:25,000)

Sampling Sites

Four sampling stations were established along Delusion Creek: stations 1 and 2 at approximately 1 km and 1.5 km, respectively, upstream from the mouth and below the lower lake (Figure 5); and stations 3 and 4 located above Upper Delusion Lake in feeder streams from remnant ice (Figure 5). Due to the extreme instability of site 3 during 1992, it was subsequently moved upstream for the 1993 sampling period. These sites will be referred to as sites 3a and 3b, respectively, for statistical analyses. Table 1 depicts average quantitative as well as qualitative characteristics for each sampling site and any difference in these measurements between years at sites 1 and 2.

Table 1. Sampling site histories for Delusion Creek.

	Site					Difference by Year	
	1	2	3a	3b	4	1	2
Age	32	28	12	11	18	NA	NA
Substrate Size (cm)							
Velocity (m/s)	0.49	0.42	NA	0.46	0.623	0.11	-0.01
Depth (cm)	21.6	23.83	NA	17.83	24.43	3.3	0.9
Algal Growth (1-5)*	1	1	1	2	2	0	0
Temperature (°C)	6.5	6.3	3.7	6	5	1.5	1.5
Stability	Unstable	Moderate	Unstable	Stable	Stable	Same	Increased

*1= negligible, 5 = extensive.

The Desire Lake Drainage was deglaciated between 1935 and 1940, and the Delight Lake Drainage between 1920 and 1925 (see Figure 1). The

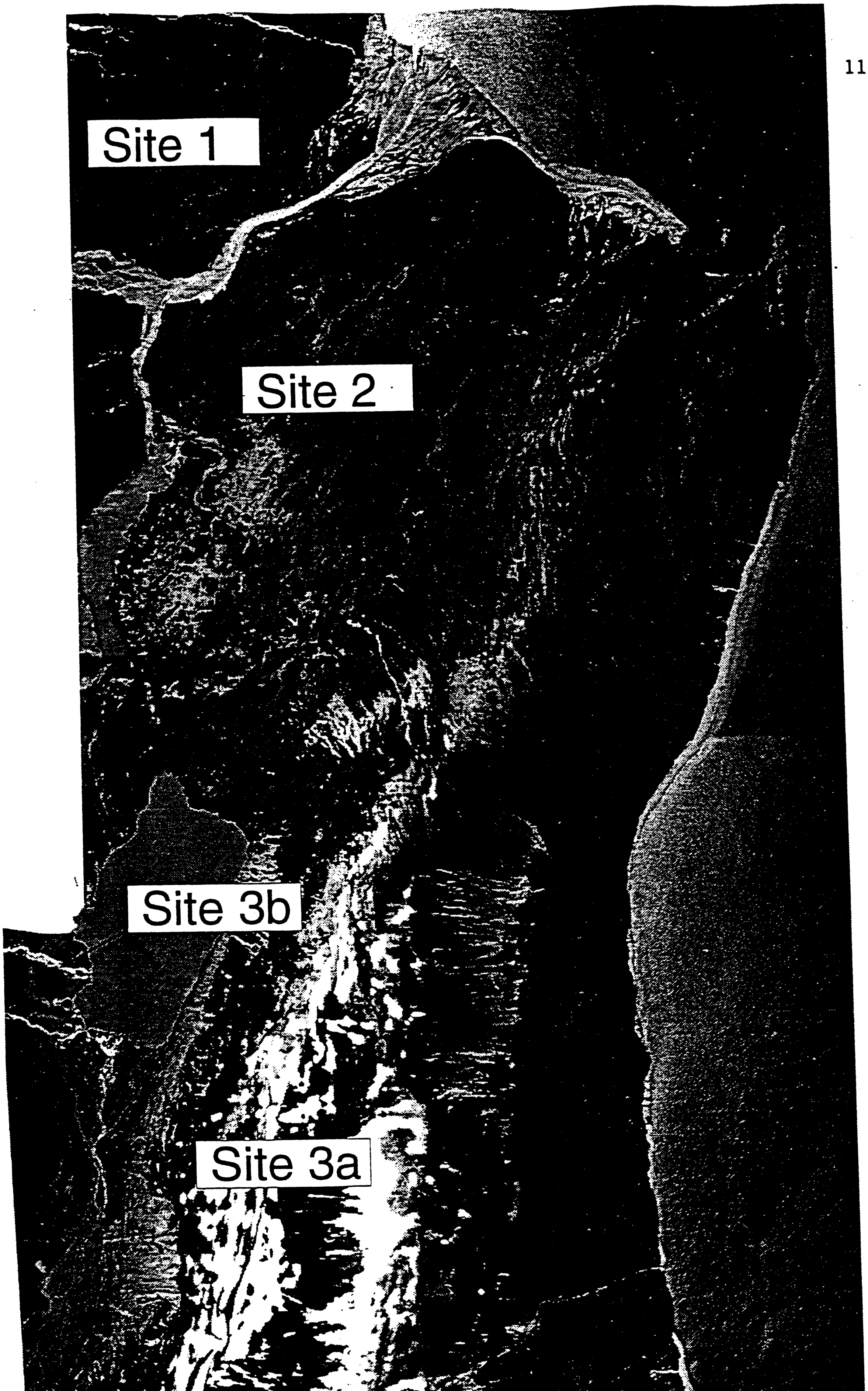


Figure 5: Stream sampling stations along Delusion Creek.

area of Desire Lake is approximately 2.5 km^2 and Delight Lake is approximately 3 km^2. Vegetation along Desire Creek is dominated by old growth alder *(Alnus* sp.), while Delight Creek supports an immature spruce (*Picea sitchensis*) forest. Delight and Desire Creeks were not sampled in 1994. Desire Creek is approximately 2 km in length and Delight Creek is approximately 3.5 km in length. All three systems are of comparable size, similar origin, and possess relatively large lakes that potentially buffer flow and settle out coarse particulates.

Recently deglaciated areas such as McCarty Fjord and Glacier Bay National Park (see Milner, 1987; Milner and Bailey, 1989; Milner, 1994) are unique in that they offer an opportunity to study colonization and development of aquatic communities through primary succession sequences on an entire watershed basis. In addition, the presence of the two older stream systems in McCarty Fjord provide a potential chronosequence, of approximately 70 years, for a comparative study of changes in biotic community structure over time in stream systems of equivalent nature.

Invertebrate Communities

Background

The importance of invertebrates to the overall functioning and health of stream ecosystems is well documented (Vannote et al., 1980; Cummins et al., 1984; Winterbourne, 1986). Invertebrates play an integral role in the processing of leaf litter as well as in the exporting of fine particulate organic matter (FPOM) to downstream communities (Luthgart and Wallace, 1992; Irons et al., 1994). "The invertebrates constitute a useful link between the quantitatively significant microorganisms and the economically important fish. Individuals are relatively large and numerous, usually have annual or seasonal life cycles, and associations are functionally organized in relation to habitat and nutritional resources" (Cummins et al., 1984). Therefore, a thorough understanding of the nominal community structure of stream invertebrates, as well as the effects of disturbance and subsequent recovery times, is crucial in stream ecology studies. Furthermore, studies examining disturbance and recovery necessarily involve successional processes (Fisher, 1990). Knowledge on the effects of and recovery processes following a disturbance will be useful in stream restoration projects and in determining regulatory standards for water quality.

Given some of the terminology involved in this discussion, it is appropriate to offer some definitions. Pickett and White (1985) provide a useful definition of disturbance as "any relatively discreet event in time that disrupts ecosystem, community, or population structure, and that changes resources, availability of substratum, or the physical environment." Using this definition, this study will emphasize the quantification of the response characteristics (discharge, invertebrate density/community structure) as the measure of disturbance in reference to nominal stream conditions. Discharge is an indicator of the relative force of the disturbance event, in this case flooding, and invertebrate density/community structure is the biotic response to the physical event. As Reice (1994) points out: "The first impact of a disturbance is always to remove organisms."

Disturbances often involve both direct and indirect effects. Direct effects are those that influence the survival, growth, or reproduction of organisms, potentially altering ecosystem structure and function (Hurlbert, 1975). Indirect effects include alterations in nutrient cycling and energy processing as well as changes to the food web (Luthgart et al., 1990).

Bender et al. (1984) divide disturbance into two types: press and pulse. A press disturbance involves a chronic, or sustained, disturbance that may alter the physical habitat within the stream. Pulse disturbances are definable and of limited duration, generally not involving physical habitat changes within the stream. Recovery from press disturbances is generally of longer duration, as full recovery may require cessation of the disturbance.

Disturbance studies involve colonization, successional, and recovery processes. Colonization involves the immigration and establishment of species that previously did not inhabit an area into newly created or disturbed areas. Recolonization involves the invasion of species that did previously inhabit an area prior to a disturbance. Succession is defined as community changes that occur at a site following a disturbance (Fisher, 1990). The river continuum concept (Vannote et al., 1980) considers that successional processes in biotic communities are absent in rivers; therefore, these systems can be viewed in a time-independent fashion. Disturbances, however, can cause the loss of species that then recover through successional processes (Statzner and Higler, 1985). Hence, rivers cannot be viewed in a time-independent fashion. One difficulty is that successional change is often superimposed and confounded by diel, seasonal, and long-term patterns that also induce community changes (Fisher, 1990).

Primary succession occurs at a site where no trace of the previous community exists (Fisher, 1990). If some remnant of the community exists (i.e., organisms in refugia), secondary succession follows. Documentation of primary succession of biotic communities in rivers, particularly where upstream sources for colonization are absent, is sparse. Colonization of artificial substrates or reconstructed stream channels could be considered primary successional changes; however, the scale is so small that the substrates are overwhelmed by rapid colonization from adjacent communities and there is no opportunity for distinct communities to exist. Detecting differences between primary and secondary succession is probably only apparent at scales that limit colonizers, which in streams probably involves reaches 10^3 to 10^4 m in length (Fisher, 1990).

Methods

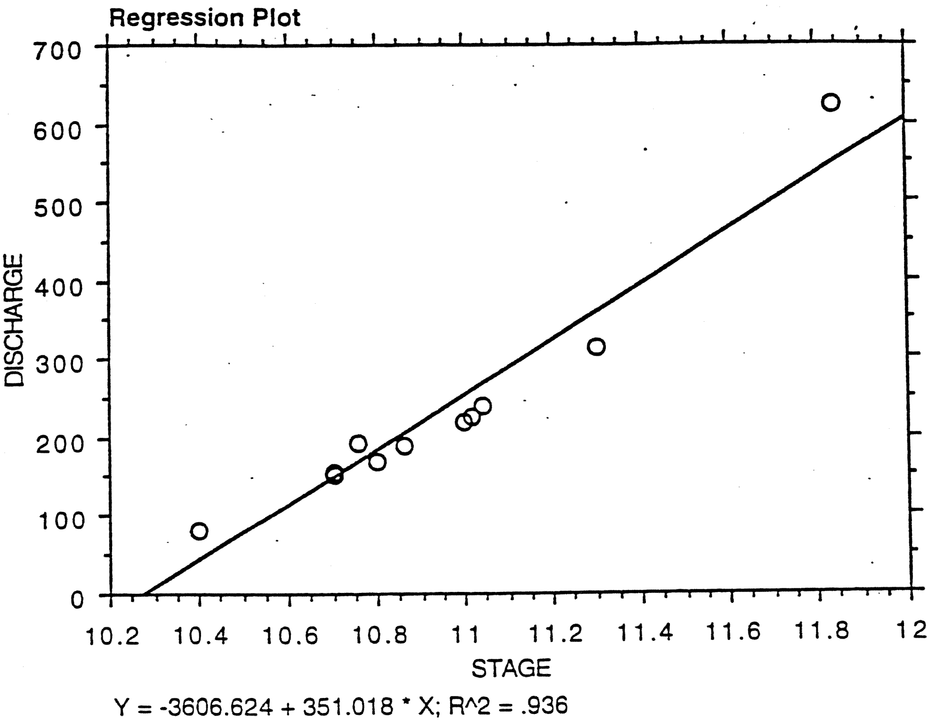
A staff gauge was established at the outfall of Lower Delusion Lake. Stream stage was recorded periodically throughout the field seasons. Discharge measurements were taken at this location using a Marsh/ McBirney flow meter at 1 and 1.5 m intervals across the width of the stream. Discharges were correlated to staff gauge height readings for the three points to assess the utility of stage heights for determining a discharge curve for the stream.

Macroinvertebrate samples were collected in Delusion Creek using a modified Surber sampler with a 353 μm mesh net. Ten Surber samples were taken at each site using a random number grid (Milner and Oswood, 1991) and preserved in 90% ethanol. Invertebrates from Surber samples were sorted in the laboratory, identified to genus (were feasible), and then stored in 70% ethanol. A reference collection is also being produced. Observation of the extent and types of algal growth and substrate embededness (qualitative), as well as velocity and depth measurements in Delusion Creek, were also made. Stream temperature was recorded at each site for most sampling periods.

Results and Discussion

A linear regression plotting discharge v. staff height from the 1993 season gave a correlation coefficient (r^2) of 0.94 (Figure 6). Stream discharge data obtained from staff gauge heights and the calculated stream discharge curve (Figure 7) indicate two major flow events during summer 1993. These occurred on 14 and 19 August with discharges exceeding 25 m^3s^{-1}. Base flow for Delusion Creek appears to be under 5.7 m^3s^{-1}. Given the relatively significant correlation between stream discharge and rainfall ($r^2 = 0.80$), rainfall records from previous years (Figures 8–12) indicate that the Delusion system has historically been subject to several spates per summer. Spates, as opposed to floods, are large and rapid increases in flow that scour the entire stream and then quickly subside (Cushing and Gaines, 1989). These events, coupled with the instability of the stream channel and bed material, have significant impacts on the aquatic biota as well as the retentiveness of coarse particulate organic matter (CPOM) of the stream.

Data from the Surber samples showed that Delusion Creek supported relatively low densities and diversities of macroinvertebrates, being composed principally of chironomids (chiefly of the *Diamesa davisi* group) and stoneflies (*Neaviperla forcipita*) of the Chloroperlidae family. In 1993 densities at station 1 did not exceed 2000 organisms/m^2 (Figure 13), station 2 densities did not exceed 1500 organisms/m^2 (Figure 14), and station 3b densities did not exceed 5000 organisms/m^2 (Figure 15) during the field season. These results show significantly higher densities than found in the Surber samples from 1992. In 1992 invertebrate densities at station 1 did not exceed 150 organisms/m^2, station 2 densities did not exceed 350 organisms/m^2, and station 3a densities did not exceed 100 organisms/m^2



Count	12
Num. Mis...	0
R	.967
R Squared	.936
Adjusted ...	.929
RMS Resi...	37.963

Figure 6. Regression summary, discharge v. stage.

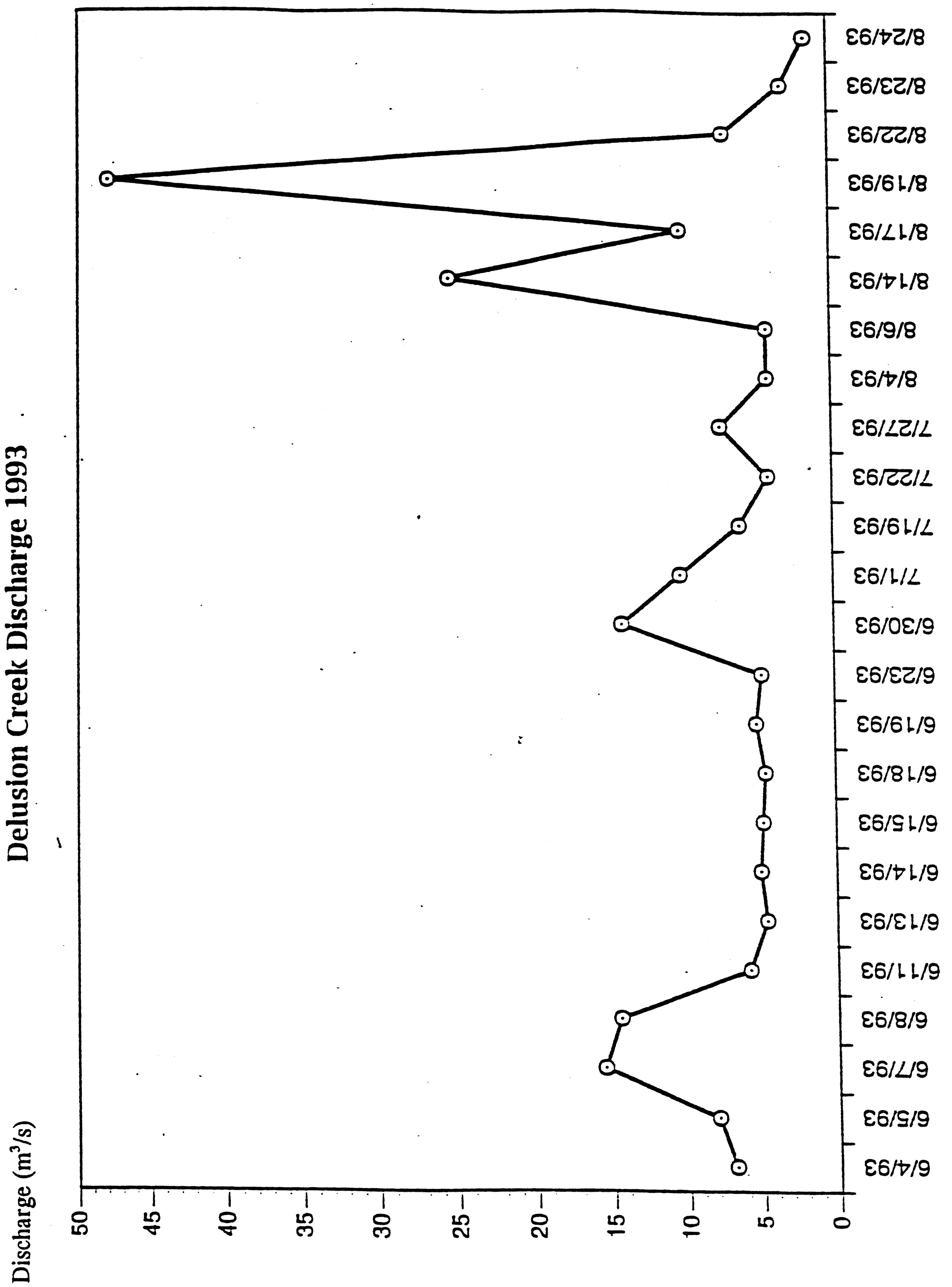


Figure 7. Delusion Creek discharge 1993.

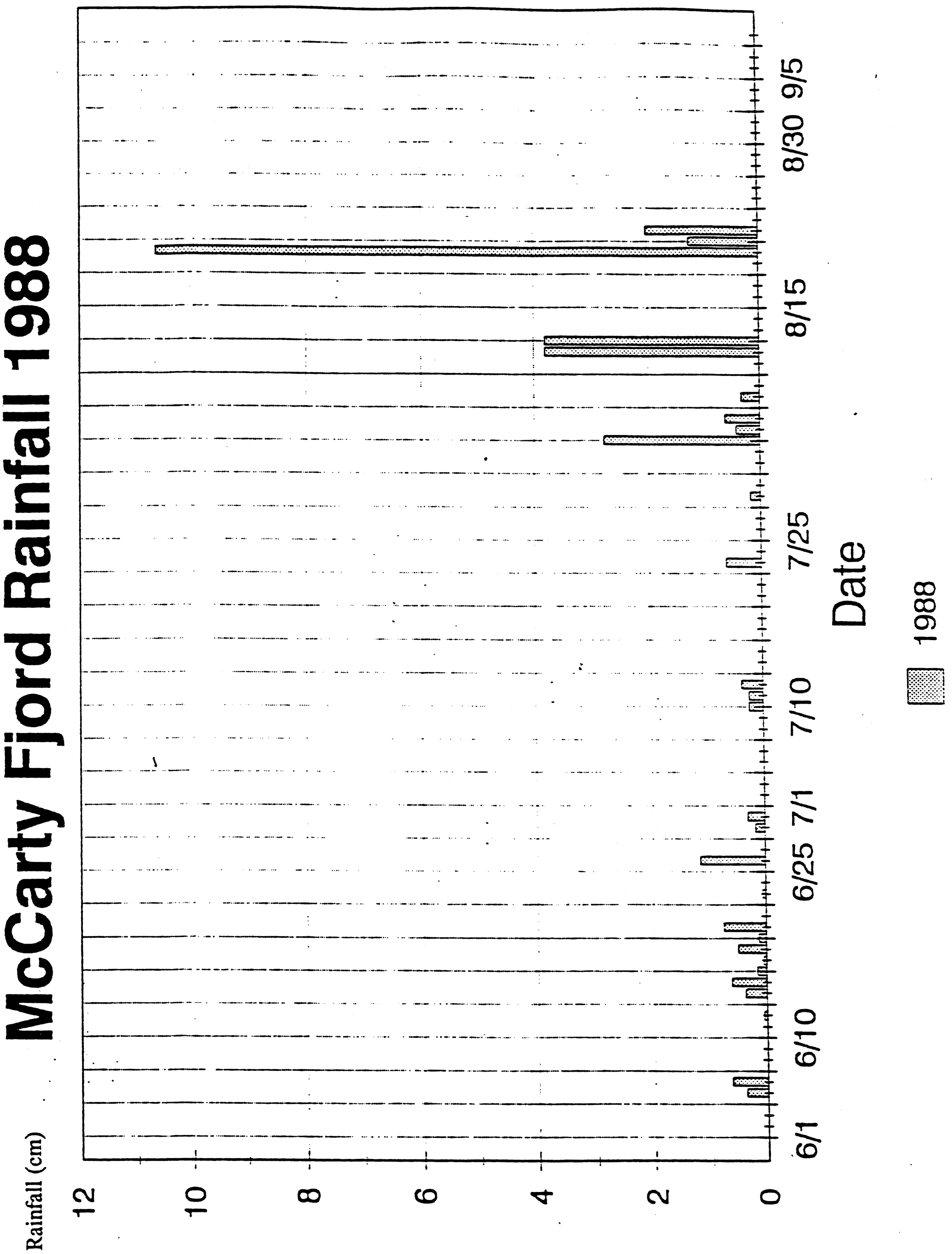


Figure 8. McCarty Fjord rainfall 1988.

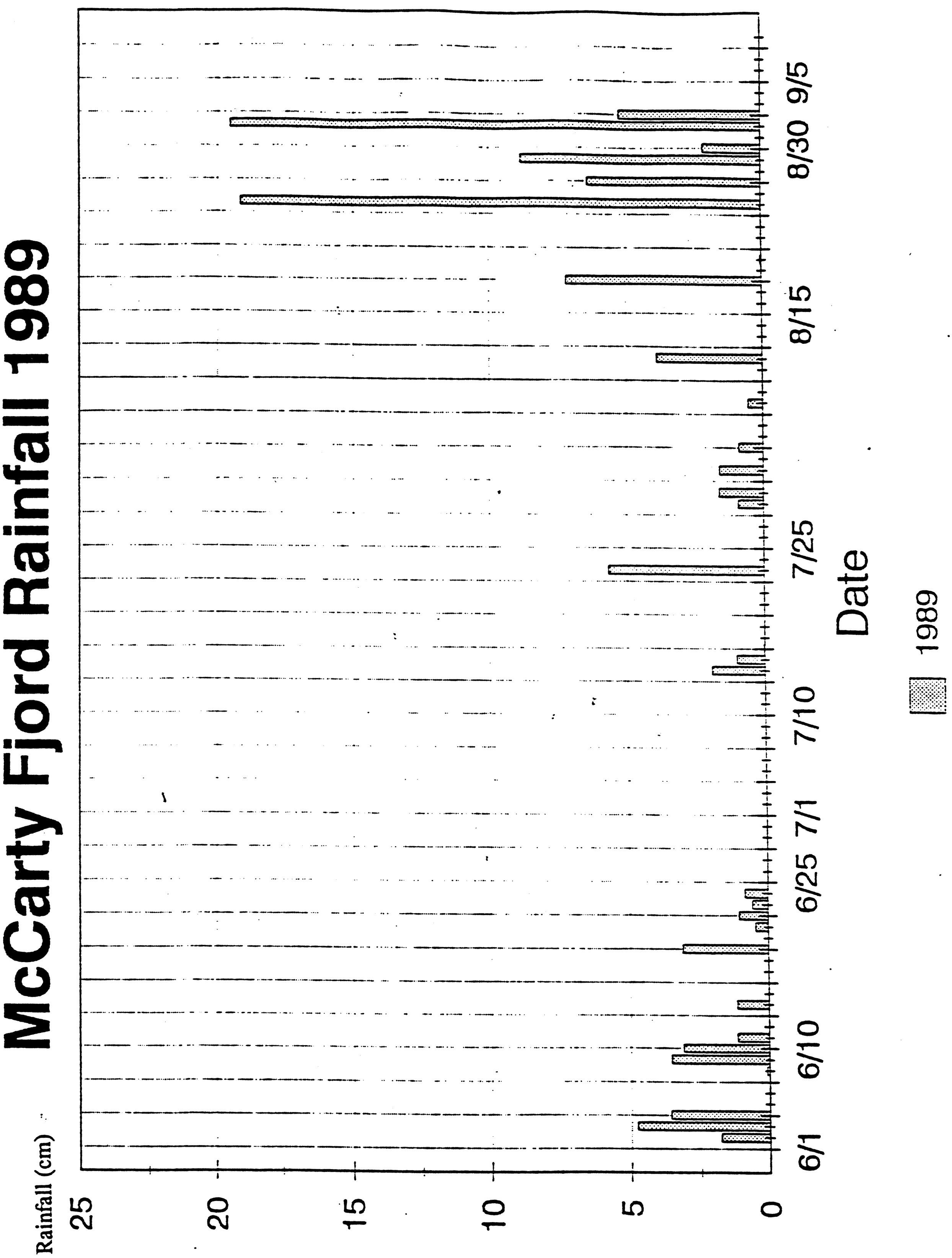


Figure 9. McCarty Fjord rainfall 1989.

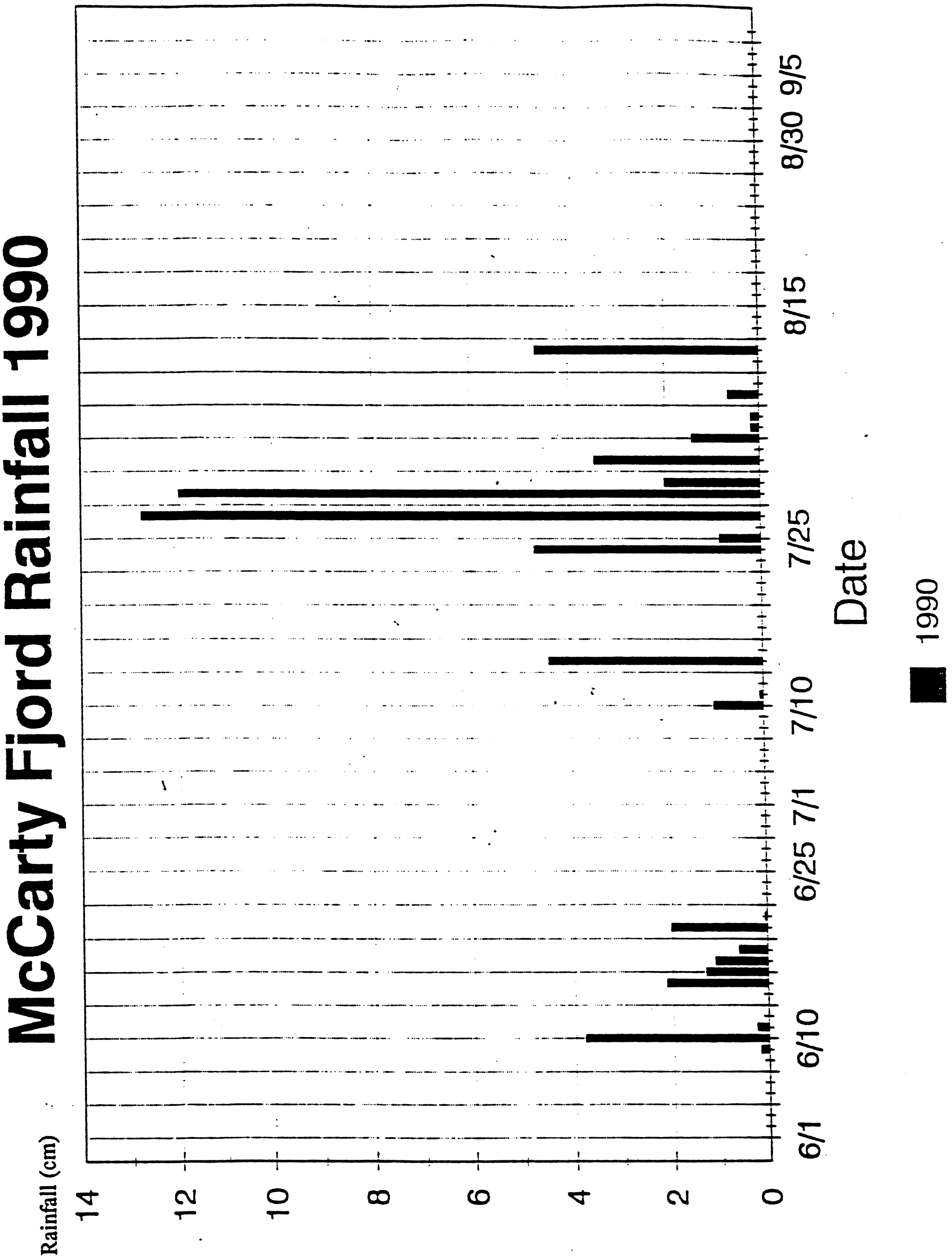


Figure 10. McCarty Fjord rainfall 1990.

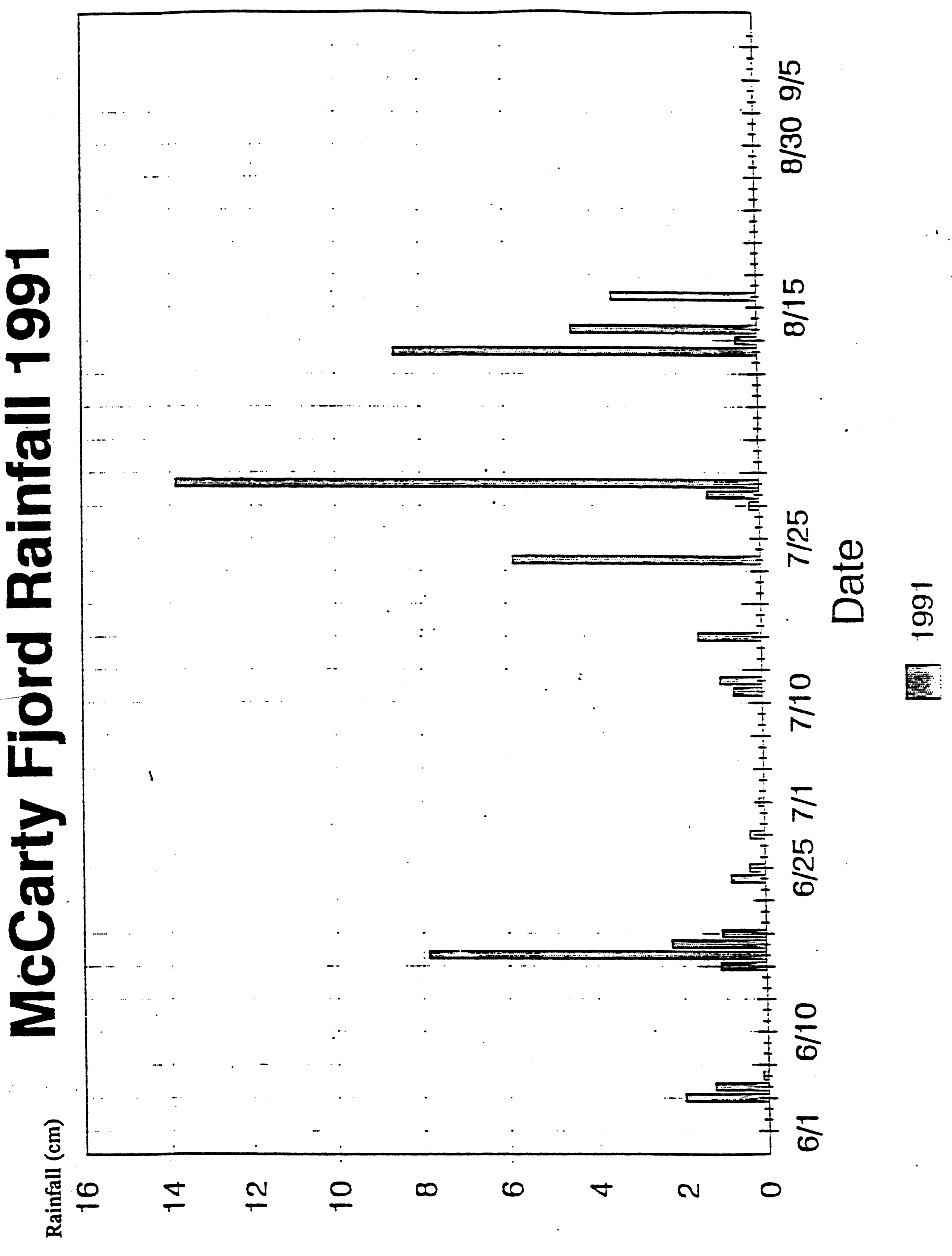


Figure 11. McCarty Fjord rainfall 1991.

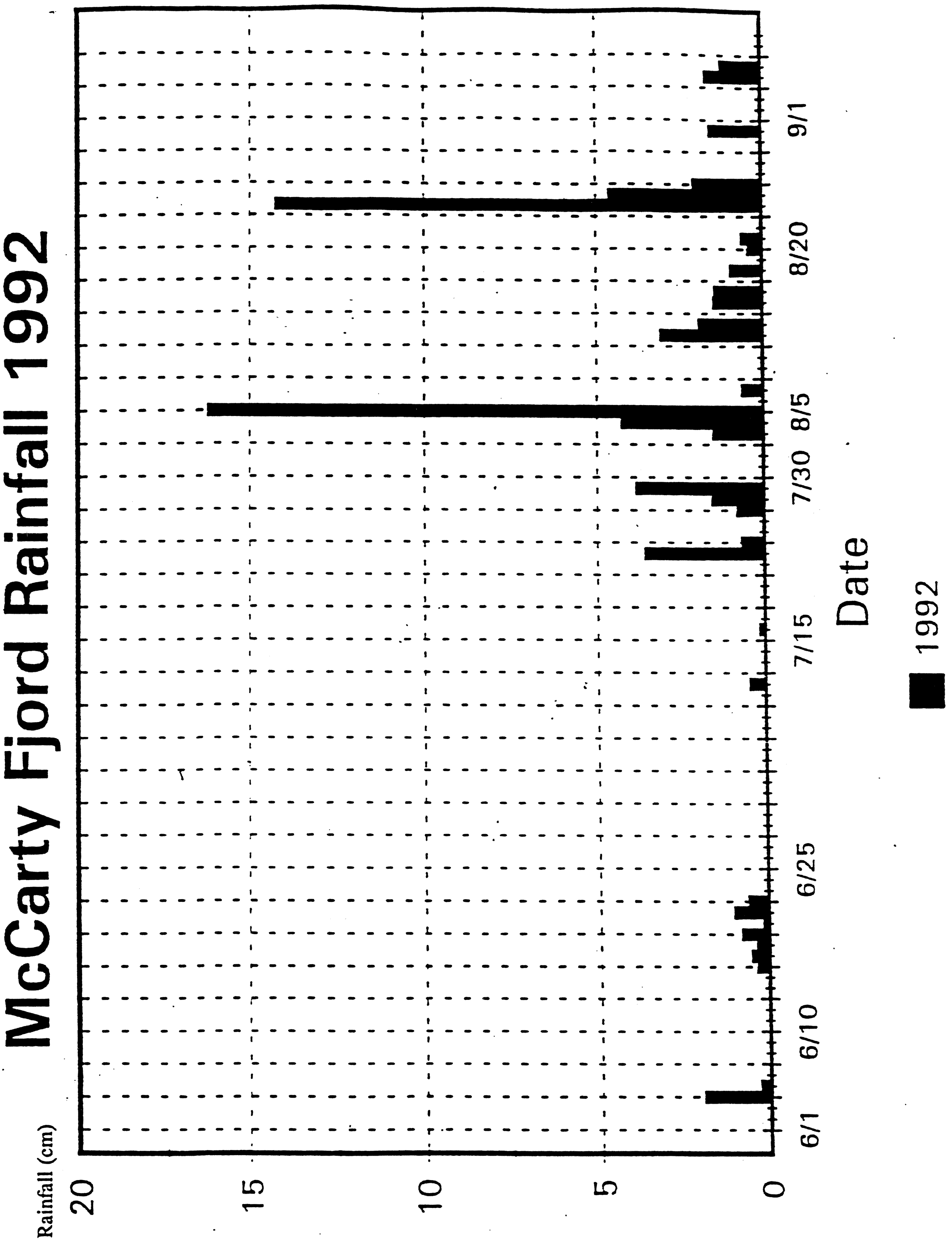


Figure 12. McCarty Fjord rainfall 1992.

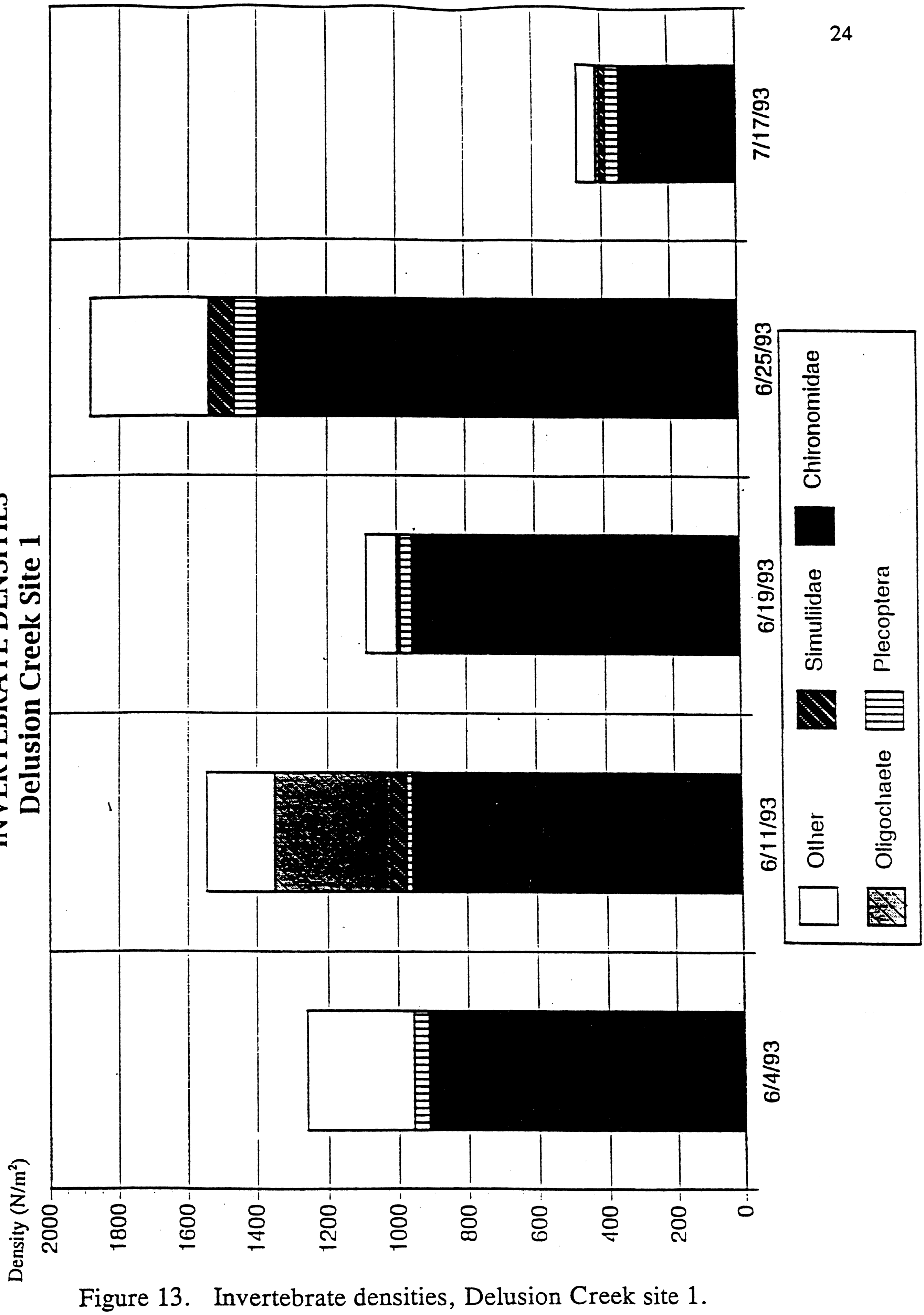


Figure 13. Invertebrate densities, Delusion Creek site 1.

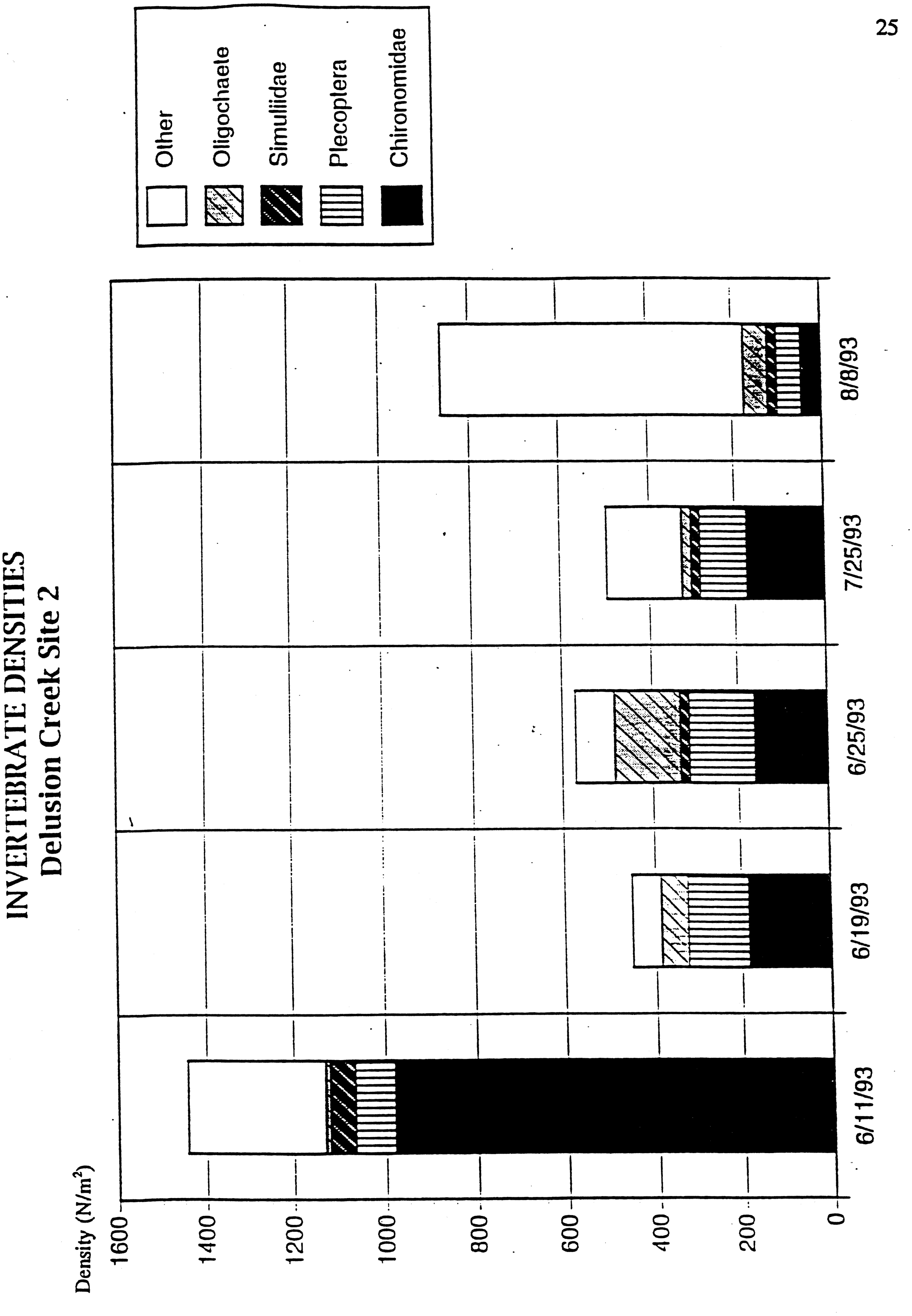


Figure 14. Invertebrate densities, Delusion Creek site 2.

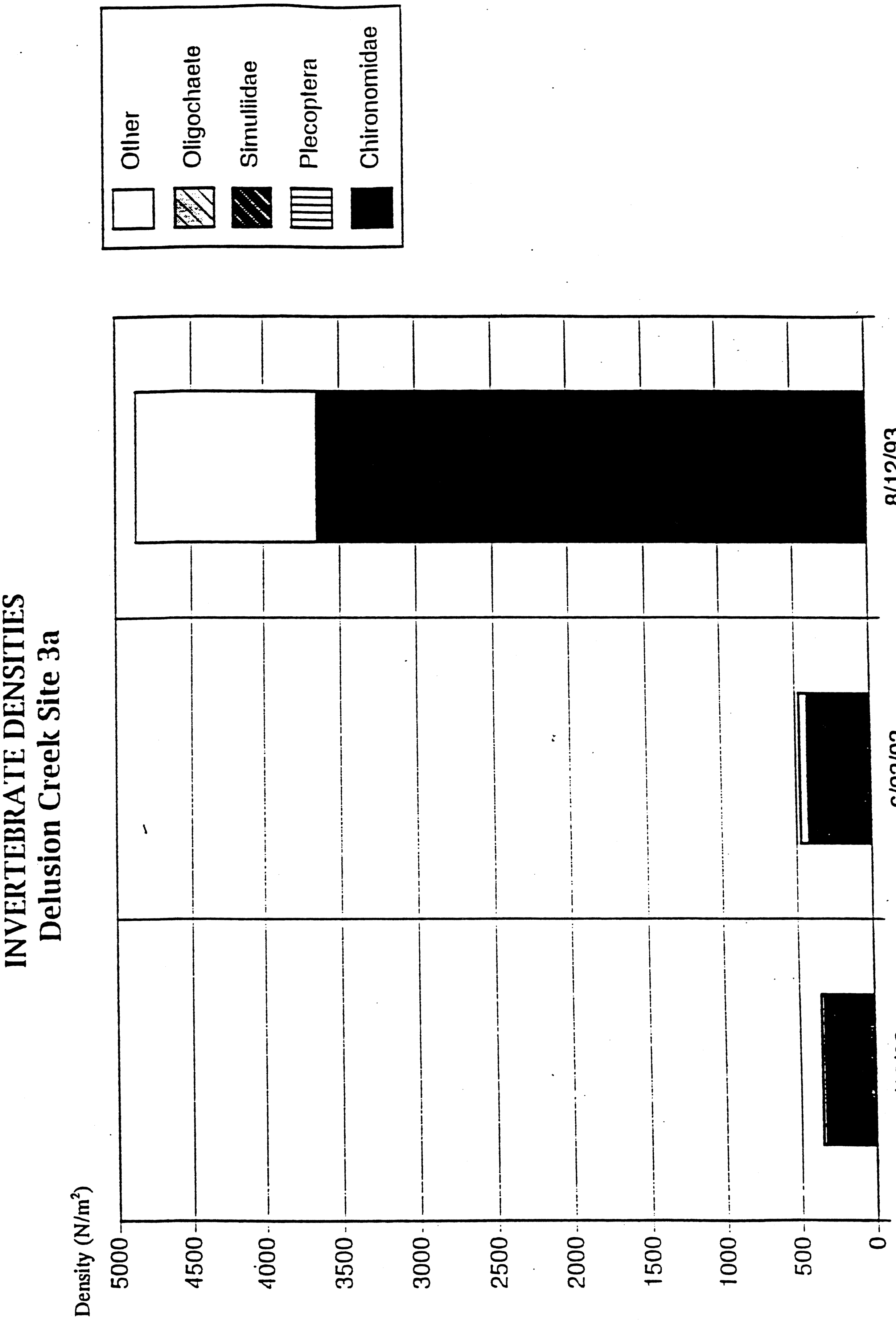


Figure 15. Invertebrate densities, Delusion Creek site 3a.

(Figures 16–18). Samples obtained at site 4 show a markedly different pattern with densities exceeding 10,000 organisms/m^2. Site 4 also exhibits the greatest diversity of taxa containing mayflies (Baetis), caddisflies (Ryacophilidae), and numerous chironomid taxa not found elsewhere.

The qualitative model of Milner and Petts (1994) suggests the typical invertebrate communities downstream of a glacier margin or as a function of time since deglaciation to be determined principally by water temperature and channel stability. Given the August water temperatures of 9 to 10°C, it is clear that the invertebrate community is being held in an early successional phase due to the instability of the channel in that, particularly at stations 1 and 2, the community is dominated by Diamesinae and Orthocladiinae chironomids and Chloroperlidae stoneflies. Indeed, the importance of channel stability is emphasized by the comparison between years (higher densities in 1993 v. 1992 due to less disturbances in June and July) and a comparison between stations 1 and 2 and 3b and 4 in 1993. The lower stations were evidently more unstable than stations higher up the watershed where diversity and abundance of invertebrates were higher.

Preliminary assessment of the primary productivity data indicate very low levels of instream primary production during the field seasons. Chlorophyll-*a* analysis from Delusion Creek water samples obtained in 1994 support this assumption with values averaging 0.1628 mgm^{-3}. Data obtained in 1992 showed low levels of primary productivity during July and August followed by a sudden increase in algal growth during the low flows of early September. This coincided with a substantial increase in the densities of macroinvertebrates. It was initially hypothesized that the sudden increase in algal growth was attributable to a lack of disturbance, but 1993 data appear to indicate otherwise. No significant algal growth occurred during the relatively stable months of June and July 1993. Therefore, the major

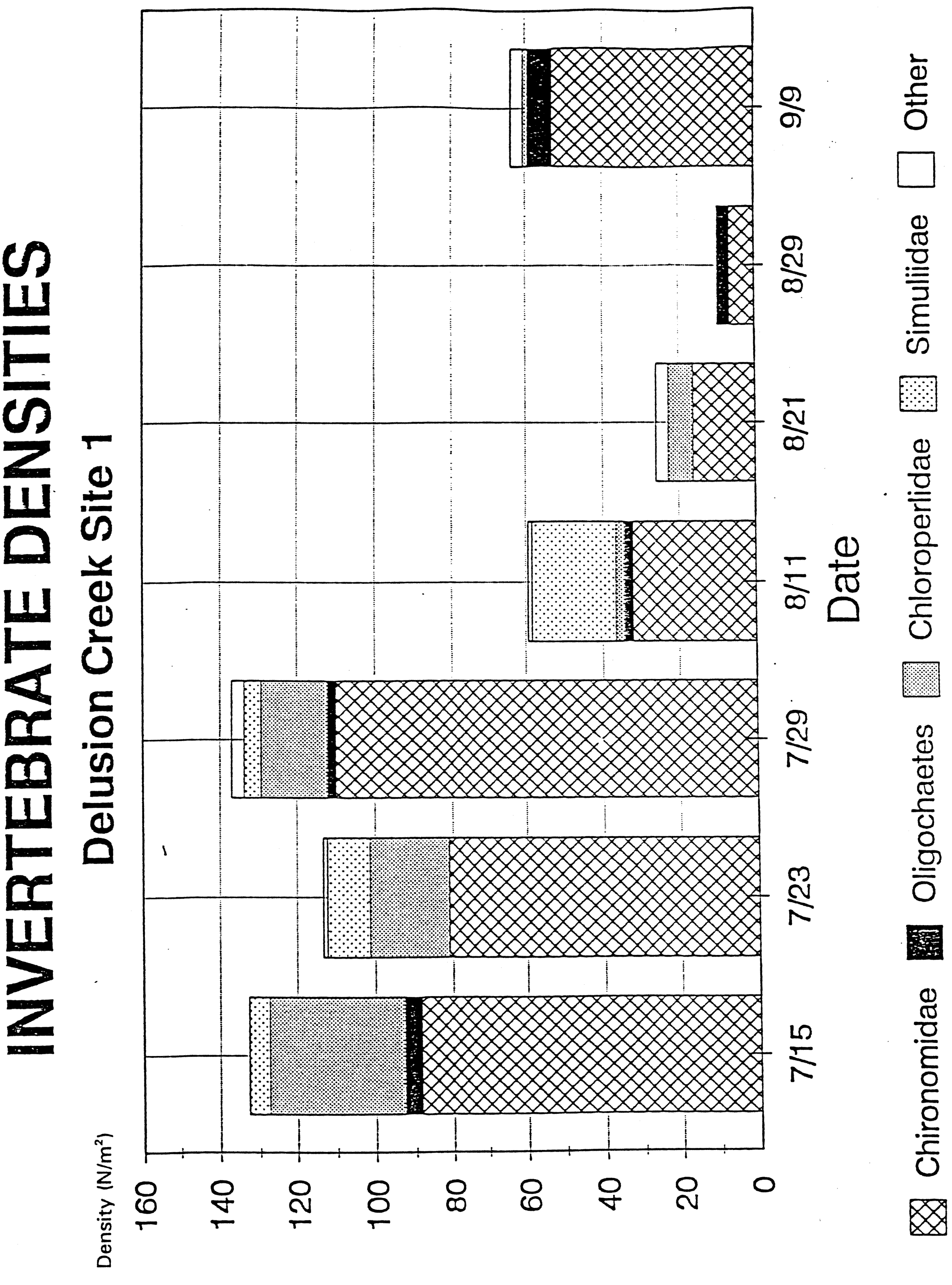


Figure 16. Invertebrate densities at Delusion Creek site 1 in 1992.

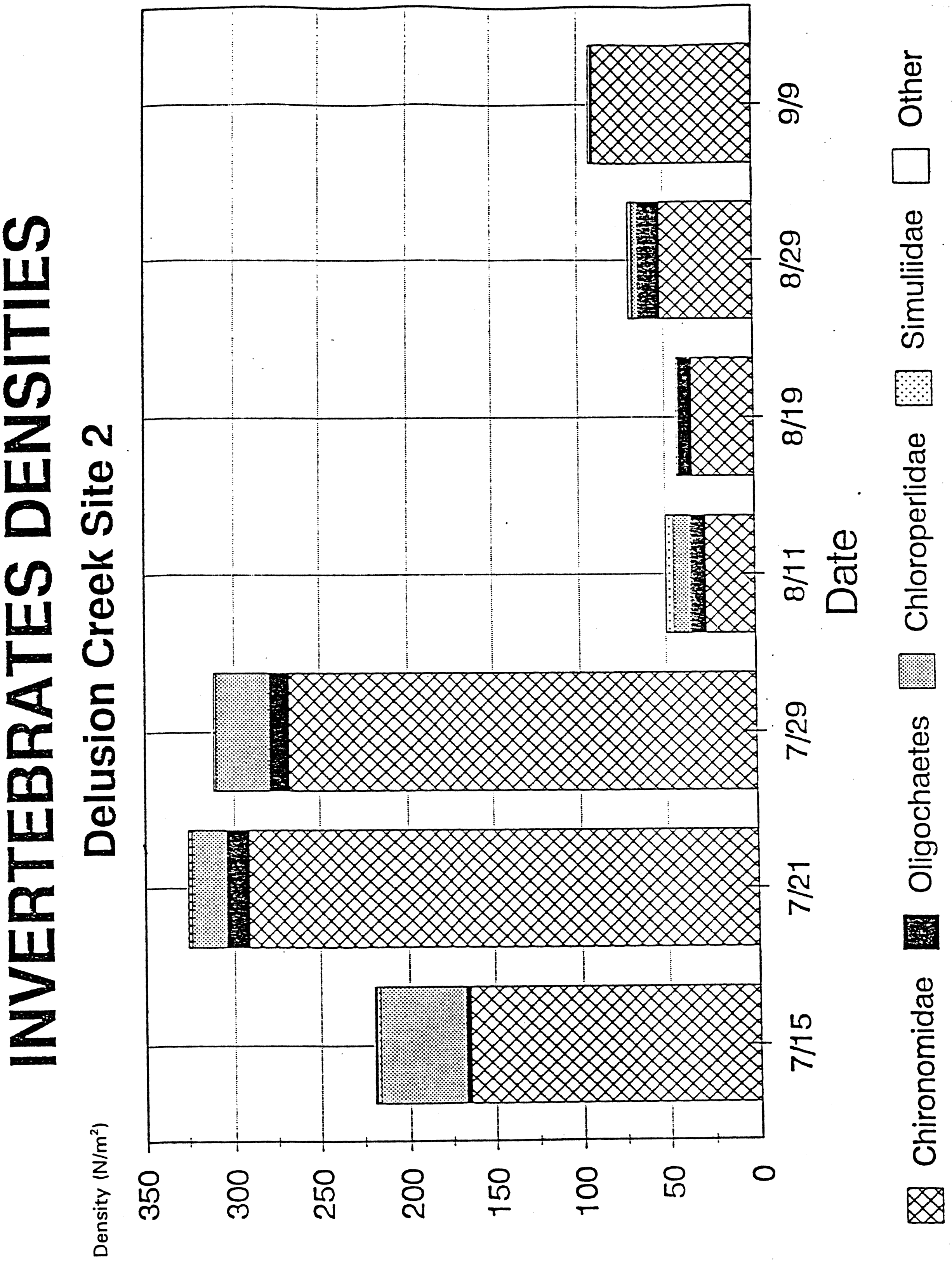


Figure 17. Invertebrate densities at Delusion Creek site 2 in 1992.

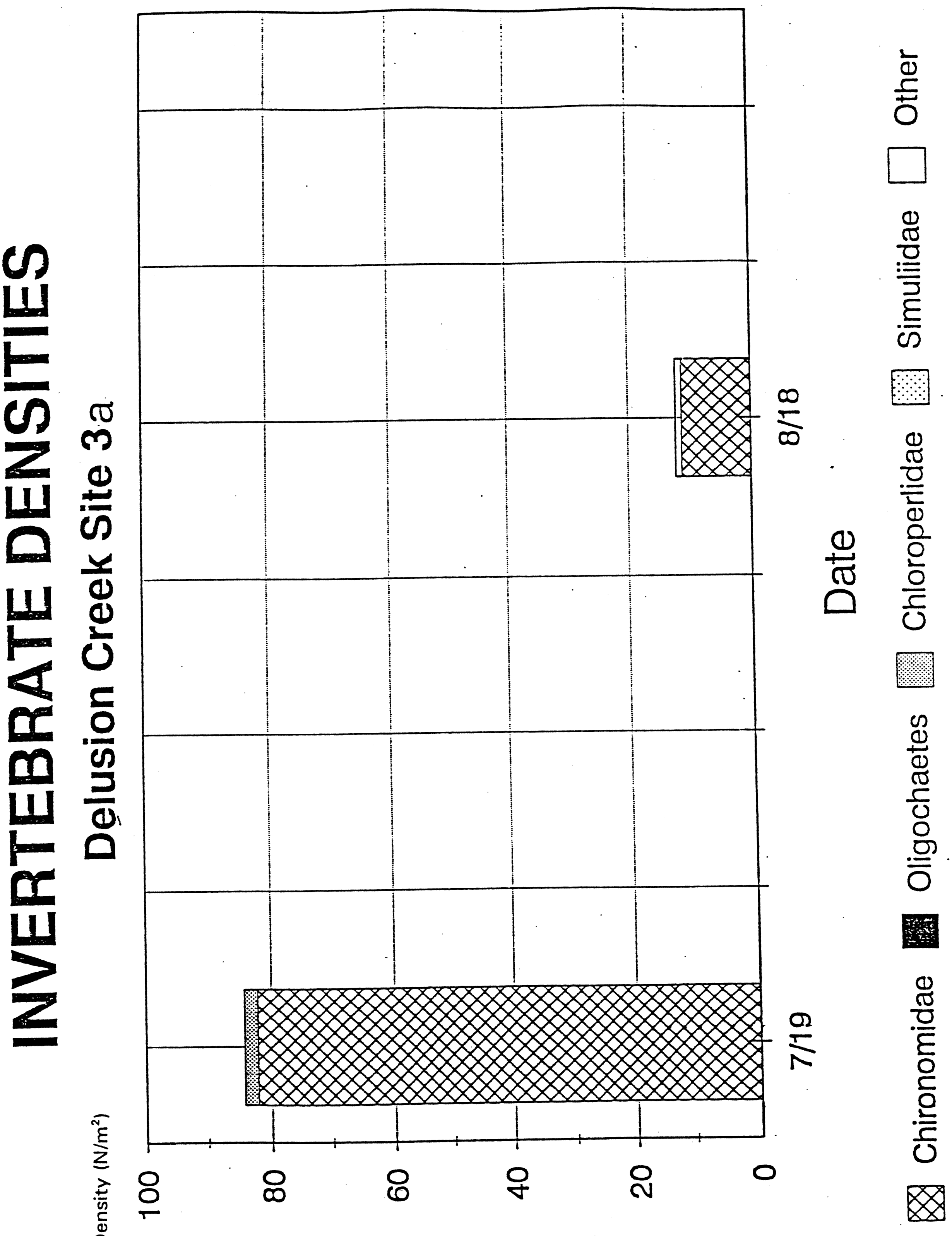


Figure 18. Invertebrate densities at Delusion Creek site 3a in 1992.

limitation to primary production is most likely attributed to the low levels of nitrogen that occur in the system (see lake chemistry data).

Recent studies (Cederholm et al., 1989; Kline et al., 1990; Piorkowski, 1995) have suggested that spawning adult salmon can contribute significant amounts of nutrients, primarily marine-derived nitrogen and carbon, to aquatic food webs. It is proposed that this biogenic recycling of nutrients is of special significance to lake and stream productivity in high latitude systems such as those found in the study and throughout coastal Alaska (see proposed model, Figure 19).

Leaf retention experiments were not conducted during the 1994 field season. Retention capacity in 1992 was deemed negligible even though stream discharge was low during the experiment. Differences between the data sets can be attributed to significant channel changes between the study years as well as to use of presoaked leaves in 1993. The generally low levels of retention found in Delusion Creek (both in 1992 and 1993) are due to the absence of large woody debris, pool habitat, and other retentive structures. Without such structures, the little CPOM that is retained during low flows is most likely sluiced from the system during spate events.

Limnological and Fisheries Investigations

Limnology

Introduction.—Limnological analyses of Upper and Lower Delusion Lakes were conducted from 1992 through 1994. These data provide an indication of the nutrient status of the two lakes and their potential ability for supporting sockeye salmon.

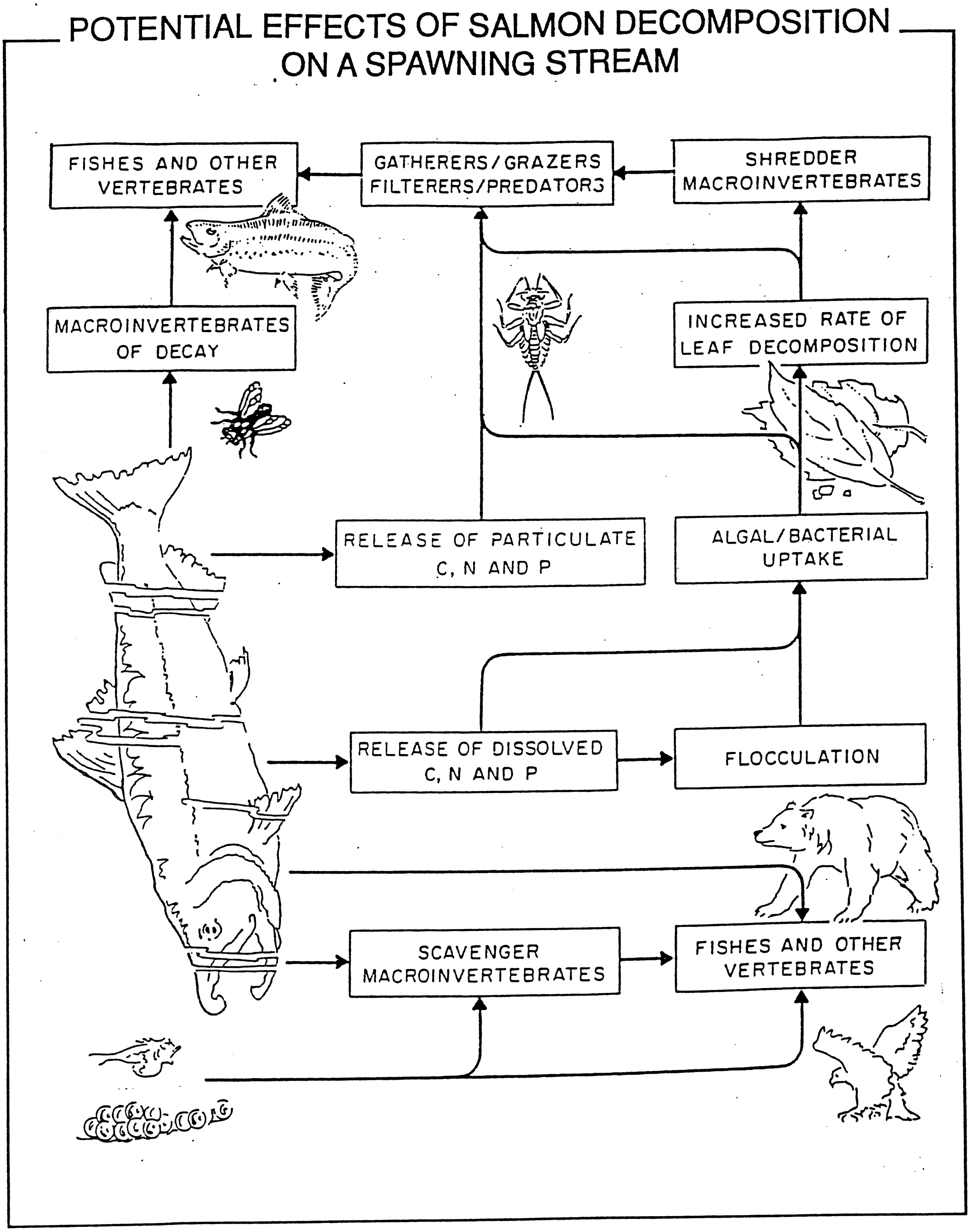


Figure 19. Potential effects of salmon decomposition on a spawning stream.

Methodology.—During 1992 and 1993, Upper and Lower Delusion Lakes were sampled on four occasions during the field season. In 1994 water samples were collected at two sampling periods in the spring.

Water samples were collected at 1 m and 10 m in 1992 and 1993, and only at 1 m in 1994 using a Kemmerer bottle with a 1 liter capacity. Water samples were collected both unfiltered and filtered. Samples were filtered through a Whatman 4.25 cm GF/F filter pad that retains all particulate matter $>0.7\ \mu m$. Both unfiltered and filtered water samples were stored frozen prior to analysis by the Alaska Department of Fish and Game (ADFG) laboratory in Soldotna for the following parameters: total phosphorus (P), total filterable phosphorus, filterable reactive phosphorus, total Kjeldahl nitrogen (N), ammonia, nitrate and nitrite, and reactive silicon. Total N was then determined by adding Kjeldahl N (organic N and ammonia N) + nitrate and nitrite. The detection limit was 1 $\mu g\ L^{-1}$ except for Kjeldahl N it was 3 $\mu g\ L^{-1}$ and 0.5 $\mu g\ L^{-1}$ for filterable reactive phosphorus (principally orthophosphate).

In addition, a water sample was collected at each depth and stored at 4°C to analyze for specific conductance, pH, alkalinity, turbidity, color, calcium, magnesium, and iron. Dissolved oxygen and temperature profiles of the lakes were also undertaken to see if either lake stratified during the summer. Duplicate vertical hauls for zooplankton were collected using a plankton net with a 253 μ mesh and a diameter of 0.5 m. Zooplankton hauls were preserved in 90% ethanol prior to enumeration and identification. To provide an indication of light penetration, a Secchi disk was lowered into the water column. Depths were noted when the disk just disappeared from sight on the way down and when it was first observed on rising. The Secchi depth in meters (SD) was the average of these two readings.

Results.—Specific conductance was low in the two lakes, typically less than 20 mhos/cm, indicating low quantities of dissolved ions, particularly calcium, magnesium, carbonates, and bicarbonates (as indicated by low alkalinity values). Typically pH was on the acidic side of neutral ranging between 5.8 to 6.0, with readings in spring 1994 to 5.5 in Upper Delusion Lake. The lakes were not stained (color less than 20 Pt units). Turbidity and light penetration were variable. In 1992, clarity decreased during the summer with SD values in Upper Delusion Lake of 5.0 m (3.0 NTU) on 15 July, decreasing to a SD of 0.5 m (16 NTU) on 1 September. The highest turbidity values were found at 10 m, reaching 120 NTU on 12 August. In 1993, turbidity values were typically less than 2 NTU (SD > 4.0 m) during all sampling occasions except for 22 August. On this date the SDs were very low, with values of 0.1 m in both lakes and turbidities exceeding 90 NTU.

Total N and Total P were variable over the three years of sampling. Total N at 1 m ranged from 40.8 g L^{-1} to a high of 208.3 g L^{-1} on 1 September 1992 (Table 2). High Total N values in 1993 were principally a result of a marked increase in organic nitrogen levels as both ammonia and nitrate + nitrite were relatively similar throughout the four sampling periods. Indeed, nitrate and nitrite were slightly lower than in June. Total P at 1 m varied from a low of 3.4 to a high of 160.2 g L^{-1} in Upper Delusion Lake on 22 August 1993. In 1993, 15 June levels of Total P and Total N were generally higher than at the other two time intervals; 30 June and 18 July (see Figures 20–23 for Total N and Total P levels for 1992 and 1993; individual constituents are given in Table 2).

In 1992 the average Total N for the three sampling periods at 1 m for Upper Delusion Lake was 112.2 $\mu g\ L^{-1}$ and for Lower Delusion Lake (4 samples) was 64.9 $\mu g\ L^{-1}$. The average Total P over four sampling periods

Table 2. Summary of water quality data for Upper and Lower Delusion Lakes 1992–1994.

Water Quality Summary - Upper and Lower Delusion Lakes 1992-1994																			
Lake	Date	Sta	Sechi Depth	Depth	Specific conductance	pH	Alkalinity	Turbidity	Color	Calcium	Magnesium	Iron	Total-P	Total filter-able-P	Filterable reactive-P	Total Kjel-dahl nitrogen	Ammonia	Nitrate + nitrite	Total nitrogen	Reactive silicon	Chlorophyl a (ug/L)
			SD - m	(m)	(umhos/cm)	(Units)	(mg/L)	(NTU)	(Pt units)	(mg/L)	(mg/L)	(ug/L)	(ug/L P)	(ug/L P)	(ug/L P)	(ug/L N)	(ug/L N)	(ug/L N)	(ug/L N)	(ug/L Si)	
DELUSION	07/15/92	Lower	1.5	1	16	5.8	1.5	1.8	3	1.6	<0.3	141	9.5	6.9	0.8	20.1	3.2	23.9	47.2	1229	0.11
DELUSION	07/15/92	Lower		10	16	5.9	1.5	0.2	5	1.6	<0.3	112	17.3	29.5	1.7	25.9	3.2	14.6	43.7	1194	<0.01
DELUSION	07/15/92	Upper	5.0	1	16	6.0	3.0	1.6	3	1.9	0.7	103	4.7	10.6	1.1	17.1	<1.7	14.6	31.7	1229	0.04
DELUSION	07/15/92	Upper		10	17	6.1	3.0	0.9	5	1.9	<0.3	42	12.8	6.6	2.1	14.2	3.2	19.2	33.4		
DELUSION	08/12/92	Lower	0.3	1	14	6.0	1.5	14.0	4	0.6	0.8	785	22.7	6.3	2.0	36.9	3.2	35.3	75.4	1299	0.07
DELUSION	08/12/92	Lower		10	13	6.3	2.0	5.0	4	1.6	<0.3	600	31.1	4.9	2.6	33.2	3.2	37.4	73.8	589	0.11
DELUSION	08/12/92	Upper	0.5	1	14	5.9	2.0	7.0	3	0.6	0.8	472	22.9	12.0	1.3	60.3	<1.7	36.4	96.7	1287	0.23
DELUSION	08/12/92	Upper		10	13	5.5	1.5	120.0	14	0.6	0.8	5499	81.4	23.1	14.1	77.8	<1.7	26.0	103.8	1369	<0.01
DELUSION	09/01/92	Lower	0.5	1	14	6.0	2.0	12.0	5	1.6	<0.3	962	25.5	21.5	12.1	37.6	3.2	26.0	66.8	1380	0.08
DELUSION	09/01/92	Lower		10	14	6.0	1.5	16.0	5	1.6	<0.3	1068	21.6	7.1	3.5	29.6	3.2	35.3	68.1	1415	<0.01
DELUSION	09/01/92	Upper	0.5	1	76	3.8		16.0	11	0.6	0.8	834	24.8	122.2	99.9	43.5	125.8	39.0	208.3	1392	0.02
DELUSION	09/01/92	Upper		10	11	6.1	2.0	28.0	8	0.6	0.8	1964	34.1	30.0	21.2	54.4	13.4	31.2	99.0	1252	<0.01
DELUSION	09/07/92	Lower	0.5	1	15	6.0	2.0	0.8	5	1.6	<0.3	752	15.1	9.8	5.5	34.0	3.2	33.3	70.5	1462	0.06
DELUSION	09/07/92	Lower		10	15	6.0	1.5	12.0	3	1.6	<0.3	730	13.3	6.2	4.0	49.3	3.2	36.9	89.4	1508	0.06
DELUSION	09/07/92	Upper	0.5	1	15	5.9	1.5	12.0		0.6	<0.3	637	21.8			31.8				1404	0.03
DELUSION	09/07/92	Upper		10.0	14	6.0	1.5	16.0		0.6	0.8	916	20.3			68.4				1392	0.07
DELUSION ST	08/13/92	1			12	6.5	2.0	0.4	4	1.0	0.7	388	23.4	3.0	1.9	31.0	<1.7	34.8	65.8	786	0.05
DELUSION ST	08/13/92	2			12	6.7	2.0	0.5	3	1.0	0.7	608	25.6	3.1	1.7	38.4	<1.7	32.2	70.6	658	0.04
DELUSION	06/15/93	Lower	6.1	1	19	5.9	2.0	1.0	6	2.0	0.2	51	28.6	6.0	4.1	36.2	5.4	47.4	83.6	1413	
DELUSION	06/15/93	Lower		10	20	5.9	2.0	1.5	6	2.0	0.8	48	11.7	5.3	3.7	39.3	6.5	41.4	80.7	1425	
DELUSION	06/15/93	Upper	5.4	1	19	5.8	2.0	1.0	6	2.0	0.2	44	25.7	11.3	4.9	42.9	15.1	48.4	91.3	1354	
DELUSION	06/15/93	Upper		10	18	6.0	2.0	1.2	5	2.0	0.2	42	7.8	5.9	3.7	52.2	4.9	43.4	95.6	1336	
DELUSION	06/30/93	Lower	4.6	1	17	5.8	2.0	1.5	5	2.0	0.8	29	7.4	3.1	2.2	20.6	5.4	31.6	52.2	1283	
DELUSION	06/30/93	Lower		10	17	5.9	2.0	1.2	4	2.0	0.8	38	4.3	18.4	7.4	25.3	16.2	35.5	60.8	1289	
DELUSION	06/30/93	Upper	5.0	1	16	5.8	2.0	1.2	5	2.0	0.2	33	6.5	5.7	2.4	40.5	6.0	31.6	72.1	1212	
DELUSION	06/30/93	Upper		10	15	5.9	2.0	1.7	5	1.0	0.2	36	8.3	4.6	3.0	44.4	10.8	32.6	77.0	1189	
DELUSION	07/18/93	Lower		1	14	5.8	2.0	0.8	5	2.0	0.8	16	3.4	3.3	1.9	19.1	3.2	21.7	40.8	1171	
DELUSION	07/18/93	Lower		10	14	5.8	1.5	1.0	4	2.0	0.8	38	6.2	5.2	2.6	42.5	7.0	23.7	66.2	1177	
DELUSION	07/19/93	Upper	7.5	1	14	5.9	2.0	1.4	4	2.0	0.2	17	8.3	5.8	2.3	87.6	13.0	19.7	107.3	1118	
DELUSION	07/19/93	Upper		10	15	5.8	2.0	1.0	5	2.0	0.2	36	5.1	4.8	2.3	26.9	7.6	21.7	48.6	1307	
DELUSION	08/22/93	Lower	0.1	1	13	5.8	2.0	93.6	29	1.0	0.2	1250	139.5	35.1	27.9	126.3	7.6	27.6	153.9	1136	
DELUSION	08/22/93	Lower		10	14	5.9	2.0	95.1	49	1.0	0.2	1436	186.4	82.4	50.8	127.9	4.3	19.7	147.6	1106	
DELUSION	08/22/93	Upper	0.1	1	14	5.9	2.0	95.0	33	2.0	0.8	890	160.2	44.2	29.1	128.0	3.2	25.7	153.7	1319	
DELUSION	08/22/93	Upper		10	16	6.5	4.0	137.0	8	2.0	0.8	1194	182.2	6.9	5.8	137.8	8.7	27.6	165.4	1082	
DELUSION	05/16/94	Lower		1	21	5.6	1.0	0.5	5	2.0	0.2	41	3.4	3.5	2.8		-0.3	52.2		1850	
DELUSION	06/11/94	Lower		1	19	5.6	2.0	3.2	4	2.0	0.2	244	5.2	3.0	2.4		-0.3	47.1		1536	
DELUSION	05/17/94	Upper		1	20	5.7	4.0	1.6	6	2.0	0.6	134	5.0	6.4	3.8		14.0	56.6		1826	
DELUSION	06/11/94	Upper		1	18	5.5	3.0	0.8	5	2.0	0.6	48	2.3	2.5	2.5		-0.3	46.4		1561	

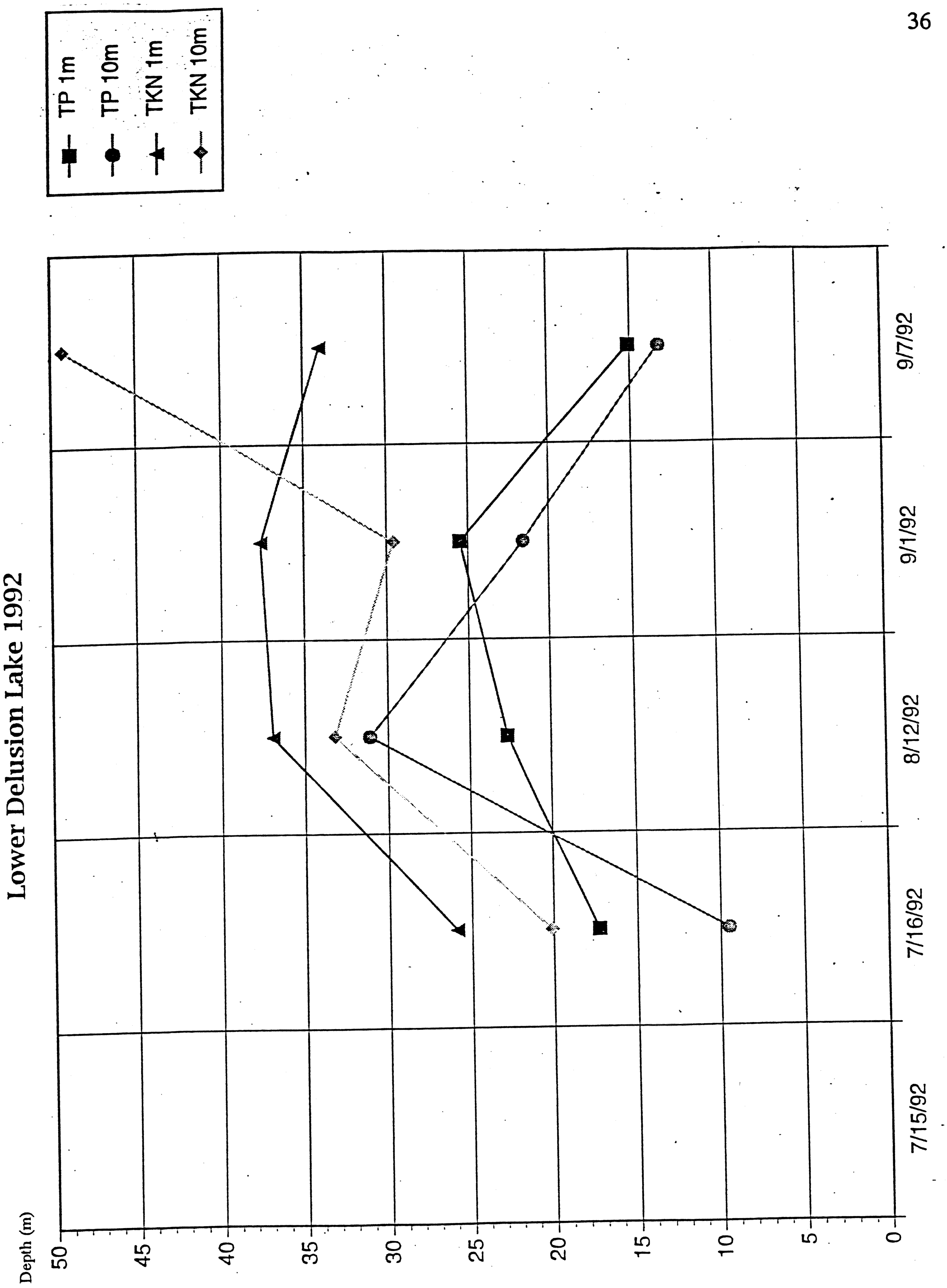


Figure 20. Lower Delusion Lake chemistry 1992.

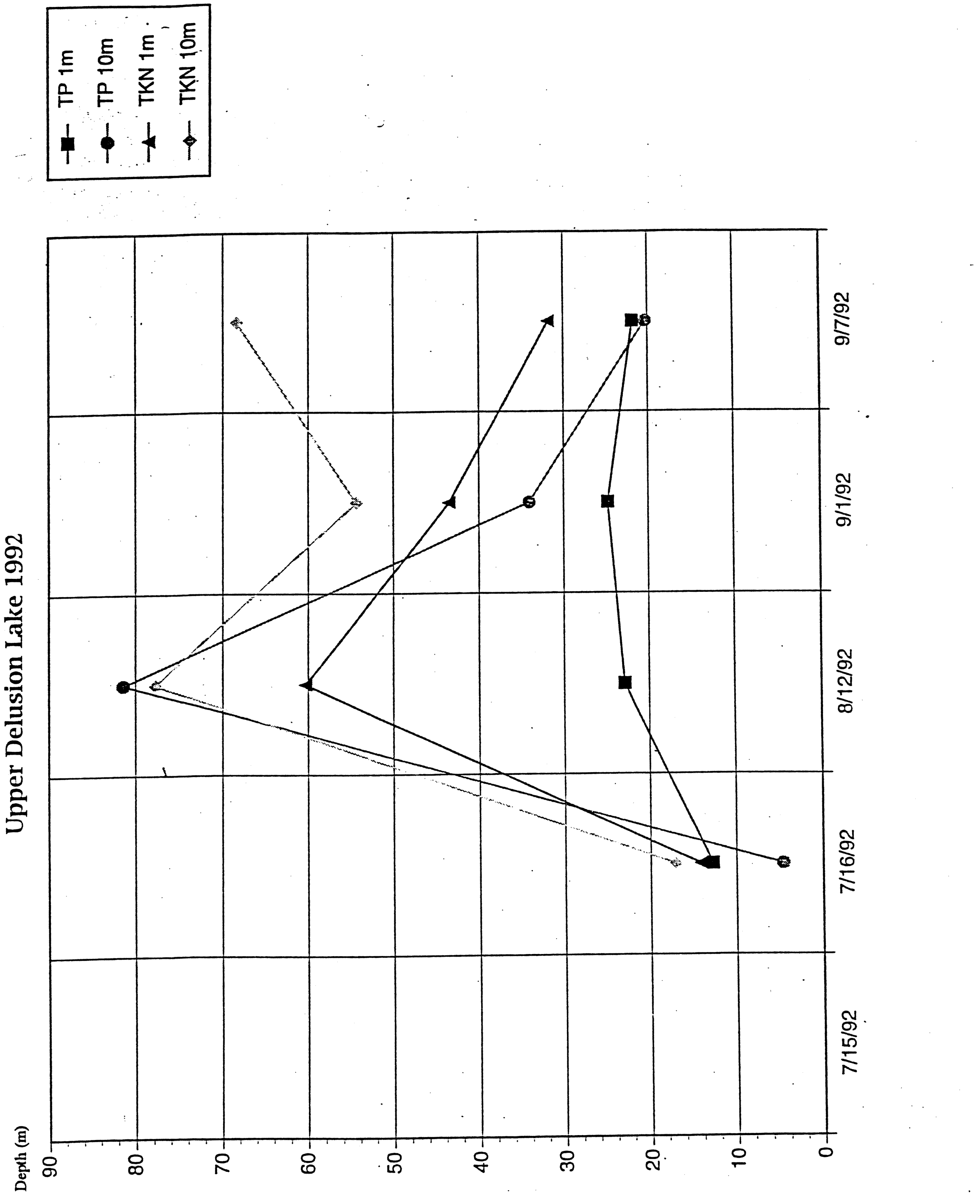


Figure 21. Upper Delusion Lake chemistry 1992.

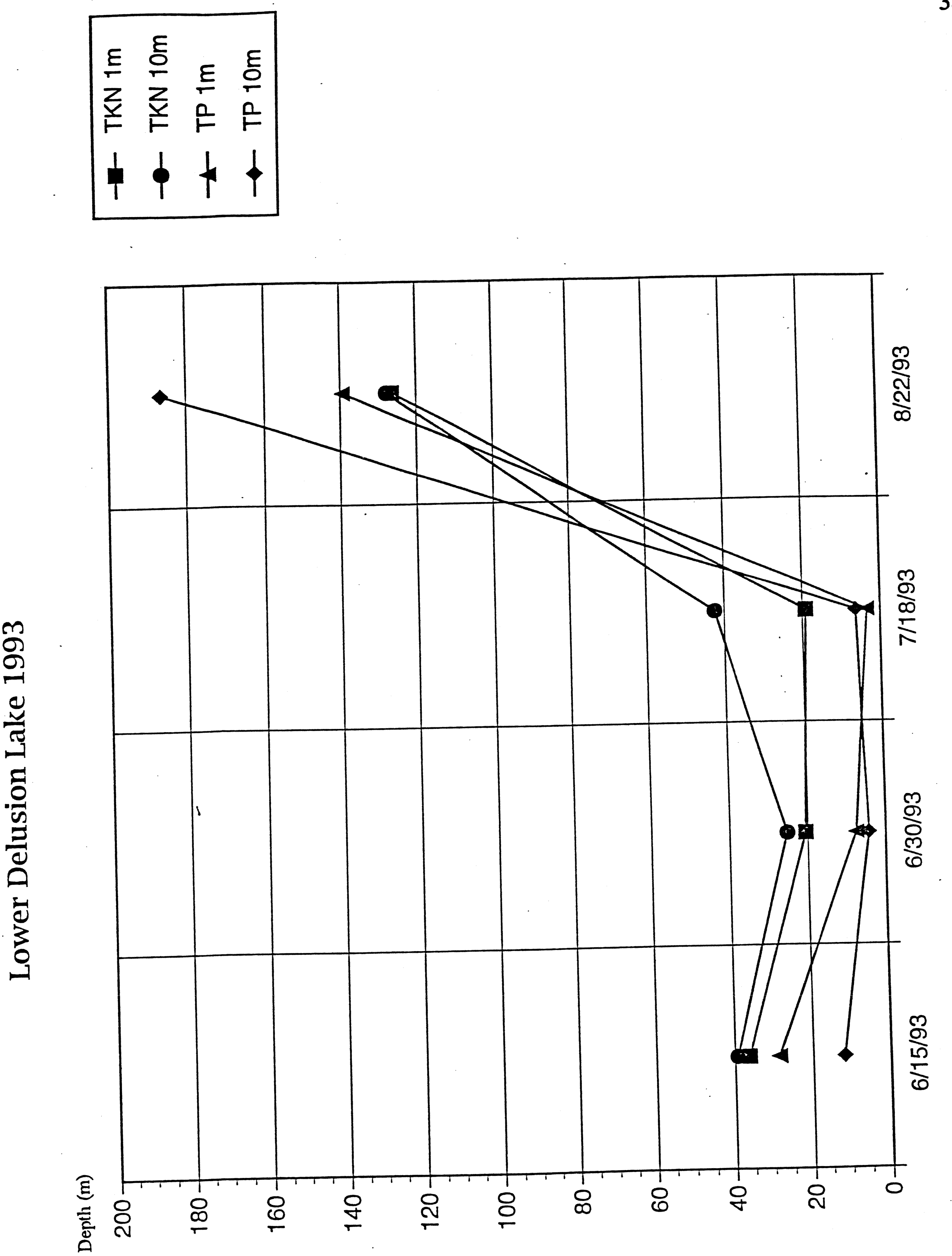


Figure 22. Lower Delusion Lake chemistry 1993.

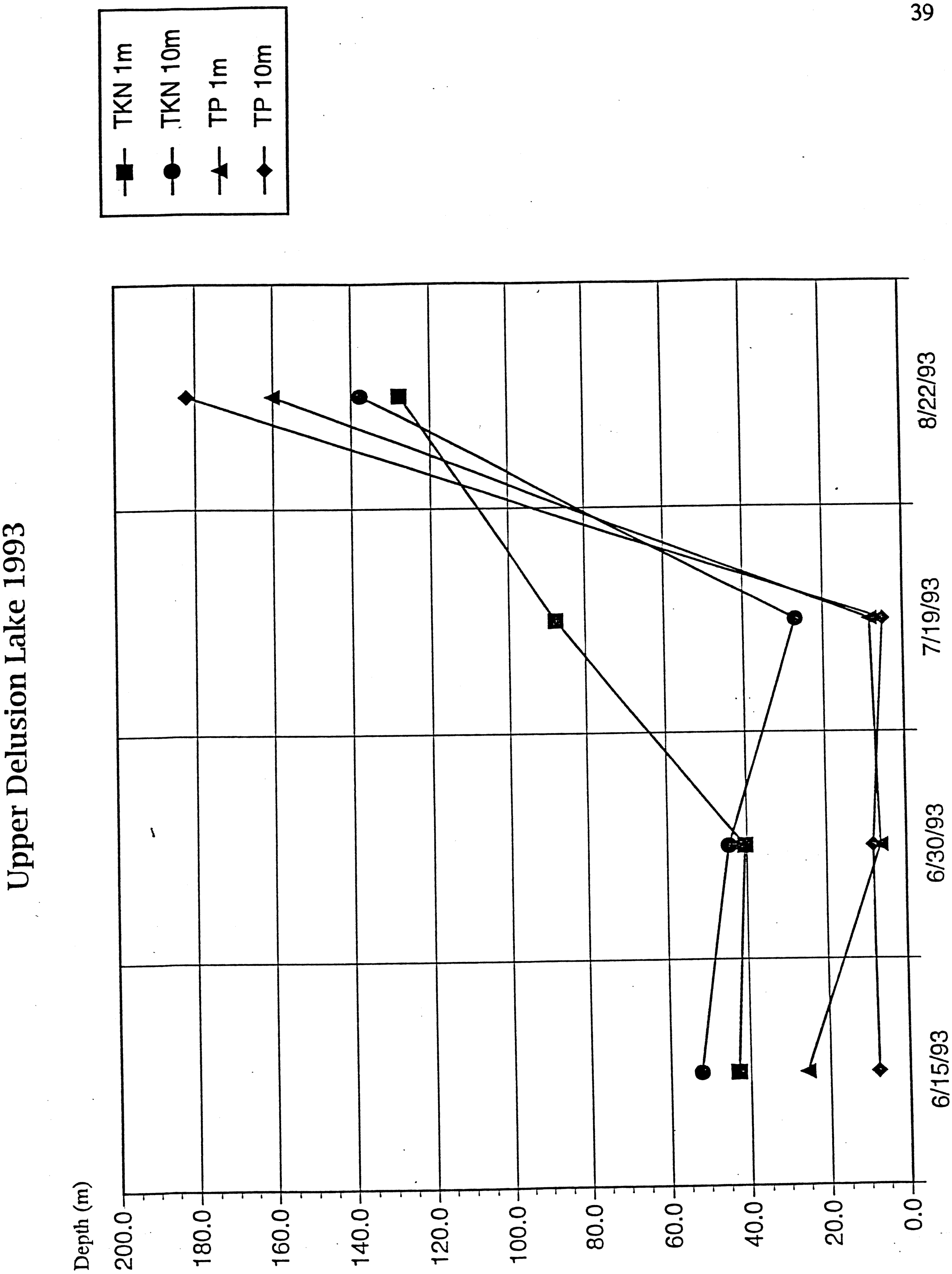


Figure 23. Upper Delusion Lake chemistry 1993.

for Upper Delusion Lake at 1 m was 18.5 $\mu g\ L^{-1}$ and for Lower Delusion Lake was 18.2 $\mu g\ L^{-1}$. The average Total N for the four sampling periods in 1993 at 1 m for Upper Delusion Lake was 106.1 $\mu g\ L^{-1}$ and for Lower Delusion Lake was 82.6 $\mu g\ L^{-1}$. The average Total P for Upper Delusion Lake in 1993 at 1 m was 50.2 $\mu g\ L^{-1}$ and for Lower Delusion Lake was 44.7 $\mu g\ L^{-1}$. These averages are markedly increased by the high levels during August and without these the average Total P for Upper Delusion Lake was 13.5 $\mu g\ L^{-1}$ in 1993 and for Lower Delusion Lake was 13.1 $\mu g\ L^{-1}$. In 1992 atomic N-P ratios were 8.0 for Upper Delusion Lake and 13.6 for Lower Delusion Lake; in 1993 they were 4.7 for Upper Delusion Lake and 4.1 for Lower Delusion Lake. These ratios indicate nitrogen to be limiting to primary production (typically 16:1 for a balanced ratio).

Discussion.—Euphotic volume (EV) is the volume of water within a lake within which photosynthesis (primary productivity as the base of the food chain leading to fish production) occurs. It is calculated by multiplying the lake surface area by the euphotic zone depth (depth to which 1% of the subsurface photosynthetically active radiation penetrates). The euphotic zone depth is approximated by the SD. One EV unit is equal to $10^6\ m^3$ of lake water and according to the rearing model of Kyle et al. (1996), the mean number of threshold-sized sockeye smolts produced per EV unit for unstained lakes was found to be 23,000. The surface area of the two lakes was determined from aerial photographs to be 537,500 m^2 (53.7 ha) for Upper Delusion Lake and 142,500 m^2 (14.3 ha) for Lower Delusion Lake. Using the SDs for the middle of June after turnover in 1993 (6.1 m in the lower lake and 5.4 in the upper lake), this would give a value of 0.87 EV units for Lower Delusion Lake and 2.79 EV units for Upper Delusion Lake for a total of 3.66 EV units. These values would translate into the lakes potentially being able to produce 84,184 sockeye salmon smolts. Taking an average ocean survival rate of smolt to adult spawner of 10%, these values would equate to the lakes being able to support over 8,000 sockeye salmon spawners. As can be seen from the SD data, these values from June 1993 are close to the maximum depths recorded and rainfall events have been shown to reduce clarity significantly. Consequently, primary productivity could be light limited during these periods and limit zooplankton production. In any event, nutrient limitations would appear to significantly influence zooplankton abundance which has always been extremely low. It is possible that the zooplankton are making diurnal fluctuations from the euphotic zone during daylight hours to avoid sockeye fry predation (as has been noted to 60 m in Skilak Lake on the Kenai River; Dana Schmidt, personal communication) and thus were not captured in vertical zooplankton hauls to 10 m. However, an attempt to capture zooplankton at night with vertical hauls showed no marked increase in zooplankton numbers.

Even with the lakes potentially able to produce larger numbers of sockeye salmon smolt than presently use this system, it is likely that production would be limited by the availability of suitable spawning sites (see page 49).

The increase in turbidity and decrease in SD observed during 1992 is probably a result of increased glacial runoff from the remnant ice sheet at the head of the watershed into the upper lake and glacially fed tributaries in the lower system. There were large rainfall and runoff events recorded in early and late August that may have contributed to the higher turbidities. Turbidities were overall lower in 1993 (resulting in increased clarity in the lakes) except for 22 August, which followed a major storm event.

The relatively high levels of Total N and Total P on 22 August 1993 would appear indicative of a pulse of these important algal nutrients into the system. Earlier we suggested that these high levels may have followed the appearance of spawning sockeye and pink salmon in early August. Studies (Cederholm et al., 1989; Kline et al., 1990) have suggested that spawning salmon may contribute significant amounts of nutrients, primarily marine-derived nitrogen and carbon, into oligotrophic lakes and nutrient-poor streams. However, the nitrogen was principally organic in nature and levels were associated with turbidities near 100 NTUs and an SD of 0.1 m. Color also increased markedly following spawning. These relatively high turbidities corresponded directly with large rainfall events between 18 and 20 August, when over 30 cm of precipitation occurred. This level of rainfall creates significant amounts of surface runoff and the potential to erode fragile soils and surface vegetation. This leaching effect could possibly have mobilized significant quantities of nitrogen and phosphorus from the watershed which were transported to the lakes causing the peaks observed. These relatively high concentrations of Total N and Total P would then be fed from the lakes to the stream and, presumably, could be a factor in the marked development of filamentous algae on the stones observed at periods in Delusion Creek, particularly in September 1992.

Both lakes showed no sign of thermal stratification and were typically isothermic for the upper 10 to 15 m during both 1992 and 1993.

Fisheries

Introduction.—Newly formed streams following glacial recession create new habitat for colonization by salmonids and recruitment to the fisheries. For example, Soseith and Milner (1995), using a simple model based on gradient and water clarity/channel stability, estimated that of the 310 streams that have been created in Glacier Bay National Park within the last 200 years, 60% contained salmonids. In Glacier Bay, Dolly Varden char have been documented to be the first colonizers of new streams, as the juveniles of this species are not bottom feeders and so are not affected by the lack of pool habitat typical of these new streams (Milner and Bailey, 1989). Juvenile coho salmon typically prefer pools below riffles and clear water to facilitate sight feeding on drifting organisms. Nevertheless, coho and, if lakes are present, sockeye salmon were found to be the first salmon species to colonize Glacier Bay streams followed by pink and chum salmon (Milner and Bailey, 1989). In a new stream in Glacier Bay, over 76% of the diet of Dolly Varden were chironomid larvae followed by simuliids at 14% for which there was a positive selection (Milner, 1994).

Methodology.—During 1992 and 1993 regular foot counts were made of spawning species within the Delusion Creek Drainage including the main channel, lake margins, and kettle ponds. ADFG also provided aerial estimates of spawning sockeye salmon for Delusion, Desire, and Delight Lakes and in 1992 ages of spawning sockeye salmon from otolith studies. Geoffrey York provided the otoliths to ADFG for Upper and Lower Delusion Lakes sockeye estimations (N= 41). A spawning sockeye salmon aged 4 with 1 year of growth in freshwater and 3 years of growth in saltwater would be categorized as 1:3.

Juvenile rearing salmonids were sampled at the Delusion Creek stations 1 and 2 during the 1992 and 1993 field seasons using minnow traps (0.64 cm mesh) baited with cured salmon eggs placed in small porous containers to prevent ingestion by captured fish. Captured juvenile salmonids were anesthetized with MS 222, identified, and fork length and weight measurements were taken.

Where sufficient fish were captured either in 1992 or 1993 (N > 20), a regression of log weight against log length was plotted and Fulton's Condition Factor (CF) calculated as w/l^3. A histogram of fish lengths was plotted to ascertain different cohort sizes.

Results.—Virtually all the juvenile salmon captured by minnow traps in Delusion Creek were Dolly Varden char. Capture rates were generally low, typically with a catch per unit effort (CPUE) of less than 0.5/trap (Table 3). The highest CPUE was 5.9 fish/trap on 18 August 1993 at site 1; these fish were all Dolly Varden char (Table 3). Capture rates for 1992 were also highest in August. On only three occasions were more than 20 fish captured, so only three regressions and three histograms were plotted.

Table 3. Number of juvenile salmon captured per minnow trap (CPUE) during 1992 and 1993.

Date	Site 1 CPUE	Site 2 CPUE
7.15.92	0.167	0.167
8.12.92	2.3	1.7
8.29.92	1.7	0.5
6.11.93	0.2	0.4
6.19.93	0.4	0.0
7.25.93	2.3	0.4
7.31.93	0.2	0.2
8.8.93	1.85	
8.18.93	5.9	

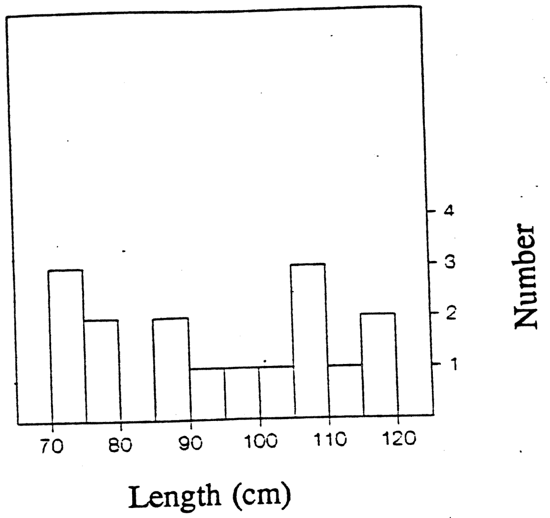
Histograms of juvenile Dolly Varden lengths (Figure 24) showed that most fish were principally 1+, taking 70 cm as a cut-off point for late July/early August fish between year classes. Condition factors were very similar for the three plots and varied between 1.13 and 1.14.

The short 1994 season ended before salmon spawners were evident in Delusion Creek. In 1992 and 1993 the field season was completed before the coho salmon run into the streams was developed, although it is evident from minnow trapping and field observations that coho salmon do utilize the Delusion Creek Drainage. However, very few juvenile coho were captured in stream sections 1 and 2 (CPUE ≤ 0.1/trap). Minnow traps were set in the margins of the lakes but no fish were captured. However, juvenile coho salmon were observed in significant numbers using the small feeders streams and kettle ponds south of Upper Delusion Lake as rearing habitat.

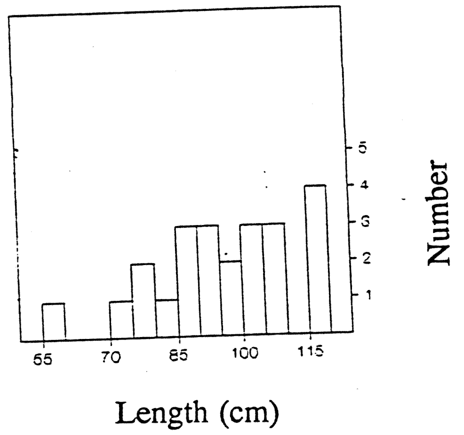
In 1992, less than 100 pink salmon (*Oncorhynchus gorbuscha*) were observed spawning at the outlet of Lower Delusion Lake. In 1993, over 100 pink salmon were observed spawning in a similar location and also in the outlet of Upper Delusion Lake. Aerial surveys by ADFG estimated that 900 sockeye salmon (*O. nerka)* spawned in 1992, while this number was estimated to be 1200 in 1993. Spawning occurred primarily along the gentle sloping beaches at the lower (south) and upper (north) ends of the lake. Two king salmon (*O. tshawytscha*) were observed in 1993 in Lower Delusion Lake.

Ninety-one percent of sockeye salmon spawners (N = 11) in Delight Lake were in age categories 1:2 and 1:3, indicating that juvenile sockeye salmon stayed in freshwater one year, while 9% remained two years (adult age categories 2:2 and 2:3) (Table 4). In Desire Lake, 68% of sockeye spawners (N = 81) indicated one-year residence of juveniles, while the remainder of spawners indicated a two-year residence. In contrast, 93% of

21 August 1992 Mean length = 93.3 cm
Mean weight = 6.95 g
r^2 = 0.96
CF = 1.13



26 July 1993 Mean length = 95.4 cm
Mean weight = 8.00 g
r^2 = 0.94
CF = 1.14



18 August 1993 Mean length = 94.8 cm
Mean weight = 7.98 g
r^2 = 0.99
CF = 1.13

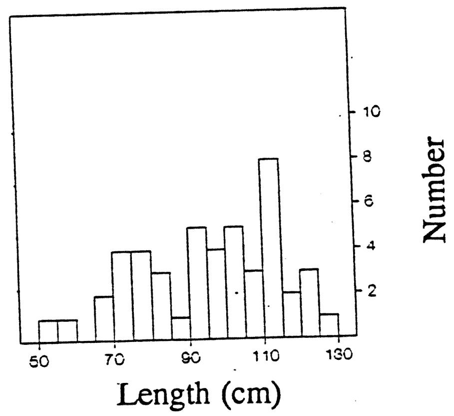


Figure 24. Length classes (5 cm) of juvenile Dolly Varden in Delusion Creek with Fulton Condition Factors.

Table 4. Age and mean length (mm) of sockeye salmon escapement into the Delusion, Desire, and Delight systems in 1992.

Delusion Lake

	Age Group			
	1.3	2.2	2.3	Total
Both Sexes	73.00	341.00	586.00	1,000.00
Percent	7.30	34.10	58.60	100.00
Sample Size	3.00	14.00	24.00	41.00
Mean Length	534.00	491.00	553.00	531.00
Std. Error	23.00	9.00	4.00	4.00

Desire Lake

	Age Group				
	1.2	1.3	2.2	2.3	Total
Both Sexes	2,791.00	5,288.00	1,176.00	2,645.00	11,900.00
Percent	23.45	44.44	9.88	22.23	100.00
Sample Size	19.00	36.00	8.00	18.00	81.00
Mean Length	481.00	544.00	500.00	540.00	524.00
Std. Error	4.00	3.00	6.00	6.00	2.00

Delight Lake

	Age Group			
	1.2	1.3	2.3	Total
Both Sexes	1,064.00	4,254.00	532.00	5,850.00
Percent	18.19	72.72	9.09	100.00
Sample Size	2.00	8.00	1.00	11.00
Mean Length	505.00	538.00	554.00	533.00
Std. Error	5.00	7.00		5.00

the sockeye salmon spawners (N = 41) from Upper Delusion Lake were aged 2.2 and 2.3, indicating that the majority of fry remained two years in freshwater before smolting.

Discussion.—Data from Delusion Creek support the contention that Dolly Varden char are the most abundant of the earlier salmonid colonizers of new streams following deglaciation, because their juveniles are more adapted for surviving in unstable channels dominated by riffles and glides with an absence of pools. Juvenile coho salmon, disadvantaged by the lack of pools due to their preference for sight feeding at the surface, were found in very low numbers in the main channel. Some significant pool-type habitat are created behind large boulders, but these are often midchannel and drifting organisms are carried wide of pools created in this manner. The Fulton CFs of 1.13 and 1.14 calculated for juvenile Dolly Varden was below the value of 1.18 recorded for Dolly Varden in Nunatak Creek, a new clear-water stream in Glacier Bay National Park (Milner and Bailey, 1989).

It is evident that four salmon species have colonized the Delusion Creek watershed. The absent species is chum salmon (*O. keta*), although it could have been missed during foot counts if numbers were extremely low and the stage was high. Slimy sculpin was also found in the system. It is fascinating that Upper Delusion Lake, which only began to form in the mid-1970s, now supports a run of over 1000 sockeye spawners. There is a close-by colonizing pool with strays from the Desire Lake and Delight Lake systems that could act as an initial seed source. Numbers of spawners in Desire and Delight in the 1980s frequently exceeded 10,000 spawners for each system, and the high for Delight was close to 30,000 spawners in 1985 (ADFG, 1992). These fisheries data from ADFG indicate that in less than 100 years sufficient numbers of sockeye salmon have colonized the Desire and Delight systems to support a commercial fishery. In high years, these two systems have supported commercial catches exceeding 50,000 red salmon, although in recent years catches have declined significantly. In 1992, low numbers of sockeye spawners prevented a commercial opening.

There is a clear relationship with the proportion of sockeye fry that have to remain in the lakes two years to smolt and the age of the lake (comparing Delusion, Desire, and Delight). This is very evident in the case of Upper Delusion Lake, where 93% of one spawning year class had remained two years in freshwater before smolting. This is not the optimum position for enhanced production, as young of the year are competing against year-old fish for limited food resources, resulting in their increased mortality.

Although the euphotic volume indicates that the Delusion Creek system could potentially support increased numbers of spawners, it is likely that this system is spawning-habitat limited. There is no suitable spawning habitat in the streams above Upper Delusion Lake. The most suitable habitat are shallow beaches along the north shore where these streams enter, and the southern shore where there is inflow from the kettle ponds. The extent of this habitat is limited. The remainder of the shoreline in Upper Delusion is too steep.

Experimental Work

Channel Experiments

Introduction.—In spring 1994, a commercial liquid fish fertilizer was introduced by means of drip-feed from Mariotte bottles into artificial channels to further investigate the potential effect of increased nutrient concentrations from the decay of salmon carcasses. This experiment mimics the effect of the release of nitrogen and phosphorus from decaying salmon carcasses into the developing stream ecosystem.

Methodology.—Four artificial channels (4m x 0.2m x 0.2m) were constructed of plywood and situated just below Delusion Creek station 1. Each channel was fed with stream water via PVC piping from a flow-regulating tank (approx 1.5 m^2). The tank received water from the stream from flexible sewer piping. Substrate was added to each channel from nearby sections of the main channel. Two control channels (3 and 4) received no treatment. A commercial fish fertilizer mix was added to channels 1 and 2 using a standard Mariotte bottle drip. Water samples were collected in triplicate on 26 May and 8 June and analyzed for Total N and Total P. Rock scrapings were taken from each channel to analyze for chlorophyll-*a* levels at the end of the experiment. Drift nets of 343 μ mesh were used at the end of each channel to collect drifting organisms. The nets were emptied every 24 hours over the course of the experiment, which ran from 26 May until 13 June 1994. On 13 June, the channels were destructively sampled and all organisms in the channels collected. Invertebrates were sorted from the drift and channel samples in the laboratory, identified to family, and enumerated.

The channel was originally set up on 20 May, but it had to be withdrawn due to rising stream levels from heavy rain and the concern that the entire system would be lost.

A t test was run between total individuals in the drift from channels 1 and 2 and channels 3 and 4 to evaluate if a significant difference existed between the enriched channels and the control channels.

Results.—Table 5 summarizes the drift numbers for the four channels for 17 days from 26 May to 13 June with the exception of 8 June.

Average total numbers for drift from the channels over the 17 days were as follows (± 1 SD).

Channel 1 = 55 (± 10)
Channel 2 = 89 (± 36)
Channel 3 = 120 (± 44)
Channel 4 = 136 (± 55)

The overall daily average for drift from the enriched channels (1 and 2) was 72 organisms and for the controls (3 and 4) was 128 organisms. The average number of invertebrates/channel at the conclusion of the experiment was 6302 for the enriched channels and 2612 for the control channels. The average Total N and Total P values for the four channels are provided in Table 6. Unfortunately, no data are available for channel 4 on 8 June. Average chlorophyll-*a* levels were 2.7 times higher in the enriched channels than the control channels.

The t test showed a very significant difference ($p < 0.001$) between numbers of individuals drifting from the enriched channels compared to the control channels.

Results.—Although qualitative observations appeared to indicate more algal growth on the nitrogen and nitrogen/phosphorus pots, the chlorophyll-*a* data showed no definite pattern.

Artificial Algae Experiment

Introduction.—To test the concept that invertebrates lack refuges on the relatively barren stones of Delusion Creek, artificial algae was attached to a number of stones that were then left in the stream for 3 weeks to allow for colonization.

Methodology.—"Aquafern," a proprietary product sold in aquarium stores, is dried algal filamentous algae. Three or four strands of this material was attached to 10 sterile stones between 7 and 12 cm, which were then placed randomly along the margins of Delusion Creek at site 1. Ten stones of equal size without artificial algae were also placed in the stream margin. After 3 weeks, the stones were removed and all invertebrates removed and enumerated.

Results.—Figure 25 shows that the majority of invertebrates were Chironomidae and that invertebrate abundances were significantly higher ($p < 0.05$) on stones with artificial algae than the control stones.

Discussion.—These data indicate that invertebrates, particularly Chironomidae, show a strong preference for the cover of algae, and this may be one of the factors that is limiting invertebrate abundance in Delusion Creek. Artificial algae may also trap organic particles that are being transported downstream and these could be of nutritional value to invertebrate colonizers.

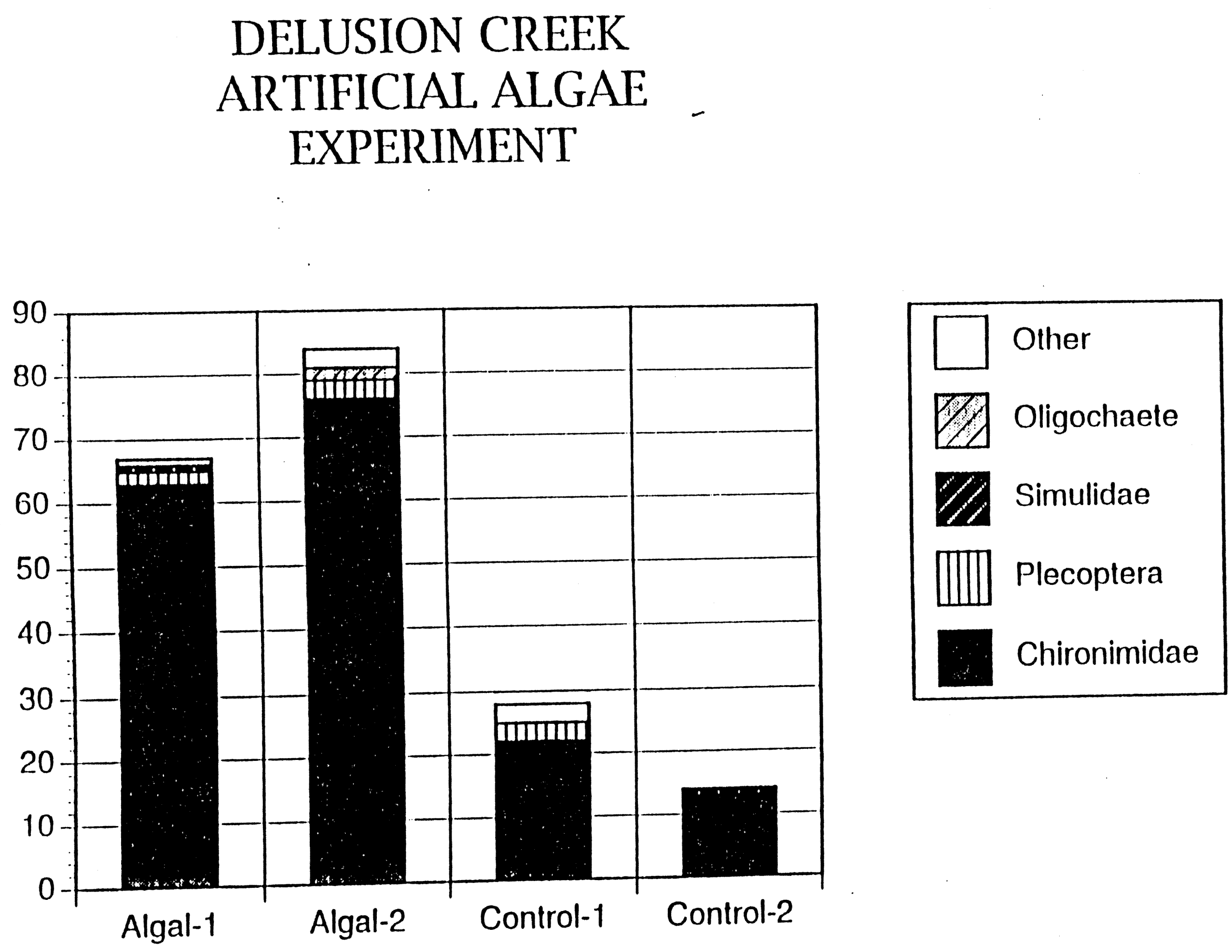


Figure 25. Delusion Creek artificial algae experiment.

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