EFFECTS OF WATERSHED CHARACTERISTICS AND DISTURBANCES ON THE WATER QUALITY OF TWO BOREAL STREAMS

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ABSTRACT

The effects of wetlands, beaver and timber harvesting on several water quality parameters were monitored on Rocky Creek, an 18.6 km^2 boreal watershed in Alberta. A fen at the head of the watershed was the main source of dissolved organic carbon (DOC), Concentrations of DOC decreased from 125 ppm at the source to 20-30 ppm near the watershed exit. Concentrations of Ca, Na, Mg, and K increased with distance downstream, probably through contributions from groundwater seepage. Beaver ponds increased the temperature and pH of the water passing through them. An exceptionally high peak flow (15 $m^3 s^{-1}$) occurred when a beaver dam failed, but the wetland near the centre of the watershed absorbed a considerable portion of the volume. Timber harvesting had no measurable effect on water quality because the riparian areas were left intact. New research should include the design and development of a watershed response model that takes into account the special features of the boreal forest and simulates the changes in water quantity and quality in response to disturbances on boreal watersheds. Inexpensive, portable semi-permanent stream-gauging structures capable of measuring flows of 0.001$m^3 s^{-1}$ should be developed for use in remote, inaccessible areas on boreal watersheds.

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INTRODUCTION

Part of the complex relationship between forests and water lies in the contribution of 1) the **forest** in regulating soil moisture, water table, streamflow, and maintaining water quality and 2) the **water** as a vital life support medium, transporting agent, chemical solvent, and catalyst. The complexity depends upon the type of forest, nature of precipitation; upon geology, topography and soils; and upon the interaction of physical and biochemical cycles within the aquatic ecosystem (Likens *et al.* 1977; Canadian Council of Resource and Environment Ministers, Task Force (CCREM) 1995).

Forest harvesting and other industrial activities have the potential to impair water quality and affect aquatic biota. Roads crossing streams, in particular, may affect stream water quality by contributing sediment and other materials through erosion or blowing dust. Removal of the forest canopy during clearcutting and the subsequent disturbance by mechanical site preparation and prescribed burning adversely affect overall microbial biomass and metabolism, and causes soil erosion (Everest and Harr 1982). This results in movement of particulate and dissolved organic matter and nutrients through forested watersheds (Fredriksen 1971; Waide *et al.* 1988), and increased concentration of suspended sediments and debris in streamwater (Toews and Brownlee 1981; Chamberlin 1982).

In western Canada, there is a notable lack of information on natural water quality of boreal forest streams. The effects of disturbances, natural or man-made, on water quality in boreal streams are also unknown. In recent years, there has been considerable industrial development in Alberta's boreal forest where new pulp mills, saw mills and other types of forest products plant have come on stream. These plants require considerable amounts of wood to sustain them, and the harvesting of this wood may be accompanied by changes in the flow and quality of streams draining affected watersheds. The quality and flows of boreal streams may be greatly influenced by the special features of the boreal forest region, i.e., mixedwoods stands, pure aspen (*Populus tremuloides* Michx.) stands, varied topography, lakes, wetland (bogs, fens and swamps; organic soils), and beaver (*Castor canadensis*) activity.

Beaver activity can have a profound effect on riparian areas and on the quality and dynamics of stream waters. Unlike industrial forestry companies, beaver are not guided by Timber Harvesting Guidelines and other ground rules - their "harvesting" is done as close to streams as possible. Beaver dams may impound a portion or the entire volume of water draining a watershed. Often, streams will be reduced to a trickle, most of which may be seepage below or over the dams. Conversely, when a heavy storm causes significant runoff response, such runoff may be sufficient to breach one or more dams. The result is a sudden surge of water and nutrients down the channel with the flow consisting of the original storm runoff plus the water that was previously stored behind the now-breached dams. Similarly, the water quality will reflect the qualitative characteristics of both the original storm runoff and the characteristics of the stored water. This needs to be demonstrated, however, because there is very little information on the effects of beaver activity on stream water quality, stream dynamics and riparian areas in the western boreal forest.

Because fens and bogs, common in the boreal forest, are characterized by organic soils and relatively high water tables, the water issuing from such areas may influence the quality of water reaching the stream channels differently from water issuing from upland areas with mineral soils.

In 1991, the Canadian Forest Service (CFS) initiated a study to address the deficiency of information with respect to water quality in boreal forest streams. The following year, the CFS became part of the Spring Creek Project - a study initiated by Daishowa-Marubeni International Ltd., a forest products company, and Alberta Department of Environmental Protection to determine 1) the impact of aspen harvesting on water yield, and 2) the time required for the vegetation to recover to the extent that the anticipated increase in water yield is restored to, or near, preharvest streamflow levels. Spring Creek was chosen because it was a boreal watershed that contained sufficient mature aspen to justify harvesting and conducting the experiment, and because it was monitored, in an undisturbed state, with respect to streamflow and meteorology during a 20-year period (1967-1987).

The objective of the CFS study was to determine the impact of a number of natural and human disturbances, including timber harvesting, on the water quality of Rocky and Bridlebit Creeks. The watersheds of both streams are part of the Spring Creek system, and are adjacent to one another. The objective was to be achieved by:

a) measuring water quality parameters to determine if there is evidence of a shift in these parameters that may indicate an impact and recovery related to forest harvesting;

b) measuring water quality parameters to identify any changes and impacts to these parameters relative to winter and all-weather roads crossing streams;

c) measuring water quality parameters of flows upstream and downstream from beaver ponds;

d) identifying the effect of wetlands on water quality parameters.

WATER QUALITY AND AQUATIC LIFE

Changes in water quality can significantly affect aquatic life. Changes in aquatic concentrations of chemicals (dissolved organic matter, nutrients, and elements) resulting from natural or other disturbances, for example, may have direct impact on the aquatic ecosystem by altering pH, dissolved oxygen, water temperature, energy pool, and available food sources sustaining aquatic biota, and may lead to changes in the structure of the food-web.

Particulate and dissolved organic matter are important food sources for fish and freshwater biota (Kaplan and Bott 1983; Swank and Crossley 1988). Dissolved organic matter is also an important component of the organic energy budget of temperate stream ecosystems (Fisher and Likens 1973) and is frequently measured as dissolved organic carbon (DOC) in studies on fresh water quality (Larson 1978; Moeller *et al.* 1979; Kaplan *et al.* 1980; Meyer and O'Hop 1983; Bourbonniere 1989; Evans *et al.* 1989). Increases in particulate organic matter and concentration of DOC may last for three years or more following forest clearcutting (Meyer *et al.* 1988). Benthic algae, fungi, and bacteria are the organisms most likely to assimilate naturally occurring DOC from the water column (Dahm 1981; Kaplan and Bott 1982, 1983; Moran and Hodson 1989).

In a study on the Coweeta watershed, Meyer *et al.* (1988) concluded that: 1) streamwater DOC changes with watershed disturbance and recovery, 2) the ultimate fate of DOC in the stream trophic structure is an important topic for future research, and 3) benthic meiofauna may prove to be an important link between DOC-utilizing bacteria and benthic macroinvertebrates. Forestry related DOC studies were also reported for forest catchments in New Zealand (Collier *et al.* 1989; Moore 1989; Moore and Jackson 1989), boreal watersheds in Quebec (Ford and Naiman 1989), and peatlands in north central North America (Urban *et al* 1989).

Suspended sediments, consisting mostly of fine soil particles that are carried along in streamflow, increase turbidity and transport plant nutrients, heavy metals, pesticides, pathogens and other potential pollutants attached to soil particles. Such particles can settle in streams and reservoirs, reducing water storage capacity, impairing fish habitat (especially spawning ability), and obstructing fish navigation as particles accumulate in water courses (Binkley and Brown 1993).

Water temperature plays a major role in influencing aquatic life and the physical and chemical parameters of the aquatic environment. Changes in temperature will affect solubility and chemical reaction equilibria (Mullins 1977, cited in CCREM 1995). Increases in temperature decrease the solubility of dissolved gases (H_2 , N_2 , CO_2 and O_2) in water. Within the range of 0-30°C, for example, oxygen solubility decreases by approximately 50%.

The biochemical processes of aquatic organisms governing metabolism, reproduction, growth and behaviour are very sensitive to temperature, and changes in temperature will affect the rates of these processes. Respiration rates, for example, increase with temperature, and lead to a higher rate of metabolism and excretion. Thus, the organism requires more oxygen in an environment which contains less than before, and may suffocate. The rates of metabolism and excretion would be expected to double for every 10°C increase in temperature (Connell and Miller 1984, cited in CCREM 1995. Warm water is conducive to the growth of many aquatic bacteria, some of which are pathogenic to fish (Brown 1991).

The concentration of dissolved oxygen in the water of small forest streams significantly influences the character and productivity of the aquatic ecosystem in these streams. It is particularly important in the intra-gravel water of the stream bed where fish spend the early part of their life cycles. Dissolved oxygen concentration is governed by the solubility of oxygen in water, the rate at which this oxygen is consumed by various processes (biochemical oxygen demand, or BOD), and the rate at which this depletion is replenished (Brown 1991). The solubility of oxygen in water increases with atmospheric pressure and decreases with temperature.

Organic material from waste products and decaying plants can lower the dissolved oxygen available for fish and aquatic invertebrates to potentially lethal levels and cause water color changes and odor problems. Oxygen in stream water may be depleted by respiration of aquatic plants, or by BOD processes such as the chemical oxidation of dissolved, suspended or deposited organic materials in the stream, and the decomposition of these materials by aquatic organisms. Oxygen depletion related to woody or logging debris is a two phase process in which the material must first leach from the debris into the stream. The second phase, which is the one usually associated with oxygen depletion, is the biochemical degradation of the leachate.

Oxygen may be restored to the water through photosynthesizing plants, or through entrainment of air into the stream as bubbles at points of turbulence. Thus oxygenation is enhanced in turbulent streams. Turbulence generally increases with stream gradient, velocity and channel bottom roughness (Brown 1991).

Most studies concerned with the effects of low oxygen levels on aquatic life deal with fish and may not be applicable to freshwater invertebrates. Davis (1975, cited in CCREM 1995), however, maintained that if all life stages of fish are protected, the invertebrate communities should also be reasonably well protected.

The pH of water approximates the activity of free hydrogen ions in water. It is defined as the negative logarithm of the hydrogen ion concentration. The direct effects of pH on aquatic organisms become more severe as the pH tends away from the natural range of 6.5 to 9.0 (CCREM 1995). In general, few fish can acclimate to pH 3.5-4.0. Some fish species, such as perch and pike, may acclimate to this pH range, but most could not reproduce. Increasing acidity (decreasing pH) mobilizes many elements, such as aluminum, which interfere with physiological processes of fish and other aquatic organisms (Binkley and Brown 1993). In alkaline waters, pH 9.0-9.5 approaches the tolerance level for many fish, but most invertebrates are unaffected. A pH ranging from 9.5 to 10.0 may be lethal to salmonids over a long period of time (Sprague 1985, cited in CCREM 1995)

Dissolved solids include a series of ions and dissolved compounds that, at sufficiently high levels, can harm fish and other organisms. Specific conductance, which is a numerical expression of water's ability to conduct an electric current, and total dissolved solids, are two measures of the overall concentration of these ions. The principal factors that influence the conductance of an aqueous solution include the nature and concentration of the solutes present, the degree to which they dissociate into ions, the amount of electrical charge on each ion, ion mobility and the temperature of the solution. Solutions of most inorganic acids, bases and salts are relatively good conductors. Organic compounds that do not dissociate in aqueous solution conduct either no or very little current. It has been estimated that, for most natural waters, conductance may be related to dissolved solids (in ppm) by multiplying the conductance by a factor ranging from 0.55 to 0.75 (CCREM 1995).

SITE DESCRIPTION

Climate, geology, soils, vegetation and fauna

The Rocky Creek (54° 56' N., 117° 46' W.) and Bridlebit Creek (54° 56' N., 117° 44' W.) watersheds are subwatersheds of the Spring Creek watershed, located about 35 km southwest of Valleyview on the southern margin of the Peace River Region, Alberta (Fig. 1). The region is an extensive plain mantled largely by glacio-lacustrine deposits and supporting parkland and boreal mixedwood ecosystems. The Peace River Region has a subhumid microthermal climate and the study area represents the cooler and wetter areas of the region. Summers are short and cool with less than four months of the year having mean temperatures over 10 °C. Most of the precipitation is generated by cyclonic activity, and convective thundershowers provide additional rainfall during the summer (Martz 1978). At Valleyview, the closest station to Rocky and Bridlebit Creeks with long-term (1951-1980) meteorological records, the mean annual temperature is 2.3°C. The average January and July temperatures are -15.9°C and 15.8°C, respectively (Atmospheric Environment Service 1982a). The average annual precipitation is 519 mm, 302 mm of which falls during May through September.

The average winter snowfall is 169 cm (Atmospheric Environment Service 1982b).

The watersheds are located in the Central Mixedwood Subregion of the Boreal Forest Natural Region of Alberta which is characterized by aspen forests and gray luvisols (Alberta Environmental Protection 1994). The watersheds are underlain by horizontally bedded sandstone, siltstone and shale of the Upper Wapiti formation. Above this is till mantled by a variable thickness of stony glacio-lacustrine deposits. The dominant soils are Braeburn and Codesa which range from clay-loam to sandy-loam (Martz 1978). Vegetation on the watersheds consists primarily of aspen forest, except on organic soils where black spruce (*Picea mariana* (Mill.) B.S.P.) and, to a lesser extent, tamarack (*Larix laricina* (Du Roi) K. Koch) are the dominant species. Disturbances to the vegetation consist mostly of seismic lines constructed for oil and gas exploration purposes.

Although Rocky Creek and Bridlebit Creek watersheds are similar in many respects, there are noticeable differences. Dimensionally the two watersheds are similar (Table 1) but Bridlebit Creek produces considerably more water annually. During the period 1967-1987, mean annual water yield from Bridlebit Creek was 2085 x 10^3 m^3 compared with 1204 x 10^3 m^3 from Rocky Creek. The proportion of organic terrain in each watershed is about the same but the distribution is different. In the Rocky Creek watershed organic soils are concentrated in the fen south of the natural lake and in the wetland near the centre of the watershed (Fig. 1), whereas in the Bridlebit Creek watershed they occur primarily along the main stream channel. Aspen is present in both watersheds and is the dominant tree species in the Rocky Creek watershed, but in the Bridlebit Creek watershed black spruce and white spruce (*Picea glauca* (Moench) Voss) form a greater proportion of the forest cover.

No fish and wildlife studies were conducted as part of this project but it is worth noting that Rocky Creek supports populations of small fish. These were most noticeable at the bridge near station 07GF006 (Fig. 1), where they occasionally attracted herons (*Ardea herodias*) and kingfishers (*Ceryle alcyon*). Rocky Creek was also inhabited by leeches (class *Hirudina*) that were sometimes drawn up with the water into the sampling bottles by the automatic samplers. Beaver were very active on Rocky Creek, Bridlebit Creek, and on streams in the area generally.

During the course of the study there were sightings of several of the larger mammals, namely, wolf (*Canis lupus*), black bear (*Ursus americanus*), moose (*Alces alces*) and deer (*Odocoileus spp.*). Conspicuous among the bird sightings were the bald eagle (*Haliaeetus leucocephalus*) and the golden eagle (*Aquila chrysaetos*).

Hydrology

Rocky Creek

The Rocky Creek watershed is a typical boreal watershed in that it is a low water yielding area compared to other hydrologic regions, and relative to its annual precipitation. It contains an abundance of natural storage facilities such as a lake, porous soils, wetlands, beaver ponds, and low slope areas distributed over its length. The dimensions of the Rocky Creek watershed are given in Table 1.

Table 1. Dimensional characteristics of Bridlebit Creek and Rocky Creek watersheds.

Watershed	Area (km^2)	Drainage density ($km\ km^{-2}$)	Length (L) (km)	Width (W) (km)	Form ratio (L/W)	Relief (m)
Rocky Creek	18.6	1.9	8.7	4.2	2.1	130
Bridlebit Creek	19.7	2.3	7.4	5.3	1.4	100

After Martz 1978

A 120-ha lake occupies the upper, northern end of the watershed, downstream from which is a large fen, characterized by organic soils supporting black spruce and some tamarack (Fig.1). Rocky Creek first manifests itself as a water track flowing from the lake through the fen. The stream channel is first clearly defined as a first order stream just downstream from the fen. The uppermost hydrometric and water sampling station (Station 1) was installed at this location. From here, Rocky Creek flows through undulating to gently rolling terrain characterized by lacustro-till. A chain of four beaver ponds is located in this portion of the channel, the slope of which is about 0.018. Station 2 was located downstream from the beaver ponds.

The next section of channel is joined by a small tributary, thereby becoming a second order stream. It has a 0.03 slope and passes through a v-shaped valley with steep sides and aspen cover. This section, the surficial material of which is till, contained stations 3 to 6 . Station 3 was located about 200 m upstream from the northern boundary of cut blocks on the watershed and station 4 was located 400 m downstream from the same boundary. The geomorphology of station 6, located at the south end of the valley, is transitional between that of the valley and the wetland just south of it.

Downstream from the valley section, the creek flows into a flat (slope < 0.005) wetland area, about 90 ha in extent, that contains a number of small beaver ponds and a teardrop-shaped natural lake. The lake is about 640 m long and is bounded by an open fen. The wetland contains significant amounts of organic soil, sedge (*Carex* spp.) meadow, willow (*Salix* spp.), lesser amounts of marshy areas and small areas of spruce. In the wetland, water flow becomes diffuse, taking advantage of available storage behind the beaver dams and available groundwater storage in the meadow areas. Channelized flow runs into and out of the small lake.

An ephemeral tributary, parallel to and feeding Rocky Creek, flows into the wetland about 1 km upstream from the lake. Station 7 was located on the ephemeral channel about 500 m upstream from the lake (Fig. 1) to monitor the contribution of analytes from the tributary to Rocky Creek. Below the wetland, the creek continues southward through more glacial till to station 8 and the main stream gauge (07GF006) located about 1.3 km upstream from its confluence with Spring Creek. The average slope of this reach is about 0.009. Stations 9 and 10 were located immediately upstream and downstream from the main stream gauge, respectively. They are the collectors of all dissolved analytes from the Rocky Creek watershed. A 4-m wide dirt road crosses Rocky Creek between the stream gauge and Station 10. Rocky Creek continues southward into Spring Creek which, in turn, drains into the Simonette River to the southwest.

The mean discharge from Rocky Creek is 0.038 $m^3 s^{-1}$ and the annual water yield is 1204 x 10^3 m^3. The mean annual runoff and runoff/precipitation ratio are 65 mm and 0.12, respectively. The low runoff from the watershed relative to precipitation can be attributed to the ready availability of storage in the lake depression, in the wetlands, and behind beaver dams. The large surface area of the lakes, the extent of the wetlands, and the total surface area of the beaver ponds facilitate evaporation from the watershed, thereby further reducing runoff.

Nearly 60% of the total annual flow runs off in the spring (March through May) following snowmelt, and about 35% of the annual flow can be attributed to summer rainstorms. The remaining 5% is low winter flow. Rocky Creek is characterized by low flows (< 0.01 $m^3 s^{-1}$) for much of the growing season. Both the beaver dams and the wetlands serve as natural reservoirs and regulate streamflow throughout the year, particularly when their available storage capacity is at a maximum. Spring runoff, and runoff from the heavier rainstorms tend to overtop the beaver dams, whereas low flows tend to appear as seepage from beneath the dams.

Bridlebit Creek

The dimensions of the Bridlebit Creek watershed, which lies adjacent to, and east of the Rocky Creek watershed, are given in Table 1. Bridlebit Creek enters Spring Creek about 2 km upstream from the point where Rocky Creek flows into Spring Creek. The mean annual discharge for Bridlebit Creek is 0.066 $m^3 s^{-1}$ and the annual water yield is 2085 x 10^3 m^3. The mean annual runoff and runoff/precipitation ratio are 106 mm and 0.20, respectively. Beaver dams and ponds are present on Bridlebit Creek.

Spring Creek

Runoff from the Spring Creek watershed can show considerable differences in response to identical precipitation events. Holocek (1988) reported runoff/precipitation ratios of 0.001 and 0.532 for two storms of the same magnitude and intensity that occurred two years apart. In the first case, very dry antecedent soil moisture conditions (high water storage capacity) prevailed on the basin, and in the second, antecedent conditions were very wet (low water storage capacity).

METHODS

Experimental design

An experimental design was proposed that would meet the project objectives stated on page 2. It required that the upper portion of the Rocky Creek watershed be designated as the control area and be excluded from any type of logging, road construction or other human-induced disturbances. It also required that a timber harvesting plan be developed for the area downstream from the designated control that would satisfy the needs of both the water yield and the water quality studies. The design entailed establishing twelve hydrometric/water sampling stations at strategic locations on Rocky and Bridlebit Creeks (Fig. 1; Table 2):

a) immediately downstream from the fen (station 1),
b) downstream from the chain of beaver ponds (station 2),

Table 2. Periods of record during which data on the water chemistry and physical characteristics, including stream discharge, were obtained from Rocky and Bridlebit Creeks.

Hydrometric/ water quality sampling station number	Elevation (m)	Location	Distance downstream from station 1 (m)	1993 (dd/mm)	1994 (dd/mm)	1995 (dd/mm)
Rocky Creek						
Precipitation		end of road	-	1/7 - 31/12	1/1 - 30/9	1/1 - 30/11
1	769	below fen	0	-	4/5 - 4/10	2/5 - 5/10
2	755	control	1123	29/6 - 4/10	29/7 - 4/10	3/5 - 5/10
2a		control		29/6 - 4/10	Discontinued	-
3	750	control	1347	30/6 - 4/10	16/7 - 4/10	2/5 - 5/10
4	731	within harvested area	1946	29/6 - 4/10	25/5 - 4/10	3/5 - 5/10
5	720	within harvested area	2440	29/6 - 4/10	28/7 - 4/10	3/5 - 5/10
6	706	within harvested area	2844	29/6 - 4/10	26/5 - 4/10	3/5 - 6/10
7	694	tributary stream	-	-	15/7 - 5/10	4/5 - 3/10
8	689 ?	downstream from wetland	5464	-	/5 - 5/10	4/5 - 3/10
9		road	6587	10/8 - 5/10	26/5 - 5/10	2/5 - 3/10
10		road	6624	30/6 - 5/10	31/5 - 6/10	2/5 - 3/10
07GF006[a]	671	road		1/6 - 28/10	18/3 - 31/10	22/3 - 31/10
Bridlebit Creek						
11		road		10/8 - 6/10	31/5. - 6/10	4/5 - 3/10
12		road		6/8 - 6/10	31/5 - 6/10	4/5 - 3/10
07GF005[a]	689	road		1/6 - 28/10	18/3 - 31/10	22/3 - 31/10

[a] Stations that are part of the Alberta Environmental Protection network.

c) upstream from, and within the timber harvested area (stations 2, 2a, and 3 versus stations 4, 5 and 6),
d) upstream and downstream from the wetland area (station 6 versus station 8), and
e) upstream and downstream from the all-weather road crossing Rocky (station 9 versus station 10) and Bridlebit (station 11 versus station 12) Creeks.

Stations 1 to 10 were to be established on Rocky Creek and stations 11 and 12 on Bridlebit Creek. Data were to be collected from this network before and after timber harvest.

Treatment - timber harvesting

Timber harvesting on the Rocky Creek watershed commenced in December 1993 and terminated in March 1994. Mature aspen was harvested from 23% of the watershed in clearcut patches distributed uniformly over the middle and lower portions of its length (Fig. 1). The clearcut blocks ranged in size from 3.5 to 55 ha. Feller bunchers were used to cut the trees and grapple skidders were used to move the trees to roadside, where they were processed with mechanical delimbers. The tops and branches were piled and burned and the logs were hauled to the mill at Peace River. The logs from blocks 101, 105, 117 and 118 were not hauled until the following winter (December 1994 to January 15, 1995).

Logging was done in accordance with the *Timber harvest planning and operating ground rules* agreed to by Daishowa Canada Co. Ltd. (now Daishowa-Marubeni International Ltd.) and the Alberta Forest Service, Alberta Forestry, Lands and Wildlife. Emphasis was placed on protecting the watercourses and wetlands from any adverse effects due to logging so treed buffer strips were left for this purpose. Along the main channel these strips averaged about 150 m in width.

All logging was done during the winter months when the ground was frozen and when environmental damage was anticipated to be minimal; most stream crossings consisted of snow bridges. No high grade roads were constructed on the watershed -- existing all-weather roads were used for access to the Rocky Creek watershed (Fig. 1). At Rocky Creek and Bridlebit Creek, near their exit points to Spring Creek, the road crossed over timber bridges. The main stream gauge (07GF006) for Rocky Creek is located just upstream from the bridge, the gauge (07GF005) on Bridlebit Creek is located at the bridge.

Field procedures

Hydrometric station and float installation

From mid-April to late-May 1993, access trails were cleared and gauging/sampling stations were selected on Rocky Creek for stations 2 through 6 (including 2a). Measuring equipment was installed at these locations during June and July. The first station (2) was operational on July 21 and all six were operational by July 25. Stations 9 and 10 (Rocky Creek) and 11 and 12 (Bridlebit Creek), located near the road, were selected and instrumented in early August and were operational by August 10. Monitoring at all ten stations ceased on October 6,1993. This marked the end of the pre-harvest measuring period.

In 1994, stations 2 through 6 (2a was discontinued), and 9 through 12 were operational by the end of May. On June 8, a flood wave resulting from a beaver dam failure completely destroyed stations 2 through 6, with a consequent loss of data. The need to restore these stations first, resulted in a delay to the establishment of stations 1, 7 and 8. Station 1 was not operational until June 27 and stations 7 and 8 until July 14 and 15, respectively. Stations 2 through 6 were re-established and operating by the end of July. The entire period of record for each of the 12 hydrometric/water sampling stations, for the two Alberta Environmental Protection stream gauges (07GF005 and 07GF006) and for the precipitation station is given in Table 2. For convenience in subsequent discussions, the reach containing stations 2, 2a and 3 is referred to as the 'control' reach and the reach containing stations 4, 5 and 6 as the 'treated' reach.

Each hydrometric station consisted of a vertically-placed 1.83- to 2.44-m long culvert, 0.46 m in diameter, that served as a stilling well, fitted with a 1- or 2-m staff gauge and a wooden instrument shelter (Fig. 2). The shelter contained a battery-operated data recorder[1] and electronics for measuring five stream characteristics: water level, temperature, dissolved oxygen, pH, and specific conductance. A float-potentiometer device, together with a float, counter weight and connecting beaded cable suspended in the stilling well, was used to monitor water levels. Water temperature was measured using a thermistor-type sensor, and dissolved oxygen was measured using an OxyGuard probe[2] which produces a millivolt output proportional to the oxygen in the water. To function properly, the oxygen probe requires a minimum stream velocity of 2 cm s^{-1}. A pH sensor[3] which utilizes a double junction electrode was used to measure water pH, and a conductivity sensor, rated to measure within the range 0 to 10 mS, was used to measure the specific conductance of water. Both the pH and the specific conductance measuring devices were calibrated in the laboratory before use in the field. The sensors were placed in an assembly made from 1.9-cm diameter plastic (PVC) pipe and mounted on a float made from wood and 7.6 cm diameter plastic (ABS) pipe (Fig. 2). The cables between the sensors in the water and the electronics in the instrument shelter were enclosed in 1.9-cm diameter armoured, flexible conduit to protect them from damage by animals. Each data recorder was set to activate the sensors, i.e., take measurements every three hours, and was down-loaded at least once a month.

The relative elevations of the staff gauges were determined, at the beginning and during each field season, from bench marks established near each hydrometric station. Stream discharge was measured at selected natural control sections using a Price-type current meter. A pygmy-type current meter was used to measure low flows. Relationships were established between stage and discharge for stations 3, 6, 7 and 8. Because stations 2, 2a and 3 were relatively close together (Fig.1) it was assumed that there was no difference in flow between these stations and, if there was, it would be less than the measurement error. Similarly, it was assumed that the flows at stations 4 and 5 were the same as the flow measured at station 6. Flows at stations 9 and 10, located near the road and gauging station 07GF006 (Fig 1), were assumed to be the same as that measured by the gauging station. Likewise,

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[1]The data recorders, temperature sensors and float-potentiometers were manufactured by Lakewood Systems Ltd., 8709-50 Avenue, Edmonton, Alberta, Canada T6E 5H4.

[2]Manufactured by Point Four Systems Inc., 2702 Clarke Street, Port Moody, British Columbia, Canada V3H 1Z1.

[3]The pH and specific conductance measuring devices were manufactured by the Signet Scientific Company, 3401 Aerojet Avenue, El Monte, California 91734-1770. USA.

flows at stations 11 and 12 on Bridlebit Creek were assumed to be the same as flows measured at gauging station 07GF005.

Precipitation data were obtained from the weather station located at the end of the north-branching road near the boundary between the Rocky Creek and Bridlebit Creek watersheds (Fig. 1 and Table 2). The June 1993 precipitation data were recorded at Valleyview Ranger Station and is used in this study because the Spring Creek precipitation gauge was not operational until July 1, 1993.

After the flood wave resulting from the beaver dam failure destroyed hydrometric stations 2 through 6, measurements were taken to determine the volume of water released, and the peak flow that resulted from this event. An analysis of the event and a description of its effects were the subjects of a paper submitted for publication in Wetlands (Hillman n.d.).

Water sampling

Each streamwater sampling station was equipped with a Streamline 800SL Portable Sampler[4] housed in a custom-built wooden box, and powered by a 12V DC battery. The automatic water sampler was calibrated by the length of water intake tubing and elevation, programmed on a timed cycle basis, and set to pump about a 300-ml water sample from the stream into a 350-ml glass bottle per time interval. A full sampling cycle consisted of 24 bottles of samples. Preharvest streamwater sampling started when the first grab sample was collected on June 30, in the 1993 growing season. The majority of samples were collected in August and September after the construction of automated water sampling stations was completed. Although the collection period was short, intensive sampling at 4-hour intervals was performed to determine if any diurnal variation existed in the streamwater DOC concentration, and if there was any bias caused by sampling at different times of the day. Reasonably good comparisons can be made from samples collected over several days when weather conditions are stable. In 1994, as a result of these tests, streamwater was sampled twice a day - at noon and midnight, and from mid-May till the end of September, nearly uninterrupted, except for about ten days from June 8, when the flood washed out five water sampling stations.

Grab-samples were taken whenever possible during any interruption or equipment failure. Intervals for streamwater sampling were increased to once in every two days in 1995, because sampling frequency tests conducted in 1993 and 1994 supported a less frequent sampling rate that would not sacrifice the integrity of results. In 1995, streamwater sampling started in early May and continued nearly uninterrupted till the beginning of October. The collected water samples were placed in coolers containing ice packs before being shipped to a 5°C cold room at the Northern Forestry Centre for storage, to await chemical analysis.

Field problems encountered during the study

Access

Travelling to and from the 12 stations was a time-consuming activity and represented a major portion

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[4] Manufacturer: American Sigma, Inc., 11601 Maple Ridge Road, Medina, N.Y. 14103. USA.

of the work effort. It involved travelling over gravel and dirt (often muddy) roads before it became necessary to use all-terrain vehicles to travel the final 9 km through the bush to the seven most upstream hydrometric stations. Clearing and maintaining trails to these seven stations was also a very time-consuming and necessary activity, especially during May and June 1993.

Beaver dam failure

The flood wave resulting from the beaver dam failure on June 8, 1994 destroyed five hydrometric stations. Not only was recorded data lost as a result, but data was also unobtainable during the time it took to restore these stations. Because of its magnitude, the event also made it extremely difficult to assess the impact of forest harvesting on stream water quality. The harvesting and hauling operations were completed in early spring 1994 and the beaver dam failure occurred on June 8, 1994. Both the control reach and the treated reach were greatly affected by the second event. Noticeable scouring and sediment deposition occurred along the channel, and debris from old beaver dams together with large trees were thrown across the channel, blocking it at several locations.

Instrumentation disturbance by animals

Generally, animals were not a serious problem. Occasionally, beaver built a dam upstream or downstream from a hydrometric station causing a drop in water level at the gauge in the first instance and backwater effects at the gauge in the second. Sometimes, an animal overturned a float containing the water quality sensors thereby leaving the sensors exposed to the air and making the resulting data invalid. These suspect data were not used in the subsequent analyses. On other occasions, large animals such as bear, moose or deer broke the guy wires supporting the stilling wells, or chewed the armoured conduit protecting the instrument cables, but no serious damage was done.

Instrumentation failure

Although the instrumentation network was usually reliable there were times when sensors malfunctioned, or a data recorder ceased to record. Because these failures usually occurred between the times when field personnel visited the stations, some portion of the record was lost.

Low flows

Rocky and Bridlebit Creeks are characterized by very low flows for much of the year. Between May 2 and October 6, 1995 for example, stream discharge from Rocky Creek at station 07GF006 was $< 0.01 m^3 s^{-1}$, 84% of the time. Ideally, to measure this low level of flow, gauges similar to the v-notch weir that measured flow at station 07GF006 should have been installed at each of the seven upstream hydrometric stations but time and resources did not permit this degree of sophistication. Satisfactory discharge measurements were obtained with the two types of current meters at flows greater than $0.01 m^3 s^{-1}$ but when water levels became too shallow, or the water velocity became negligible we tended to discard the measurements and rely on discharge values extrapolated from the stage-discharge rating curves. Other problems associated with low flows include dissolved oxygen measurements that were unreliable when flow velocities fell below $2 cm s^{-1}$, and invalid pH, temperature, specific conductance and dissolved oxygen data that occurred when the water level dropped to the extent that the sensors were exposed to the air.

It was not possible to measure flows at station 1 (Fig. 1) because the flow from the fen was so diffuse and water velocity was minimal. Furthermore, there was backwater resulting from the beaver dam located about 30 m downstream from station 1.

Laboratory procedures

Water sample preparation

The total volume of water collected in each bottle was measured and recorded. The entire sample was filtered with a 0.5 micron glass fiber filter, 47 mm in diameter (MSI cat. No. G15WP04700). Two 20-ml aliquots of filtrate were stored in separate glass vials in a 4°C refrigerator before chemical analysis. The filter was weighed before and air-dried after filtration. The deposit on the filter paper, representing the total quantity of suspended sediments contained in each streamwater sample, was air-dried and preserved for future analysis. The concentration of suspended sediments was calculated from the total weight of sediments and the recorded total volume of water.

Dissolved organic carbon analysis

An automated Dohrmann Model DC-190 Total Organic Carbon Analyzer[5] equipped with an autosampler and a Panasonic KX-P1180i Multi-Mode printer was used to analyse dissolved organic carbon (DOC) in water. The instrument was calibrated with a series of 1-100 ppm carbon standard solutions of potassium hydrogen phthalate ($HOCOC_6H_4COOK$; 1000 ppm carbon, supplied by Dohrmann Division, Rosemount Analytical Inc.). The calibration curve is a perfect straight line within this range of carbon concentrations under normal operational conditions. A 50 ppm carbon standard solution was then analysed four times, and the mean signal response stored in the analyser. A 5-ml aliquot of filtered water sample was transferred into an autosampler vial and injected into the analyser. Signals generated from the carbon content of water samples were calculated and converted into ppm carbon concentration automatically by the analyser by comparison with that of the 50-ppm carbon standard. Four analyses per water sample were performed, and their mean and standard deviation recorded on the printer. Occasionally, instrumental baseline drift was observed. To ensure that accurate analytical results were obtained, a vial of 50 ppm carbon standard solution was inserted between every eight water samples in the analytical sequence. The mean value of DOC concentration of each sample was entered manually into a PC database for further calculation and data processing.

Elemental analysis

Streamwater samples were screen tested for elemental content by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). The spectrometer consisted of an excitation source (RF generator), a sample introduction system (nebulizer, spray chamber, and torch), an optical resolving system (primary slit, diffraction grating, secondary optics, and photomultipliers), and an electronic

[5]Supplier: Folio Instruments Inc., 5475 Royal Mount Ave., Unit 124, Mount-Royal, Quebec, Canada H4P 1J3.

data capture and storage system (measuring electronics and microcomputer) (Kalra and Maynard 1991). The prefiltered water samples were acidified with HCl before analysis. Fifteen elements were analysed, namely Ca, Na, Mg, S, Fe, K, Mn, P, Al, Zn, Pb, Cu, As, Ni, and Ti. Subsequent sample analyses were focussed on these species.

Nutrient analysis

Ammonium (NH_4-N) and nitrate (NO_3-N) nitrogen were determined by a Technicon AutoAnalyzer equipped with a sampler, a manifold, a proportioning pump, a heating bath, a colorimeter, and a recorder. Two separate processes are required to quantify these two different species of nitrogen-compounds in each sample. In determining the amount of NH_4-N present, the Bertholet reaction was used: a blue indophenol complex, that can be quantified by a colorimeter, occurs when ammonia is reacted with sodium phenoxide followed by sodium hypochlorite addition. Nitrates (NO_3-N) were reduced to nitrite by a copper-cadmium reductor column. In this method, nitrite ion reacts with sulfanilamide under acidic conditions to form a diazo compound. This couples with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a reddish purple azo dye that may be quantified by a colorimeter (Kalra and Maynard 1991).

RESULTS AND DISCUSSION

Rocky Creek

Precipitation-discharge relationships

Because stream water quality is affected by precipitation inputs to the watershed and may vary with streamflow, it is important to examine the precipitation-discharge relationships. Some of the more important hydrological indices pertaining to these relationships for Rocky Creek in 1993 - 95 are presented (Table 3).

The Rocky Creek precipitation-discharge patterns for the three years of study (Fig. 3) show how difficult it is to predict the response of a typical boreal watershed to different precipitation events. In June 1993, three separate rainstorms of 54.2, 23.5 and 18.4 mm caused Rocky Creek discharge to peak at about 0.2 $m^3 s^{-1}$ on three separate occasions, although close together, during a 6 - 7 day period in which a total of 101 mm of rain fell (Fig. 3a). Apart from a lesser response to lower rainfall in early July, this was the only significant runoff event during the measuring period in 1993. There was very little flow after mid-July, indicating that the approximately 67 mm of rainfall that fell between mid-July and the end of September was either detained in storage or lost through evapotranspiration.

In June 1994, accumulated rainfall of nearly 90 mm apparently produced two pronounced hydrographs - one that peaked at 0.95 $m^3 s^{-1}$ and the other at 2.07 $m^3 s^{-1}$ (Fig. 3b). These very noticeable responses to relatively insignificant accumulated rainfall can be explained in terms of basin storage. The dam failure that occurred on June 8 caused a loss in upstream storage - the drained beaver ponds - and, together with the precipitation, resulted in the filling of downstream storage capacity, primarily in the wetland. The first prominent peak marks the time when the considerably dampened flood wave caused by the dam failure reached the gauge. The second prominent peak was

Table 3. Hydrological indices for the Rocky Creek watershed.

Year	1993	1994	1995
Period of record (days)	June 1 - Sept. 30 (122)	March 18 - Sept. 30 (197)	March 22 - Sept.30 (193)
Precipitation (mm)	206	302	302
Mean discharge ($m^3 s^{-1}$)	0.014	0.083	0.023
Time discharge < 0.01 $m^3 s^{-1}$ (%)	83	58	72
Water yield (m^3)	144.4×10^3	1412.7×10^3	390.1×10^3
Runoff depth (mm)	8	76	21
Runoff/Precipitation	0.04	0.25	0.07

due to the reduction in storage capacity on the basin. This reduction was temporary, however, because the beaver soon restored the broken dam to its original state.

A pronounced peak (1.11 $m^3 s^{-1}$) occurred again in early July 1994 following a five-day period in which 63 mm of rain fell. By contrast, 46 mm of accumulated precipitation for August 7 -11, 1994 produced no response in discharge (Fig.3b). The opposite effect occurred on September 4, 1995 when discharge rose from negligible flow to 0.52 $m^3 s^{-1}$, but no rain had fallen for 10 days (Fig. 3c). This phenomenon was also recorded on the same day at station 8, about 1 km upstream from station 07GF006 (Fig. 4b) where the discharge increased from 0.033 to 0.16 $m^3 s^{-1}$. Evidently, water was suddenly released from storage, an occurrence that suggests another beaver dam failure. A corresponding increase in discharge was not detected at the upstream stations, 1 through 6 (Fig.4a), so it was assumed that the beaver dam failure occurred in the wetland downstream from station 6.

The patterns for 1994 and 1995 (Figs. 3b and 3c) show that, as was the case for most years, spring runoff resulting from snowmelt occurred during March through May and represented 45% and 57% of the total flow measured in the March to September period of 1994 and 1995, respectively.

The peak flow and spring runoff events discussed so far are times when changes in water quality might be expected. Other events during which water quality changes were likely to occur include the smaller peak flow shown for July 1994, and the peak flows recorded in July and August 1995.

The mean discharge for the entire measurement period was 0.032 $m^3 s^{-1}$, and the maximum recorded was 2.07 $m^3 s^{-1}$, on June 14, 1994. A minimum flow of 0 $m^3 s^{-1}$ was recorded in August of each of the three years and also in June and July of two out of the three years. For the period March through September, flows were lowest in August and September averaging 0.008 and 0.007 $m^3 s^{-1}$, respectively, for the three years of measurement.

Discharge variability along Rocky Creek

The 1995 discharge data for four stations on Rocky Creek, two upstream and two downstream from the wetland near the centre of the watershed (Figs. 1 and. 4), illustrate how the wetland modifies streamflow in response to storms of different magnitude and the availability of wetland storage capacity. The peak flows at stations 3 and 6 (0.071 and 0.091 $m^3 s^{-1}$, respectively) on June 25, resulting from moderate rainfall, are higher than the corresponding flows at stations 8 and 10 (0.006 and 0.001 $m^3 s^{-1}$, respectively). Thus the difference must have been absorbed by the wetland. The same reasoning and conclusion apply also to the peak flows recorded on July 4.

The next significant peak flow event occurred in response to a 36-mm rainfall on July 29. In this case the wetland was unable to absorb the runoff and consequently peak flows at stations 8 and 10 were greater than at stations 3 and 6. On August 12, following moderate rainfall, flows at stations 3 and 6 peaked at 0.04 and 0.035 $m^3 s^{-1}$, respectively. Downstream from the wetland, at stations 8 and 10, the flows peaked at 0.135 and 0.251 $m^3 s^{-1}$, respectively. The greater flows downstream suggest that the wetland's storage capacity was full - probably as a result of the 36-mm storm that occurred on July 29.

The discharge at station 6 tended to be lower than discharge at station 3, except during low flows (< 0.01 $m^3 s^{-1}$) and peak flows (Fig. 4a). It is believed that the difference was lost as subsurface flow in the rocky reach between stations 3 and 6. At low flows the differences are probably more apparent than real because they are approaching the magnitude of error expected when measuring with a current meter. During peak flows resulting from major storms, greater volumes of water are released to the channel and, because the drainage area at station 6 is greater than that at station 3, the discharge will be greater at station 6. Loss may still occur as subsurface flow but it will be minimal compared with the total volume of water in the channel.

A similar pattern exists for stations 8 and 10 (Fig. 4b). For most of the time discharge at station 8 was higher than that at station 10. The differences may be attributed to the regulating effect of a chain of small beaver ponds that lie between stations 8 and 10. If the water holding capacity of the beaver ponds are low during peak flows, when water volumes are high, then the regulating effect of the beaver ponds will be minimal.

Dissolved organic carbon (DOC)

Evaluating the effectiveness of the operational ground rules[6] for aspen harvesting in protecting streamwater from excessive input of dissolved organic carbon through surface runoff was one of the principal aims of the water quality study. In the following discussion, the results are presented in terms of DOC concentrations (ppm), DOC loading to the stream (kg d^{-1}), stream discharge ($m^3 h^{-1}$) and rainfall (mm). The DOC loading rate is the product of DOC concentration and stream discharge.

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[6] Timber harvest planning and operating ground rules. 1990. Daishowa Canada Co. Ltd. and Alberta Forest Service, Alberta Forestry, Lands and Wildlife. Pub. No.: Ref. 46 (ISBN: 0-86499-715-9).

Stream discharge is expressed in $m^3 h^{-1}$ rather than the more conventional $m^3 s^{-1}$ to facilitate graphical presentation and comparison. Julian days are used instead of conventional days for the same reason.

Diurnal effect on DOC concentration

In 1993, streamwater samples were collected on four consecutive days at 0:00, 4:00, 8:00, 12:00, 16:00, and 20:00 hours, to determine if there were any differences between samples taken at different times of the day. Results at all sampling stations indicated that there were no significant differences in DOC concentrations among samples taken at different times of the day. An example of the results (for station 3) is given in Table 4.

Table 4. DOC concentrations in samples collected from station 3 on Rocky Creek every four hours on four consecutive days in July 1993.

Hour of the Day	DOC Concentration (ppm) July 15	July 16	July 17	July 18	Mean	S.D.	% C.V.
0:00	49.9	49.3	49.2	50.6	49.8	0.65	1.30
4:00	49.8	50.1	49.7	50.5	50.0	0.36	0.72
8:00	50.0	49.4	50.0	49.7	49.8	0.29	0.58
12:00	49.3	48.8	48.7	49.0	49.0	0.26	0.54
16:00	49.8	49.5	49.6	48.9	49.5	0.39	0.78
20:00	50.0	49.3	49.4	48.7	49.4	0.53	1.08
Mean	49.8	49.4	49.4	49.6	49.6	0.52	1.06
S.D.	0.26	0.42	0.45	0.83		Overall	
% CV	0.52	0.85	0.91	1.68			

As a result of these findings, sampling in 1994 was reduced to twice a day, at noon and midnight, without sacrificing the integrity of the data. In 1995, sampling was further reduced to once every two days, mainly for operational reasons. Results, however, indicated that the 2-day sampling interval was adequate to explain the relation between DOC concentrations and stream discharge, and also between the loading rates of DOC and discharge.

Stream DOC in the preharvest year (1993)

Before August 1993, when the stream gauging/water sampling network became fully operational, only scattered data was obtained. The most intensive sampling was done in August and September, a very dry period characterized by very low discharge rates (Fig. 3a).

Stations 2 and 3 in the control reach are only 224 m apart and the results obtained from these sites were similar. Because DOC and stream discharge data were more complete for station 3, station 3 was considered to be representative of the control reach and only data from this station are presented for all three years (Fig. 5). Similarly, the results from stations 4, 5 and 6 in the treated reach were approximately the same, therefore only results from one of the stations, (#5), are shown for the treated reach for the three-year period (Fig. 6).

Results from station 9, upstream from the Rocky Creek road crossing, were similar to those of station 10 located downstream from the crossing, therefore only the results from station 10 are presented for the three years (Fig. 7). Likewise, for the Bridlebit Creek road crossing (stations 11 and 12), only the data for station 11 upstream from the crossing are shown (Fig. 8).

Certain trends can be detected in the 1993 data (Figs. 5a to 8a): 1) DOC concentrations varied from about 15 to 50 ppm, with highest concentrations in summer and lowest in the fall; 2) DOC concentrations tended to be stable over time and did not change as much as stream discharge; 3) variation in DOC loading rates closely resembled the variation in stream discharge; 4) during the dry periods when flows were low, DOC concentration tended to follow the rise and fall pattern of stream discharge; 5) the DOC concentration at station 11, near the outlet of the Bridlebit Creek watershed, was twice that of station 10 near the outlet of the Rocky Creek watershed.

The most important finding related to the 1993 data is that DOC concentrations along Rocky Creek decreased in the downstream direction (Fig. 9a). At the uppermost station on the Rocky Creek watershed (#3 in Fig. 9a) concentrations ranged between 40 and 50 ppm, whereas at station 10 near the watershed outlet most concentrations were less than 20 ppm. This observation suggests that the main source of DOC is the fen system and possibly the large lake in the uppermost portion of the watershed. There may be some natural self-purification effect in the rocky channel of the treated reach and through the wetland area downstream.

Stream DOC in the first postharvest year (1994)

In contrast to the short 1993 sampling period when most samples were collected during low flow (0 - 20 $m^3 h^{-1}$) conditions, the sampling period for 1994 extended from mid-May to early October. During this time several storm and substantial runoff events, including the flood resulting from the beaver dam failure, occurred (Fig. 3b). It was also the first year that data from stations 1 and 8 were available (Figs. 10a and 11a).

The DOC concentrations below the fen (station 1) were markedly different from those at the lower stations (Figs. 5b, 6b, 7c, 8c, 10a, and 11a). Not only were the concentrations at station 1 considerably higher but the seasonal patterns were also very different. These results tend to confirm the suggestion raised in the 1993 data discussion - that the poor fen and possibly the large lake at the head of the watershed are the main sources of DOC for Rocky Creek. A few water samples taken from the lake, near the shore and close to the fen on August 2, 1994 yielded an average DOC concentration of 39 ppm. This is much higher than the 2.2 to 12 ppm DOC usually found in lakes (Thurman 1985) and suggests that the fen may supply DOC to the lake when flow conditions are right. Concentrations of DOC are greatest in wetland areas compared to other types of natural waters because of the build up of organic acids in the water from the decomposition and leaching of mosses and emergent plants and abundant surface detritus (Thurman 1985).

At station 1 the concentrations increased from about 50 ppm in early July to about 125 ppm in late September. This may be attributed to heavy rains (Fig. 3b) flushing organic carbon from plants and plant litter into the fen waters. In contrast, DOC concentrations at the lower stations (#3, 5, 10 and 11) declined during the corresponding time periods in both 1993 and 1994 (Figs. 9a and 9b). The DOC concentrations for the lower stations varied much less than those of station 1. At some stations the concentrations increased in May, remained unchanged or fluctuated slightly in June, and decreased between July and September (Figs. 6b, 7c and 8c). All the lower stations registered declines between July and September.

There was no noticeable increase of DOC concentrations in the stream channel within the treated reach, because DOC levels at Station 5 remained lower than that at Station 3, and so did the levels at Station 10. There was no noticeable difference in DOC concentrations between Station 8, 9, and 10, which may indicate minimal or no impact of the road crossing on streamwater DOC content.

Relatively high runoff from the watersheds occurred in June and July, 1994. The highest discharges recorded at sampling times on Rocky Creek (stations 10) and Bridlebit Creek (station 11) were 3500 and 7500 $m^3 h^{-1}$ (Figs. 7b and 8b), respectively. Because DOC concentrations remained relatively constant with time, the DOC loading rate was roughly proportional to stream discharge, and the DOC loading curve closely resembled the hydrograph (Figs. 5 to 8, and 11).

As was the case in 1993, DOC concentration levels decreased in the downstream direction in 1994 (Fig. 9b), the greatest reduction occurring between stations 1 and 3 in the fall. Evidently, the chain of beaver ponds located in this reach affected DOC concentrations. The stream DOC concentrations near the exit from the Bridlebit Creek watershed (station 11) were again consistently higher than the stream concentrations near the exit to the Rocky Creek watershed (station 10). The difference may be attributed to the location of the main source of DOC - the organic soils on the watersheds. On Rocky Creek, the fen is located near the head of the watershed whereas on Bridlebit Creek the organic soils are located primarily along the main channel, reaching almost to station 11.

Stream DOC in the second postharvest year (1995)

The results for 1995 (Figs. 5c, 6c, 7d-e, 8d-e, 9c, 10b and 11b) confirm the findings for 1994 and provide a basis for drawing a number of conclusions. It is clear that the organic soils on the Rocky Creek watershed are the main source of dissolved organic carbon. According to Thurman's (1985) list of the approximate concentrations of DOC in natural waters, an organic soil such as a bog contains considerably more DOC (30 ppm) than other natural water bodies. The list shows that groundwater contains only 0.7 ppm , precipitation 1.1 ppm, lakes 2.2 to 12 ppm, and rivers 7 ppm.

The stream DOC concentrations near the outlet from the Bridlebit Creek watershed was 1.5 to 2 times that of the stream DOC concentrations near the outlet from the Rocky Creek watershed (Table 5). It was shown that, on the Rocky Creek watershed, the primary source of DOC was the fen which is remote from the watershed outlet, and that DOC concentrations decreased downstream toward the

Table 5. DOC concentration levels near the exit points of Rocky Creek and Bridlebit Creek.

Year	Range of DOC concentrations (ppm)	
	Station 10	Station 11
1993	15 - 25	30 - 36
1994	20 - 32	30 - 50
1995	15 - 22	28 - 42

outlet (Figure 9). On Bridlebit Creek, the organic soils are located along the channel and extend downstream almost to the main stream gauge. We can speculate that this difference in the distribution of organic soils may be the reason why DOC concentrations at the Bridlebit Creek road crossing are higher than at the Rocky Creek crossing.

The results of this 3-year study indicate that DOC concentrations at each station do not change very much with time. The DOC loading rate is proportional to stream discharge and varies much more than DOC concentration. Consequently, stream discharge is a more important factor than DOC concentration in transporting large quantities of DOC through the watershed. Any hydrological changes associated with timber harvesting will also affect DOC loading rates.

It is clear from the large difference in DOC concentrations between stations 1 and 3 that the series of beaver ponds in this reach played an important role in reducing DOC concentrations. This result is contrary to the findings of Smith *et al.* (1991) who reported elevated DOC concentrations as a result of beaver activity.

There is no evidence that timber harvesting had any effect on DOC concentrations. The concentrations at station 5 in the treated reach were consistently below those at station 3, located in the control reach. The difference in concentrations between the two sites did not change significantly over the three year period.

Chemical elements

Groups of streamwater samples, collected at various distances along Rocky Creek (with Station 1 at 'downstream distance 0 m') and from three time periods each year for 1993, 1994, and 1995, were analysed for elemental contents. Each group of samples was sampled over a short time period between three days and two weeks. The median date and mean concentration of each group are used in the following discussion.

Among 15 elements detected in streamwater samples, there were six abundant elements with concentrations consistently greater than 1 ppm, namely Ca, Na, Mg, S, Fe, K (in order of abundance). Four elements, Mn, P, Al and Zn were detected at less than 1 ppm, but greater than 0.1 ppm. Zn was > 0.1 ppm but detected only at station 1. Five elements, Pb, Cu, As, Ni and Ti were found in trace amounts (< 0.1 ppm).

The six abundant elements found in Rocky Creek were reported in similar order of abundance from a subalpine watershed (Singh and Kalra 1984), a coniferous swamp[7], and 23 fens (Vitt and Chee 1990) in Alberta. Similar results for the minor and trace elements were also reported by these researchers. Results of the six most abundant elements will be discussed in the following sections.

Calcium, the most abundant element

The concentrations of Ca, the highest among all elements detected in Rocky Creek, ranged between 9 and 56.6 ppm. Calcium concentrations increased continuously over the distance downstream during all nine sampling time periods and during both high and low stream discharge (Fig. 12). Calcium concentrations measured at station 1 in 1994 and 1995 were the lowest in the stream system indicating that the lake/fen system located at the upper end of Rocky Creek was not the major source. The data suggest that Ca is added to the channel continuously through groundwater seepage over the entire length of the water course.

Although the Ca profile over the downstream distance did not change, samples taken at high flow rates contained lower Ca concentrations than those taken at low flow rates, which is an indication of a diluting effect (Table 6; Fig. 12). Because of the apparent Ca dilution by increased stream flow

Table 6. Ca concentrations (ppm) at station 3 (control reach) and at station 10 (near the road) during low and high flows.

Sampling Date	Flow Rate	Ca Concentration (ppm)	
		Station 3	Station 10
Aug 17, 1993	Low	27.7	56.6
Sep 06, 1993	Low	25.2	50.1
Sep 22, 1993	Low	29.5	51.0
May 18, 1994	High	13.4	27.0
Jun 09, 1994	High	9.0	26.3
Jun 21, 1994	High	13.2	32.9
Jun 07, 1995	High	11.4	40.7
Jul 27, 1995	Medium	24.3	45.4
Sep 12, 1995	Low	21.0	51.3

(Table 6), increases in Ca concentrations due to logging are unlikely. However, samples collected during high flow in the preharvesting year, 1993, and during low flow in the first postharvest year,

[7] Hillman, G.R. manuscript, "Preliminary effects of forest drainage in Alberta, Canada on groundwater table levels and stream water quality". Northern Forestry Centre, Edmonton, Alberta.

1994, were not analysed for Ca content, so we could not draw conclusions through direct comparison.

It is interesting to note that Ca concentrations in relation to the fen types (Vitt and Chee 1990) showed Ca increases from poor fens (1.4-1.6 ppm) to moderate-rich fens (19.5-22.1 ppm), and to extreme-rich fens (56.5-67.7 ppm). These results are nearly identical to the longitudinal increases in Ca concentration in Rocky Creek, if one considers the upper lake/fen system (4-6 ppm Ca) as a poor fen, the series of beaver ponds (10-20 ppm Ca) as the equivalent of a moderate-rich fen, and the wetland (30-57 ppm Ca) as an extreme-rich fen (Fig. 12).

Other abundant elements

Concentrations of the other abundant elements, Na, Mg, S, Fe and K, in Rocky Creek measured at the same time periods as for Ca (Table 6) are illustrated in order of their abundance (Figs. 13, 14, 15, 16 and 17, respectively).

Concentrations of the elements Na, Mg, and K followed trends similar to Ca by increasing in the downstream direction but at lower concentrations than Ca. Na concentrations reached 23 ppm at station 6 during low flow on 22 September 1993 (Fig. 13). The highest concentrations of Mg (12 ppm) and K (3 ppm) occurred at station 10 (Figs. 14 and 17). The most probable source of these elements was groundwater seepage over the length of the watercourse.

The highest concentrations of S were found in the stony treated reach (stations 5 and 6) located between 2000 m and 3000 m downstream from station 1. However, concentrations of S remained low both upstream and downstream from the treated reach, indicating that the treated reach was the main source of S input to this stream system and that the wetland near the centre of the watershed may have played a major role in retaining S, effectively preventing it from proceeding further downstream (Fig. 15).

The pattern of Fe concentrations was the reverse of that shown by other elements in Rocky Creek. Concentrations were highest in the control reach (Fig. 16) and then declined downstream over the entire length of the stream. It is interesting to note that Fe concentrations reached near-zero levels at stations 8 and 10 in all collected samples indicating, perhaps, a very effective retention of Fe by the wetland.

Nutrients

Both nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) concentrations in streamwater were determined. A larger number (1438) of samples were analysed but only a very few showed detectable amounts of nutrients in 1993 and 1994. Consistently measurable amounts of NO_3-N were found only in the 1995 samples (Table 7). Some detectable amounts of NH_4-N were also found in the 1995 samples (Table 8). No distinct pattern was evident on either the treated or the control reaches of Rocky Creek, or on Bridlebit Creek to indicate there was any impact from human disturbances.

Table 7. Concentrations of NO_3-N in streamwater from Rocky Creek and Bridlebit Creek in 1995.

Station No.	NO_3-N Concentration (ppm)		
	Batch 22 16/5 - 1/7/95	Batch 23 5/7 - 20/8/95	Batch 24 23/8 - 2/10/95
1	0.20 ± 0.01	0.01 ± 0.00	0.04 ± 0.02
3	0.21 ± 0.12	0.02 ± 0.04	0.09 ± 0.02
5	0.24 ± 0.11	0.05 ± 0.06	0.07 ± 0.03
8	0.27 ± 0.13	0.10 ± 0.07	0.11 ± 0.05
10	0.17 ± 0.14	0.22 ± 0.17	0.84 ± 0.64
11 (Bridlebit)	0.06 ± 0.07	0.37 ± 0.25	0.77 ± 0.78

Table 8. Concentrations of NH_4-N in streamwater from Rocky Creek and Bridlebit Creek in 1995.

Station No.	NH_4-N Concentration (ppm)		
	Batch 22 16/5 - 1/7/95	Batch 23 5/7 - 20/8/95	Batch 24 23/8 - 2/10/95
1	0.07 ± 0.03	0	0.23 ± 0.13
3	0	0	0
5	0	0	0
8	0	0	0.05 ± 0.06
10	0	0	0.14 ± 0.20
11 (Bridlebit)	0.16 ± 0.14	0	0.03 ± 0.06

Water temperature

The mean monthly water temperatures were computed using all valid data as opposed to the standard practice of using only the daily maximum and daily minimum to compute mean daily temperature. The mean monthly water temperature profiles for Rocky Creek (Fig. 18) indicate that the water was warmest in July and that in some instances (Fig. 18b) the monthly mean exceeded 20°C.

Water temperatures at station 1 tended to be lower than temperatures at the other stations because the water at station 1 was continually being replenished by cooler groundwater from the fen sheltered by coniferous forest. The reach between stations 1 and 2 is about 1 km long and contains four relatively large beaver ponds. Summer (June - August) temperatures were higher at station 2 than at station 1 and the difference may be attributed to the ponds. Research has indicated that there is a definite warming of streams during the summer as water passes through either large ponds or a series of ponds (Olson and Hubert 1994). However, McRae and Edwards (1994) discovered that removal of beaver dams did not generally reduce the difference between upstream and downstream water temperatures.

Temperatures in the control reach (stations 2, 2a and 3) were generally higher than those in the treated reach (stations 4, 5, and 6). The differences can be explained in terms of topography and tree cover. The control reach is relatively flat and exposed whereas in the treated reach Rocky Creek lies in a valley bottom and is protected by riparian vegetation that includes aspen cover. Because channel slopes are steeper in the treated reach, the tendency for water to pond there and absorb solar heat is less. Water in both reaches was very shallow most of the time, forming a thin layer over the cobble-sized rocks and mud that formed the channel bed.

The lowest mean monthly water temperatures on Rocky Creek were recorded at station 7 (Figs. 18b and 18c). This station is located on a small tributary draining part of the wetland and lies downstream from two or three beaver ponds (Fig.1). The area drained by the tributary is well-protected from the sun by vegetation so the water tends to remain cool during the summer months.

The mean monthly water temperatures for station 8 were among the highest recorded on Rocky Creek (Fig. 18). They may be attributed to the ponded condition of the stream at this point, the relative openness of the site, and its location downstream from the small lake that feeds the stream directly (Fig. 1). The water in the small lake, being exposed to the sun, readily absorbs heat so that warmer water is transferred to the stream below. Thus water temperatures downstream from the wetland at station 8 are warmer than those upstream from the wetland at station 6. A comparison of data from stations 8 and 9 indicate that water moving between these two stations experienced only a slight drop in temperature.

The maximum water temperatures recorded ranged from 29.5°C and 29.3°C in 1994 at stations 2 and 10, respectively, to 13.9°C in 1995 at station 7. Stations 2 and 10 are two of the more exposed of the 12 stations and the shallow, slow-moving water there, is readily warmed by the summer sun. Temperatures of 29°C are high for an aquatic environment and, if sustained, are lethal for fish. The high water temperatures were not sustained, however, and fell to 17°C overnight at both stations. By contrast, at station 7, where the lowest maximum temperature was recorded, the overnight temperature drop was only 2°C. These data exemplify what occurred generally; water temperatures at the exposed sites, e.g., station 2, tended to be higher and have greater amplitudes than water temperatures recorded at the more protected sites such as station 6 (Fig. 19a). The maximum recorded water temperatures for each station and each year occurred in the afternoon, during the 1500-1800 hr. period.

Stream temperature is greatly influenced by storm periods and the volume of flow. Cooler air and water temperatures usually prevail during rainy periods when clouds hide the sun, and water temperatures are lower during times of increased flow (Fig. 19b). Because water has a high heat capacity, it takes longer for increasing volumes of water to reach a given temperature. Thus, in the example given (Fig. 19b), each of the four major peak flows of 0.953, 2.07, 1.11 and 0.285 $m^3 s^{-1}$ were preceded by water cooling as a result of weather conditions (cloud and rain), followed by further cooling as the volume of water increased to a maximum. Each peak flow was accompanied by a corresponding water temperature trough or low.

To determine if forest harvesting (or the beaver dam failure) had any effect on stream temperature, a simple linear regression was carried out by comparing mean water temperatures in the control reach (stations 2, 2a and 3) with mean temperatures in the treated reach (stations 4, 5 and 6). This was done for the preharvest period (1993) and repeated for the postharvest period (1994-95). Temperatures were in the 1°C to 27°C range. As expected, the results showed a strong correlation between temperatures in the two reaches with r^2 values of 0.94 and 0.90 for the preharvest and postharvest periods, respectively. The slope of the postharvest regression line was slightly greater and the intercept slightly lower than for the preharvest regression line (Fig. 19c).

If the preharvest regression is used to predict water temperatures in the treated reach when water temperatures in the control reach are 10°C and 20°C, the predicted values are 9.1°C and 16.5°C, respectively. If the postharvest regression is used, 9.5°C and 17.4°C are obtained. The differences of 0.4°C and 0.9°C, respectively, are less than the standard error estimate of y (1.14°C for the postharvest regression) and suggest that little change occurred in the relationship between water temperatures in the control reach and those in the treated reach during the postharvest period. No tree felling was done on the riparian areas nor in the valley containing the treated reach, therefore no significant changes in water temperature were anticipated. A snow bridge used for timber-hauling in winter 1993-94, and crossing the creek between stations 3 and 4 (Fig. 1), was the only instance where the harvesting operation disturbed the upper portion of the creek directly, but it had no effect on summer water temperatures.

Dissolved oxygen

The dissolved oxygen data for stations 1 and 7 were not used in the analyses because water velocities at these stations were insufficient to properly activate the dissolved oxygen sensors. Data from the other 8 stations on Rocky Creek indicated average dissolved oxygen concentrations of 6.5 mg l^{-1} in 1993 and 5.1 mg l^{-1} in 1994 and 1995. These values are close to the lower limits for cold- and warm-water biota recommended by Davis (1975, cited in CCREM 1995) for Canadian environmental conditions. He recommended lower limits of 8 mg l^{-1} at 0°C and 5 mg l^{-1} at 25°C for cold-water biota, and 7 mg l^{-1} at 0°C and 4 mg l^{-1} at 25°C for warm-water biota.

The dissolved oxygen profiles for 1993 (Fig. 20a) show that concentrations were lower on the control reach (stations 2, 2a and 3) than on the treated reach (stations 4, 5 and 6). In general, the same patterns were detected for 1994 and 1995 (Figs. 20b and 20c). Contributing factors here are water temperature and stream physical characteristics. On the treated reach water temperatures were lower(Fig. 18a), the stream gradient steeper, water velocities higher and the channel bed rougher than on the control reach. Water contains more oxygen at the lower temperatures, and oxygen entrainment is better facilitated by the stated hydraulic conditions.

Dissolved oxygen may have been lost as the water passed through the beaver ponds upstream from station 2. Losses of dissolved oxygen have been observed in streams as they pass through beaver ponds where there are increased bacterial activity and higher water temperatures that hold less dissolved oxygen (Olson and Hubert 1994: Smith *et al.* 1991).

The small difference in dissolved oxygen concentrations between stations 6 and 8 (Figs. 20b and 20c) indicates that the wetland did not significantly affect dissolved oxygen. In 1994 concentrations were higher at station 8, and in 1995 they were higher at station 6.

Dissolved oxygen concentrations were lower in 1994 and 1995 than in 1993 (Fig. 20). This change cannot be attributed to timber harvesting because the difference was approximately the same at each station and the same pattern was maintained each year. It is clear that, since the dissolved oxygen values are higher in the treated reach than in the control reach, the dissolved oxygen status of the creek has not suffered as a result of either forest harvesting or the beaver dam failure.

Water pH

The overall mean pH for the three years of measurement on Rocky Creek ranged from 4.7 units at station 1 to 8.0 units at station 10. The average for 9 of the 10 stations ranged between 6.9 and 8.0 pH units, indicating that the Rocky Creek waters were relatively neutral with respect to pH - an important requirement for an hospitable aquatic environment. The acidic nature (pH = 4.7) of the water at station 1 (Figure 21c) can be attributed to the groundwater emerging from the peatland at this point. Water in peatlands such as bogs and poor fens characteristically have pH values in the 3.7 - 5.5 range (Zoltai 1988). The peatland upstream from station 1 is a poor fen and the mean pH value of 4.7 obtained for station 1 is typical for water from this kind of peatland.

The low pH at station 1 can be attributed to the accumulation of organic acids, such as fulvic and humic acids, in the water. The organic acids are also associated with the high concentrations of DOC at station 1. Another reason for the low pH is the ion exchange of metals onto peat, which release hydrogen ions into the water (Thurman 1985). This may account for the low levels of metal elements detected in the water at station 1 compared to the other sites (Figs. 12-14, 16-17).

The overall (1993-95) mean water pH for Rocky Creek at station 2 was 6.9, or 2.2 units higher than the pH at station 1. Evidently, the pH was influenced by the presence of the beaver ponds in the reach between the two stations, and the water passing through them rendered less acid. This acid-neutralizing effect of the beaver ponds is consistent with the findings of Smith *et al.* (1991) with respect to beaver activity in an acidic second-order Adirondack Mountain stream system. They found pH was elevated following water transport through a beaver impoundment.

The mean monthly pH data show (Fig. 21) that the water pHs at stations 2, 2a and 3 in the control reach were approximately the same, with an overall mean of 7.0. The same was true for stations 4, 5 and 6 in the treated reach, where the overall mean was 7.4 pH units. Thus, pH increased as one progressed downstream.

In the control section where stations 2, 2a and 3 were located the water flowed over a grass and mud channel bottom. Downstream, in the treated reach where stations 4, 5 and 6 were located, the channel bottom was covered with cobble-sized (76 - 254 mm diameter) pebbles. The calcareous nature ($CaCO_3$?) of this material may have contributed to the pH increase in this reach through buffering action. The pattern was repeated for each of the three years, although in 1994 the pH was lower at station 6 than at stations 4 and 5 (Fig. 21b).

Below station 6, the stream passes through the wetland. The effect of the wetland on water pH is not clear. As stated earlier, the pH of wetlands is usually lower than the pH of other water bodies whereas beaver ponds tend to elevate pH. The net effect of the wetland and beaver ponds on pH at station 8 appeared to be: no increase in 1994 (Fig. 21b) and a slight increase in 1995 (Fig.21c).

The water pH at stations 9 and 10 near the road, tended to be lower than the pH at stations 5 and 6 in 1993 (Fig. 21a) but was among the highest in 1994 and 1995 (Figs. 21b and 21c). The more complete data for 1995 suggest that pH increases in the downstream direction. The higher pH values at stations 9 and 10 may be attributed to the effects of beaver ponds upstream from these stations and to the road bed material blown or washed into the creek near the bridge.

The results, exemplified by the 1995 data (Fig. 21c), indicate that the lowest pH was recorded at station 1, the greatest change in pH, an increase, occurred between stations 1 and 2, and that pH increased in the downstream direction. This is compatible with the trend in DOC concentrations in which the greatest concentration of DOC was recorded at station 1, the greatest decrease in DOC occurred between stations 1 and 3 (Fig. 9) and DOC concentrations decreased (the water became less acid) in the downstream direction.

The data show (Fig. 21) that, with the exception of the outflow pH from the poor fen (station 1), the pH for Rocky Creek falls well within the natural range of 6.5 to 9.0 - the range considered most desirable for aquatic organisms (CCREM 1995). Neither the forest harvesting nor the beaver dam failure appeared to have adversely affected water pH.

Specific conductance

The specific conductance profile for 1993 (Fig. 22a) shows that specific conductance, and hence total dissolved solids, increased progressively downstream from station 2 to station 10. The lack of substantial precipitation during this period (Fig. 3a) made the possibility of large amounts of total dissolved solids being flushed into Rocky Creek unlikely. There was a fairly abrupt increase in specific conductance going from the control reach (stations 2, 2a, and 3) to the treated reach (stations 4, 5 and 6). This trend coincided with the increase in concentrations of the three most abundant elements Ca, Na, Mg (Figs. 12, 13, and 14).

Both specific conductance and concentrations of these elements increased in the downstream direction from station 2 to station 10. These patterns suggest that the elements were being supplied to the channel through groundwater seepage, and that groundwater was supplying the elements in greater quantities in the treated reach than in the control reach. Alternatively, the rocky materials in the treated reach could be providing some portion of the elements.

Specific conductance in the control reach was low in all three years which was consistent with the low concentrations of elements recorded for stations within the reach during those years. Concentrations of individual elements in the control reach rarely exceeded 5 ppm. Equally low specific conductance levels were recorded near the fen at station 1 in 1994 and 1995 (Figs. 22b and

22c). They corresponded to the lowest concentrations of elements recorded for Rocky Creek (Figs. 12 to 17), with the exception of negligible concentrations of Fe at station 10. The pattern for stations 2 through 6 in 1993 was repeated, in a general way, in 1994 and 1995 even though it was complicated by rainfall events.

Stream water quality at the road crossings

Rocky Creek

Dissolved organic carbon and chemical elements

The dissolved organic carbon concentrations measured upstream from the road crossing at Rocky Creek were not noticeably different from those measured downstream from the crossing. The overall means for the two stations differed by 1 ppm (Table 9). Noticeable differences did occur during May 1994 and in September and October, 1995. In May 1994, upstream concentrations were sometimes 20 to 30 ppm higher than downstream concentrations. In the September-October 1995 period, concentrations upstream from the crossing were about 8 ppm less than at the downstream station.

Table 9. Average concentrations (ppm) of dissolved organic carbon and the most abundant chemical elements upstream and downstream from the road at Rocky Creek and Bridlebit Creek.

	DOC	Ca	Na	Mg	S	Fe	K
			Rocky Creek				
Station 9 (upstream)	24.3	41.5	15.8	8.61	1.56	0.304	2.57
Station 10 (downstream)	23.3	38.5	15.5	8.02	1.89	0.268	2.50
			Bridlebit Creek				
Station 11 (upstream)	36.3	32.3	14.3	5.94	2.92	0.435	1.61
Station 12 (downstream)	36.7	33.1	14.0	6.05	2.83	0.462	1.59

In general, chemical element concentrations downstream from the road were close to the upstream values for the entire measuring period. Exceptions occurred on June 3, 1994 and during the period July 9 to August 20, 1995 when downstream concentrations of most of the micro-elements Mn, P, Al, Zn, Pb, Cu, As, Ni, and Ti were higher. The concentrations diverged in these instances because the upstream concentrations were below the detection limits.

Average concentrations (1993-95) of the most abundant chemical elements upstream and downstream from the road, with the exception of calcium, were virtually identical (Table 9). In only one instance (sulphur) did the downstream concentration exceed that upstream. In the case of the micro-elements the reverse was true (Table 10). Downstream concentrations slightly exceeded

Table 10. Average concentrations (ppm) of micro-elements upstream and downstream from the road at Rocky Creek and Bridlebit Creek.

	Mn	P	Al	Zn	Pb	Cu	As	Ni	Ti
				Rocky Creek					
Station 9 (upstream)	0.132	0.0636	0.0215	0.0160	0.0038	0.0089	0.0190	0.0017	0.0005
Station 10 (downstream)	0.0685	0.0620	0.0334	0.0258	0.0163	0.0183	0.0292	0.0081	0.0052
				Bridlebit Creek					
Station 11 (upstream)	0.0198	0.0911	0.0783	0.0296	0.0117	0.0180	0.0233	0.0064	0.0063
Station 12 (downstream)	0.0183	0.1009	0.0704	0.0264	0.0078	0.0145	0.0149	0.0039	0.0040

upstream concentrations for all micro-elements but Mn and P. Average concentrations of all the micro-elements, both upstream and downstream, fell below the maximum recommended for freshwater aquatic life, or fell within the range of environmental concentrations found in western Canada (CCREM 1995). Consequently, it appears that neither timber harvesting nor the road crossing had any adverse effects on dissolved organic carbon and the chemical water quality of Rocky Creek.

Water temperature

High mean monthly water temperatures were recorded at stations 9 and 10, near the road, in September 1993 and throughout 1994 and 1995 (Fig. 18). The open nature of the road area may have contributed to the sustained high temperatures. In 1993, the mean monthly temperatures at station 9 were about 5°C higher than those at station 10 (Fig. 18a), but in 1994 and 1995 temperatures were slightly higher downstream at station 10 (Figs. 18b and 18c). The slight warming effect may be due to the presence of the stilling pond behind the v-notch weir (station 07GF006) located between stations 9 and 10. The mean temperatures at stations 9 and 10 for the entire measurement period (Table 11) show only a one degree difference which, together with the small differences registered in 1994 and 1995, suggests that the timber harvesting and road crossing had minimal impact on water temperature.

Dissolved oxygen

The pattern of dissolved oxygen concentrations at stations 9 and 10 is similar to that of water

Table 11. Comparisons of means, for the entire measurement period, of four water quality variables upstream and downstream from the road crossings on Rocky Creek and Bridlebit Creek.

Variable	Rocky Creek		Bridlebit Creek	
	upstream (station 9)	downstream (station 10)	upstream (station 11)	downstream (station 12)
Temperature (°C)	13.2 $\pm$ 3.6[a]	14.2 $\pm$ 4.2	15.0 $\pm$ 4.2	13.9 $\pm$ 4.0
Dissolved oxygen (mg l^{-1})	4.45 $\pm$ 1.11	5.34 $\pm$ 1.16	4.92 $\pm$ 1.72	5.62 $\pm$ 2.32
pH	7.84 $\pm$ 0.30	8.0 $\pm$ 0.22	7.34 $\pm$ 0.25	7.61 $\pm$ 0.46
Specific conductance (mS)	0.269 $\pm$ 0.067	0.227 $\pm$ 0.063	0.169 $\pm$ 0.038	0.182 $\pm$ 0.048

[a] Standard deviation

temperature, i.e., concentrations were higher at station 9 in 1993, but slightly higher at station 10 in 1994 and 1995 (Fig. 20). The overall means (Table 11) indicate only a small difference in concentrations between the two stations, a difference that may be related to the more turbulent conditions that prevail in the stream at station 10 rather than to timber harvesting or road effects.

pH

The mean pH values at stations 9 and 10 in 1993 were 7.53 and 7.48, respectively (Fig. 21a), but by 1995 they had risen to 8.22 and 8.31, an increase of 0.69 and 0.83 units, respectively (Fig. 21c). Because these stations are downstream from all the cut blocks it is possible that the increase in pH over time at both stations can be attributed to timber harvesting. These results are inconclusive, however, because corresponding stations on the Bridlebit Creek watershed, where no trees were harvested, also recorded monthly pH values exceeding 8.0 units. The road crossing apparently had no effect on pH because there was very little difference in pH between stations 9 and 10 (Table 11).

Specific conductance

The mean monthly specific conductance values for stations 9 and 10 were remarkably and consistently similar in 1993 and 1994 (Figs. 22a and 22b). In 1995, the mean monthly values were about 0.1 mS lower at station 10 than at station 9 (Fig. 22c), indicating that total dissolved solids at station 10 was less. The reason for this difference is not clear because there was little difference in the overall average concentrations of the most abundant chemical elements (Table 9).

Bridlebit Creek

Dissolved organic carbon and chemical elements

Except for a few isolated instances, the DOC concentrations downstream from the road crossing on

Bridlebit Creek matched the upstream concentrations very closely throughout the measuring period. This is reflected in the almost identical mean values for the period (Table 9).

As was the case in Rocky Creek, concentrations of the most abundant elements (Ca, Na, Mg, S, Fe and K) in Bridlebit Creek downstream from the road closely matched the upstream values throughout the measuring period. The very small differences between the upstream mean values (Table 9) indicate the road crossing had little or no effect on the concentrations of these elements in Bridlebit Creek. Differences in micro-element concentrations between upstream and downstream stations were also minimal although in September 1975 the differences tended to increase. On these occasions upstream concentrations were greater. The mean concentrations of all the micro-elements, except phosphorus, in Bridlebit Creek downstream from the road crossing, were lower than the corresponding upstream concentrations (Table 10).

Water temperature

The mean monthly water temperatures of Bridlebit Creek upstream (station 11)and downstream (station 12) from the road crossing were markedly similar for all three years during which temperatures were measured (Fig. 23). On the average, water temperature was about one degree warmer upstream compared to downstream (Table 11).

Dissolved oxygen

The pattern of dissolved oxygen concentrations for the road crossing at Bridlebit Creek is similar to that for the road crossing at Rocky Creek, i.e., the upstream mean values were slightly higher in 1993 and the downstream values higher in 1994 and 1995 (Figs. 20 and 23). These results reflect the similar site conditions that exist at the two crossings. In each case water at the upstream site was relatively deep, slow-moving and fairly placid, whereas water at the downstream site was shallow, moved more swiftly and was turbulent - conditions which facilitate entrainment of oxygen. Overall mean oxygen concentrations (Table 11) were higher for the downstream sites.

pH

The monthly means show there was no difference in water pH between the upstream and downstream stations in 1993 (Fig. 23a). The pH at the downstream station was 0.1 to 0.7 units higher than the pH at the upstream station in 1994 (Fig. 23b) and about 0.5 to 0.6 units higher in May and June, 1995 (Fig. 23c). As was the case for Rocky Creek, water pH of Bridlebit Creek exceeded 8.0 units upstream and downstream from the road crossing in 1995 (Fig. 23c). On average, pH downstream from the road crossing was 0.27 units higher than pH upstream from the crossing (Table 11).

Specific conductance

The specific conductances of the water upstream and downstream from the Bridlebit Creek road crossing follow very similar patterns both monthly and from year to year. Differences in monthly means between the two stations are small (Fig. 23), as is the difference between the overall averages (Table 11).

Effects of watershed characteristics and disturbances

The results of the study show that the natural ecological systems of the Rocky Creek watershed are very dynamic. When processes are changing at different times on different parts of the watershed it is difficult to predict the watershed's response to disturbance without detailed knowledge of these processes.

The northern third of the Rocky Creek watershed is occupied by the lake and the fen. Practically no measurements were taken in either the lake or the fen so the water quality in each remains unknown. The water issuing from the fen, and measured at station 1 (Fig. 1), characterizes the net effect of both the lake and the fen combined. The water at station 1 reflected more the quality of the fen than the lake. It was characterized by high concentrations of dissolved organic carbon, low pH, low specific conductance, low concentrations of elements, and relatively low water temperatures. The fen was evidently the main source of DOC.

Downstream from station 1, beaver ponds, which are natural disturbances to the ecosystem, modified the water quality substantially. At station 2, downstream from the ponds, DOC concentrations were reduced, elemental concentrations increased, water temperatures raised and the pH elevated by approximately two units. Water quality was similar among stations 2, 2a and 3, located in the control (undisturbed) reach, upstream from the timber harvested area. The same was true of water quality at stations 4, 5 and 6 in the treated reach, within the harvested area.

The results showed that water quality in the treated reach was more favourable for aquatic life than the water quality in the control reach, before and after timber harvest. In the treated reach, DOC concentrations and water temperatures were lower, while dissolved oxygen and pH were higher. Specific conductance and concentrations of the most abundant elements, Ca, Na, Mg, S and K, were higher in the treated reach, probably as a result of contributions from groundwater flow.

Hartmann and and Scrivener (1990, cited in D.A. Westworth and Associates Ltd. 1992) listed a number of physical changes to fish habitat that may result from timber harvesting: large organic debris input, litter and slash input, increased temperature, decreased dissolved oxygen, release of nutrients, water yield changes, increased light to the stream, and removal of streamside vegetation. Our results and observations on Rocky Creek showed that practically none of these changes occurred on the treated reach after harvesting. The effects of timber harvesting on nutrients in Rocky Creek is unclear and requires further analysis. The effects of timber harvest on water yield is beyond the scope of this study.

The riparian areas and the steep-sided valley that characterizes the treated reach were reserved as buffer strips and no vehicles or other equipment went into these areas, therefore they were not directly affected by timber harvest. The control reach was similarly reserved except for one snow bridge that was constructed across Rocky Creek in winter 1993-94 for winter log-hauling purposes.

The beaver dam failure of June 8, 1994, a natural disturbance that released about 7500 m^3 of water, had a significant impact on both the control and treated reaches of Rocky Creek (Hillman n.d.). The estimated peak of the resulting flood wave was 15 $m^3 s^{-1}$ which is 3.5 times the maximum discharge recorded for the creek over 23 years. The flood wave scoured some channel sections and deposited sediment in others. Large trees and debris from old beaver dams were carried downstream and deposited in piles across the channel and adjacent banks. The flood wave was dampened to 6% of the estimated peak as it passed through the wetland below station 6. Flood waves from similar beaver dam failures that occurred on the adjacent Wolverine Creek watershed (11.1 ha) in 1968 and 1969 peaked at 34 and 22.9 $m^3 s^{-1}$, respectively (J. Taggart, Alberta Environmental Protection; personal communication). These events and the beaver dam failure identified earlier for September 1995 (Figs. 3c and 4) illustrate the impact that beaver activity has on stream ecology, and the importance of wetlands on streamflow regulation.

There were a number of trends that operated in the longitudinal direction, i.e., along the channel. They were consistent over the distance from station 1 at the fen to station 10 at the road crossing for some water quality parameters; for others, the trends were consistent only as far as station 6. DOC concentrations, for example, decreased from a maximum at station 1 to a minimum at station 10, so there was a steady loss of DOC downstream. The maximum DOC concentration recorded at station 1 was 125 ppm. In contrast, DOC concentrations near the exit point of the watershed (station 10) rarely exceeded 20-30 ppm (Fig. 9). Concentrations of metallic elements, Ca, Na, Mg and K increased downstream, reaching maxima at station 10. Water temperature showed a steady decline from a maximum at station 2 to a minimum at station 6 and then increased at stations 8 through 10. Conversely, pH tended to increase in the downstream direction.

It was frequently observed, especially during low flows, that stream discharge at a particular station was less than that of a station some distance upstream (Fig. 4). This decrease was attributed to transfer to subsurface flow and to storage in beaver impoundments. Another factor is measurement error during very low flows. Some of the flows encountered on Rocky Creek could not be measured with standard Price and pygmy current meters; these flow rates were obtained through extrapolation of the appropriate stage-discharge relation.

New and existing techniques for measuring very low flows on first and second order boreal streams should be explored. Some ideas on this subject appeared in a recent issue of ***Stream Notes*** produced by the Stream Systems Technology Center (1996) that included descriptions of a portable weir plate and portable Parshall flumes that measure flows less than 0.001 $m^3 s^{-1}$. Such devices may be particularly appropriate for short-term research in remote areas where access is difficult, and when time and resources are limiting.

It is useful at this point in the discussion to compare the mean values of some of the Rocky Creek water quality parameters with those of another boreal stream. A paper by Clifford (1978) lists quarterly and annual averages of several physical and chemical constituents of the Bigoray River located about 225 km southeast of Rocky Creek. The Bigoray River is a third order boreal stream that drains organic terrain, is frequented by beaver and is tributary to the Pembina River. Black spruce, tamarack and *Populus* species are the dominant trees on the watershed.

A comparison of the quarterly averages (July - September, 1993-95) for Rocky Creek with those of the Bigoray River (Table 12) shows similarities with respect to water temperature, specific conductance, pH and dissolved oxygen. The difference in flow is understandable because the Bigoray River drains 87.3 km^2 which is nearly five times the area of the Rocky Creek watershed.

Table 12. Quarterly (July - September) averages of physical and chemical constituents at Rocky Creek and Bigoray River, Alberta.

	Rocky Creek	Bigoray River
Mean water temperature (°C)	12.8	13.0
Max daily water temperature change (°C)	12	3
Flow ($m^3\ s^{-1}$)	0.021	0.93
Specific conductance (mS)	0.214	0.236
pH	7.3	7.9
Dissolved oxygen ($mg\ l^{-1}$)	5.6	6.2
Total precipitation (mm)	151	191

The other notable exception is the diurnal water temperature fluctuation (Table 12) which can be explained in terms of flow volume. Because the Bigoray River flow is greater than the flow at Rocky Creek, water in the Bigoray River takes longer to warm up. Rocky Creek becomes extremely shallow and sluggish during the July - September period and, as the flow volume decreases, the water temperature fluctuations more closely match the fluctuations of the ambient air temperature.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Rocky Creek drainage area, which contains two lakes, a fen, a centrally located wetland, several beaver ponds and aspen forest, is a typical boreal watershed. Rocky Creek is characterized by low flows for much of the year and may dry up completely in the summer months.

Water issuing from the fen at the upper, northern end of the watershed contained the highest concentrations of DOC indicating that the fen was the primary source of dissolved organic carbon for the watershed. The water also had the lowest pH and element concentrations, and generally lower temperatures than water from other locations along the creek.

Beaver activity had a significant effect on both water quality and quantity. Water downstream from beaver ponds tended to be warmer, have higher pH and lower DOC concentrations than water upstream from the ponds. Failure of beaver dams resulted in the almost instantaneous release of large amounts of water that caused noticeable changes in channel configuration through scour and deposition. The regulatory influence of wetlands was naturally demonstrated when the wetland near the centre of the watershed dampened the peak flow (15 $m^3\ s^{-1}$) released by a failed beaver dam to 6%, or 0.95 $m^3\ s^{-1}$.

Water quality in the treated reach was more favourable for aquatic life than water quality in the control reach, before and after timber harvest. The water quality in both reaches, however, was satisfactory for aquatic life - at least for the water quality parameters studied. In the treated reach, DOC concentrations and water temperatures were lower, while dissolved oxygen and pH were higher.

The preservation of the riparian environment was the main reason why no noticeable change in water quality was detected in the treated reach. Damage caused by the beaver dam failure affected both the control and the treated reaches but was limited to narrow strips immediately adjacent to the stream. Application of the timber harvest planning and operating ground rules, agreed upon by DMI and the Alberta Forest Service, to the logging plan for Rocky Creek was evidently effective in maintaining water quality in the treated reach. The evidence so far indicates that the chemical and physical water quality at the Rocky Creek road crossing was not affected by the road crossing or by the upstream timber harvest. Further analyses of these data and sediment data for both Rocky Creek and Bridlebit Creek crossings are required.

Some water quality parameters showed a consistent trend from the head to the outlet of the watershed. Thus DOC concentrations decreased with distance from the DOC source (the fen) until, near the watershed exit point, concentrations were only 25% of that at the source. Conversely, concentrations of metallic elements increased in the downstream direction as a result of contributions from groundwater seepage.

The very low flows encountered on Rocky Creek are typical of many first and second order boreal streams, particularly where beaver are active. On several occasions they could not be measured with current meters. In a study of this nature, where low flow is measured at several locations along a stream, there is a need for semi-permanent gauging structures that are inexpensive, portable and capable of measuring flows of $0.001 m^3 s^{-1}$. The design and development of such structures are worthy of further research.

The Rocky Creek watershed is a complex unit that incorporates many of the features found in boreal regions. Because it is so complex, it is difficult to design a model that effectively simulates the processes that occur on the watershed, and also simulates the changes in water quantity and quality in response to disturbances. To the authors' knowledge, existing watershed response models do not take into account the sometimes major effects of beaver activity and wetland storage capability. The design of a successful watershed response model that incorporates these special features of the boreal landscape will be a valuable tool for future studies of boreal watersheds. Consequently, it merits further research, particularly when industrial activity in the boreal forest has increased considerably during the past few years.

Recommendations

1. Daishowa-Marubeni International Limited (DMI) should continue to use the timber harvest planning and operating ground rules, agreed upon by DMI and the Alberta Forest Service, to guide its logging operations and to provide full protection to riparian areas.

2. The concept of using a control reach and a treated reach to evaluate the impact of timber

harvesting on stream water quality proved to be invaluable to the success of this short-term study on a forested watershed. We recommend that it be considered for similar studies in future, especially when it is difficult during the present economic climate to obtain support for long-term studies such as investigations involving the measurement of paired watersheds over decades.

3. A watershed response model should be designed and tested to 1) take into account the special features of the boreal forest and 2) simulate the changes in water quantity and quality in response to disturbances on boreal watersheds.

4. New or existing semi-permanent gauging structures that are inexpensive, portable and capable of measuring flows of $0.001 m^3 s^{-1}$ should be designed and tested. Such structures would be very useful for stream-gauging in remote, inaccessible areas on boreal watersheds.

ACKNOWLEDGMENTS

We are grateful to Daishowa-Marubeni International Limited (DMI) and Alberta Environmental Protection (AEP) for supporting our research on the Rocky Creek watershed. DMI also designed and implemented the logging plan for the watershed. We thank Bob Wynes (DMI) and John Taggart (AEP) for their encouragement and for reviewing this manuscript. We are also indebted to Jim Anderson (Grande Prairie office), Gerry Coles and D. Graham (Edmonton office) of the Technical Services Division, AEP for providing us with streamflow and precipitation data for Rocky and Bridlebit Creeks. Completion of the study would not have been possible without the extra efforts and hours put in by field technicians Bruce Robson, Susan Ball and Lauri Lywak, and by the many students hired under COSEP and Public Service Commission programs. We gratefully acknowledge the help of staff at the Grande Prairie Forest HQ and the Valleyview Ranger Station who provided us with equipment, storage space and assistance in the field. The cooperation of Marc Zubel and his colleagues of the Hydrogeology Branch, AEP is also much appreciated. Funding for this research was provided by the Canada-Alberta Partnership In Forestry Agreement and by the Manning Diversified Forest Products Research Fund.

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APPENDIX I

Figures 1 to 23

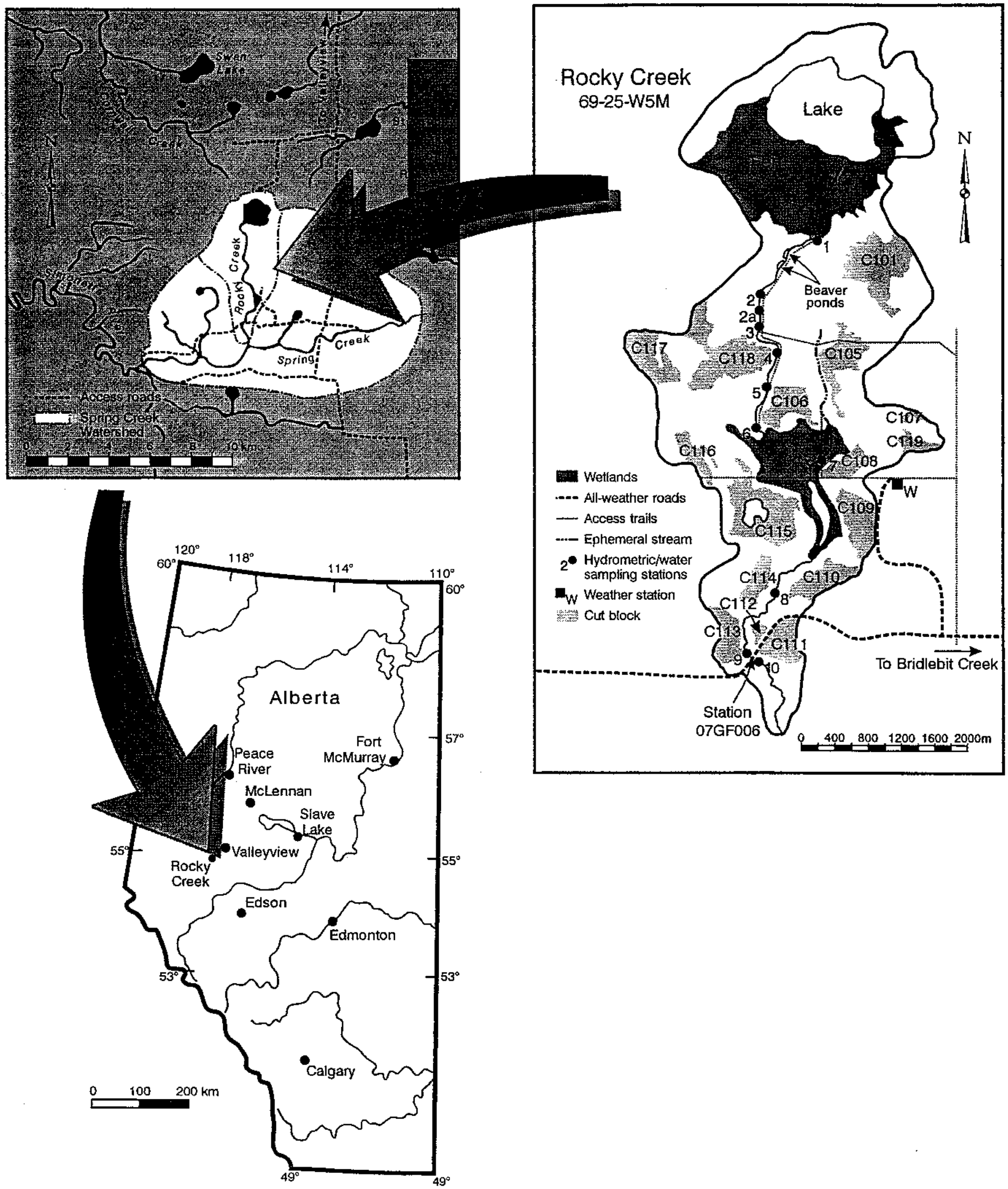


Figure 1. The Rocky Creek watershed: location, cut blocks, instrumentation and wetlands.

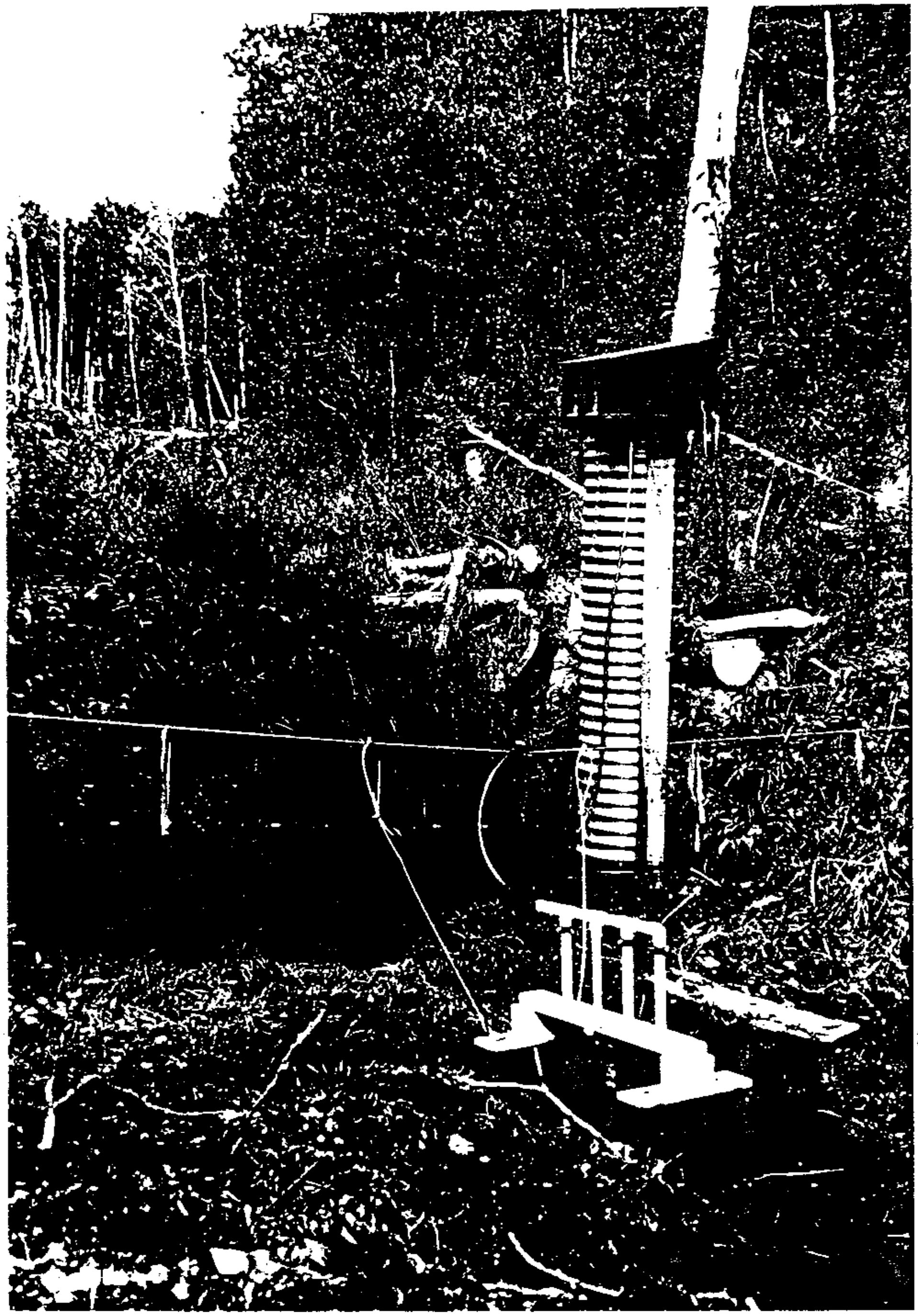


Figure 2. Stream gauge with a float supporting pH, specific conductance, water temperature and dissolved oxygen sensors.

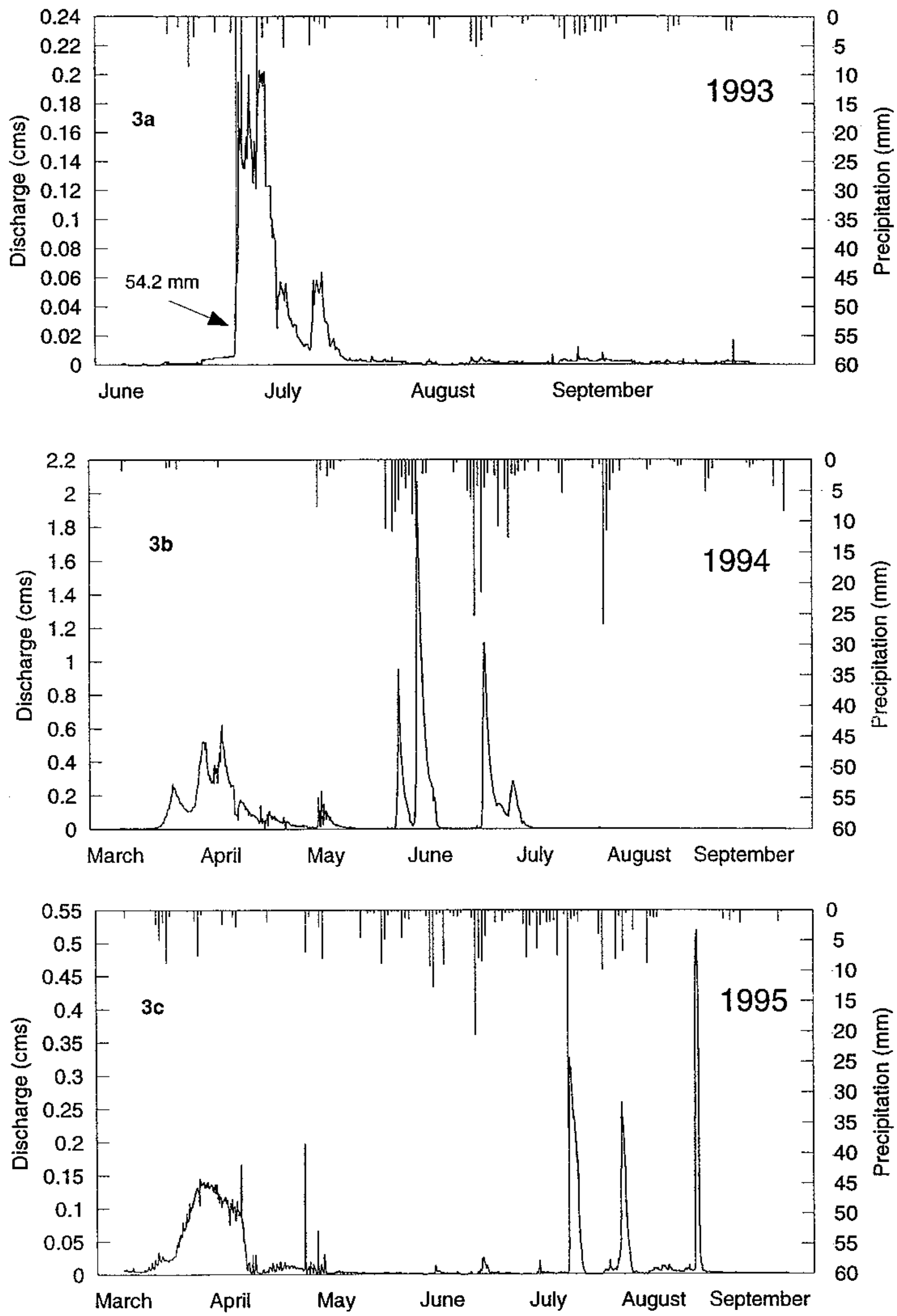


Figure 3. Precipitation - discharge record for Rocky Creek. Discharge measured at station 07GF006.

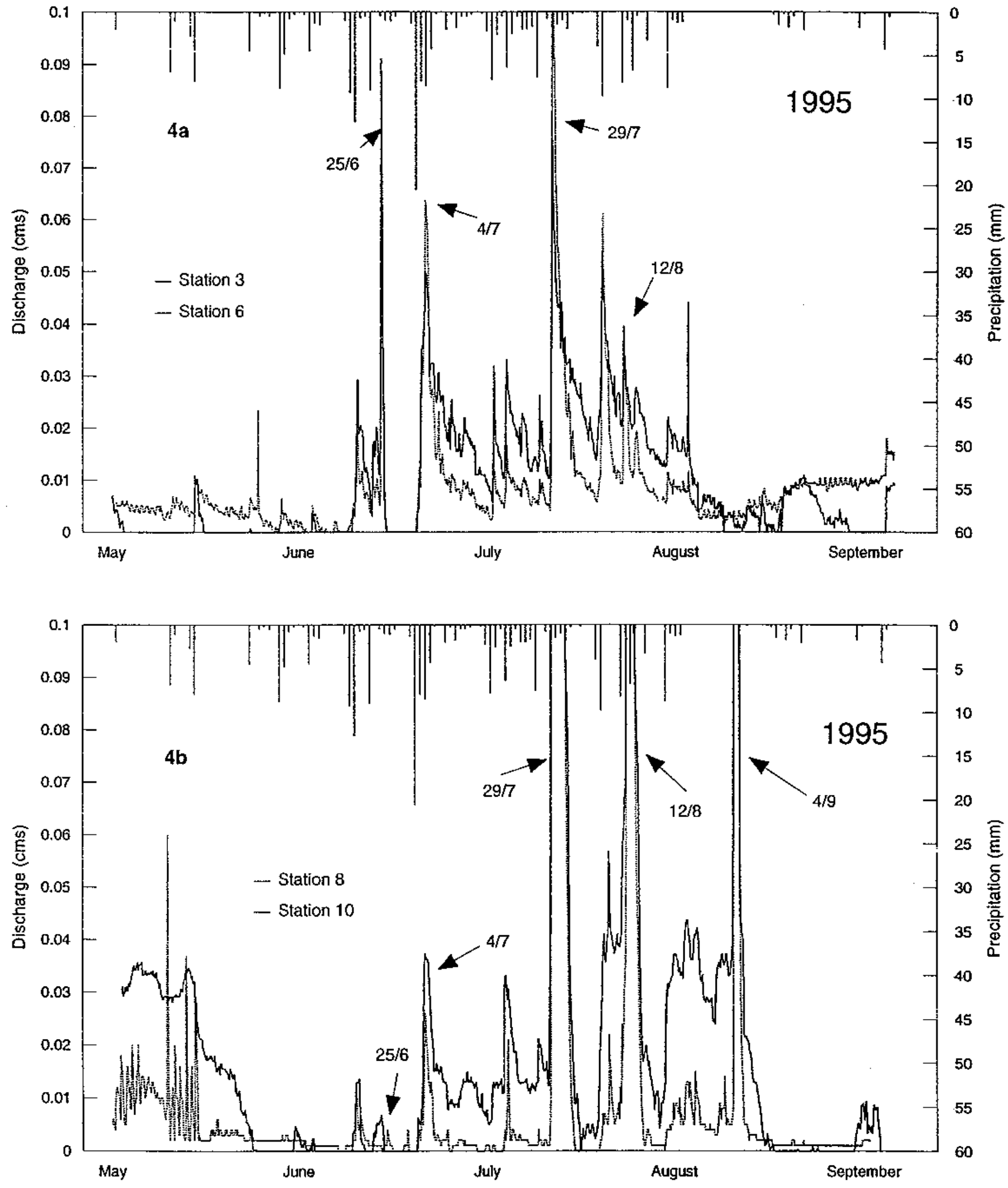


Figure 4. Rocky Creek discharge upstream (a) and downstream (b) from the wetland. (Dates (dd/mm) are indicated by arrows).

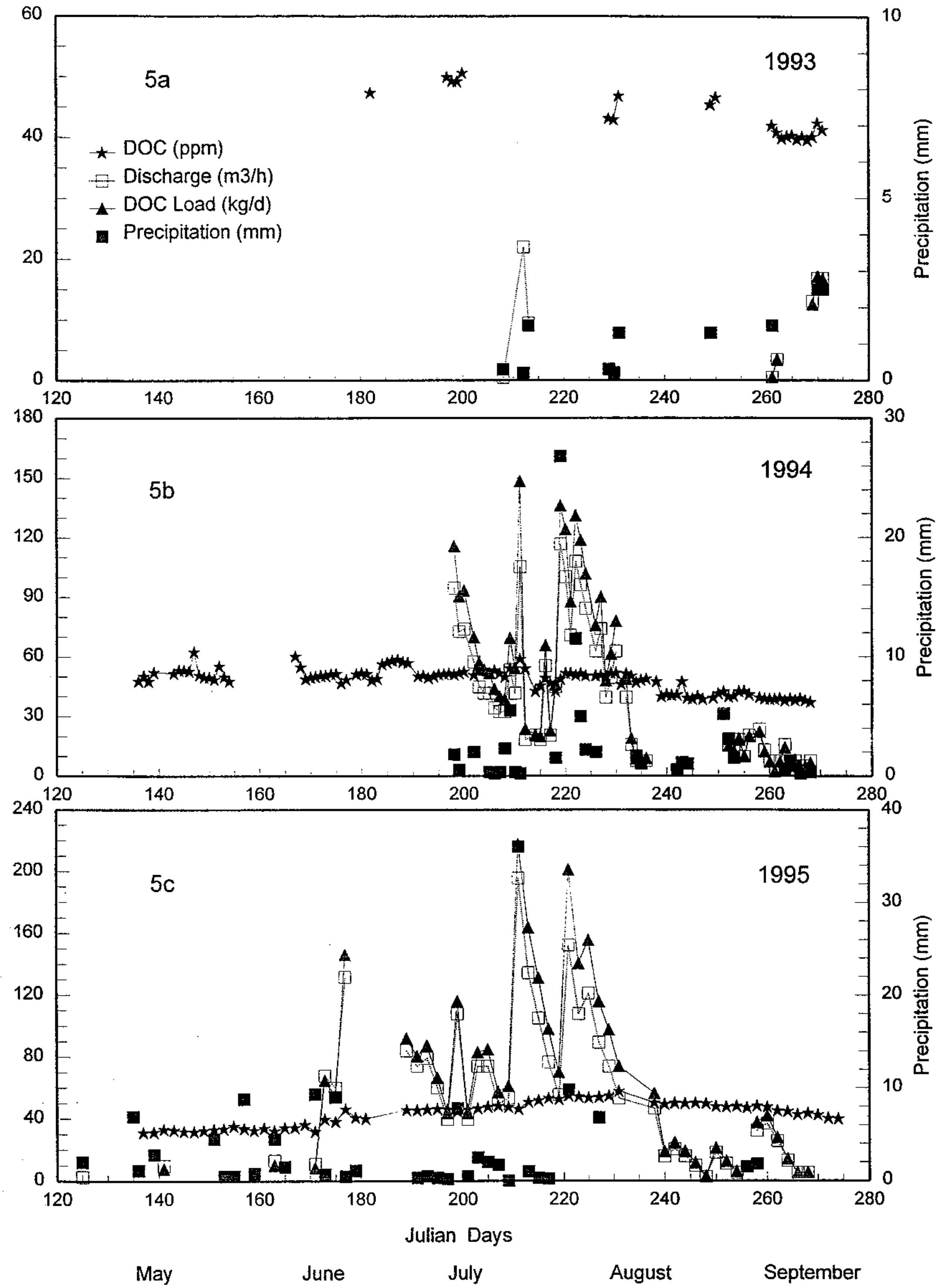


Figure 5. DOC concentrations, DOC loading, discharge and precipitation at station 3.

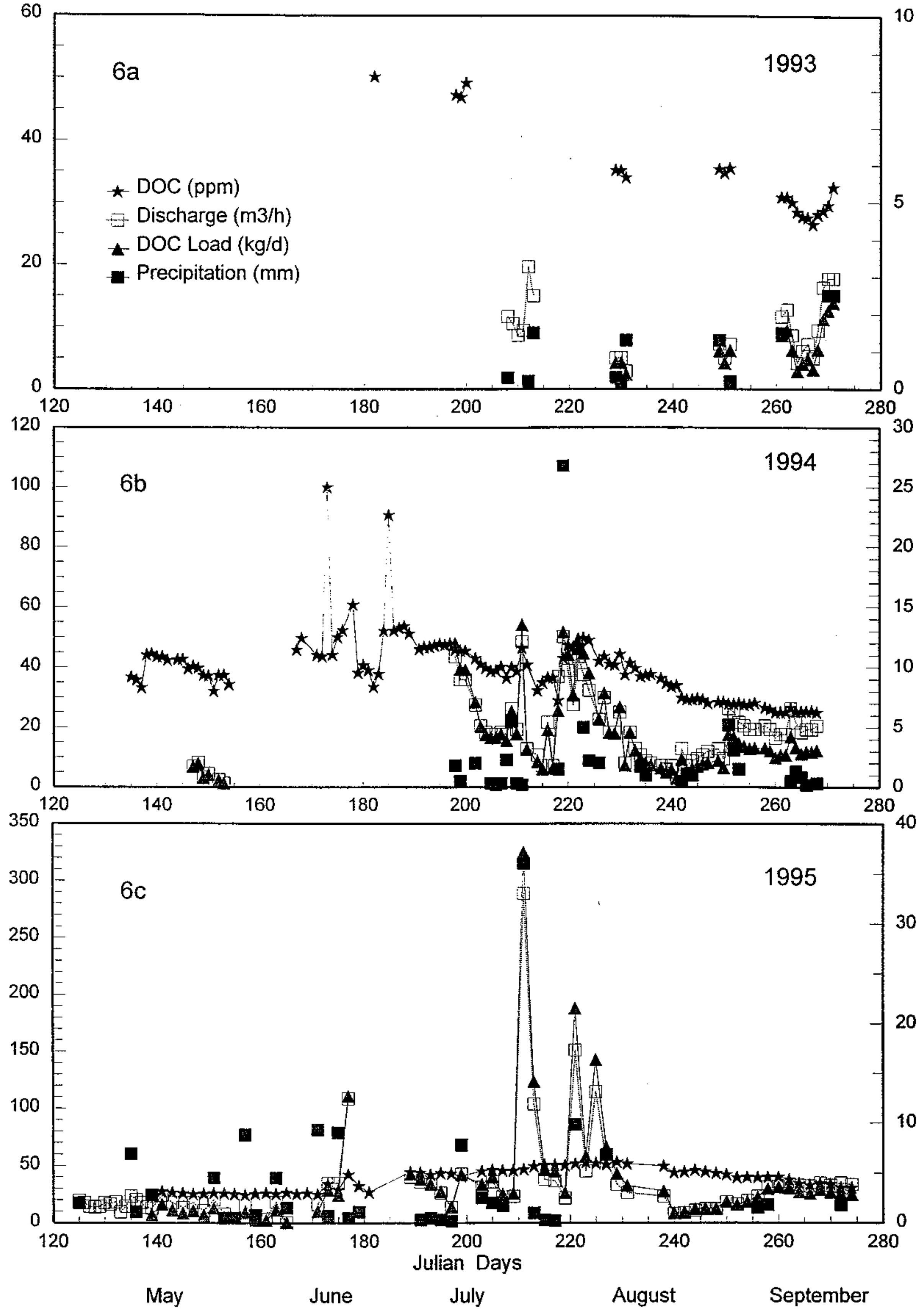


Figure 6. DOC concentrations, DOC loading, discharge and precipitation at station 5.

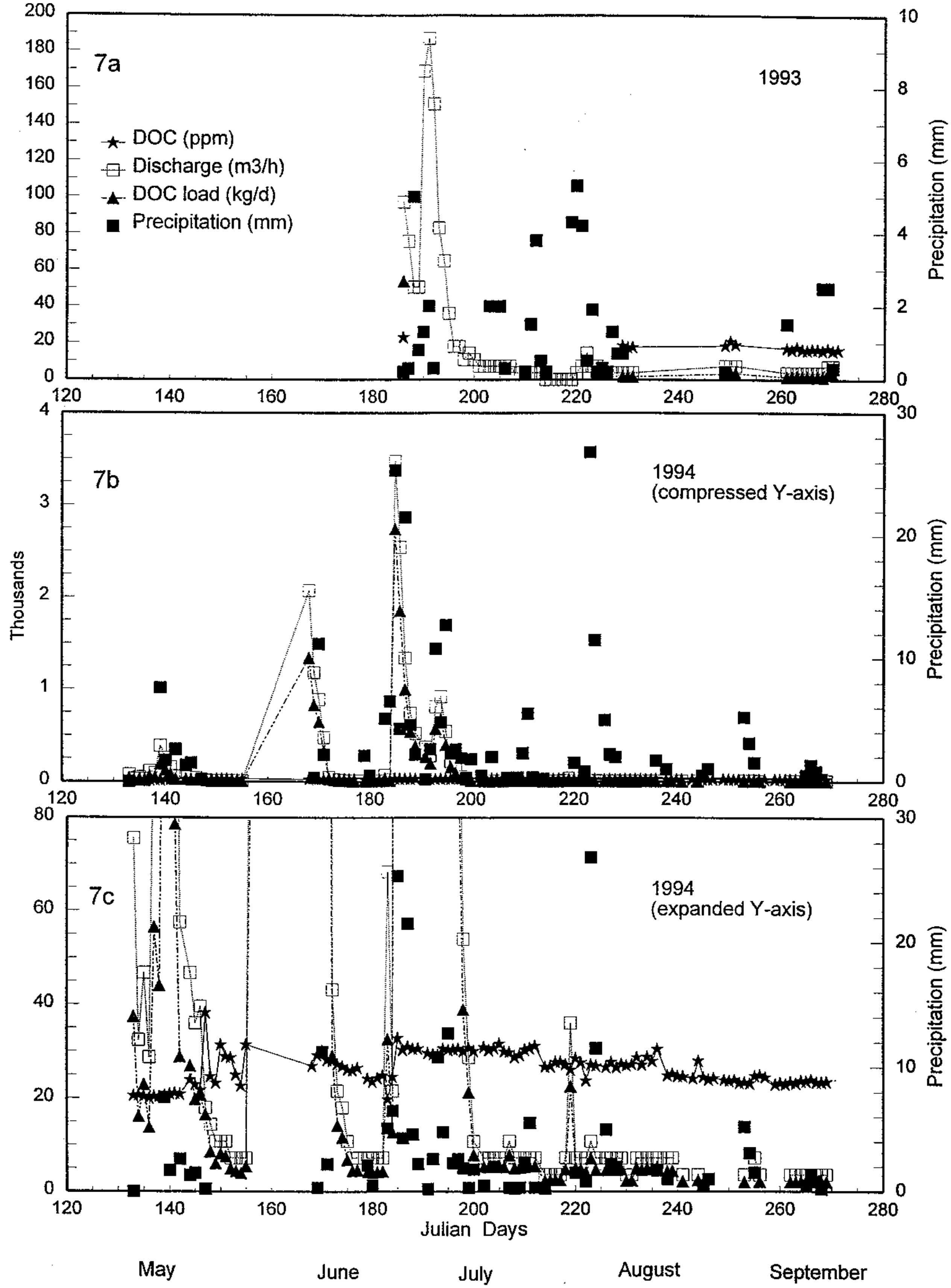


Figure 7a-7c. DOC concentrations, DOC loading, discharge and precipitation at station 10.

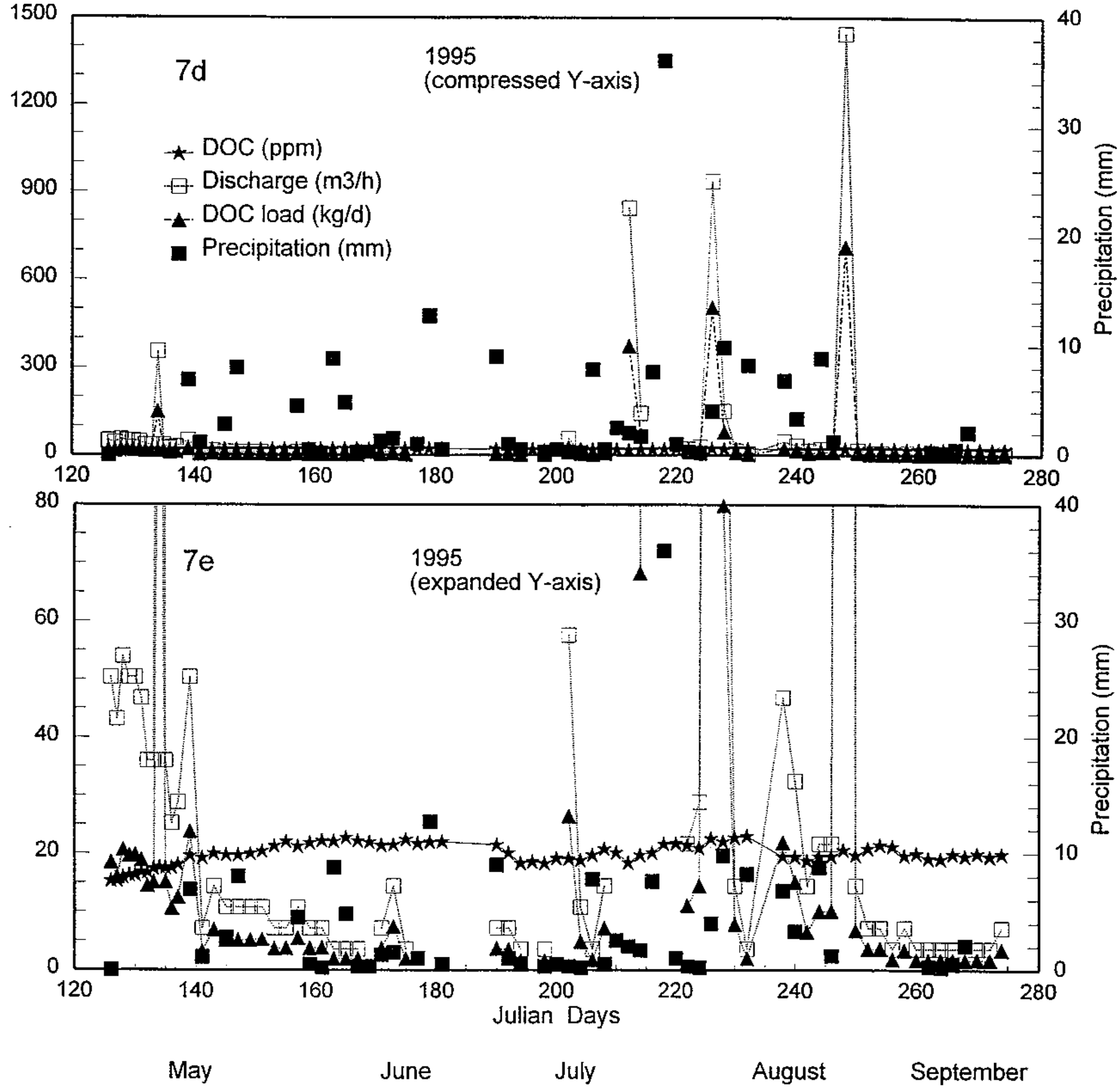


Figure 7d-7e. DOC concentrations, DOC loading, discharge and precipitation at station 10.

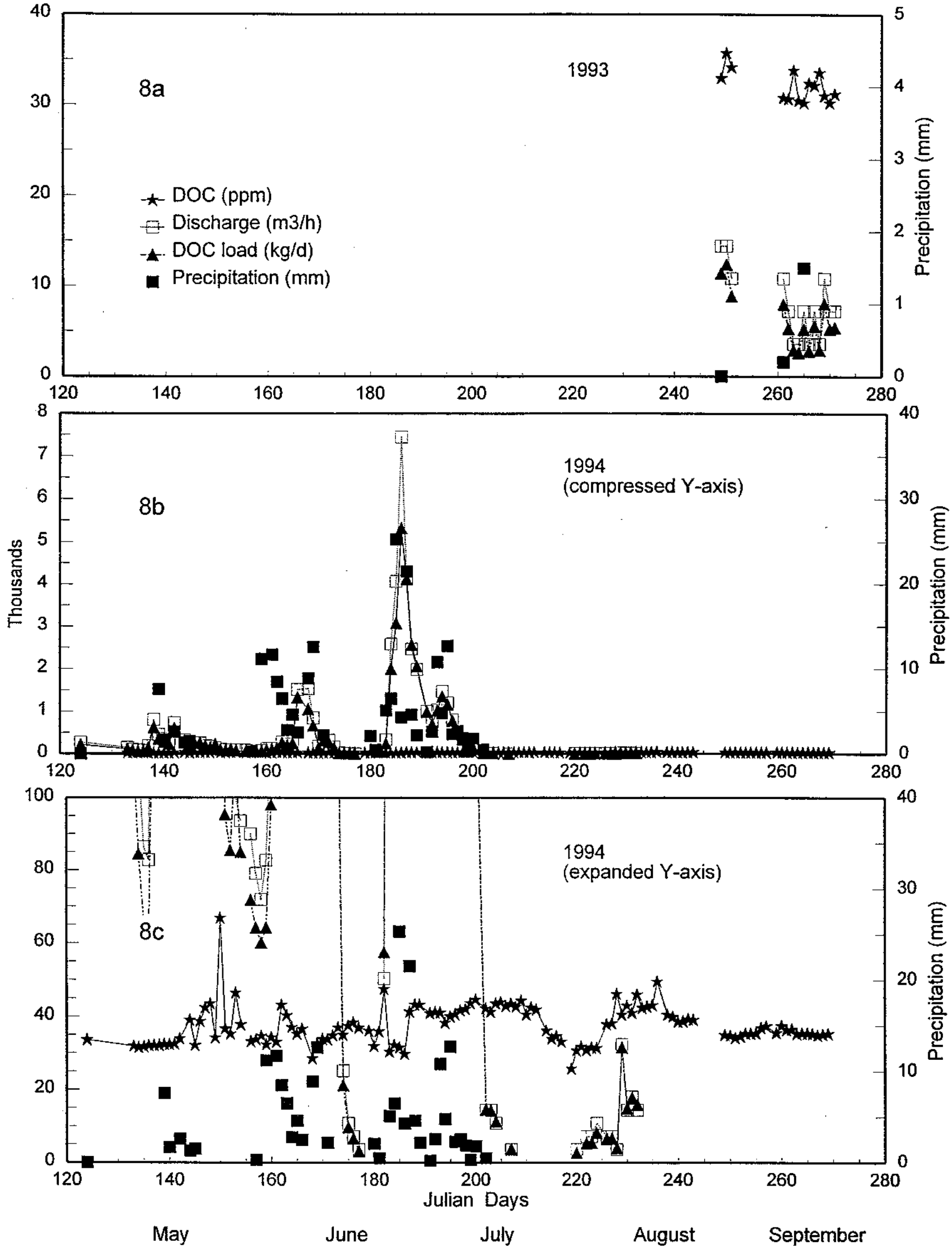


Figure 8a-8c. DOC concentrations, DOC loading, discharge and precipitation at station 11.

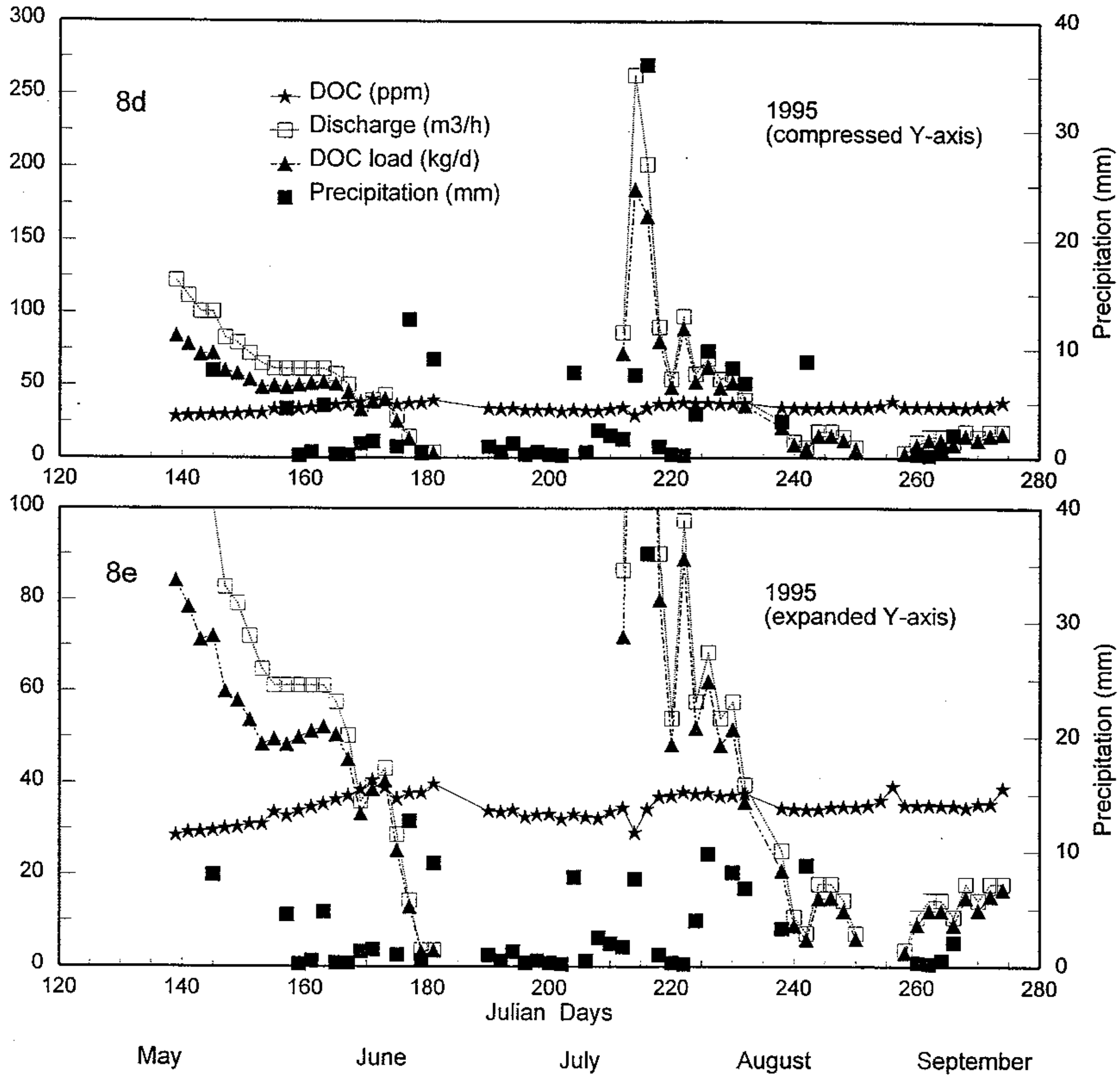


Figure 8d-8e. DOC concentrations, DOC loading, discharge and precipitation at station 11.

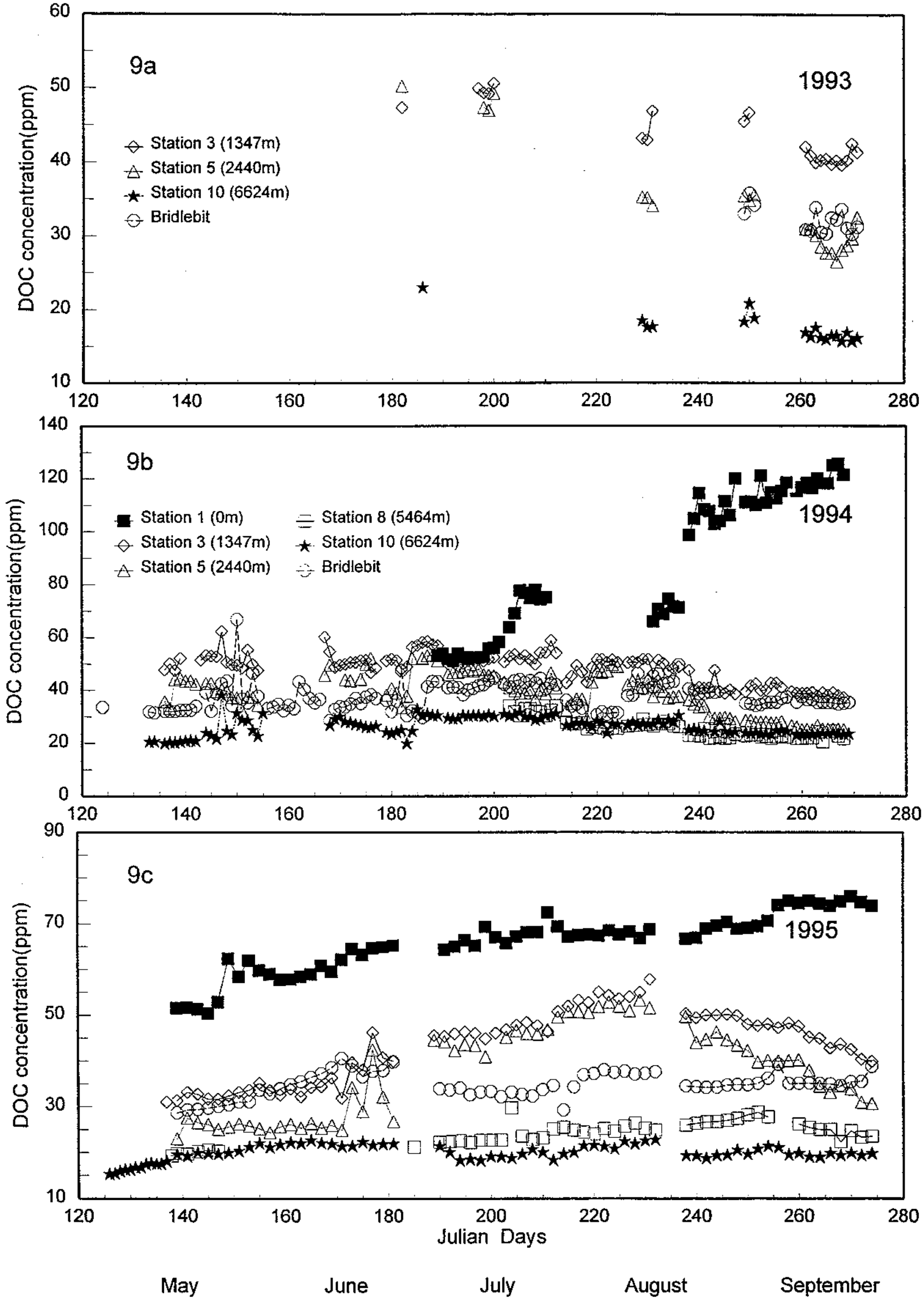


Figure 9. DOC concentrations at various stations in three years (1993-95).

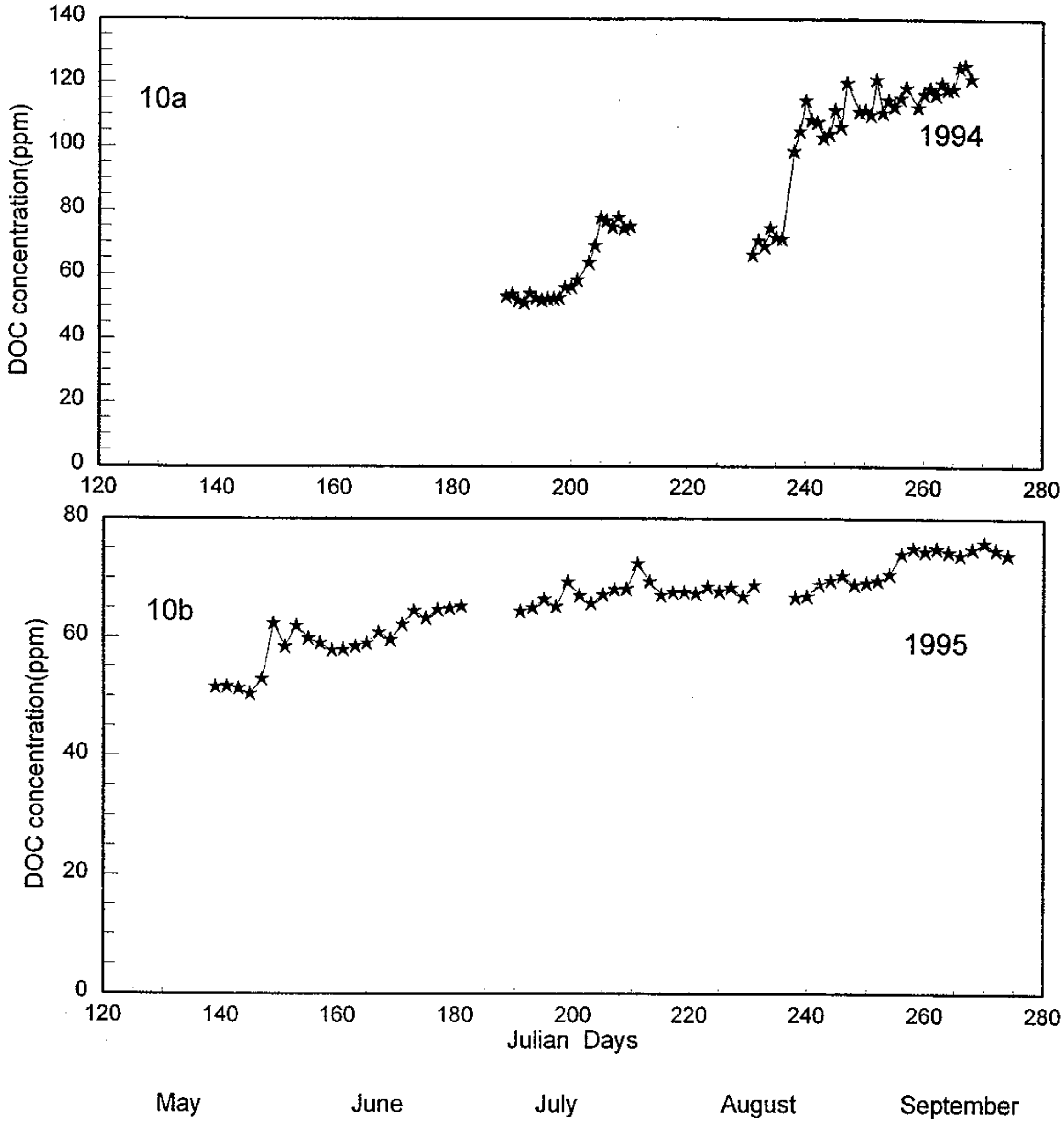


Figure 10. DOC concentrations at station 1.

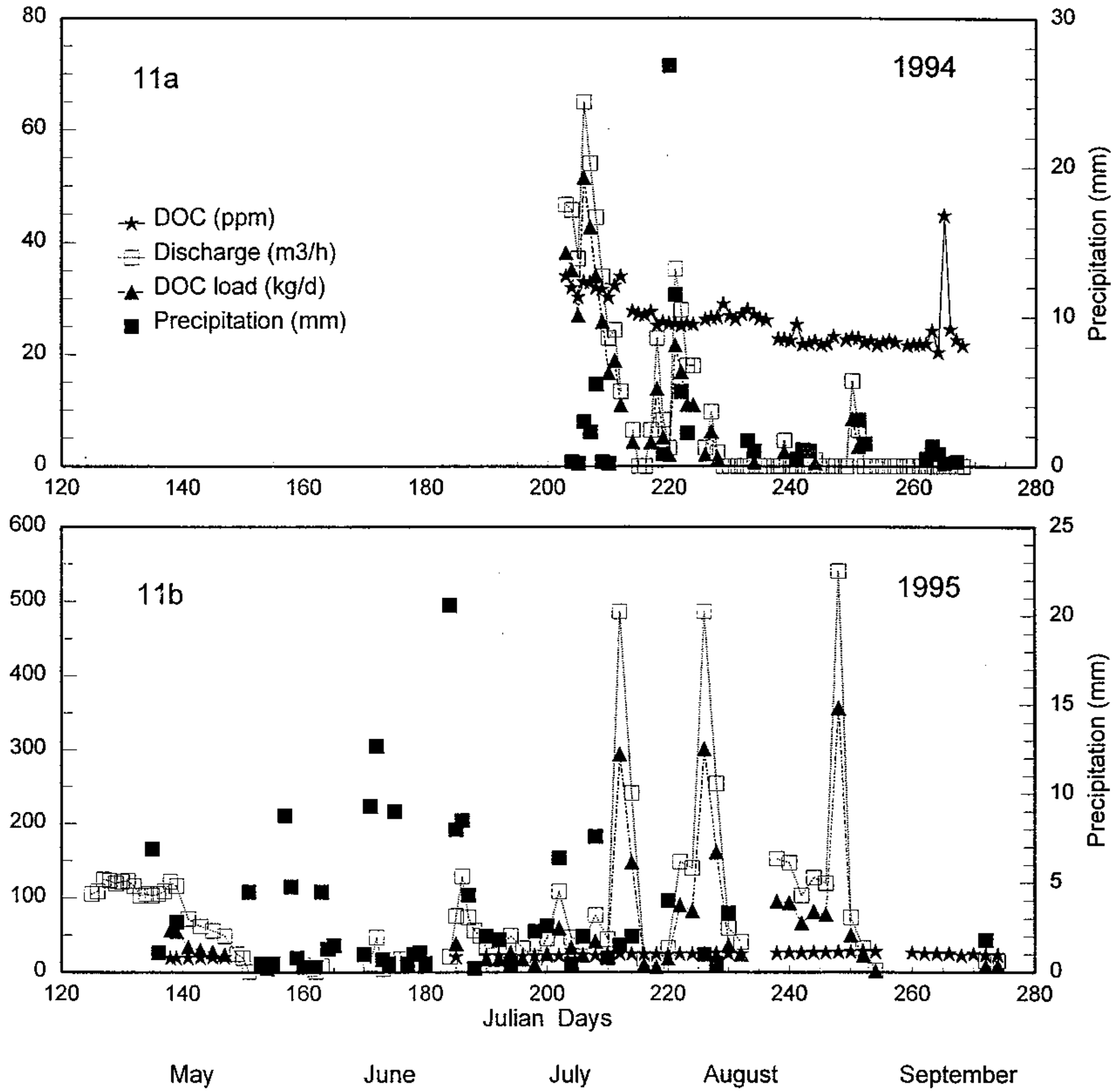


Figure 11. DOC concentrations, DOC loading, discharge and precipitation at station 8.

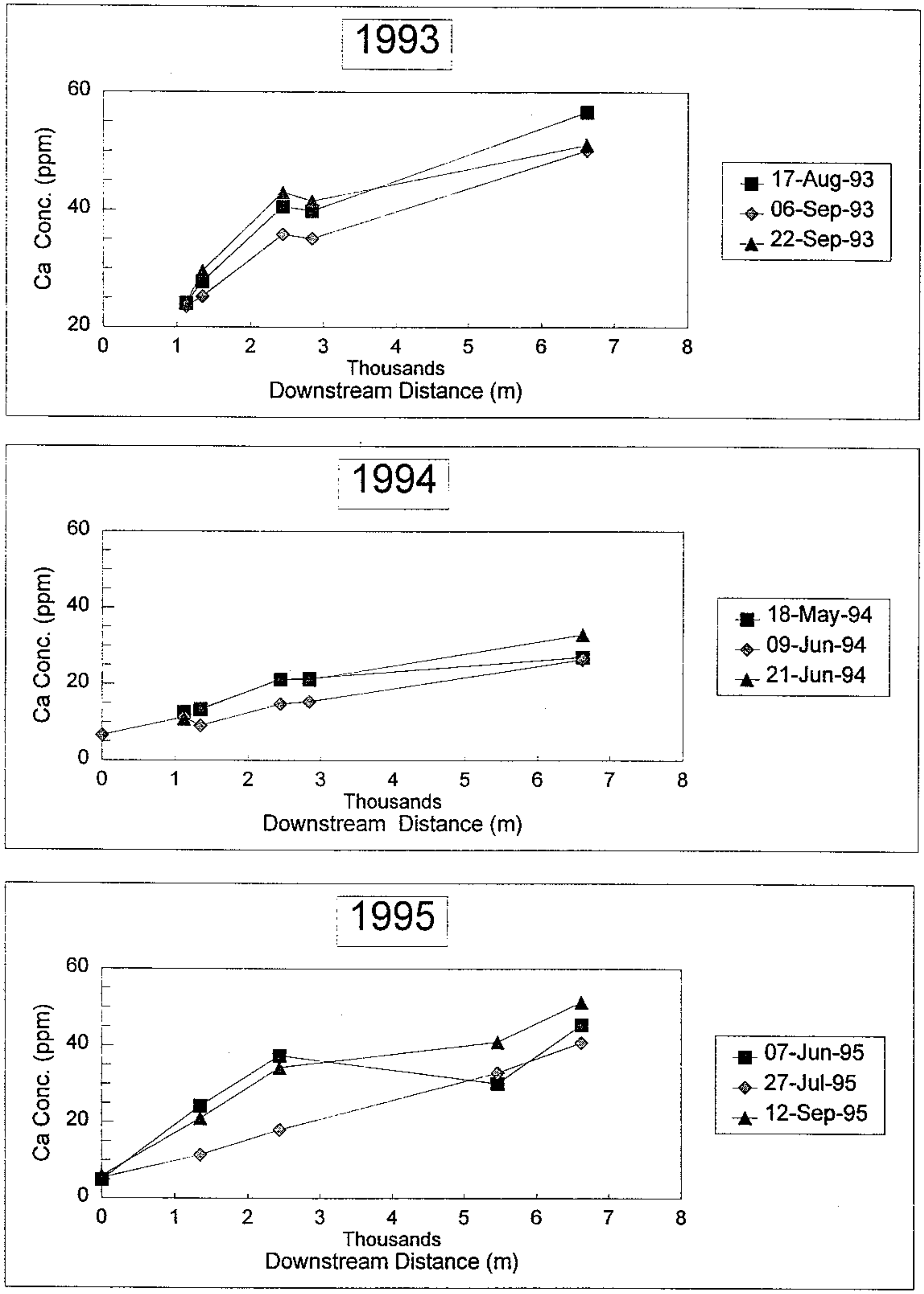


Figure 12. Ca concentrations in Rocky Creek. (The correspondence between each staion and its distance downstream from station 1 is given in Table 2).

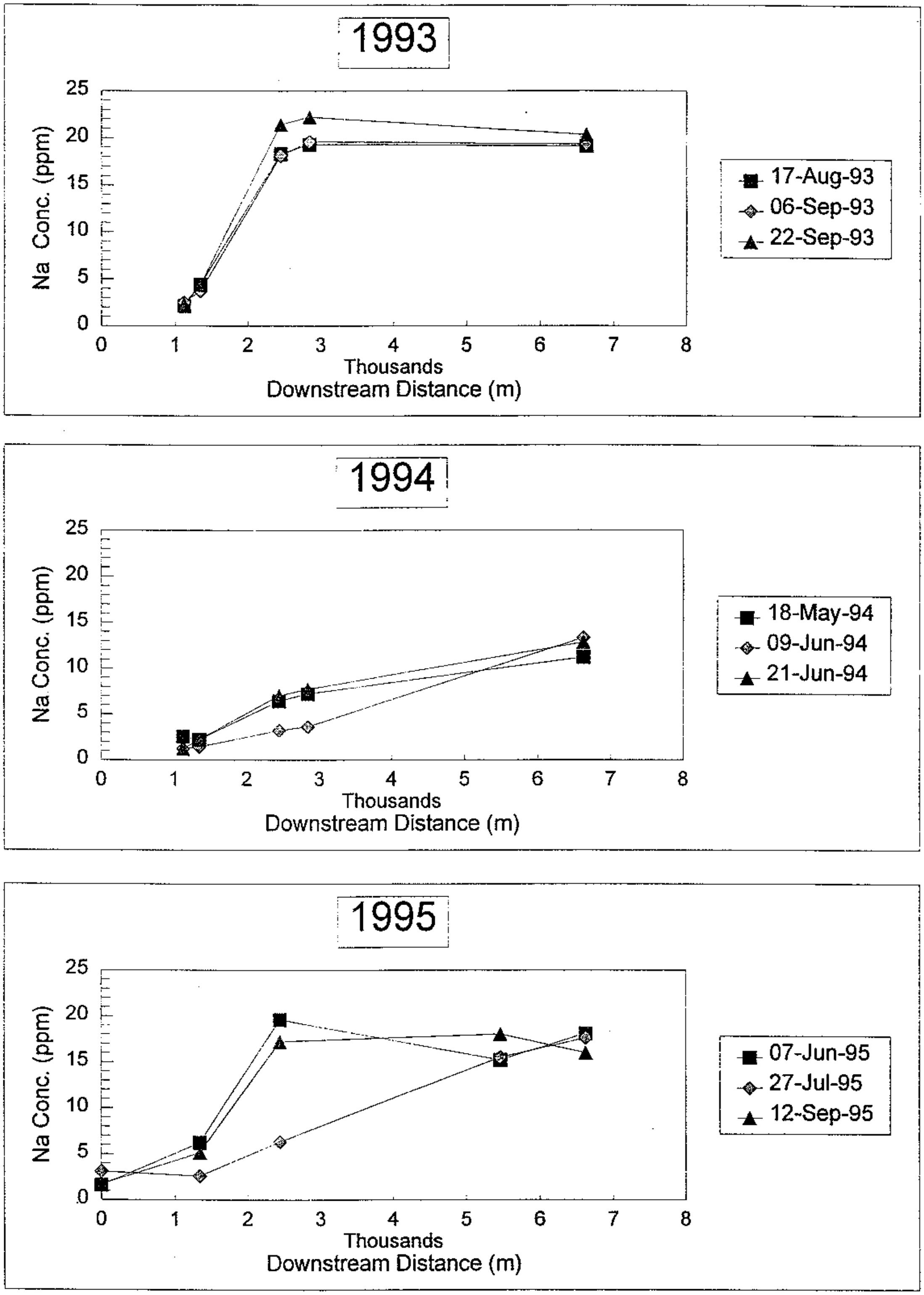


Figure 13. Na concentrations in Rocky Creek.

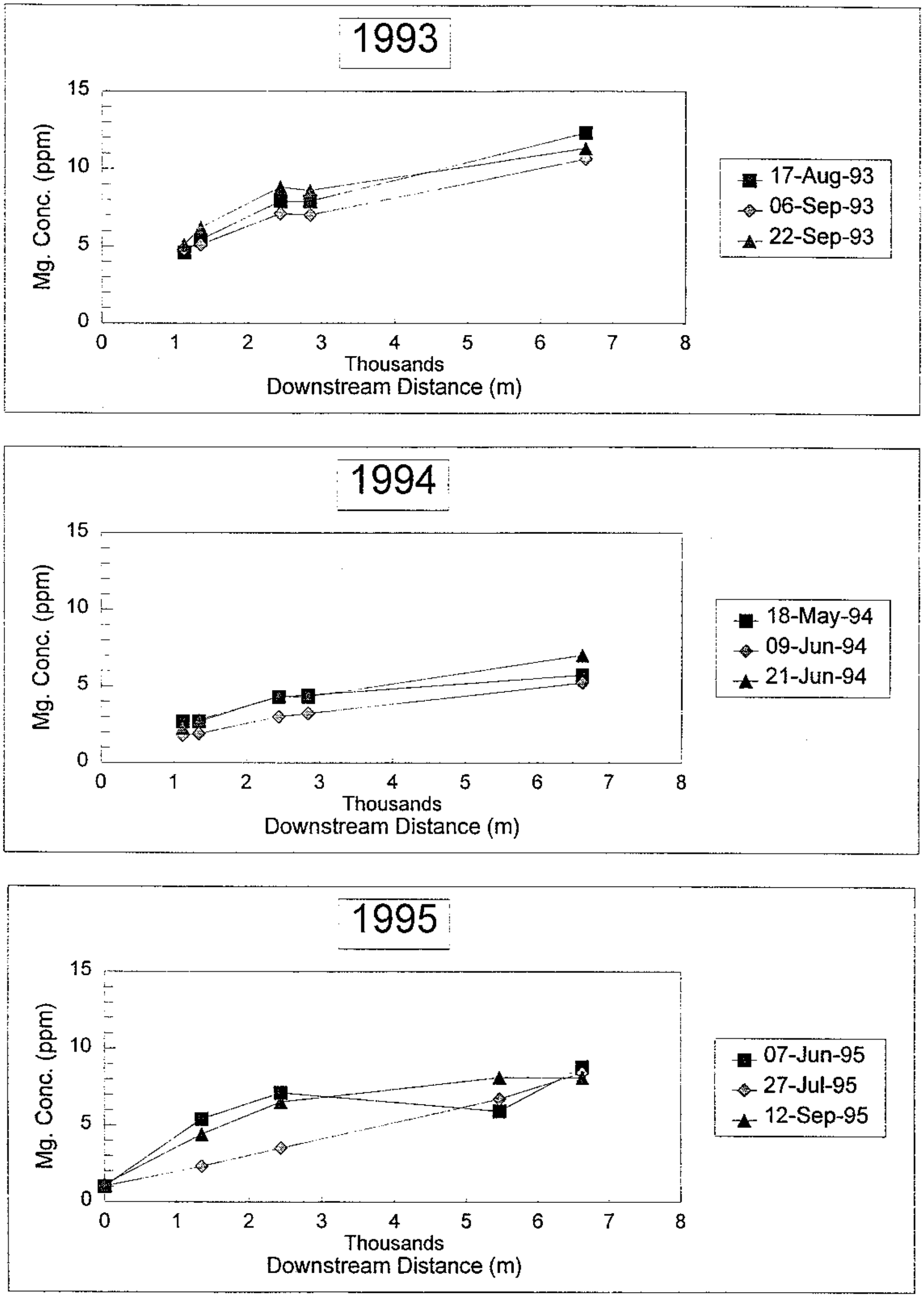


Figure 14. Mg concentrations in Rocky Creek.

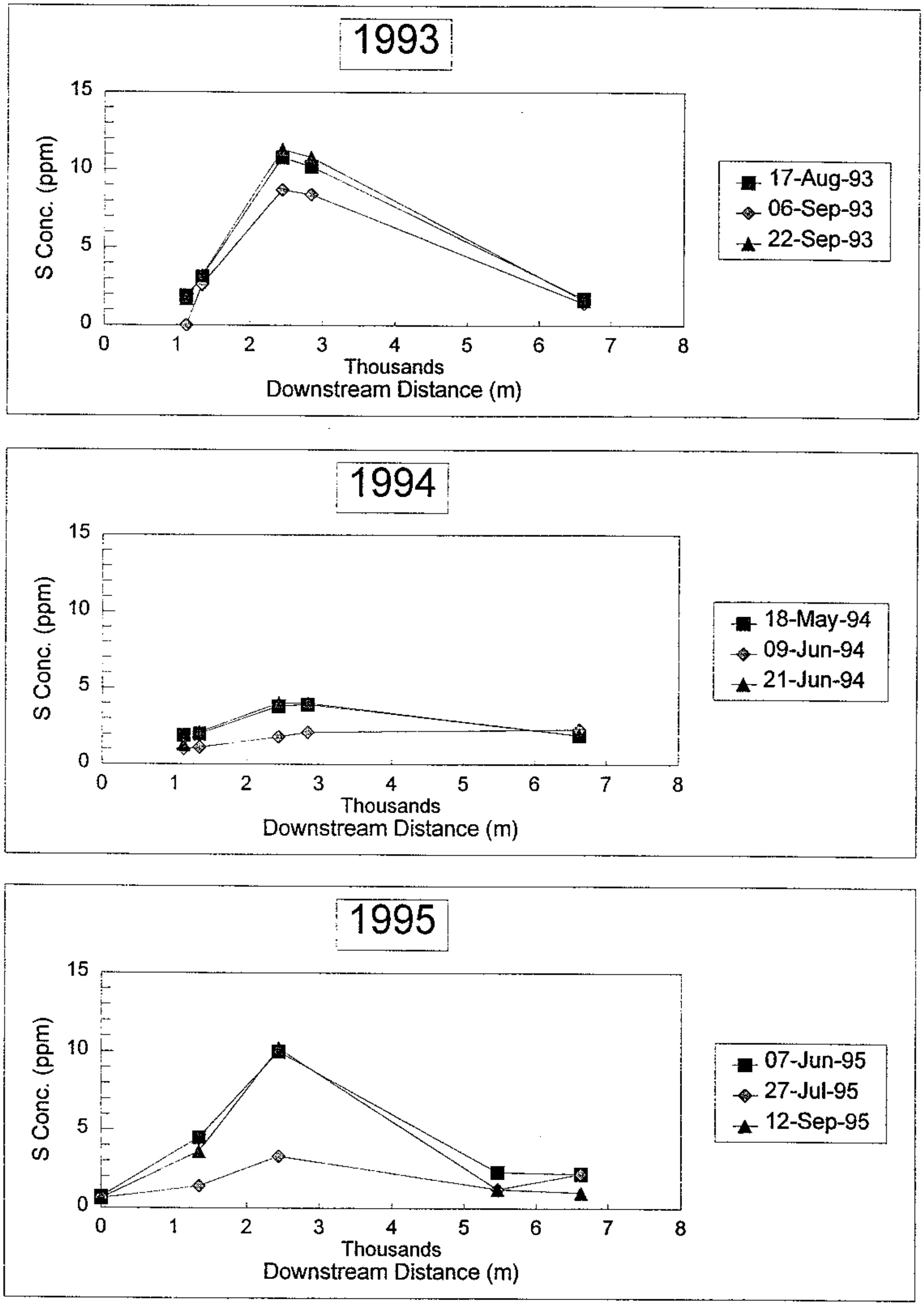


Figure 15. S concentrations in Rocky Creek.

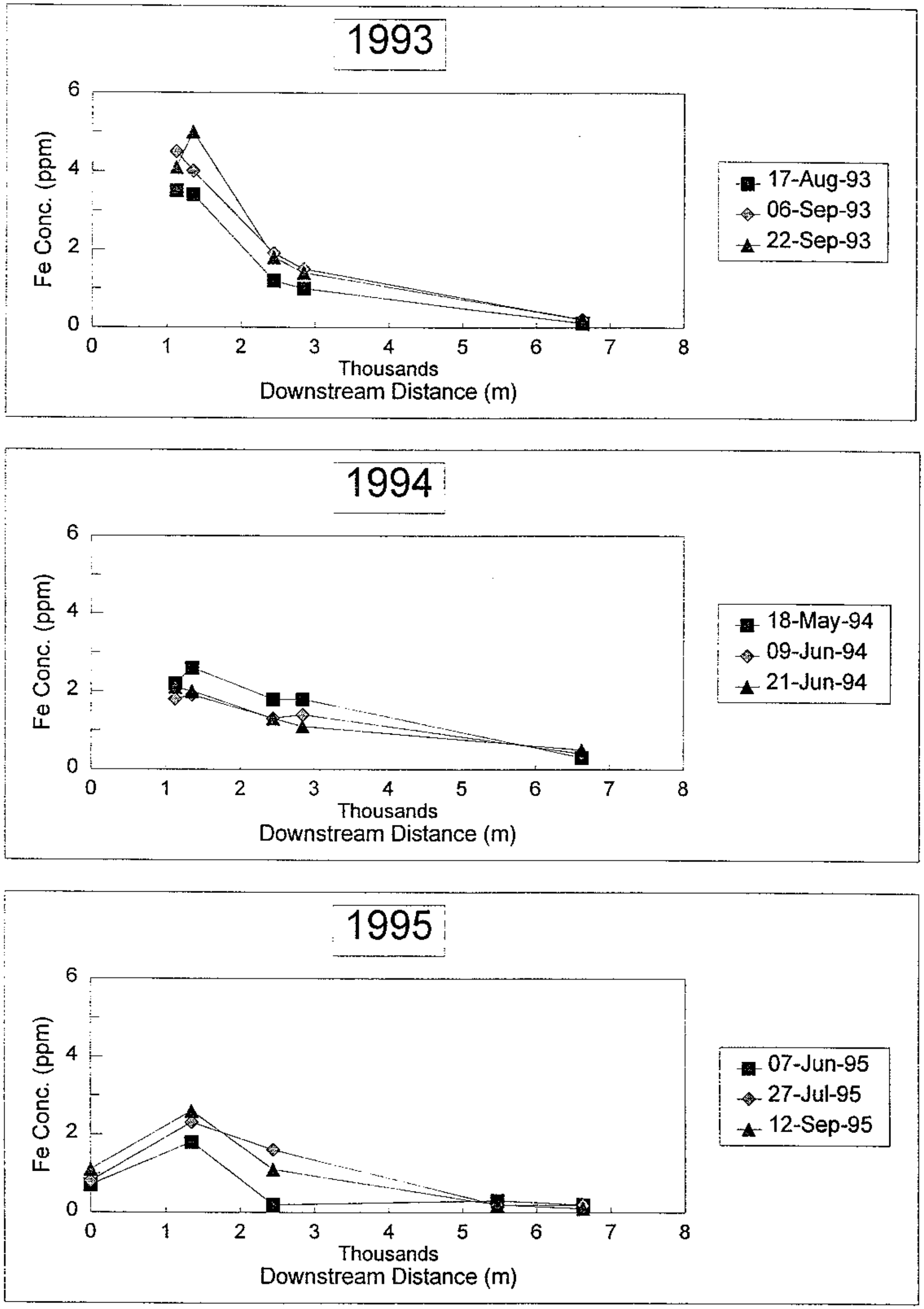


Figure 16. Fe concentrations in Rocky Creek.

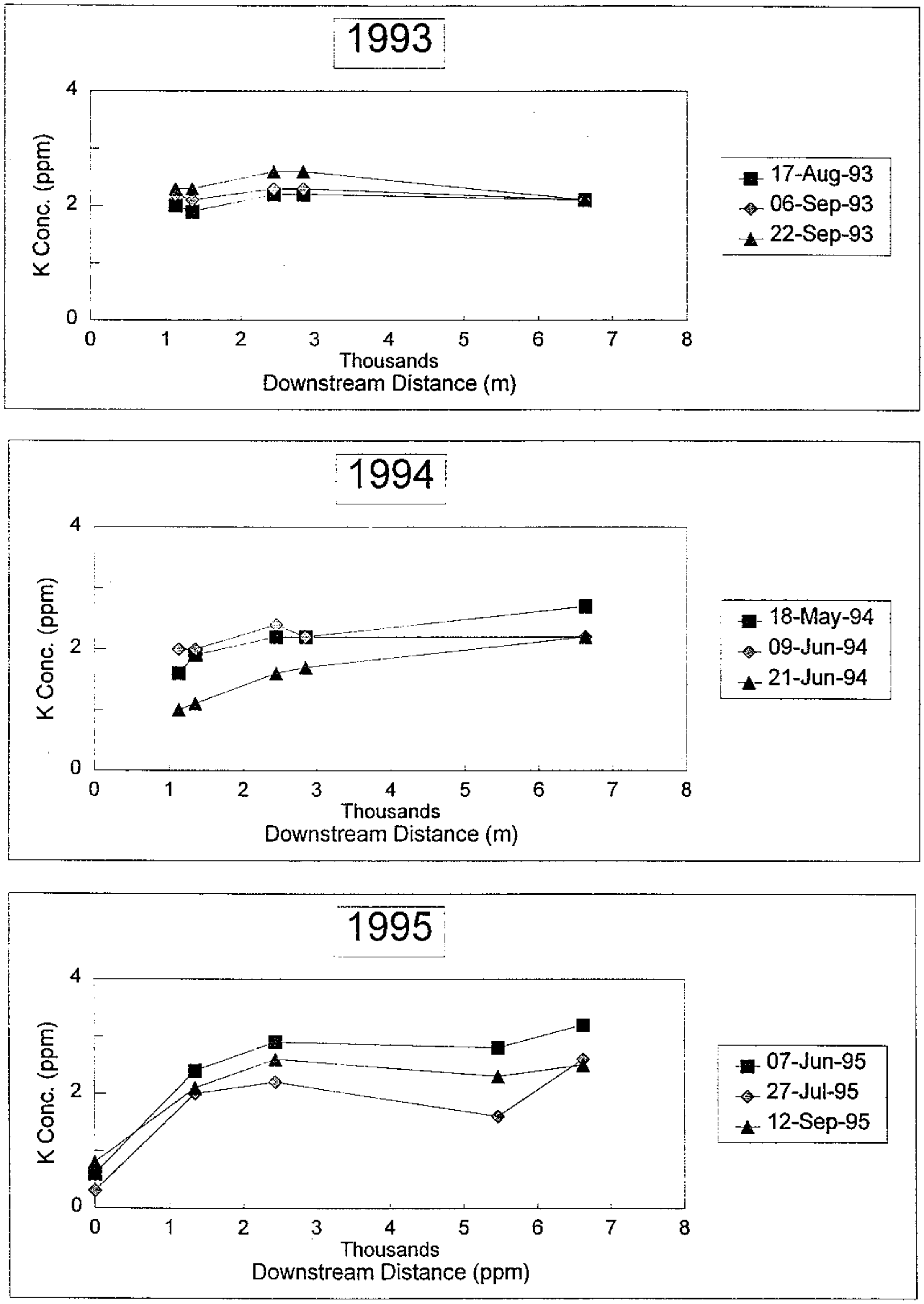
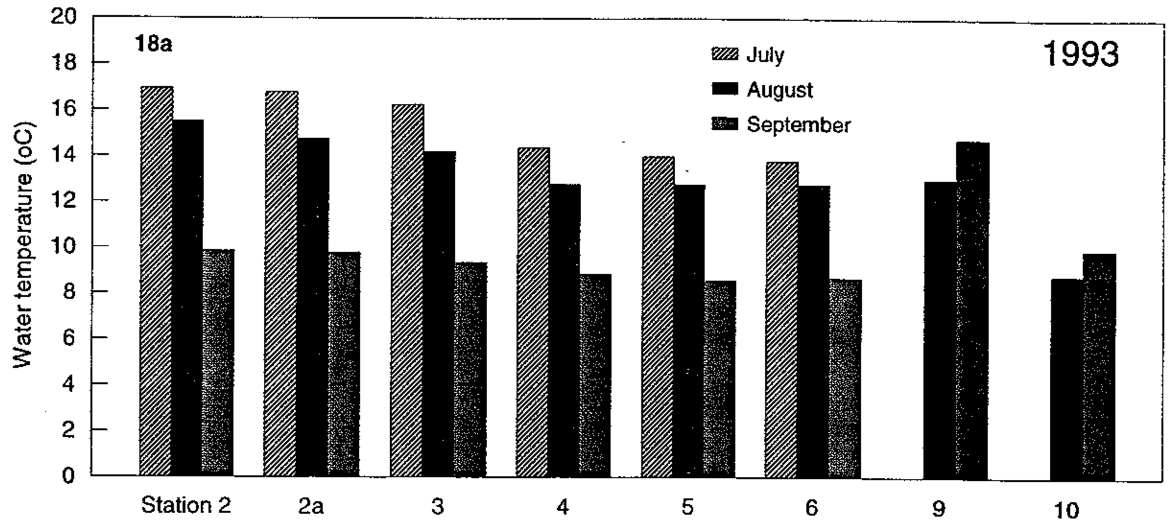
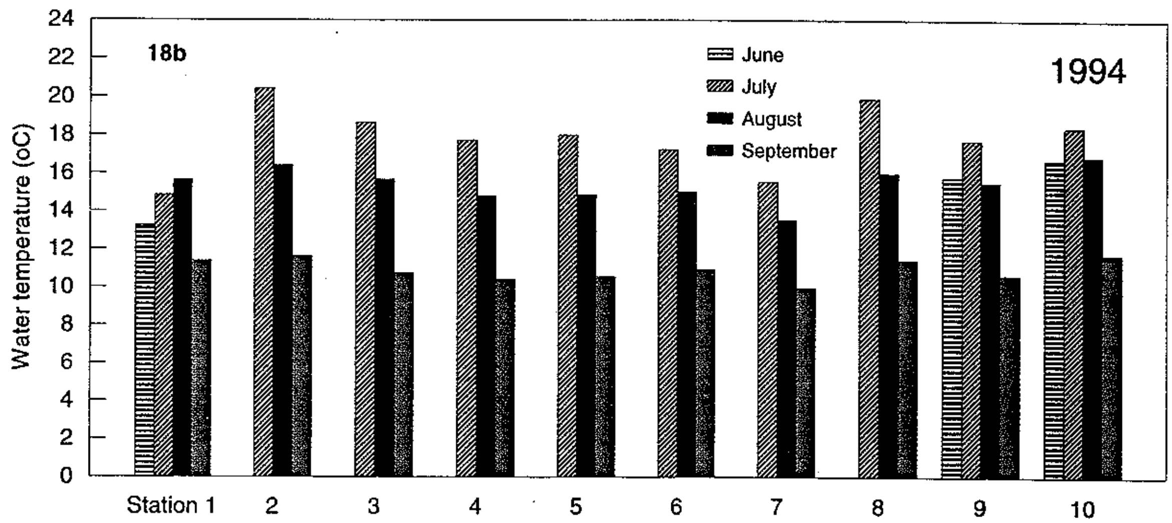


Figure 17. K concentrations in Rocky Creek.





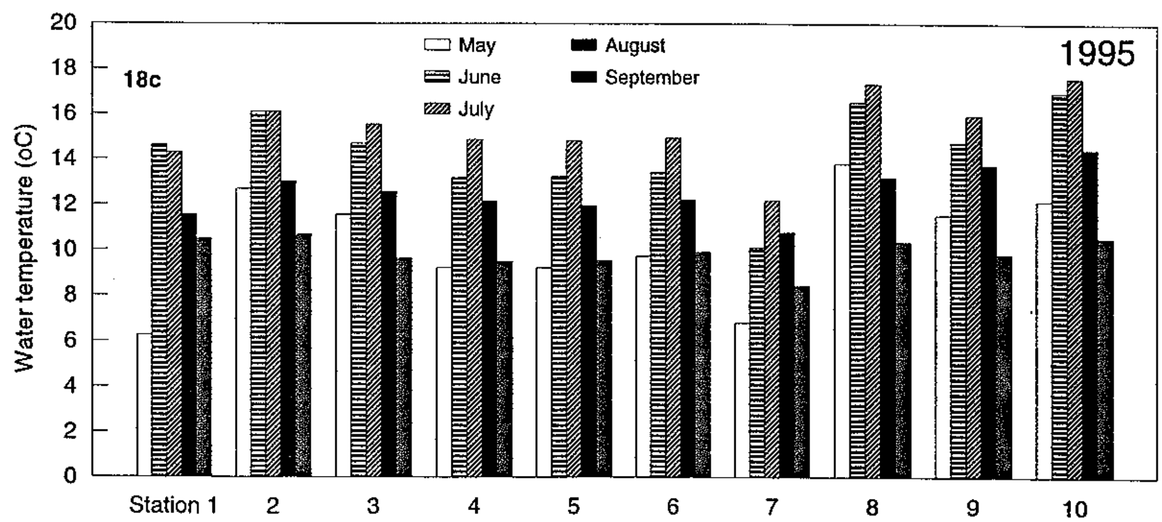


Figure 18. Water temperature profiles for Rocky Creek.

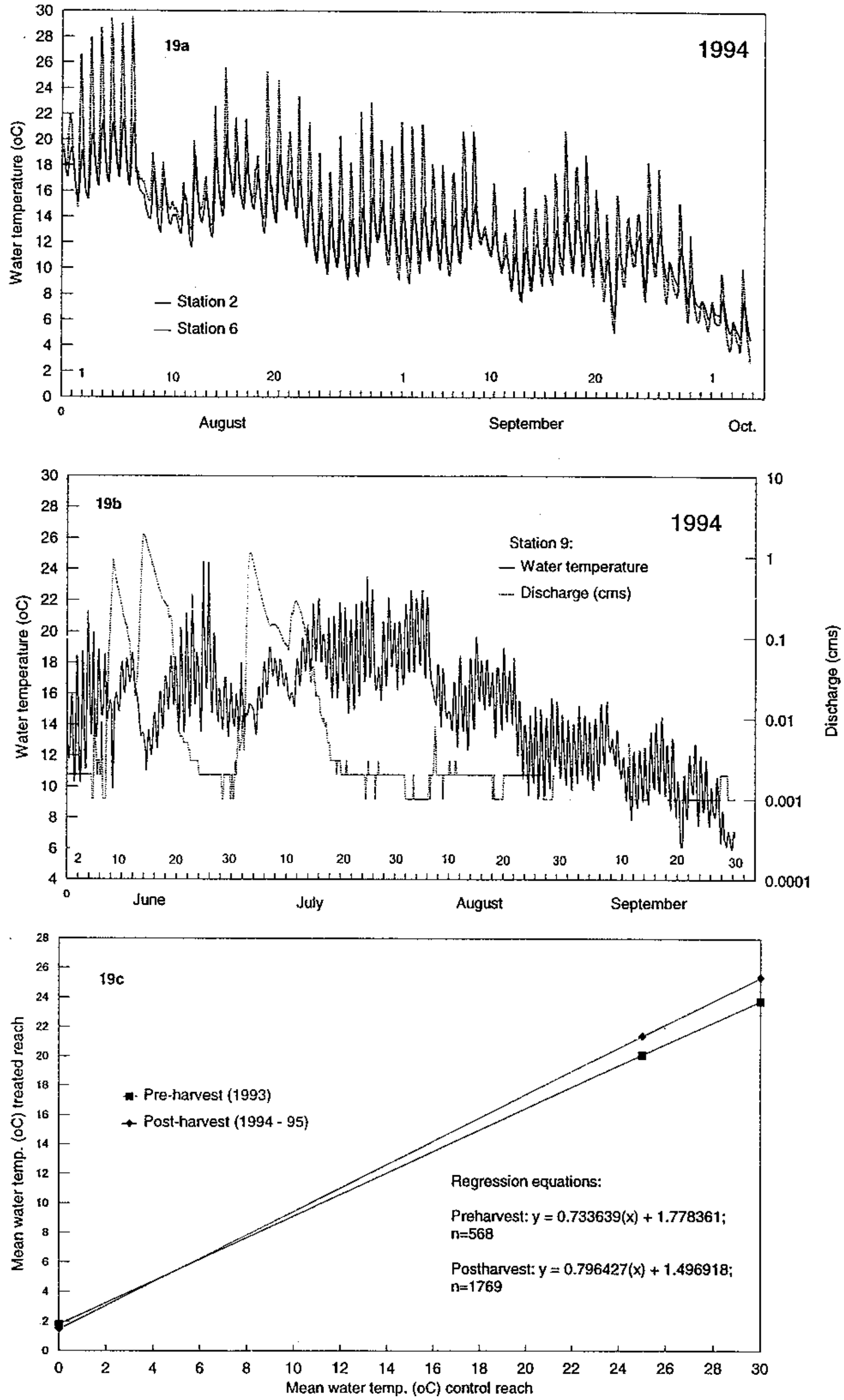


Figure 19. Graphs showing a) comparison between water temperatures at an open site (station 2) and a protected site (station 6), b) the influence of stormflow on water temperature, and c) regressions of control reach water temperatures versus treated reach water temperatures for the preharvest (1993) and the postharvest (1994-95) periods.

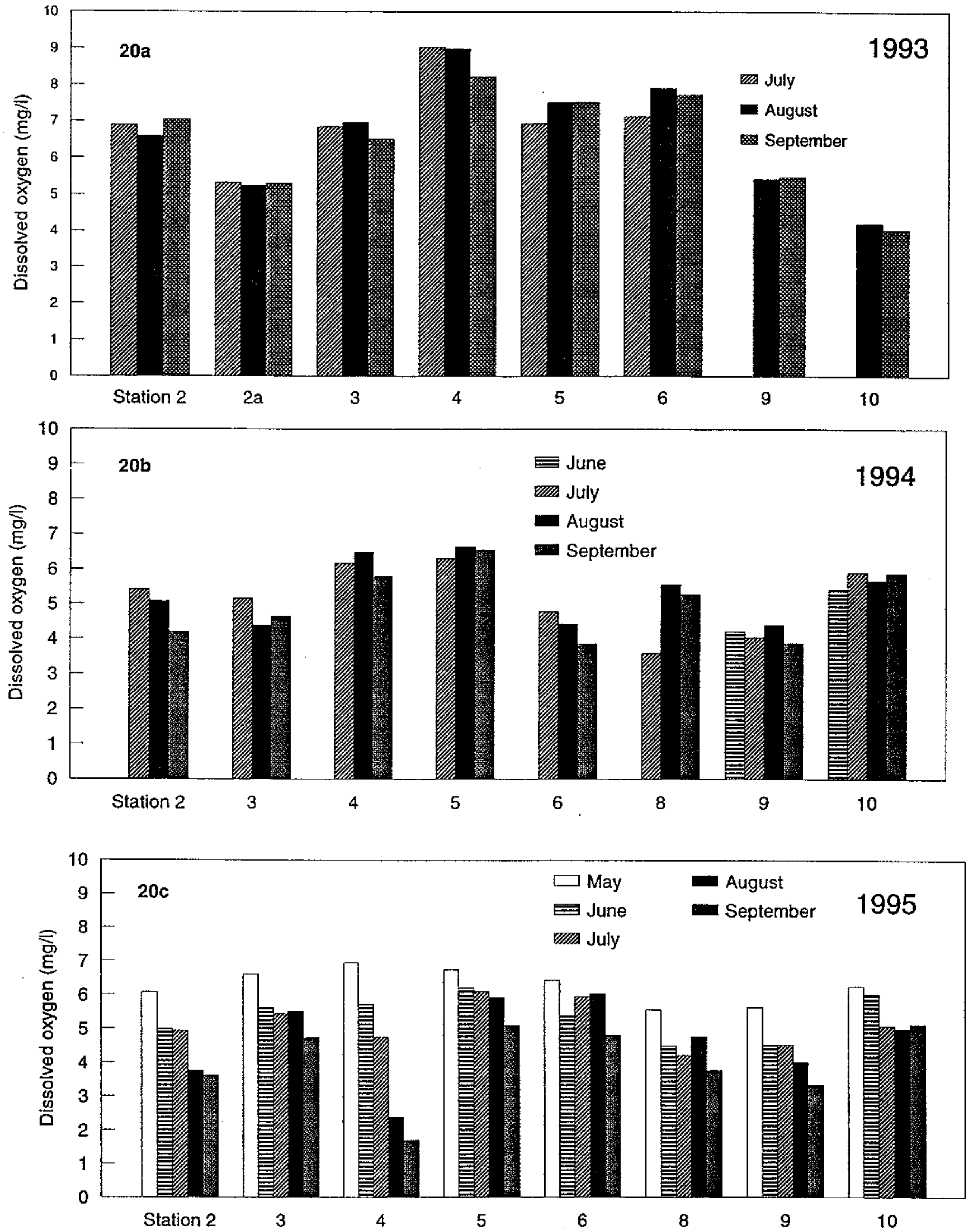


Figure 20. Dissolved oxygen profiles for Rocky Creek.

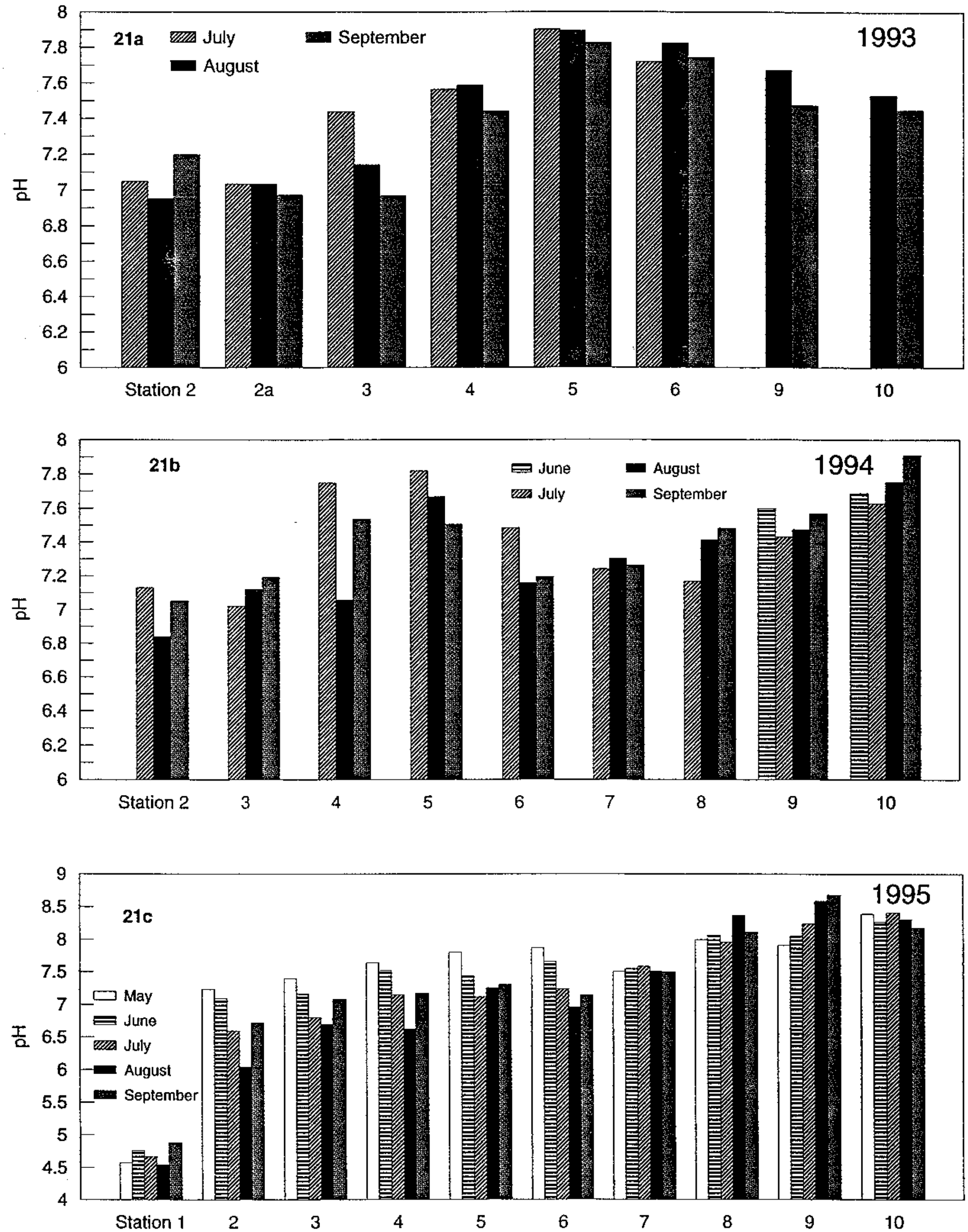


Figure 21. Water pH profiles for Rocky Creek.

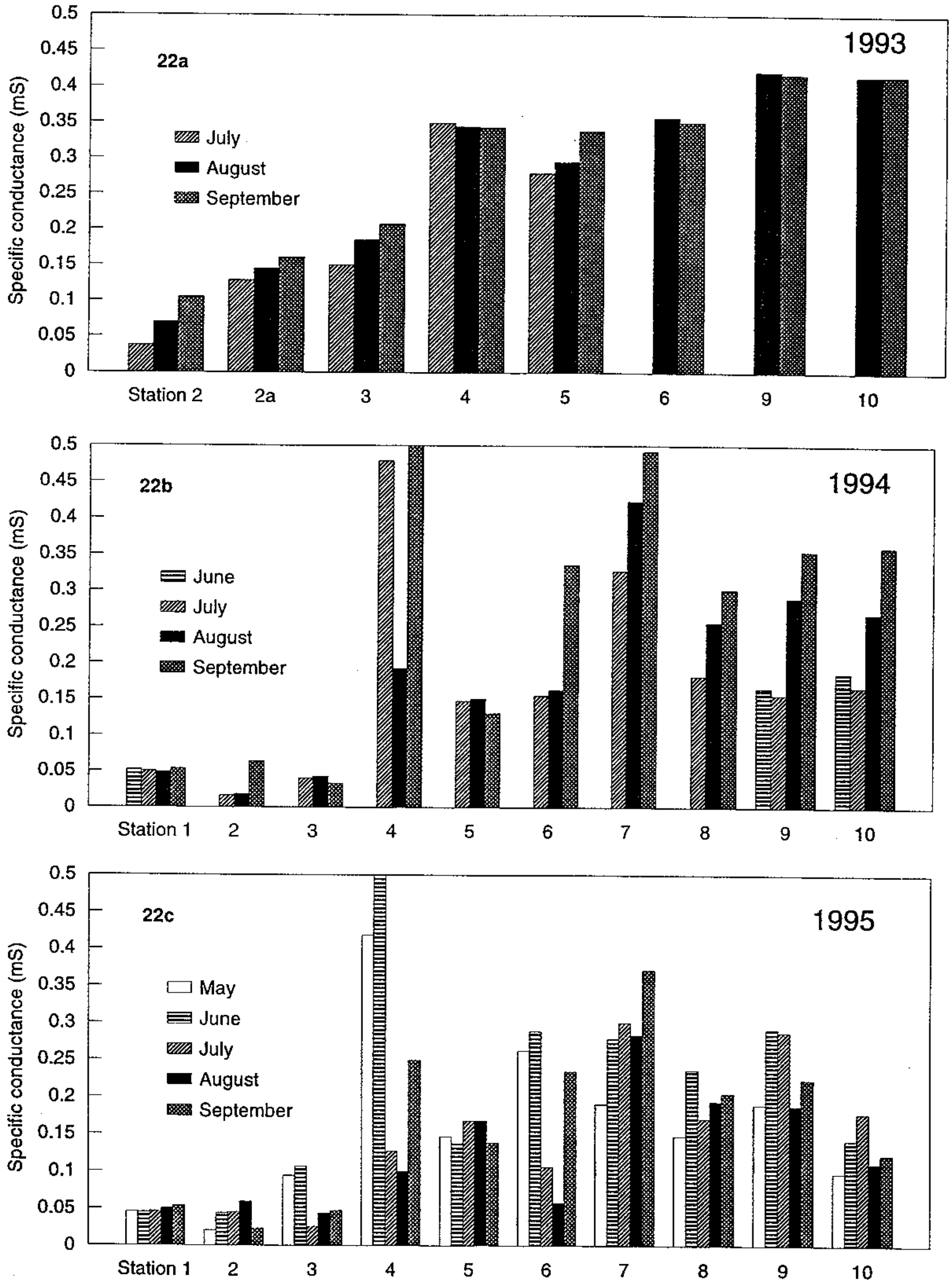


Figure 22. Specific conductance profiles for Rocky Creek.

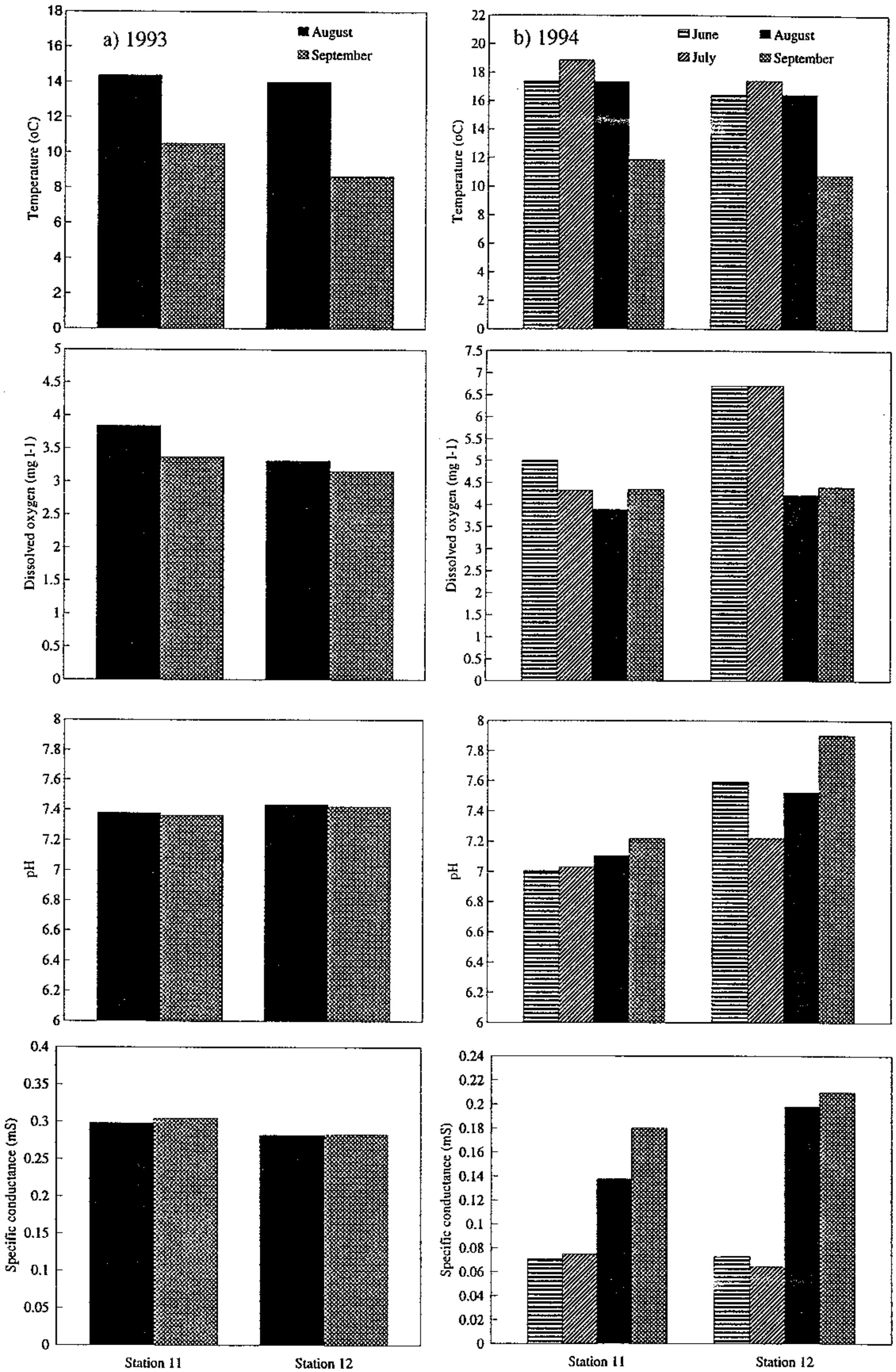


Figure 23. Comparisons of four water quality variables upstream (station 11) and downstream (station 12) from the road on Bridlebit Creek.

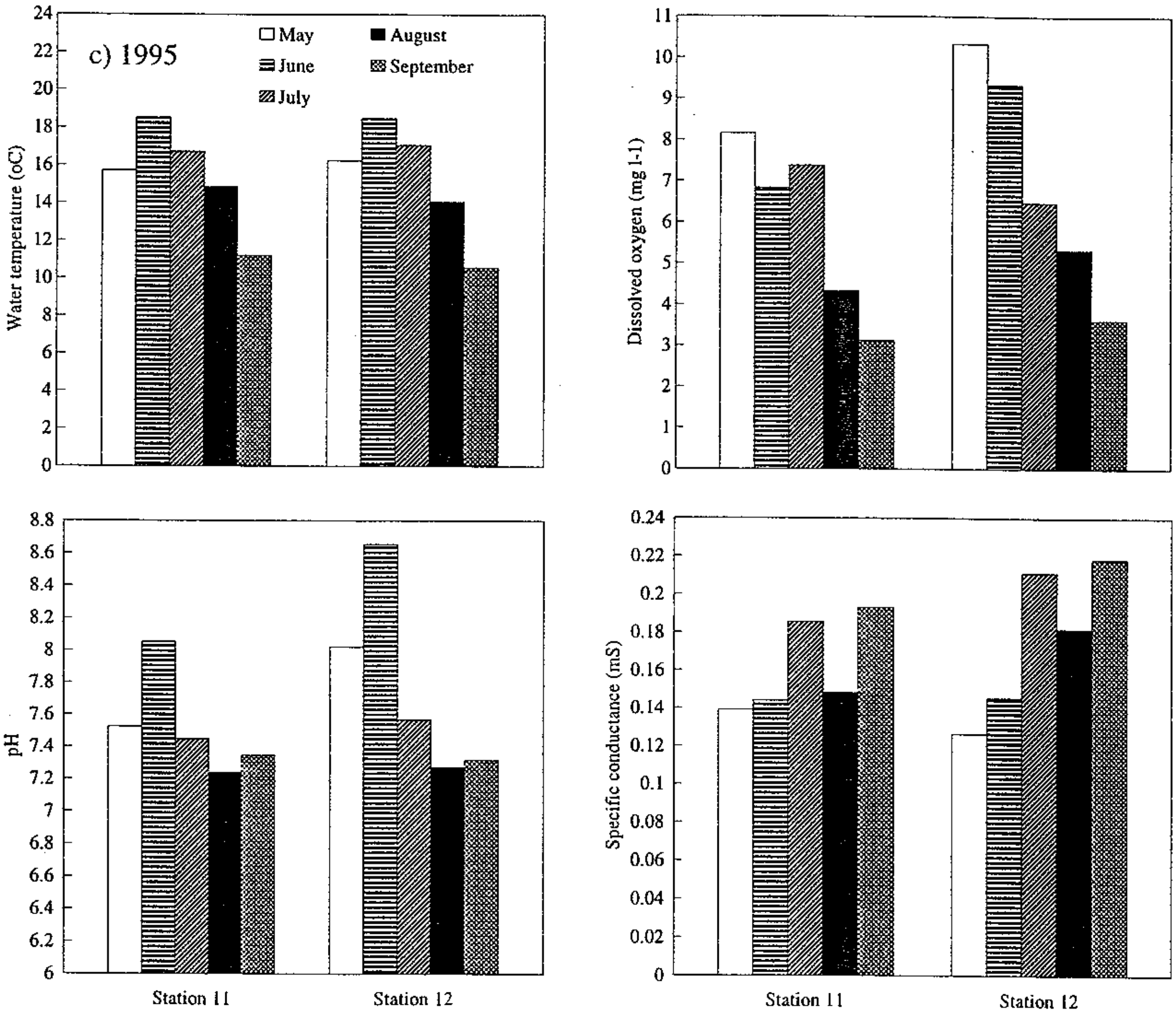


Figure 23. Comparisons of four water quality variables upstream (station 11) and downstream (station 12) from the road on Bridlebit Creek.