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OBSERVATIONS ON THE DISPERSAL OF SALINE GROUNDWATER IN THE BEAVER CREEK DIVERSION SYSTEM, 1976-1978

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FOREWORD

Syncrude Canada Ltd. is producing synthetic crude oil from a surface mine on the eastern portion of Crown Lease 17, Alberta. This study was commissioned to describe the dispersal of saline groundwater in the Beaver Creek Diversion System.

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ABSTRACT

The dispersal of saline groundwater in the Beaver Creek Diversion System is described using data from a two-year physical limnology monitor of the system. Emphasis is placed on processes influencing temporal and spatial patterns in circulation, stratification and saline water distributions.

Owing to its density, the high salinity effluent tends to sink upon entering the reservoir, thus setting up vertical stratification. Wind mixing during the ice-free season is effective only to depths of 4-5 m so that impondment occurs in the deepest portions of the system; however, convective processes in spring and autumn effectively mix the entire water column. Annual variations in salinity and chlorinity are strongly coupled to pumping operations, which increase concentrations, and natural streamflows which decrease concentrations. Overall salt and chloride ion concentrations are highest in Beaver Creek Basin, where effluent enters the system, and progressively decrease toward Spillway Basin where the reservoir's outflow enters Poplar Creek.

The time-dependent behaviour of the system is further examined using both a mass budget approach and a 'filling-box' numerical model. Results from these calculations, combined with the field observations, show that the effectiveness of the reservoir as a means of mine effluent disposal is strongly dependent upon the seasonality of natural streamflows. Furthermore, inter-annual variations in flow may be sufficiently large to offset any long term trends. Thus far, disposal operations have not significantly degraded the quality of the reservoir in terms of chloride concentrations.

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1. INTRODUCTION

The Beaver Creek Reservoir near Mildred Lake, Alberta (Figure 1) was built in 1975 by Syncrude Canada Ltd. as a means of diverting the natural steamflow of Beaver Creek away from the mine and plant areas. This was accomplished by laying a 3 km long earthfill dam across Beaver Creek south of the mine site and re-channelling the flow southward to the Athabasca River via Poplar Creek. Later, when it became operationally necessary to remove chloride-rich groundwater from the mine, Syncrude was granted permission to discharge this effluent into the diversion system, providing chloride levels in the water entering Poplar Creek did not exceed 400 ppm above ambient.

Two environmental concerns are associated with this method of disposal. First, as stated above, the chlorinity of water leaving the reservoir must remain below 400 ppm above ambient. Second, chlorinity levels within the reservoir must remain below the tolerance level of established aquatic life. The latter cirterion is important in that the diversion system is a highly productive freshwater biological community.

Prior to the commencement of disposal into Beaver Creek Reservoir, the Environmental Affairs Department of Syncrude Canada Ltd. commissioned an independent study (Carmack, 1976) to describe the morphometric and hydraulic characteristics of the reservoir and to project chloride concentrations in the system. In that study it was concluded that chlorinity levels within the system would likely remain well below tolerance levels; however, owing to possible local build-ups resulting from salt stratification and seasonality effects (i.e. variations in streamflow, mine water discharge, ice formation, etc.), an on-going field surveillance program was recommended.

Mine effluent was first pumped into Beaver Creek Reservoir late in 1976 and the disposal program became fully operational in spring, 1977.

Concurrently, a physical limnology program consisting of monthly monitors (cf. Section 2) was initiated by M. Aleksiuk, Section Head, Aquatic Environments, and his associates.

The present study reports on the findings of data obtained over a two-year period of saline groundwater disposal and field surveillance. Our present objectives are:

1. Evaluate the suitability of the original experimental design and the apparent quality of the field data (Section 2).
2. Summarize observations of flow rates and characteristics of inflow/outflow waters during the study period (Section 3.1).
3. Describe seasonal trends in the vertical distribution of temperature, salinity and chlorinity with particular reference to saline groundwater dispersion (Section 3.2).
4. Examine the general features of stratification and circulation in the major basins of the system with a view toward vertical and lateral heterogeneities (Section 3.3).
5. Formulate and test the feasibility of a chloride mass balance for Beaver Creek Basin (Section 4).
6. Design and verify a predictive numerical model of the time-dependent distributions of temperature, salinity and chlorinity for the major basins of the Beaver Creek Diversion (Section 5).

2. STUDY AREA AND METHODS

2.1 Area Description

The bathymetry of the Beaver Creek Diversion System (Figure 1) was compiled from existing topographic maps of the area prior to flooding (Carmack, 1976). The system consists of three intergrading basins designated Beaver Creek Basin, Ruth Lake Basin, and Spillway Basin. Within Beaver Creek Basin the lake bottom is smooth and gently sloping except where cut by the pre-impoundment Beaver Creek stream channel where depths reach approximately 12 m. Beaver Creek Basin connects to Ruth Lake Basin via a dredged channel 15-30 m wide and 20-50 cm deep. The Ruth Lake Basin floor is uniformly smooth and shallow with a maximum depth of about 3 m. Ruth Lake Basin intergrades to Spillway Basin through a channel and then a shallow muskeg swamp. Spillway Basin, at the extreme southeastern end of the diversion system, exhibits a pronounced bottom slope and a maximum depth of almost 20 m. This basin is further divided by a road causeway mid-way along its length which effects an apparent sill depth (cf. Section 3.3) of approximately 6 m. Finally, water leaves the system at Spillway Dam by passing over a stationary weir and along a 200 m long concrete spillway (vertical drop of 60 m) where it subsequently enters Poplar Creek.

Mine effluent enters the system at the north end of Beaver Creek Basin. Here the effluent is pumped over the dam from a shallow holding pond into the reservoir. Pumping is carried out intermittently throughout the ice-free season.

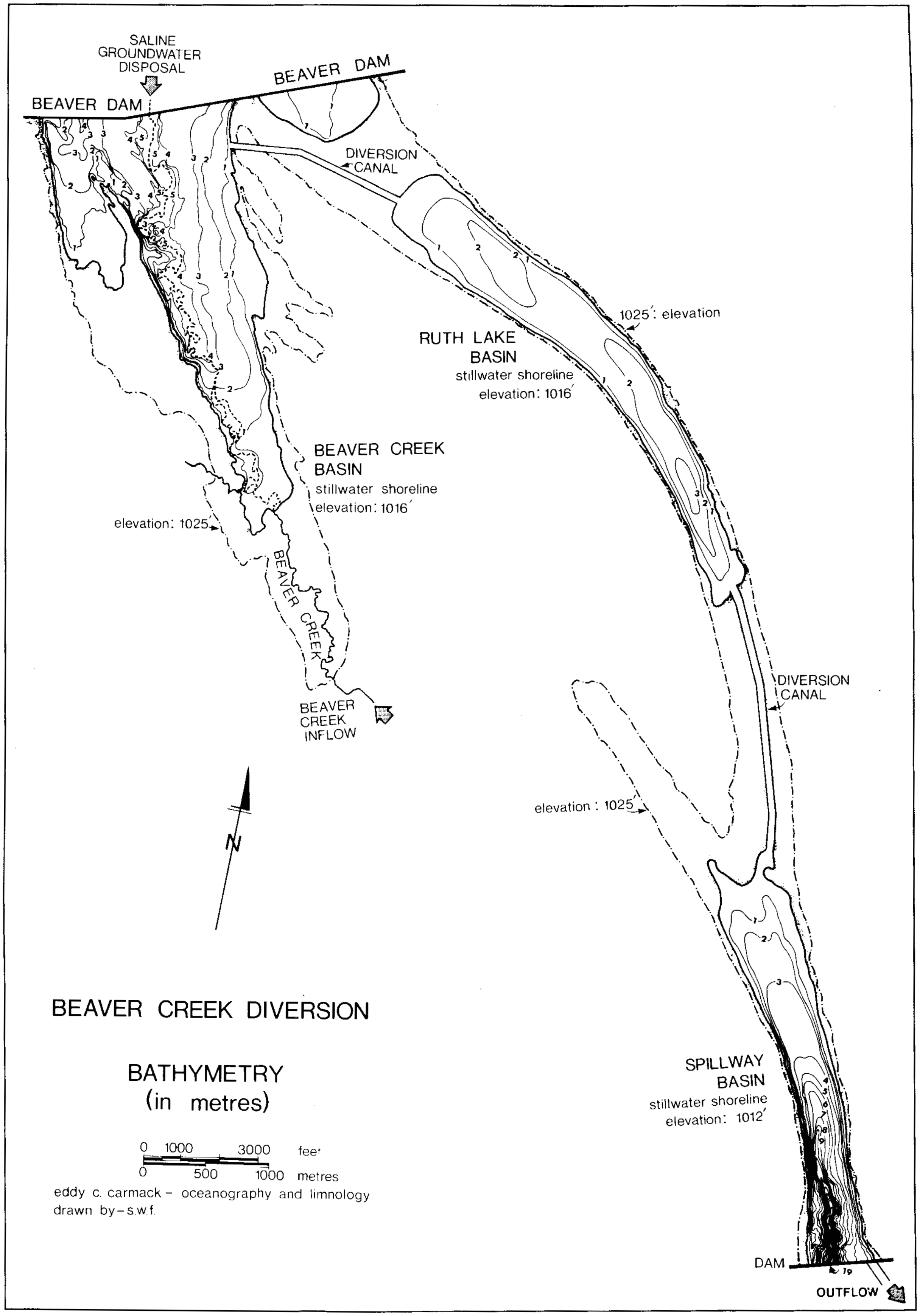


Figure 1. Bathymetry of Beaver Creek Reservoir.

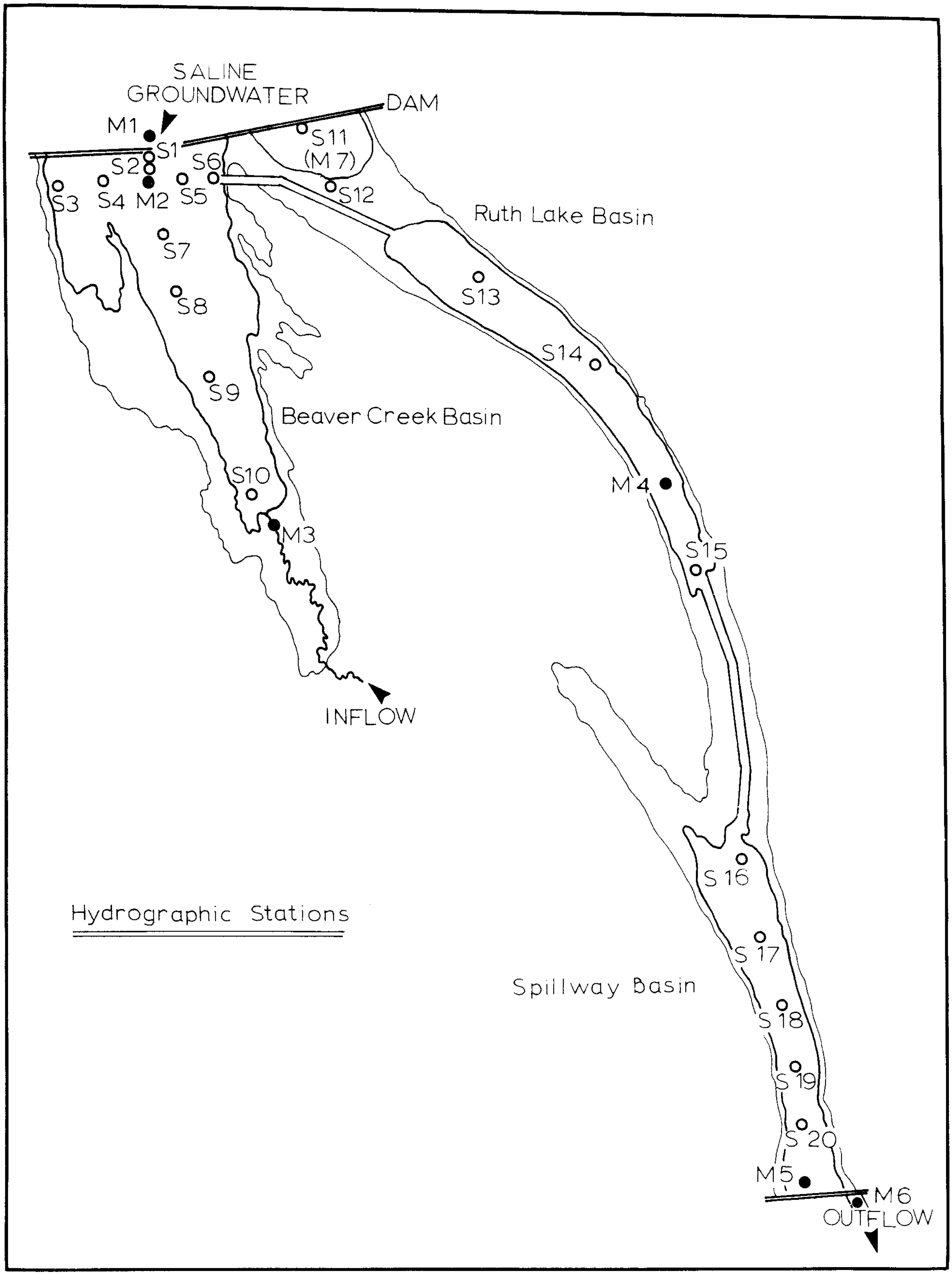
The morphometric properties of Beaver Creek Reservoir are listed in Table 1. From the viewpoint of saline groundwater disposal, the most important characteristics here are the volumes of water contained in each component of the diversion system. The total volume is approximately 11.6 x 10^6 m^3; of this volume, Beaver Creek Basin contains 42%, Ruth Lake Basin contains 16% and Spillway Basin holds 42%. Furthermore, the very shallow mean depth of the system ($\bar{z} \simeq 2$ m) suggests that most of this water volume may be easily and rapidly stirred by the wind. However, hypsographic curves for the system (cf. Carmack, 1976) are characterized by a sharp break in curvature at 3-5 m depth with approximately 10% of the water volume occurring below this depth within the flood stream channels of Beaver Creek and Spillway Basins. This latter volume of water would be expected to be especially susceptible to salt stratification during disposal operations.

2.2 Experimental Design

Following the recommendations laid out in Carmack (1976), a surveillance network of six master and twenty slave sampling stations were established on Beaver Creek Reservoir (Figure 2). Field sampling for this study commenced on 13 December 1976 and continued until 18 October 1978 at approximately one-month intervals between sampling cruises (Table 2). At each station, *in situ* profiles of temperature, conductivity (standardized to 25°C, or C_{25}) and dissolved oxygen were obtained at one-metre depth intervals. In addition, water samples were obtained at one-metre depth intervals at master stations; these were subsequently analyzed for the major ions: Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, and Cl^-, by Syncrude Operations Laboratory. The sum of these ions (ΣI in ppm) is taken as a measure of water salinity (cf. Wetzel, 1975).

Table 1. Morphometry of the Beaver Creek Diversion.

Property	Beaver Creek	Ruth Lake	Spillway	Total System
Elevation (ft)	1016	1016	1012	
Length (km)	3.4	3.8	3.3	
Area (km^2)	2.20	1.50	1.40	5.10
Volume ($x\ 10^6\ m^3$)	4.9	1.8	4.9	11.6
Mean Depth (m)	2.2	1.2	3.5	2.3
Maximum Depth (m)	≃10	≃3	≃18	≃18



2: Locations of hydrographic stations.

Table 2. Sampling history of surveillance cruises during the study period. Numbers interior to the table indicate maximum depth (m). The letter F indicates that the water column at this time was frozen to the bottom. Blank spaces indicate no sample was taken.

		1977													1978											
		13 DEC	18 JAN	1-3 MAR	12-14 APR	2-5 MAY	18-19 MAY	7-9 JUN	22-24 JUN	5-6 JUL	2-5 AUG	6-9 SEP	3-7 OCT	11 NOV	19-30 JAN	27-28 FEB	20-22 MAR	17-19 APR	23-29 MAY	19-21 JUN	17-20 JUL	18-23 AUG	18-20 SEP	16-18 OCT	Total Number	Mean Depth
Beaver Creek	M1	2	2	2		2	2	1	<1	<1	<1	<1	1	<1	1	2	1	1	<1	<1	<1	<1	1	1	22	1
	M2	10	10	10	10	10	10	9	9	9	7	9	9		9	9	9	9	9	10	9	10	7	6	222	9
	M3	2	2	2	2	2	2	1	1	9	1	1	1	1	1	1	1	1	1	1	1	2	2	1	23	1
	S1	5	5		5	5	5	6	4	5	2	2	6		9	9	9	9	10	9	8	10	7	8	21	6
	S2	9	10		8	8	6	6	11	8	9	9	9		9	10	10	10	7	7	10	10	10	8	21	9
	S3	3	3		3	3	3	2	2	1	1	1	1		1	1	1	1	3	2	2	2	1	2	21	2
	S4	3	3		3	3	2	2	2	2	2	1	2		2	3	2	2	3	3	3	3	3	3	21	2
	S5	3	3		3	3	2	2	2	2	2	2	2		1	2	2	2	2	3	2	2	3	3	21	2
	S6	2	2		1	1	1	1	1	1	1	<1	1	<1	1	1	1	1	1	1	1	1	2	<1	22	1
	S7	9	10		10	9	8	6	9	8	7	6	8		5	5	5	5	6	8	7	4	7	8	21	7
	S8	8	8		8	6	4	6	7	8	4	6	7		6	5	5	5	6	7	8	7	7	6	21	6
	S9	6	6		6	7	7	6	6	6	6	3	6		4	4	4	4	4	5	5	5	4	6	21	5
	S10	4	4		4	4	3	3	7	4	3	1	3	3	2	2	2	1	2	5	4	4	3	3	22	3
Ruth Lake	M4	2	2	2		2	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	2	2	1	21	1
	M7							<1	1	<1	<1	<1	<1	<1	F	F	F	1							8	1
	S11	2	1			1	1	<1	<1	<1	<1		<1	<1	F	F	F	F	1	<1			1		13	1
	S12	1	1			1	1	1	<1	1		<1	<1	<1	F	F	F	F	1	<1	<1	<1	1	<1	16	1
	S13	2	1			2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	11	1	2	21	1
	S14	2	2			2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2	21	1
	S15	1	1			1	1	1	<1	1	<1	<1	<1	<1	1		1	1	1	1		1	1	1	19	1
Spillway	M5	7	7	7		13	13	13	12	12	15	15	14		13	13	13		17	16	17	18	17	16	20	13
	M6	1	2			1	1	1	<1	<1	<1	<1	<1	<1	1	1	>1	1	<1	<1	1	1	1	<1	21	1
	S16	2	1			1	1	1	1	1	1	1	1		F	1	F		1	1	1	1	1	1	16	1
	S17	3	3			6	6	6	5	6	6	6	8		5	5	5		3	3	3	3	3	2	19	5
	S18	7	7			7	7	7	7	7	7	7	9		7	7	7		10	10	10	10	10	10	19	8
	S19	7	7			7	7	7	7	7	7	7	10		5	6	6		11	11	10	10	10	9	19	8
	S20	7	6			11	13	11	10	11	12	12	10		11	11	11		15	14	14	14	13	12	19	11

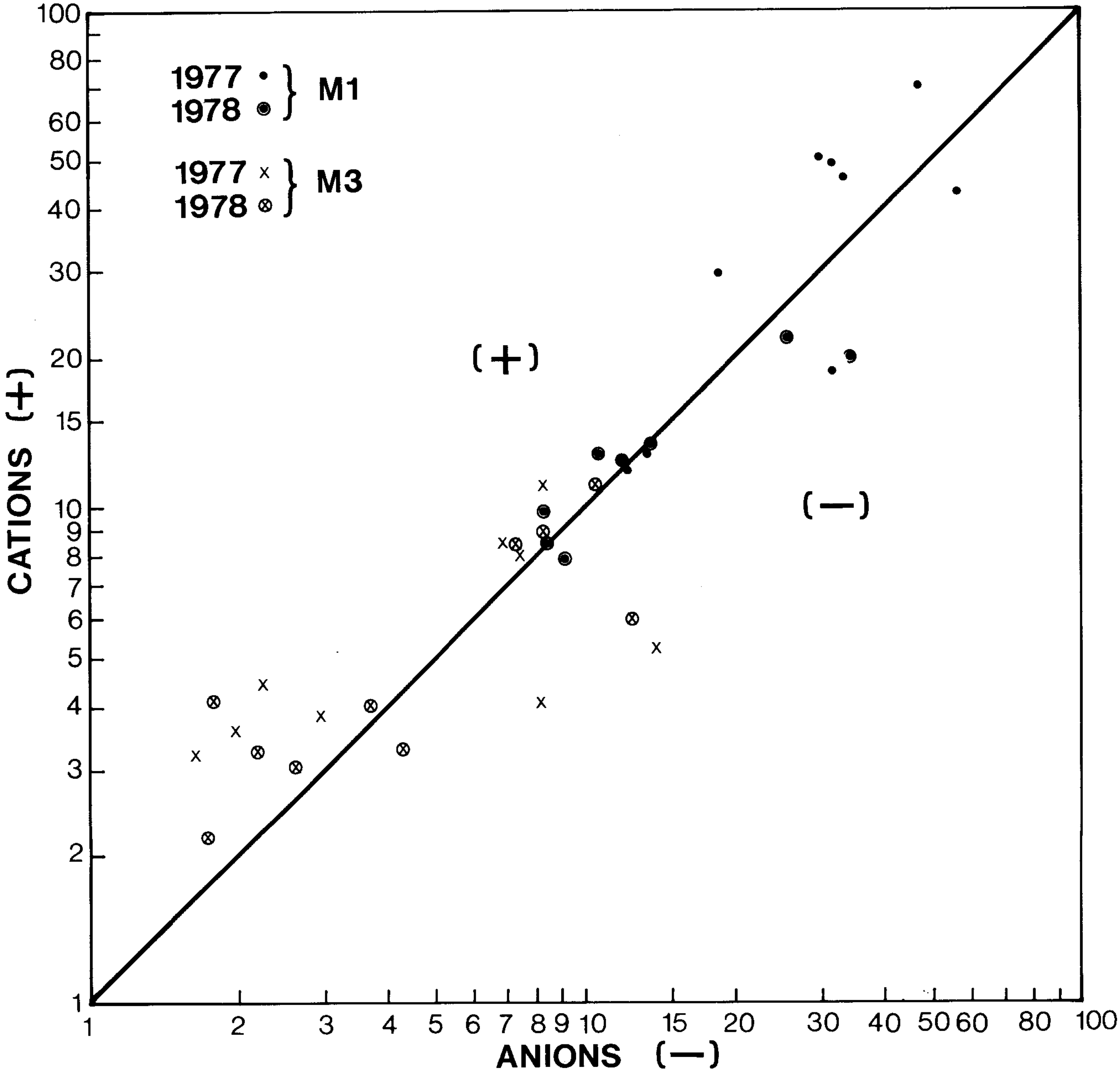
The rationale behind the above experimental design lies in the fact that conductivity/temperature/depth (CTD) profiles are relatively quick and easy to obtain, whereas water sample measurements require considerable field and laboratory time. Initially it was hoped that by establishing the $C/\Sigma I$ proportionality at a small number of master stations, this relation-

2.3 Evaluation of Salinity Data

Salinity. Wetzel (1975) notes that the total salinity of inland waters is usually dominated by four major cations, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) and by three major anions, bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), and chloride (Cl^-). In some systems other ions (i.e. nitrate; cf. Hutchinson, 1957) may be important. However, baseline water quality measurements by Syncrude Canada Ltd. support the assumption that the sum of the above seven ions (ΣI) is a good measure of total salinity. In most inland waters,the proportion of major ions tends toward $Ca^{2+} > Mg^{2+} > Na^+ > K$, and $HCO_3^- > SO_4^{2-} > Cl^-$; in water of marine origin these ratios are biased toward higher Na^+ and Cl^- concentrations.

A means of testing the above assumption while at the same time checking the quality of the laboratory analysis is by comparing the proportions of cations to anions expressed as equivalents per litre. Assuming ionic equilibrium in the system, a balance should result. If one charge typically out-weighs the other (i.e. $\Sigma(+) > \Sigma(-)$), a "missing" constituent is suggested. If a random discrepancy is apparent, then technical error is suspected.

The results of this comparison for both Beaver Creek inflow water (M3) and mine water (M1) are shown on a log-log plot in Figure 3. (Note: log-log plots are useful in displaying data over a wide range in parametric values; they are also often used to cosmetically represent data that have much scatter.) Even on a log-log plot, the present data base shows a disappointing degree of scatter. Most often (≃70%), the equivalent proportion of cations out-weighs that of the anions. Although the data is probably sufficient to indicate trends, it will be difficult to derive firm conclusions from individual measurements.



3: Correlation diagram showing the equivalent proportions of cations ($\Sigma(+)$) and anions ($\Sigma(-)$) in mine water (M1) and Beaver Creek (M3) water samples.

Conductivity-25 vs Salinity. The results of this comparison are shown on the log-log plot in Figure 4. Only the 1978 data are used in this comparison for reasons mentioned earlier. Again, the correlation is sufficient to indicate trends, but is lacking in precision. A linear least-squares fit to this data yielded the following regression:

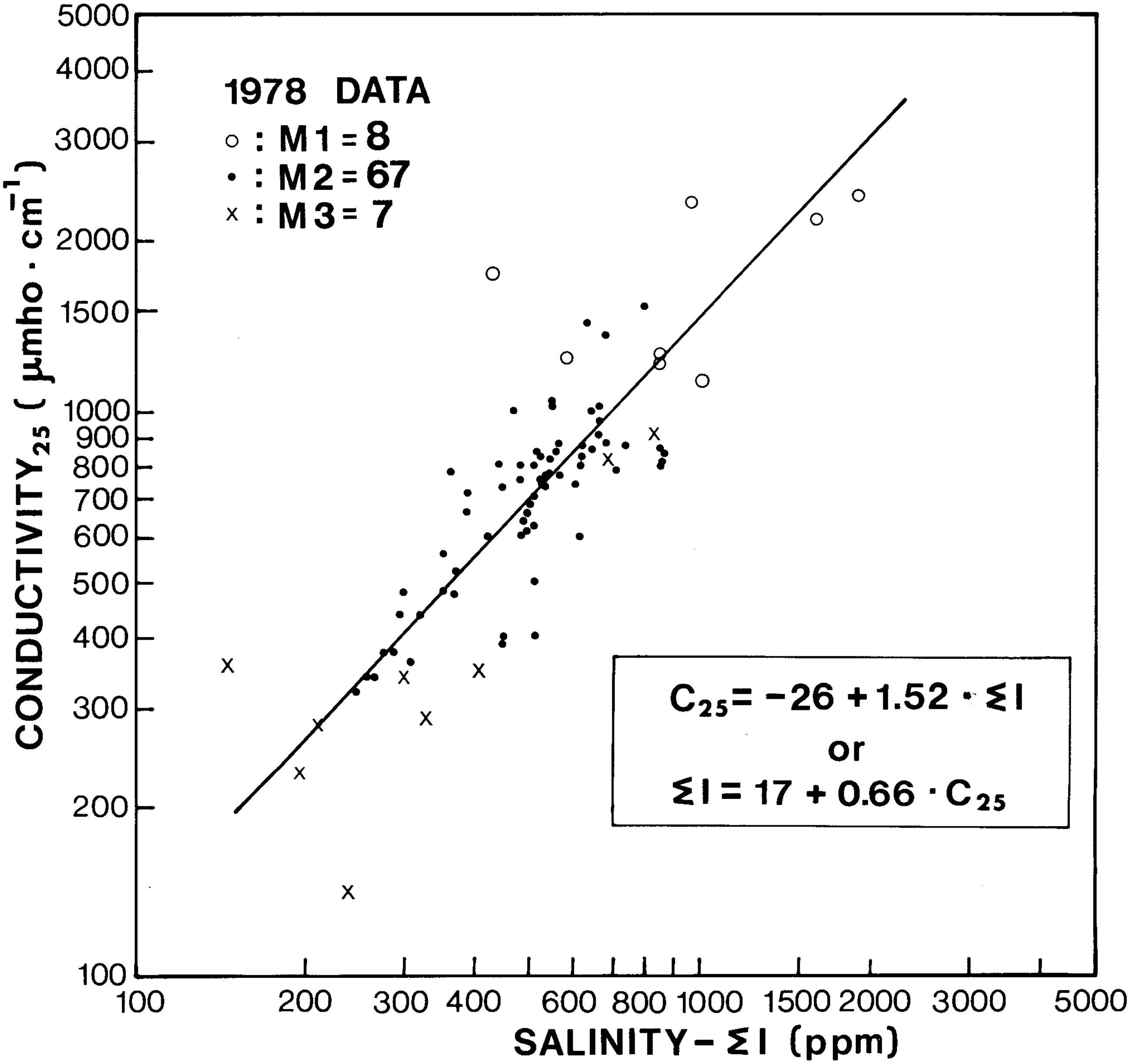
$$\Sigma I(\text{ppm}) \simeq 20 + 0.66[C_{25}(\mu\text{mho cm}^{-1}0)].$$

The r^2 term for this fit is rather high, above 0.9; however, over small intervals, one's confidence is much reduced. For example, in Figure 4 a conductivity reading of 800 μmho cm^{-1} may correspond to salinity values ranging from 360 to 800 ppm. This variance may be due to (a) variations in the ion composition of individual water samples; (b) difficulties in obtaining water samples at the exact depth of the corresponding conductivity reading; (c) probe response time problems; or (d) improper instrument calibration. It was noted, however, that $C_{25}/\Sigma I$ correlations from individual monitors typically faired better. Hence, conductivity may be used as an indicator of total salinity on individual monitors but is less reliable for interseasonal comparisons. Again, data obtained by the Montedoro-Whitney machine must be viewed with caution.

In summary, a high conductivity reading is a good indication of high salinity values; whether or not a particular sample is rich in chloride, however, must be verified by sample collection and laboratory analysis.

2.4 Water Mass Identification

Despite the technical short-comings outlined in Section 2.3, the ionic concentration measurements offer a tool for estimating the percentage composition of mine water in any given water sample by using the triangle diagram method (cf. Hutchinson, 1957). Assume that the two principal water



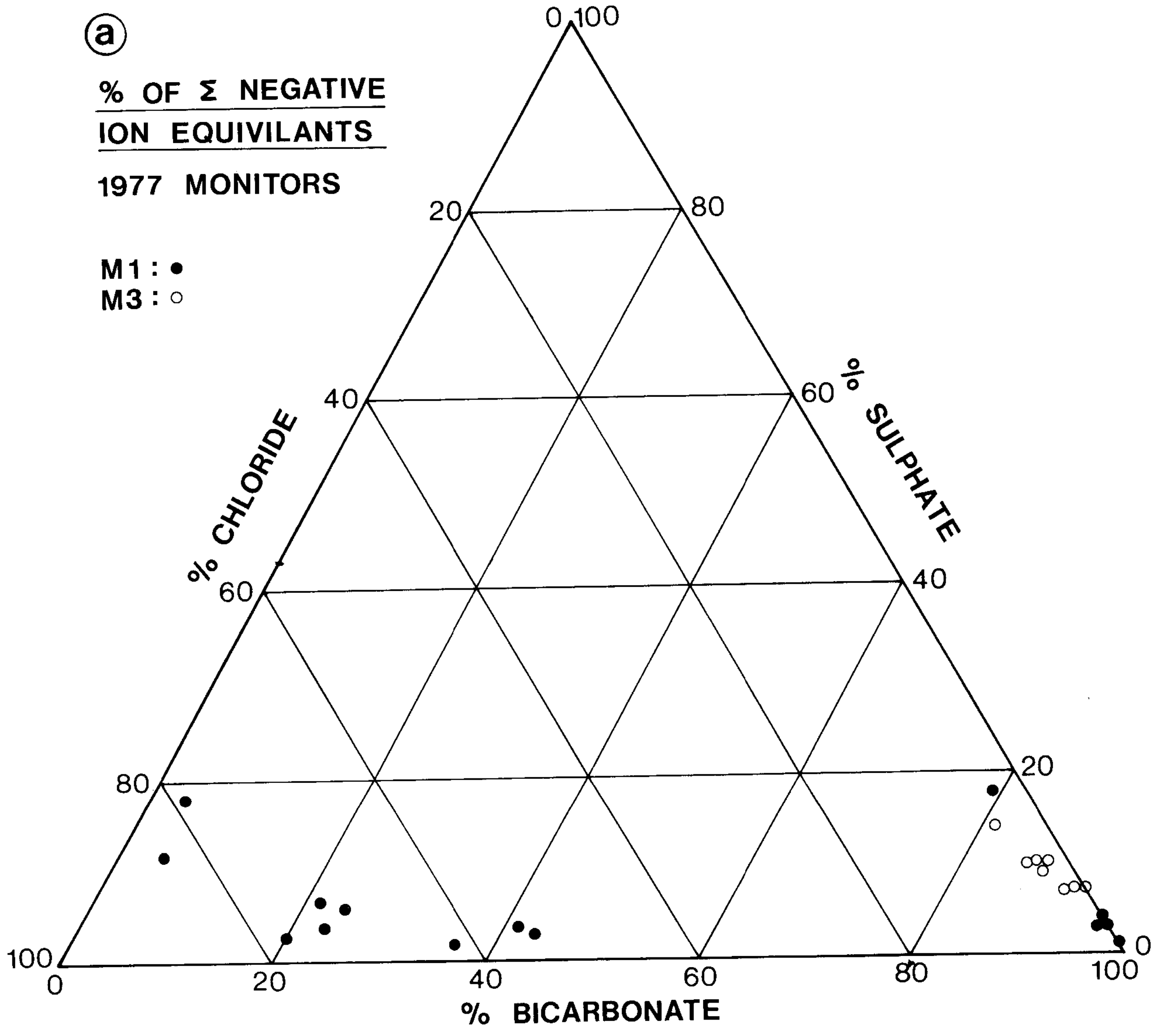
4: Correlation diagram of conductivity-25 versus total salinity at Station M2 in 1978.

types entering the diversion system are Beaver Creek water and mine saline groundwater. Our problem, then, is to derive a general method of identifying the parent water type (or mixture) of any given water sample obtained from the reservoir (cf. Boyle et al, 1974). This is complicated by the fact that the ionic concentrations of both parent water types vary with time. However, when expressed in terms of equivalents per litre, saline groundwater has an (anion) proportional distribution typical of seawater (i.e. rich in Cl^-), whereas Beaver Creek water has proportions typical of inland waters (i.e. rich in HCO_3^-). When plotted on a triangle diagram the two water types are distinct, regardless of total salinity. On the other hand, this methodology cannot be used to distinguish between saline groundwater pumped into the system and that entering via seepage.

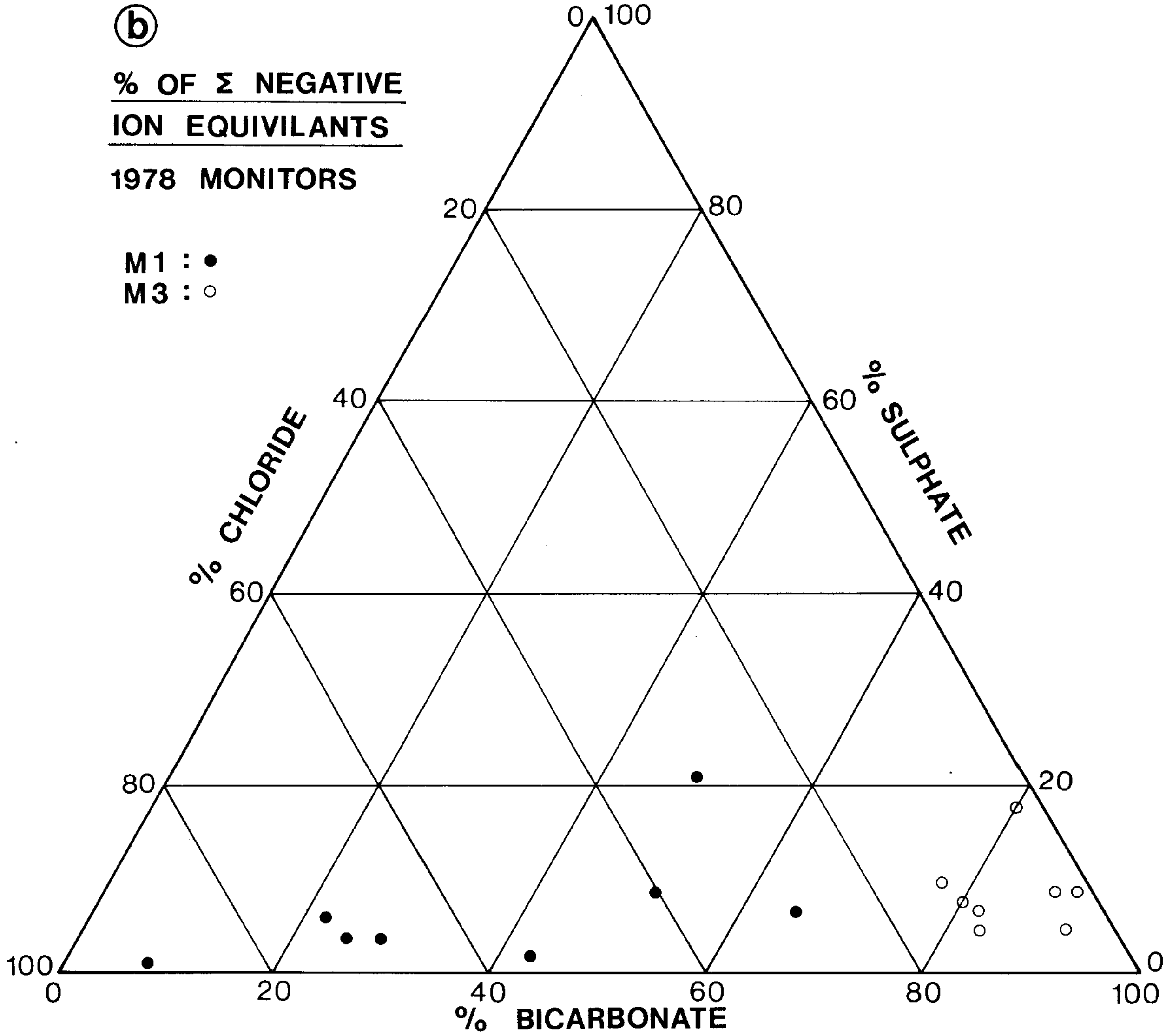
Results of this comparison are illustrated in Figures 5a,b for 1977 and 1978, respectively. Beaver Creek water (Station M3) occupies the lower right-hand (HCO_3^-) corner of the diagrams, while saline groundwater (Station M1) tends toward the lower left-hand (Cl^-) corner. The mine effluent data points would probably fit even more tightly into the lower right-hand (Cl^-) corner if this water were not diluted by surface runoff in the holding pond.

The important point here is that this identification method is largely independent of year and season. It follows that the percentage composition of any water sample within the reservoir can be estimated from its position relative to a straight line joining the mean positions of the two input water types. Later in this report, we will simplify this concept and use the ratio $Cl^-/\Sigma I$ as a rough indicator of the relative concentration of mine effluent in a given water sample.

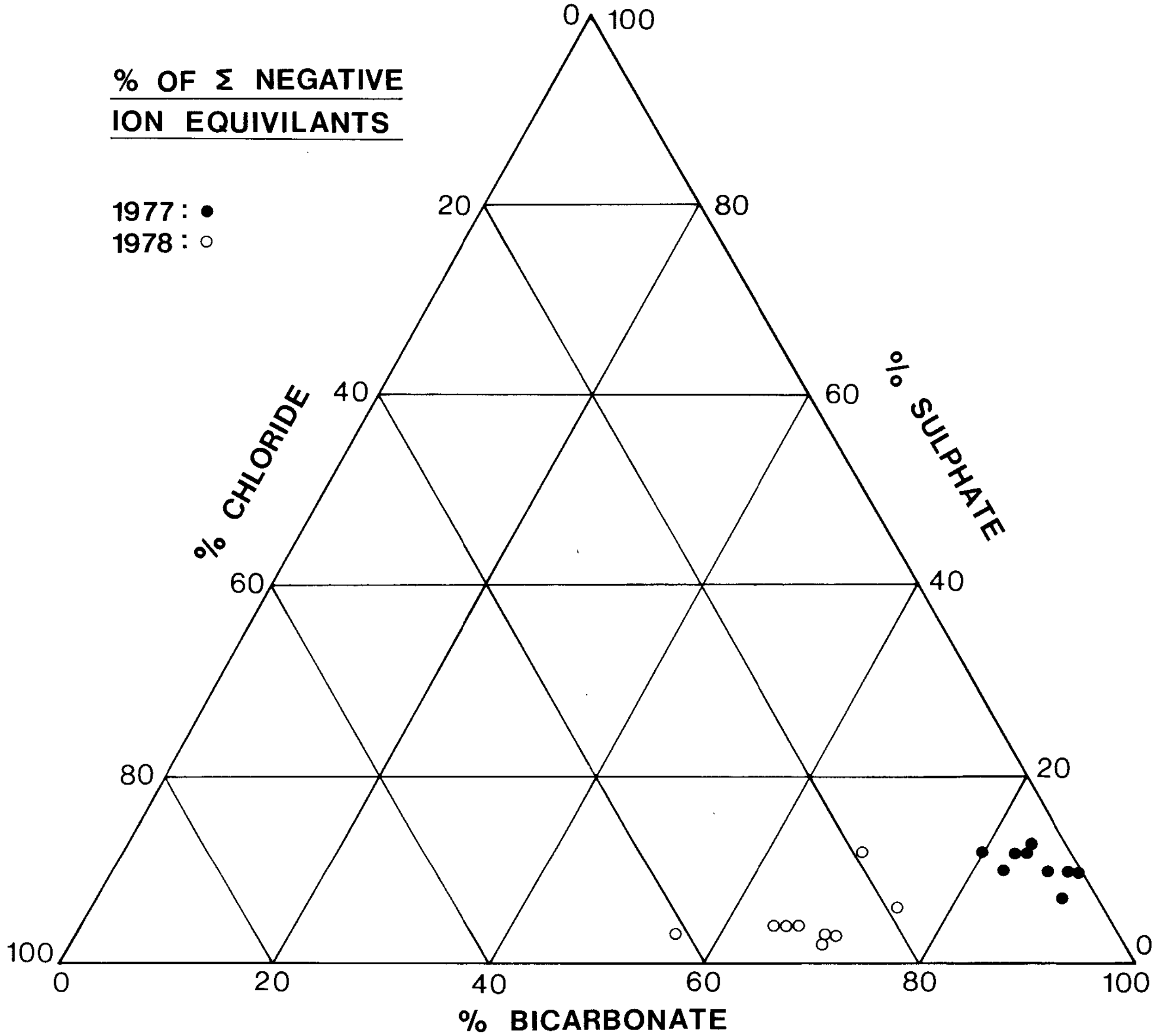
Before leaving this topic, it is instructive to examine the water mass characteristics of water leaving the reservoir. Figure 6 shows a triangle diagram representation for the outflow water (Station M6). All 1977 values



5: Triangle diagrams for the equivalent proportions of chloride, bicarbonate, and sulphate in mine water (M1) and Beaver Creek (M3) water samples for (a) 1977 and (b) 1978.



b
% OF Σ NEGATIVE
ION EQUIVILANTS
1978 MONITORS
M1 : ●
M3 : ○
% CHLORIDE
% SULPHATE
% BICARBONATE
0
100
20
80
40
60
60
40
80
20
100
0
0
20
40
60
80
100



6: Triangle diagram for the equivalent proportions of chloride, bicarbonate and sulphate in outflow water (M6).

are observed to cluster very tightly into the HCO_3^- corner suggesting very little saline groundwater in the outflow. In 1978, the outflow water showed a displacement toward higher chloride proportions, probably due to pumping operations and natural seepage into the system. Still, the percentage of saline groundwater in water leaving the system in 1978 is small, suggesting that the reservoir acts as a fairly effective mechanism for the dilution of saline groundwater.

3. OBSERVATIONS

3.1 Inflow/Outflow Characteristics

Flow. The mean monthly flow rates of Beaver Creek inflow, saline groundwater discharge, and outflow (i.e. Beaver Creek plus mine water discharge) are listed in Table 3. The latter calculation assumes no significant tributary streams enter the system, groundwater seepage and storage are negligible, and rainfall is locally balanced by evaporation: a more complete discussion of regional hydrology is given by Coward and Crawford (1977). In general, the natural flows are high in summer and low in winter. Interannual variations in streamflow, however, are very large : not only are the hydrographs for 1977 and 1978 widely divergent from each other, they are both different from the mean hydrograph calculated for the period 1972-74 (cf. Carmack, 1976). Flow-through is the main mechanism of basin flushing, hence the effectiveness of the system as a means of diluting effluent on a year-to-year basis is strongly dependent on regional rainfall conditions. The year 1978, for example, was an abnormally wet year, and thus a particularly good year for saline groundwater disposal.

Table 3 also lists the hydraulic parameter, residence time, calculated as the time required to fill a water cavity for a given inflow rate. During disposal months (April-November), this parameter ranged from ≈140-680 days in 1977 and 32-930 days in 1978 (the 32-day value corresponds to the record-level runoff in September, 1978). The annual (i.e. disposal months) mean values are 304 and 270 days, respectively.

Table 4 summarizes the physical and chemical characteristics of the inflow (Beaver Creek and mine effluent) and outflow (to Poplar Creek) waters during the study years. Some seasonal trends in salinity and chlorinity are

Table 3. Monthly mean streamflow, mine discharge and bulk residence time. Beaver Creek streamflows are based on gauge measurements at Water Survey of Canada Station No. 07 DA 018.

1977

	Flow ($m^3 sec^{-1}$)			Residence Time (days)			
	Beaver Creek	Mine Water	Total	Beaver Creek	Ruth Lake	Spillway	Total
JAN	0		0	∞	∞	∞	∞
FEB	0		0	∞	∞	∞	∞
MAR	>0.01		>0.01	≃16 yrs	≃10 yrs	≃15 yrs	≃41 yrs
APR	0.82	0.15	0.97	59	37	58	154
MAY	1.12		1.12	51	32	50	133
JUN	0.98	0.02	1.00	57	36	56	149
JUL	0.46		0.46	124	78	122	325
AUG	0.41		0.41	139	88	138	364
SEP	0.23	0.04	0.27	211	133	209	553
OCT	0.32	0.04	0.36	158	100	157	415
NOV	0.19	0.03	0.22	258	163	257	679
DEC	0.06		0.06	949	598	941	≃7 yrs
1978							
JAN	0.03		0.03	≃5 yrs	≃3 yrs	≃5 yrs	≃14 yrs
FEB	>0.01		>0.01	≃16 yrs	≃10 yrs	≃15 yrs	≃41 yrs
MAR	0		0	∞	∞	∞	∞
APR	0.69		0.69	82	52	82	216
MAY	1.27	0.04	1.31	43	27	43	114
JUN	0.52	0.08	0.60	95	60	94	249
JUL	0.11	0.05	0.16	356	224	353	933
AUG	0.48	0.16	0.64	89	56	88	233
SEP	4.50	0.22	4.72	12	7	12	32
OCT	1.55	0.21	1.76	32	30	32	85
NOV							
DEC							

Table 4. Physical and Chemical Properties of Inflow and Outflow Water (Based on monthly surveys)

a) 1977

	Temperature (°C)			Conductivity-25			Salinity (ppm)			Chlorinity (ppm)		
	BC	MW	SW	BC	MW	SW	BC	MW	SW	BC	MW	SW
JAN	≈0	0.9	0.1	640	1100	320	588	877	254	4	140	14
FEB	≈0	0.5	0.4	-	-	-	-	-	-	-	-	-
MAR	≈0	0.6	0.8*	770	1150	320*	734	965	249*	6	157	14*
APR	0.5	-	-	305	-	-	236	-	-	6	-	-
MAY(2)	5.3	10.9	11.6	Q	Q	Q	192	1930	245	2	750	9
JUN(2)	16.8	20.4	20.0	210	2635	580	178	2090	285	>1	820	6
JUL	17.0	23.0	1919	210	2964	370	228	2398	283	1	760	14
AUG	17.5	19.6	17.7	Q	Q	Q	667	3809	618	1	950	13
SEP	9.7	16.1	13.4*	Q	Q	Q	607	4096	525	3	1500	26
OCT	7.4	6.7	7.1	Q	Q	Q	1000	3618	972	3	1100	36
NOV	0.6	1.8	3.7	Q	Q	Q	-	-			-	
DEC		-						-			-	

b) 1978

	Temperature (°C)			Conductivity-25			Salinity (ppm)			Chlorinity (ppm)		
	BC	MW	SW	BC	MW	SW	BC	MW	SW	BC	MW	SW
JAN	0.2	2.5	0.1*	336	1240	570*	591	825	365*	30	104	44*
FEB	0.5	1.5	0.6*	820	1260	524*	685	582	374*	4	118	48*
MAR	1.1	0	0.5	910	12700	610	828	8276	623	49	4500	186
APR	0.2	4.2	2.0	400	1740	440	Q	413	535	Q	181	65
MAY	9.1	10.2	13.0	224	2360	440	196	(959)	308	2	(286)	24
JUN	13.0	22.5	17.6	280	1220	340	210	850	309	10	350	44
JUL	18.5	18.8	19.6	290	2200	430	313	1605	339	18	633	48
AUG	12.0	19.0	15.0	320	2400	440	303	1894	385	6	866	51
SEP	10.0	9.0	11.0	340	-	440	144	615	339	1	85	46
OCT	5.0	6.4	8.0	124	1160	280	235	967	208	44	294	28
NOV	-	-	-	-	-	-	-	-	-	-	-	-
DEC	-	-	-	-	-	-	-	-	-	-	-	-

Conductivity-25 in μmho cm^{-1}

Q = questionable data

BC = Beaver Creek Inflow (M3)

MW = mine water holding pool (M1)

SW = Spillway outflow (M6) or *M5 (1 m) when M6 not sampled readily apparent:

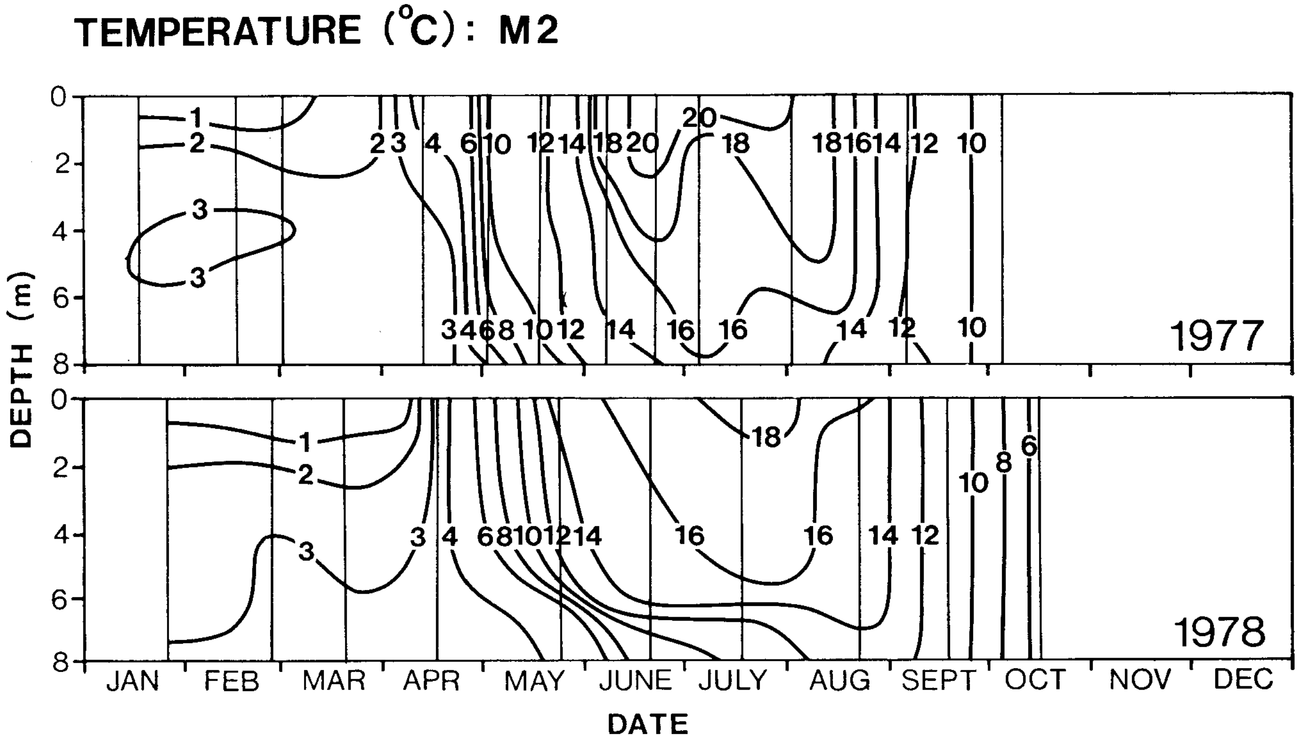
1. The salinity of Beaver Creek inflow (Station M3) undergoes large seasonal variations, from ≃180-1000 ppm in 1977 and from ≃140-830 ppm in 1978. Typically, salinity varies inversely with discharge; that is, it is low in spring and summer and high in winter. Chloride levels, however, are usually on the order of 10 ppm and seldom rise above 40 ppm.
2. Mine water (Station M1) salinities are generally quite high and exhibit large variations, from ≃400-8000 ppm, during the study period. Similarly, chloride levels are high and variable, from ≃100 to over 4000 ppm. These values, however, are typically lower than those obtained from analysis of direct pumping samples. This is because water in the holding pond (Station M1) is diluted by surface runoff; this also presumably accounts for the large annual variability.
3. Outflow values of salinity and chlorinity are nearly always (October 1978 excluded) higher than those of natural inflow waters. (This is due not only to pumping operations but also possibly to an unknown amount of groundwater seepage.) In 1977, the outflow chlorinity increased from 6-10 ppm in early summer to 36 ppm at the time of autumn overturn. Similar levels (44-48 ppm) continued in January-February, 1978. The highest value (186 ppm) was observed in March, 1978 and this is difficult to explain. (Indeed, all salinity and chlorinity values from this particular monitor are anomalously high, perhaps suggesting technical error.) Chlorinity levels drop in May concurrent with the freshet and then gradually increase to ≃50 ppm in late summer. The sudden drop in September-October is the result of heavy runoff. The important point to note

here is that at no time during this two year study have critical chlorinity values (i.e. 400 ppm above ambient) been observed. Discounting the questionable March 1978 value, outflow levels are typically 50 ppm or less. As a note of caution, however, one can only speculate as to what chlorinity levels would have been realized had the record-level rainfall in autumn 1978 been replaced with a drought.

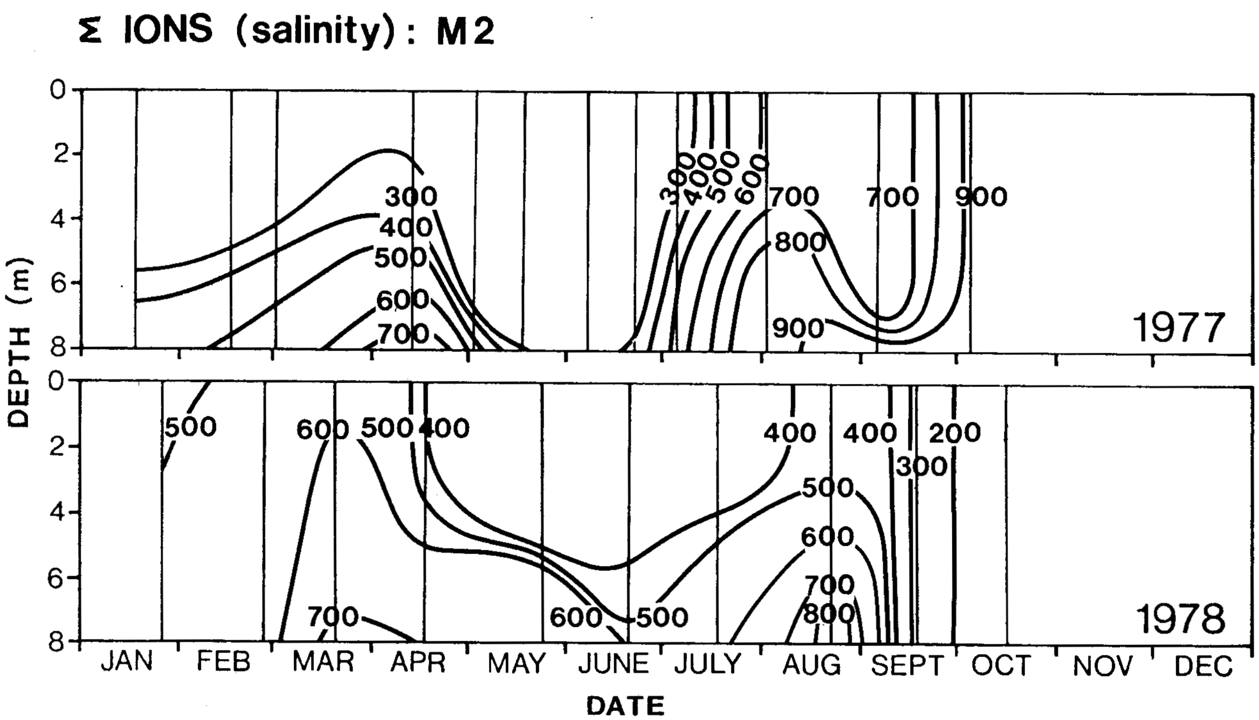
Finally, we consider the observed temperature trends of inflow/outflow waters as these are an important consideration of reservoir stratification. Mine water, due to its initial impoundment in a shallow holding pond, reaches higher temperatures in summer and cools more rapidly in autumn than other waters of the system. This is later shown to have an important effect on the behaviour of the effluent plume. Beaver Creek inflow typically remains colder than the outflow water, the latter being approximately equal to reservoir surface water temperatures. On the basis of temperature alone this water would be expected to sink upon entering the system (Carmack et al, 1979), however, the much higher salinities of the mine water effluent largely offset this tendency.

3.2 Seasonal Trends in Reservoir Characteristics

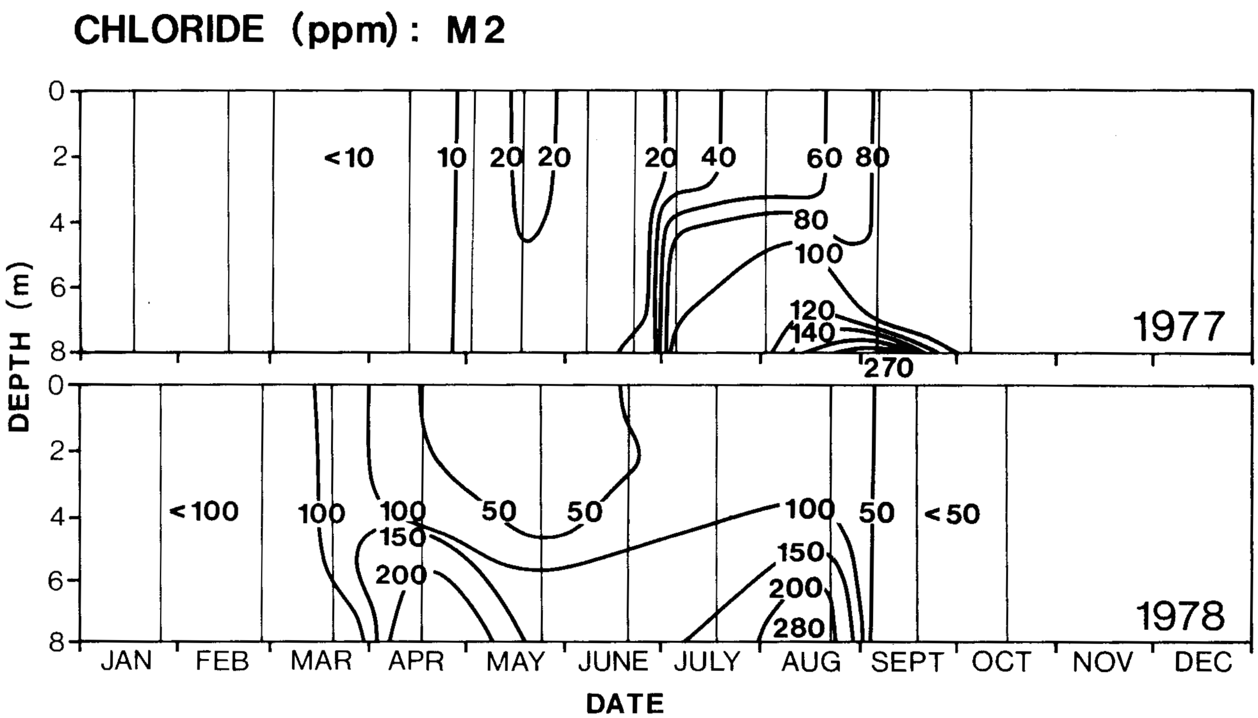
We here describe time-depth diagrams for temperature, salinity, chlorinity, conductivity-25 and % chlorinity/salinity from master stations in the two main basins of the system, Beaver Creek Basin (Figures 7-11) and Spillway Basin (Figures 12-16). Owing to its shallow depth and vertical homogeneity, Ruth Lake is represented (Figure 17) by measurements obtained at a depth of 1 metre. The ratio % chlorinity/salinity, as mentioned earlier, can be taken as the relative richness of mine water - but not the actual percent composition.



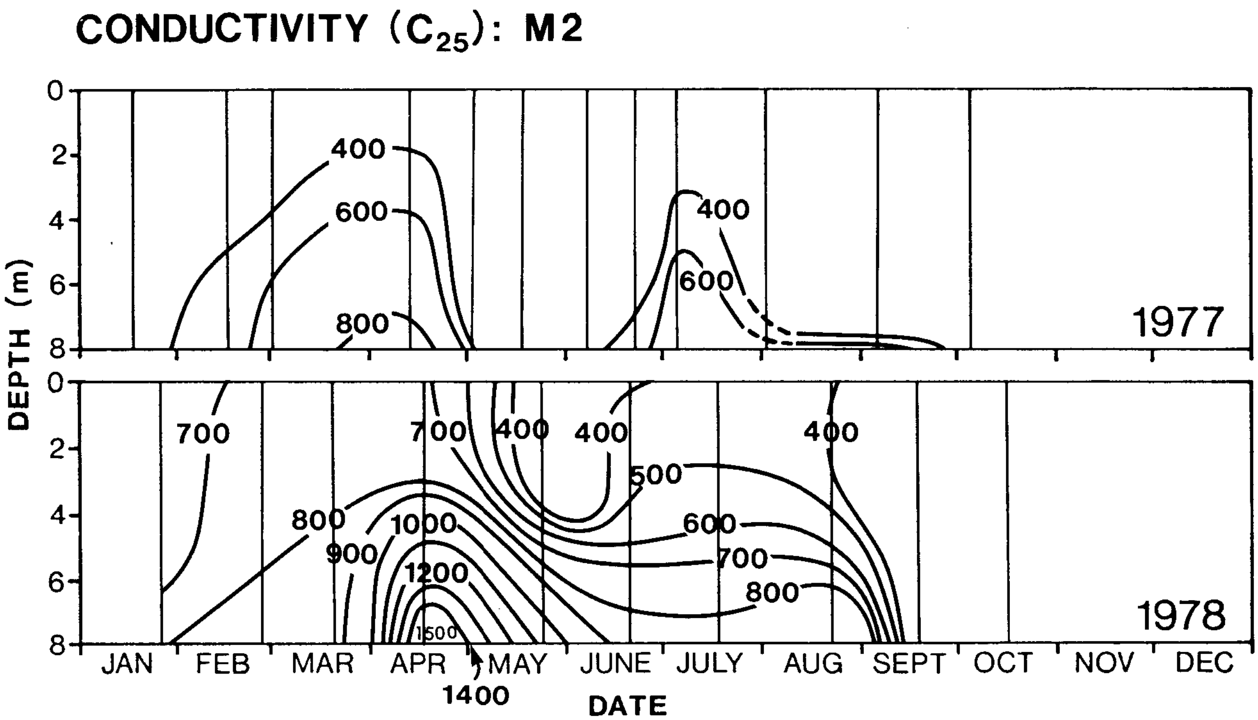
7: Time-depth diagrams of temperature in Beaver Creek Basin for 1977 and 1978. Vertical lines indicate sampling dates.



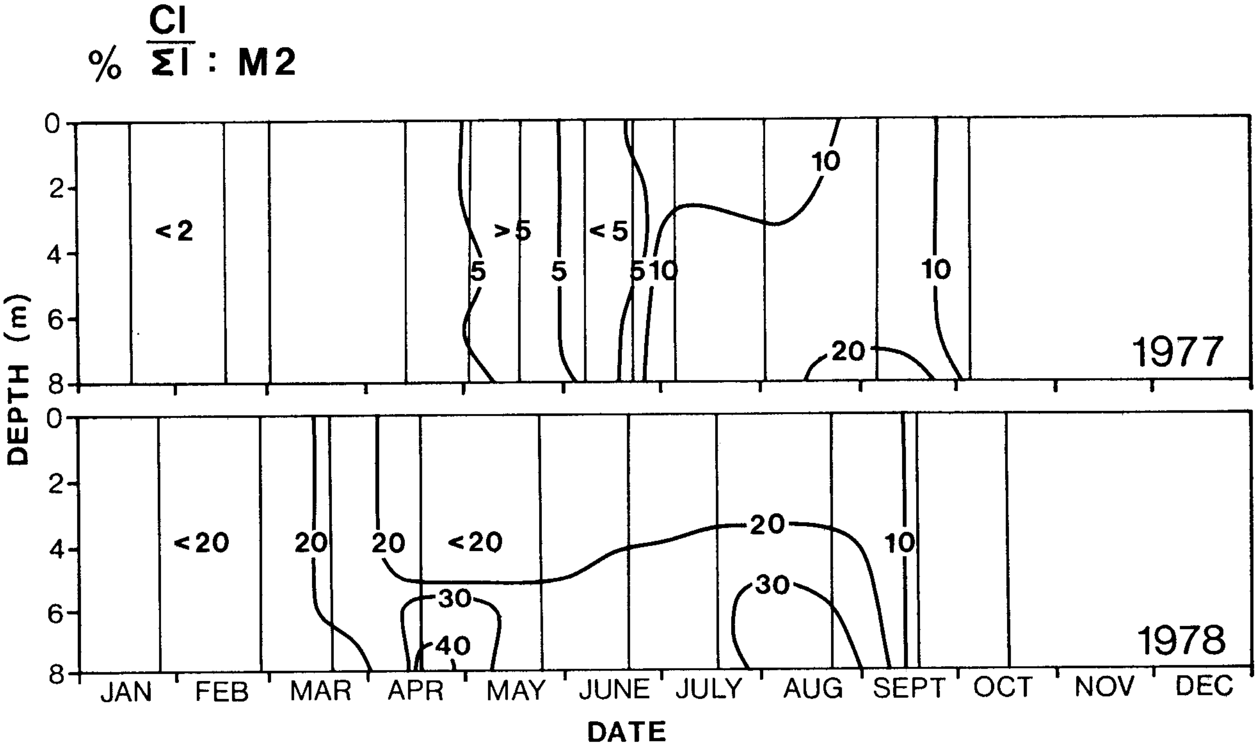
8: Time-depth diagrams of salinity in Beaver Creek Basin for 1977 and 1978. Vertical lines indicate sampling dates.



9: Time-depth diagrams of chlorinity in Beaver Creek Basin for 1977 and 1978. Vertical lines indicate sampling dates.



10: Time-depth diagrams of conductivity-25 in Beaver Creek Basin for 1977 and 1978. Vertical lines indicate sampling dates.



11: Time-depth diagrams of % chlorinity/salinity in Beaver Creek Basin for 1977 and 1978. Vertical lines indicate sampling dates.

Temperature. The reservoir undergoes full convective circulation twice yearly, in spring and in autumn. Spring overturn takes place between mid-April and late May as indicated by the vertical arrangement of isotherms near 4°C (Carmack, 1979). Autumn overturn begins in late August ($T \simeq 10$-12°C) and continues through October. Ice formation in early November requires that the entire system cool to and below about 4°C.

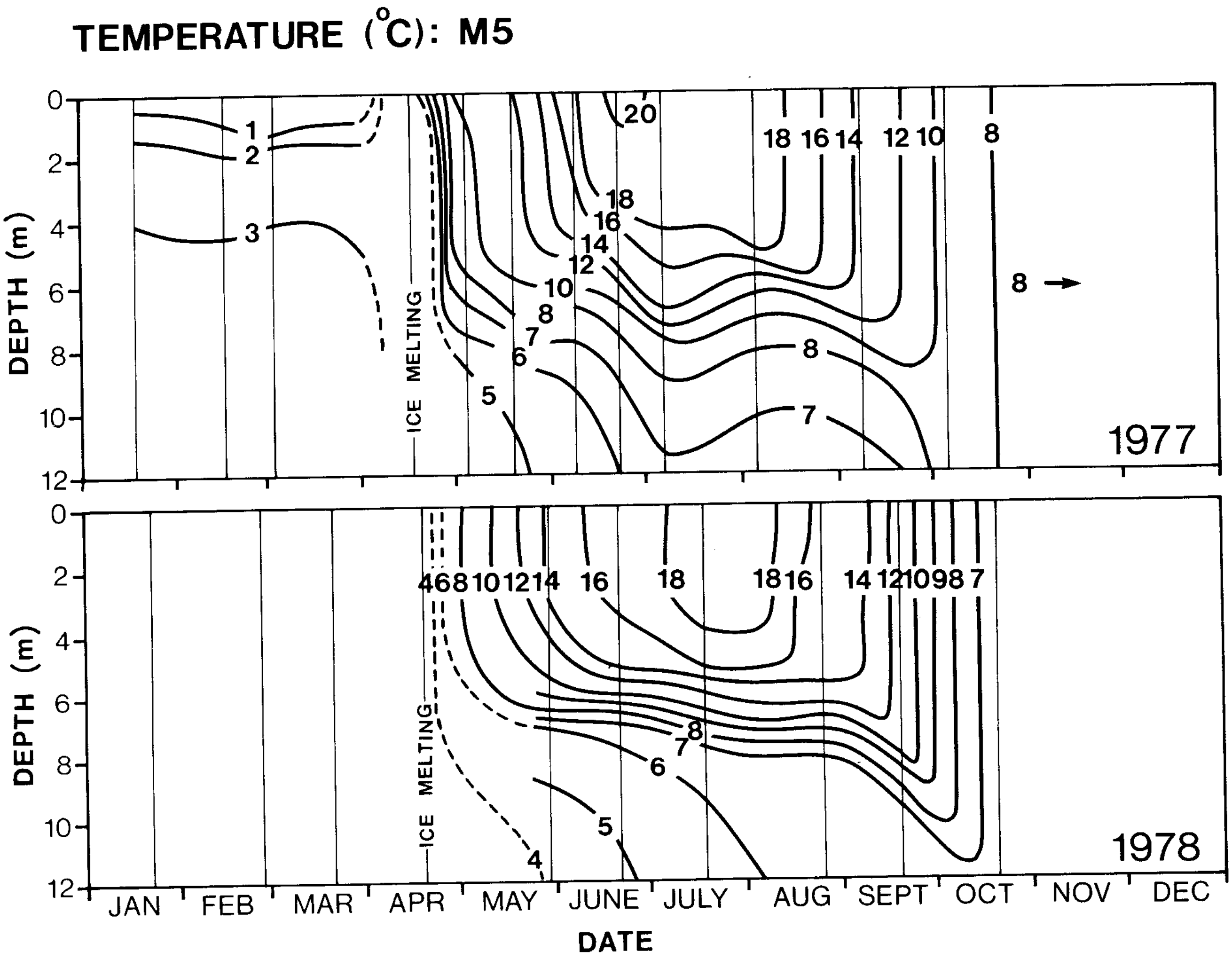
During the periods of summer stratification the upper 4-5 m of the reservoir are typically well-mixed as a result of wind stirring. Bottom temperatures are not constant but instead increase through summer and reach a maximum in late July. This latter trend is especially evident in Beaver Creek Basin which, as a result, typically displays weaker vertical temperature stratification.

Winter stratification persists throughout the ice-covered period and is generally characterized by reverse thermal stratification (i.e. temperature increasing with depth). On occasion, however, mid-depth temperature inversions are observed. The probable origin of these inversion features is discussed in Section 3.3.

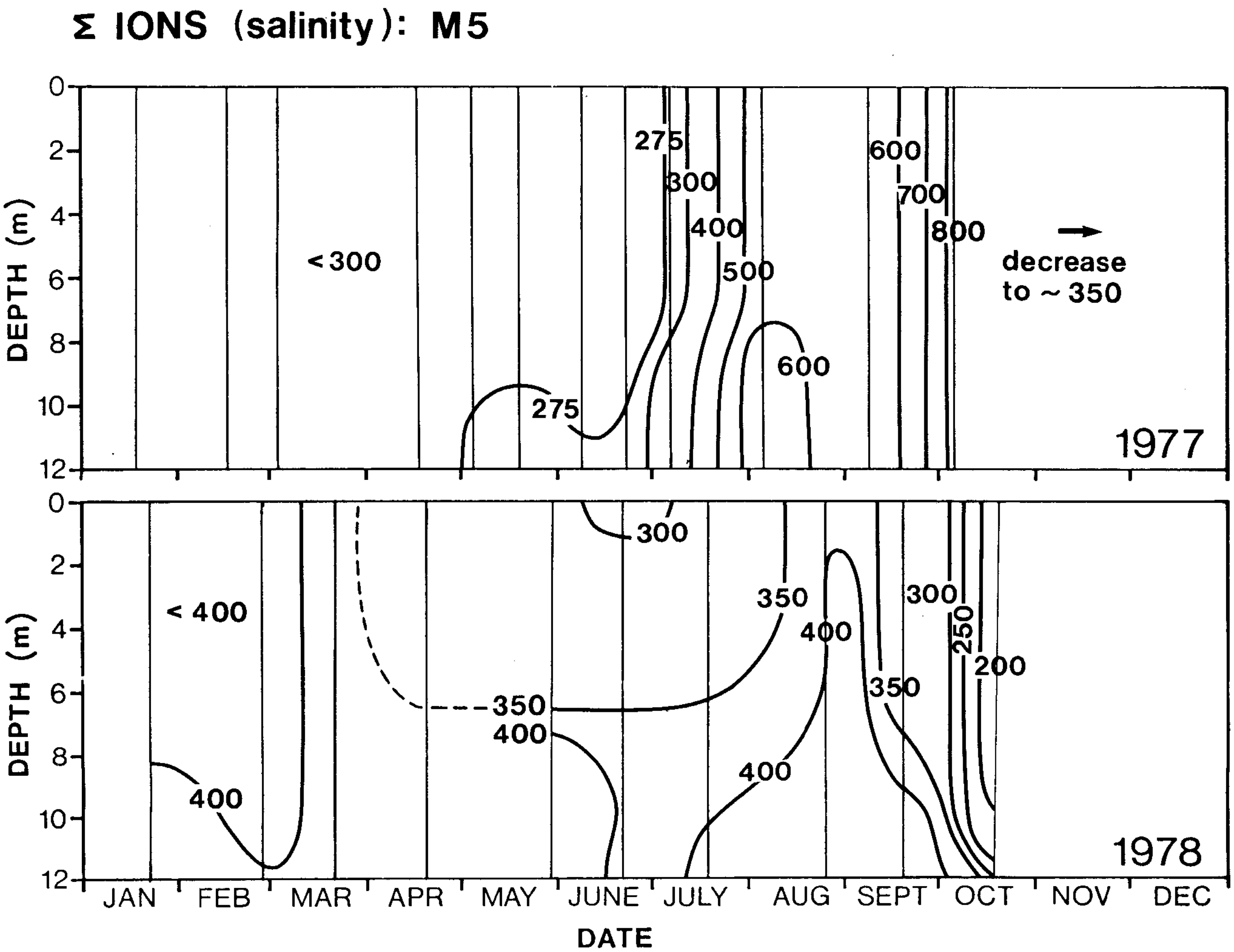
Salinity. Consider first the seasonal behaviour of Beaver Creek Basin (Figure 8). With the exception of the autumn period, both years revealed similar trends.

First of all, there is typically a monotonic increase in salt content with depth suggesting that the inputs of high salinity mine water sink rapidly to depth before spreading laterally in the system. In both years, however, there was a marked build-up of saline bottom water toward the end of the winter season. Since no pumping takes place during the winter months, this build-up probably represents groundwater seepage.

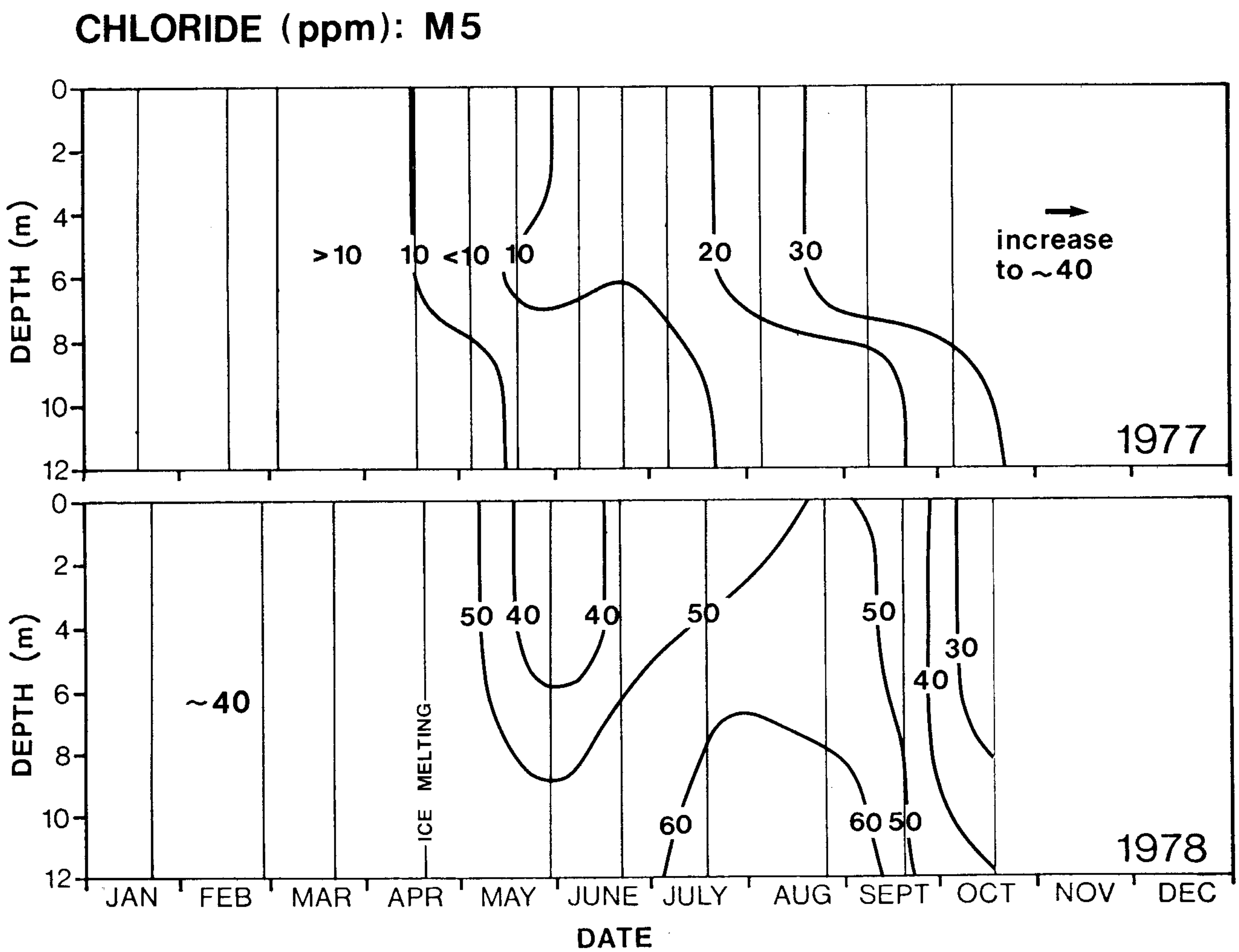
Following spring overturn and concurrent with the early summer freshet, the system is markedly diluted by freshwater inputs (cf. Tables 3,4). This



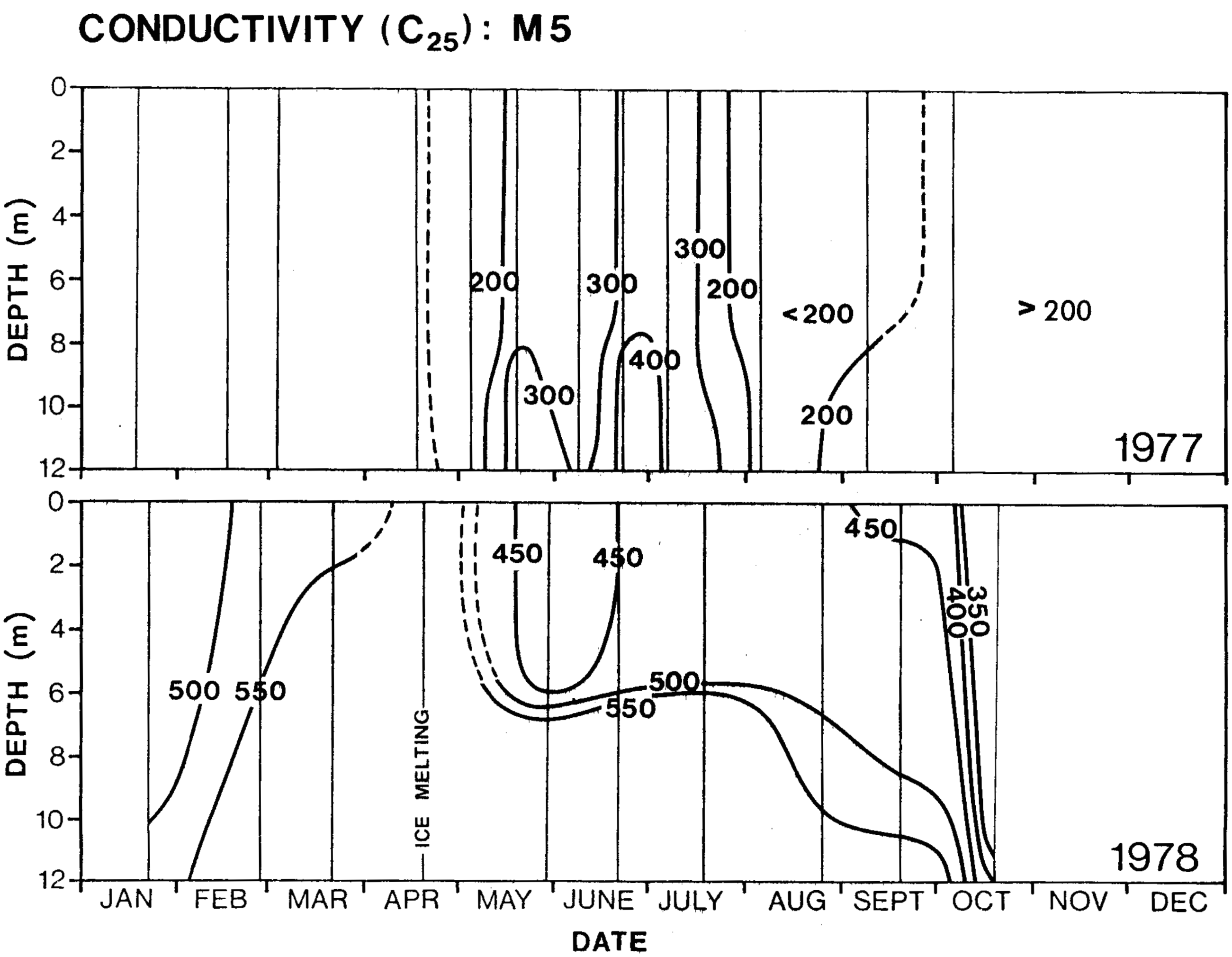
12: Time-depth diagrams of temperature in Spillway Basin for 1977 and 1978. Vertical lines indicate sampling dates.



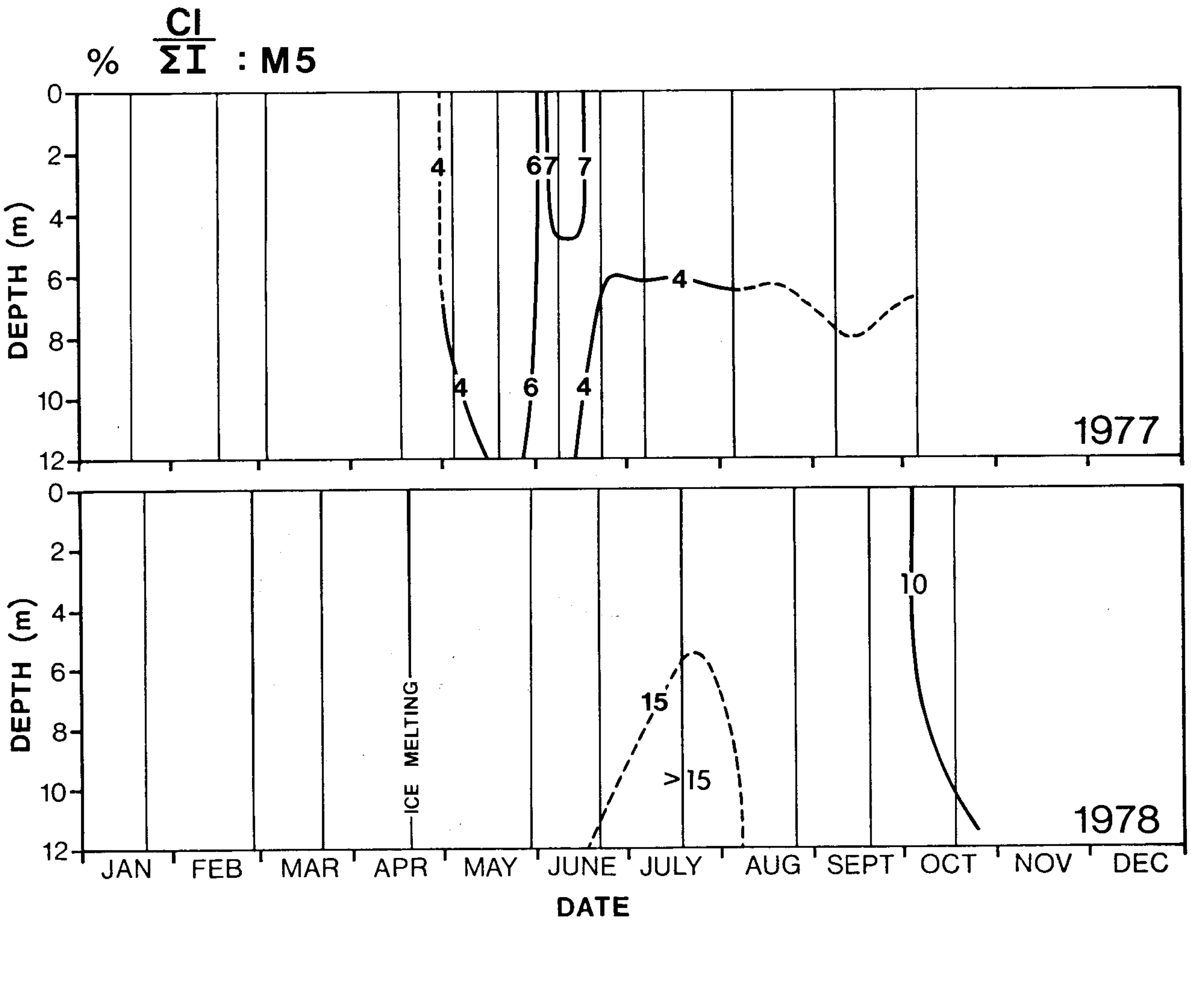
13: Time-depth diagrams of salinity in Spillway Basin for 1977 and 1978. Vertical lines indicate sampling dates.



14: Time-depth diagrams of chlorinity in Spillway Basin for 1977 and 1978. Vertical lines indicate sampling dates.



15: Time-depth diagrams of conductivity-25 in Spillway Basin for 1977 and 1978. Vertical lines indicate sampling dates.



16: Time-depth diagrams of % chlorinity/salinity in Spillway Basin for 1977 and 1978. Vertical lines indicate sampling dates.

process was especially pronounced in June, 1977 owing to the higher spring streamflows of that year.

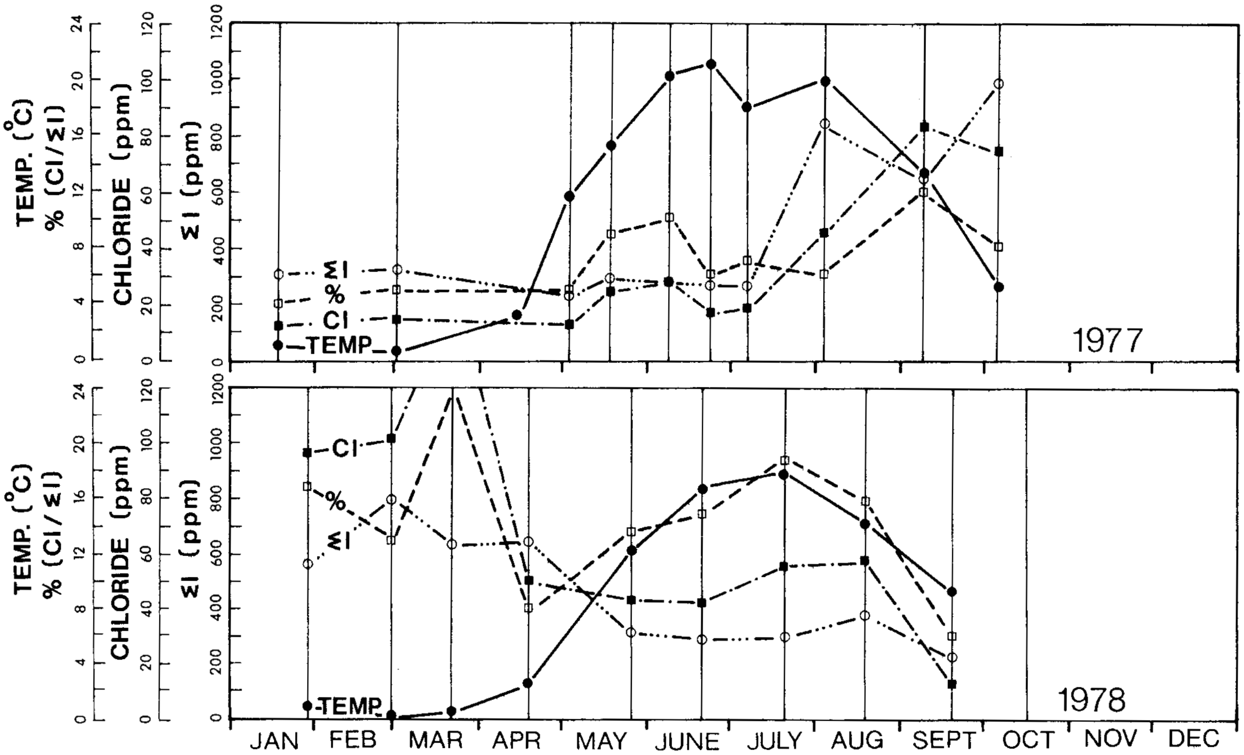
Between July and August there is a relatively rapid increase in near-bottom salinity values as a result of saline groundwater pumping operations. In 1977 this trend continued until autumn overturn*. This demonstrates the combined effects of continued pumping and low surface runoff. During the autumn of 1978, on the other hand, the region received very high rainfall and surface runoff. This, combined with vertical mixing during autumn overturn, was extremely effective in flushing the basin of saline water. Indeed, it proved so effective that salinity values at the end of September were actually lower than those observed in the previous winter.

Turning briefly to the salinity-history diagram for Spillway Basin (Figure 13), we note a seasonal trend similar to that observed in Beaver Creek Basin. However, both the absolute values and the magnitude of vertical gradients are smaller. It is interesting to note that the diluting influence of the September 1978 runoff appears to be delayed by about one month, which is approximately equal to the bulk residence time of the system during this period (Table 3).

In Ruth Lake (Figure 17) salinity values are generally intermediate between those of Beaver Creek and Spillway Basin surface waters. Beginning with values near 300 ppm in 1977, they remain relatively constant until July-October at which time an increase to 600-900 ppm is observed. These concentrations persist throughout winter, then drop to 300-400 ppm during summer. Again, the diluting effects of the September 1978 runoff are apparent.

Chlorinity. In both Beaver Creek Basin (Figure 9) and Spillway Basin (Figure 14) the winter 1977 chlorinity levels are low throughout the water

*At this point, it is useful to note an apparent decrease in salinity values of almost 50% between October 1977 and January 1978. At present we have no explanation for this other than to suggest technical error in the October data.



17: History of temperature, salinity, chlorinity, and % chlorinity/salinity in Ruth Lake Basin. Vertical lines indicate sampling dates.

column. The values observed in Spillway Basin are higher than those in Beaver Creek Basin, possibly reflecting groundwater seepage. These observations suggest that very little saline groundwater was initially present in the system.

The 1977 winter build-up in salinity seen in Beaver Creek Basin is not reflected in the corresponding chlorinity history, whereas the 1978 winter build-up is matched by a concurrent chlorinity increase. The first condition suggests that the salinity increase is due to a low chloride goundwater input, while the second circumstance suggests seepages of chloride-rich groundwater.

Beaver Creek Basin chlorinity values begin to increase in May, 1977, and show (for this one time only) weak reverse stratification at the end of May. Values drop slightly in June due to runoff, and then increase rapidly through July-September. Toward the end of summer, surface values approach 80-90 ppm while bottom values increase to ≃270 ppm. Following autumn overturn, a near homogeneous water column (≃75 ppm) is observed.

The year 1978 begins with chlorinity values of approximately 75 ppm in Beaver Creek Basin; a marked increase (≃20-fold) over values from the previous winter. This relatively high chlorinity suggests that during 1977 the system was not fully flushed of effluent inputs. There is some rationale behind this observation, since saline groundwater pumping was carried out in late summer and autumn, long after the bulk of the yearly runoff had passed through the system. From an operational point of view, it would be better to begin pumping operations earlier in the season commensurate with the natural hydrological cycle.

Early summer is again characterized by a decrease in chlorinity, especially in the upper 4-5 m of the water column. Near-bottom chlorinity values then increase throughout middle and late summer, reaching ≃280 ppm prior to overturn.

The freshening effects of the September streamflow are dramatic, and chlorinity levels in Beaver Creek Basin are actually lower at the end of 1978 than at the beginning. This is a marked contrast to 1977.

Spillway Basin, at the end of the diversion system, typically shows both lower chlorinity levels and a more sluggish seasonal progress. Chloride concentrations in 1977 increase gradually from ≃10-15 ppm in January to ≃25-35 ppm in autumn. Throughout this year the system shows weak reverse stratification. (Evidently the source water from Beaver Creek and Ruth Lake Basin was warm and insufficiently saline to sink.)

The 1978 seasonal pattern in Spillway Basin is quite similar to that in Beaver Creek Basin but with much reduced concentrations. An early summer freshening is evident, followed by a gradual build-up. The most dramatic effects of the September flooding are not observed until one month later.

Other. Time-depth diagrams for C_{25} (Figures 10 and 15) are included here mainly for completeness. Although the basic seasonal trends in C_{25} roughly parallel those for salinity, these diagrams should be viewed with caution. As noted earlier, C_{25} may be useful for comparisons within a given monitor but lack reliability for seasonal trend analysis.

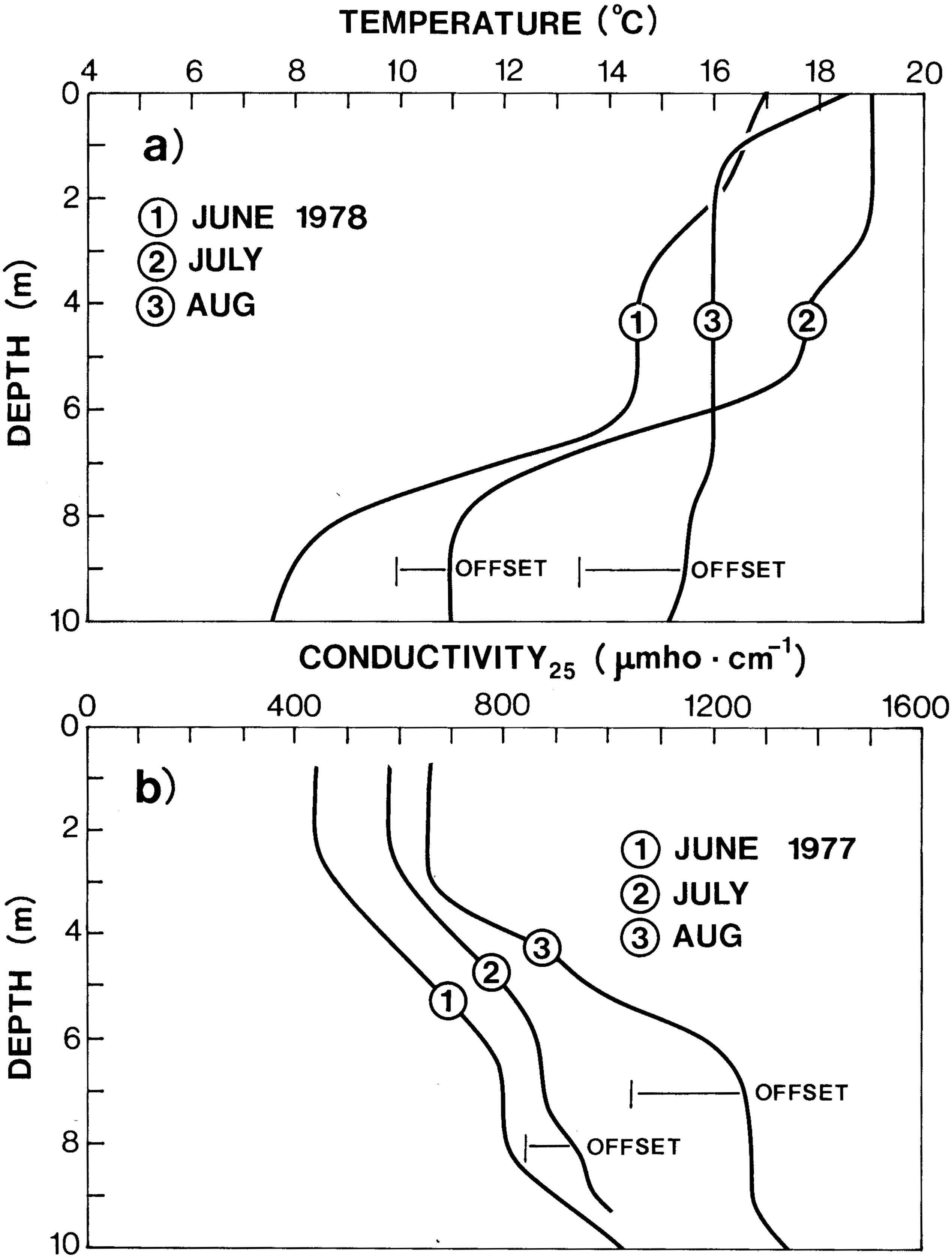
The ratio, % chlorinity/salinity (Figures 11 and 16), is useful for rough and ready checks on the relative richness of mine water in a given water mass. Most of the salient features in these plots are covered in the above discussion. If serious concern over the composition of a given water mass should arise in the future (i.e. a very high $\%Cl/\Sigma I$ ratio), then reference should be made to the triangle diagram method outlined in Section 2 for more positive identification.

3.3 Stratification and Circulation

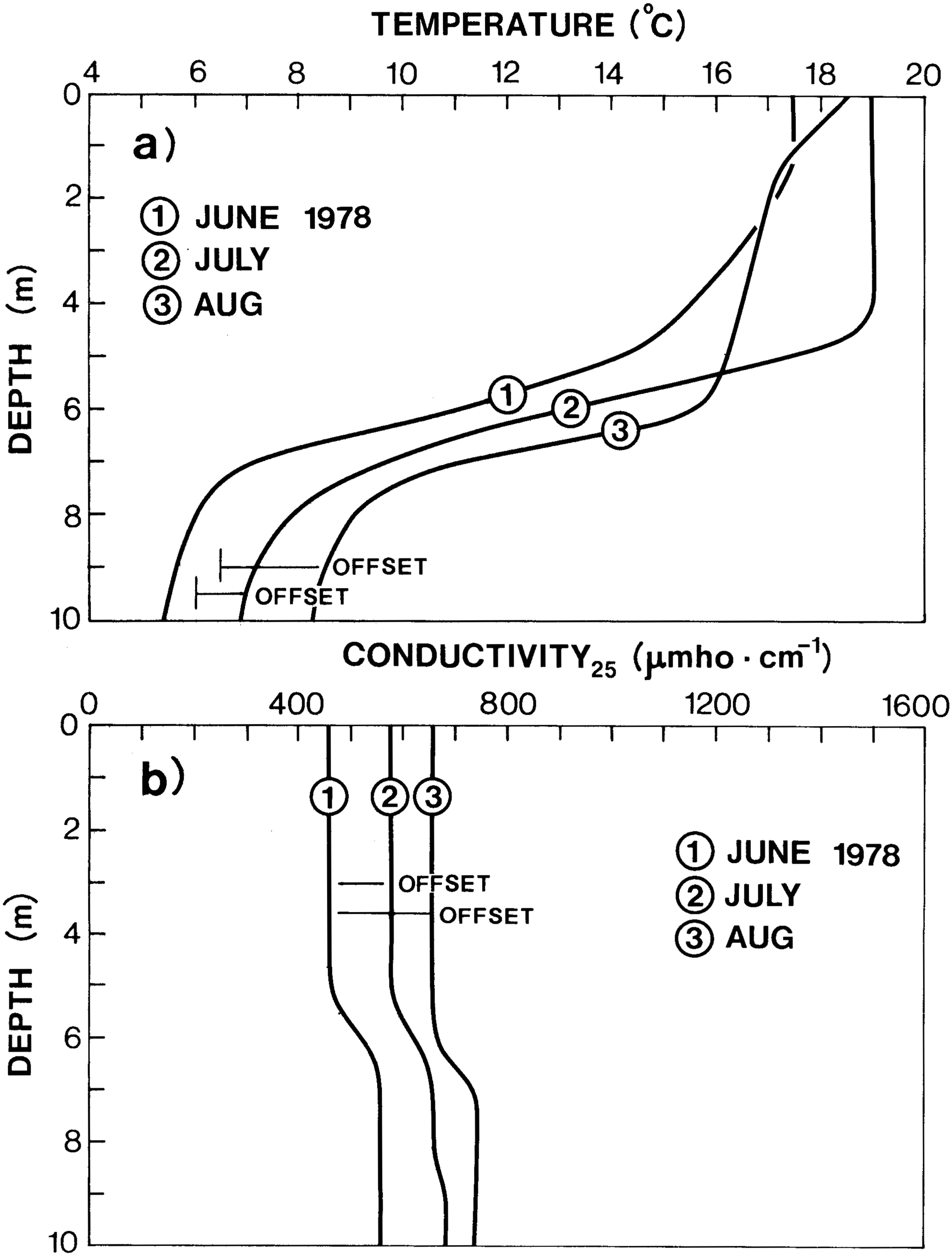
During the course of this study, over 500 individual profiles of temperature and conductivity-25 were obtained. We here present selected profiles and sections which appear to typify the summer and winter patterns of stratification and circulation, and comment briefly on their salient features.

Summer. Vertical profiles of temperature and conductivity-25 for Beaver Creek Basin and Spillway Basin are shown in Figures 18a,b and 19a,b, respectively, for 1978. Both basins reveal monotonic stratification fields with T decreasing with depth and C_{25} increasing with depth. Beaver Creek exhibits far stronger C_{25} gradients with depth and a more dramatic summer build-up than does Spillway Basin. This is undoubtably due to its proximity to the pumping site. On the other hand, Beaver Creek Basin displays weaker vertical temperature gradients and a more rapid increase in bottom temperatures during summer. Since both basins possess roughly similar fetch and morphometric characteristics, we interpret this difference as resulting from the input of relatively warm mine water which, by virtue of its high salinity, sinks and carries heat to depth (Koh and Brooks, 1975). Some support for this reasoning comes from modelling results (Section 5) which, by including both temperature and salinity in the equation of state, yield results similar to those noted above.

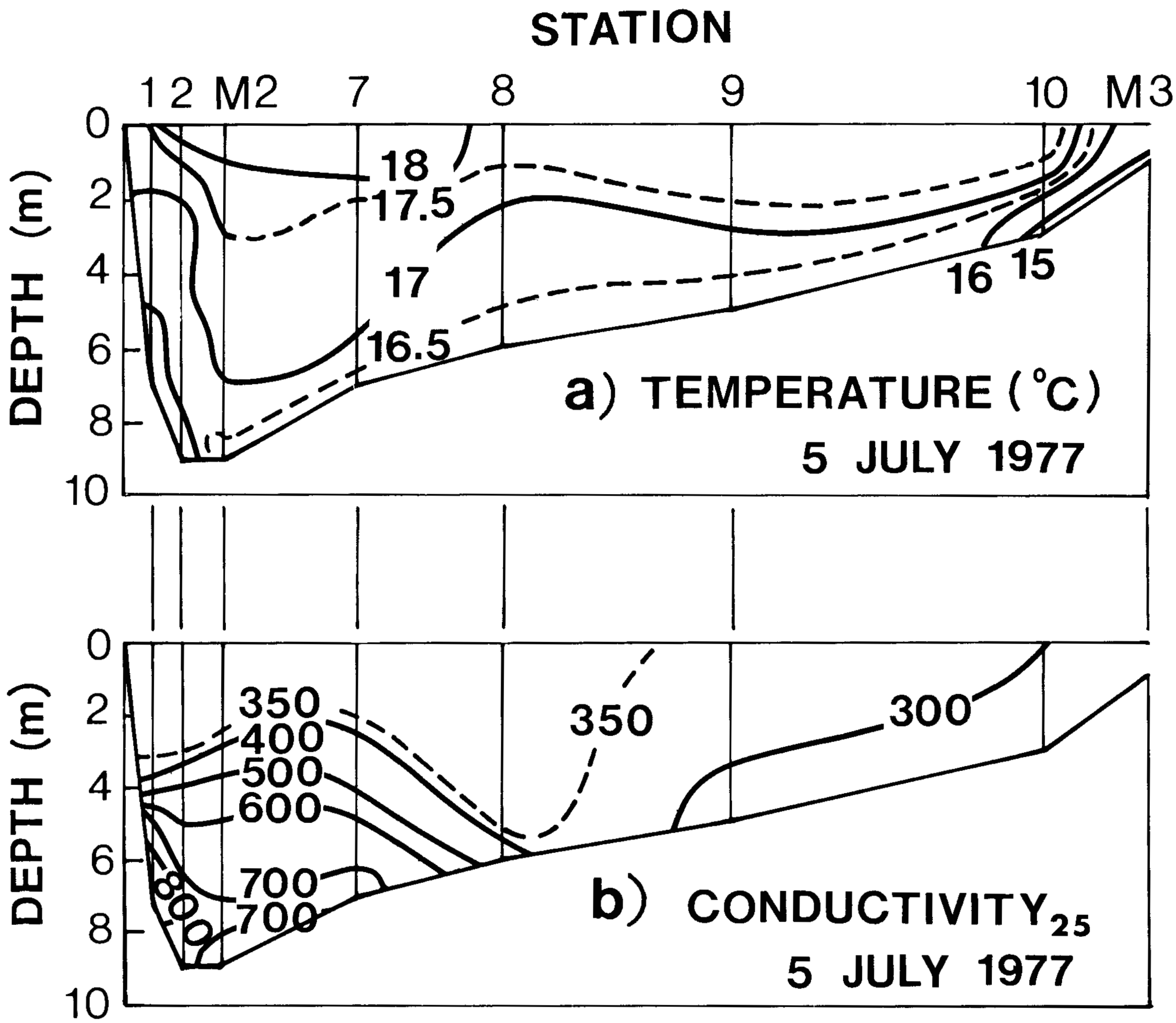
Lateral variations in stratification may be examined via longitudinal sections of temperature and salinity. Examples typifying summer conditions are shown in Figures 20-23 and 24-25 for Beaver Creek and Spillway Basins, respectively. (Note that in these sections the bottom is shown equal to mean sampling depth for each station and is depicted as smooth and gently sloping; in actual fact, the flooded stream channels are sinuous and



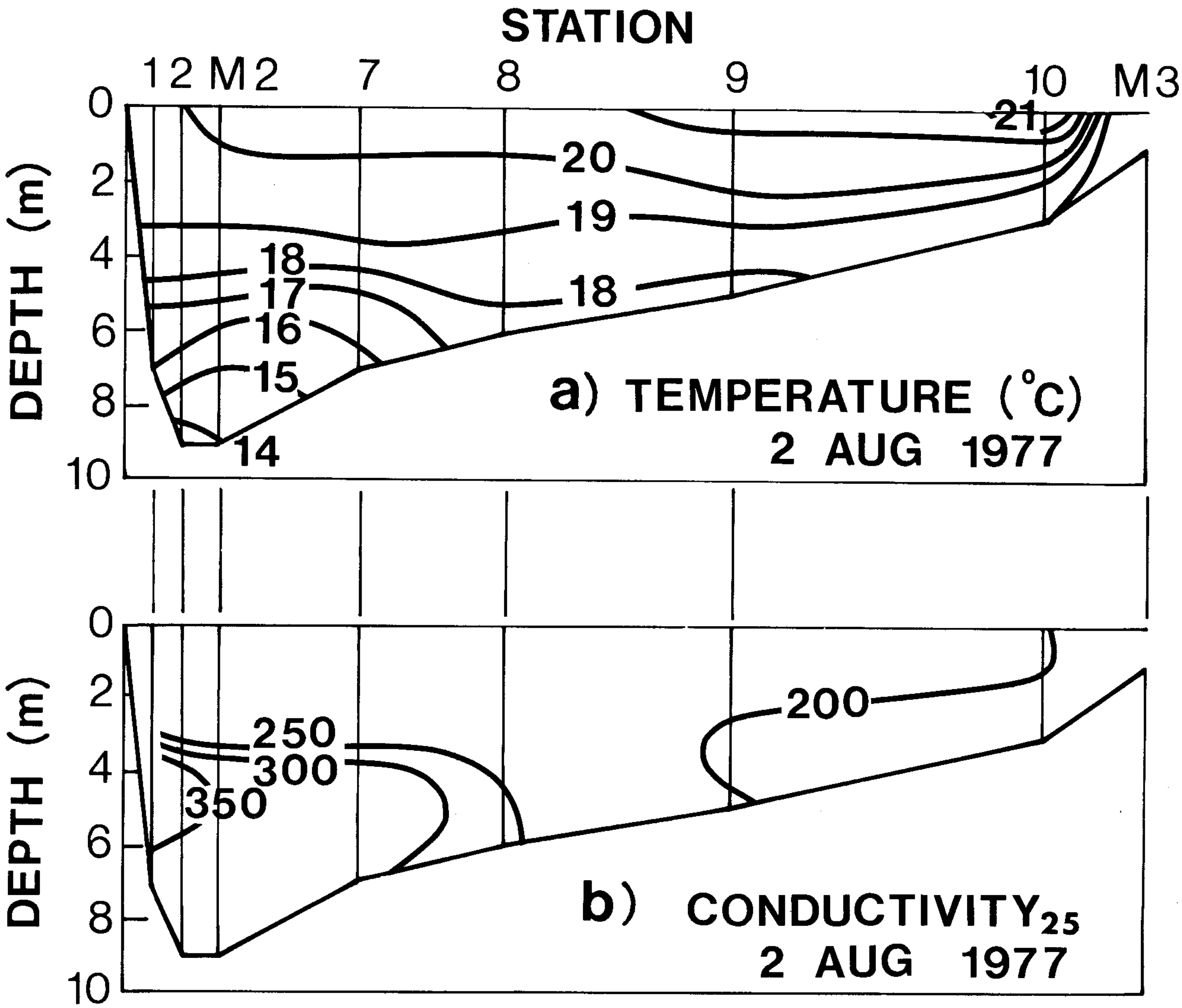
18: Vertical profiles of (a) temperature and (b) conductivity-25 for Beaver Creek Basin, Summer 1978.



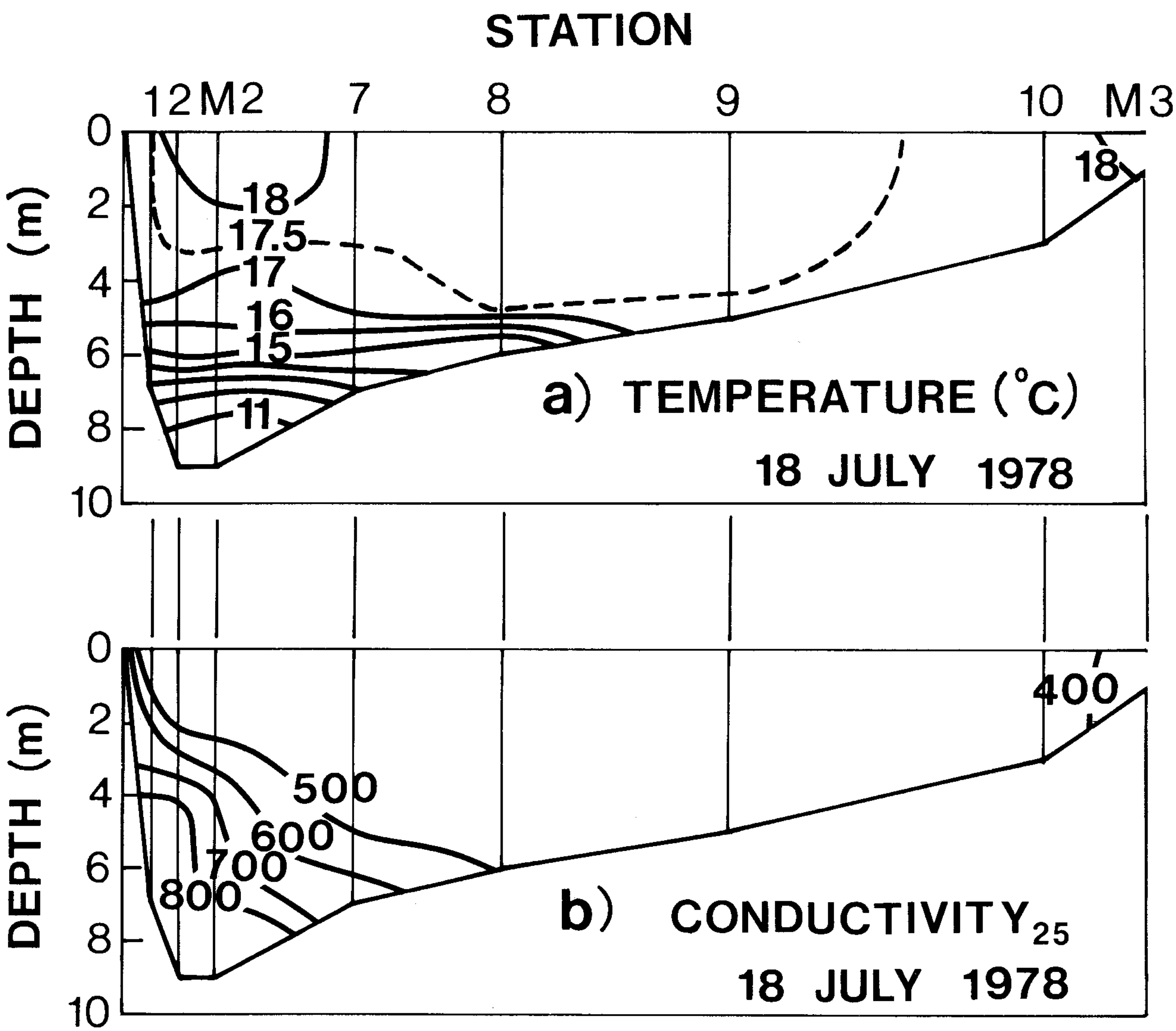
19: Vertical profiles of (a) temperature and (b) conductivity-25 for Spillway Basin, Summer 1978.



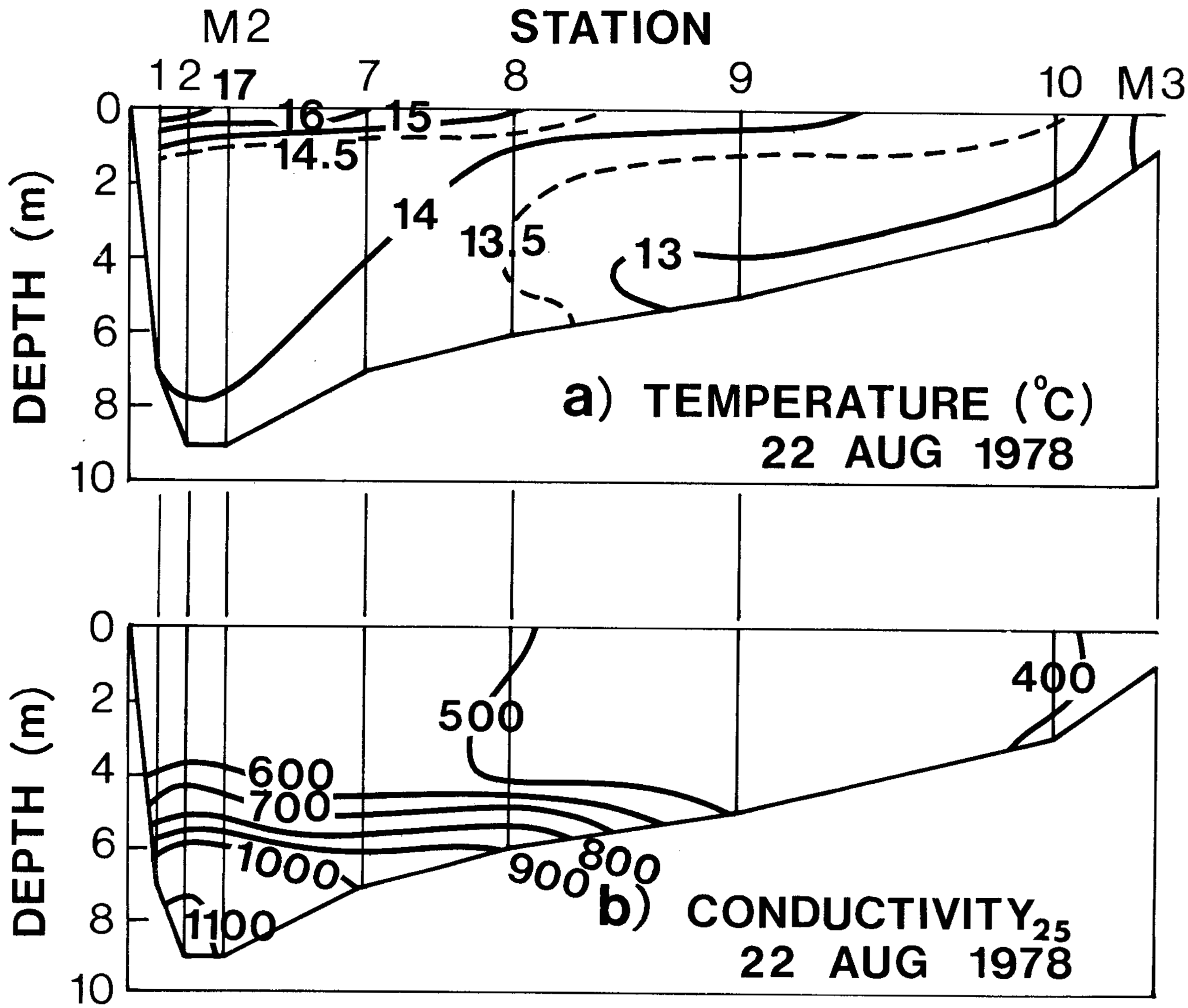
20: Longitudinal sections of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, July 1977.



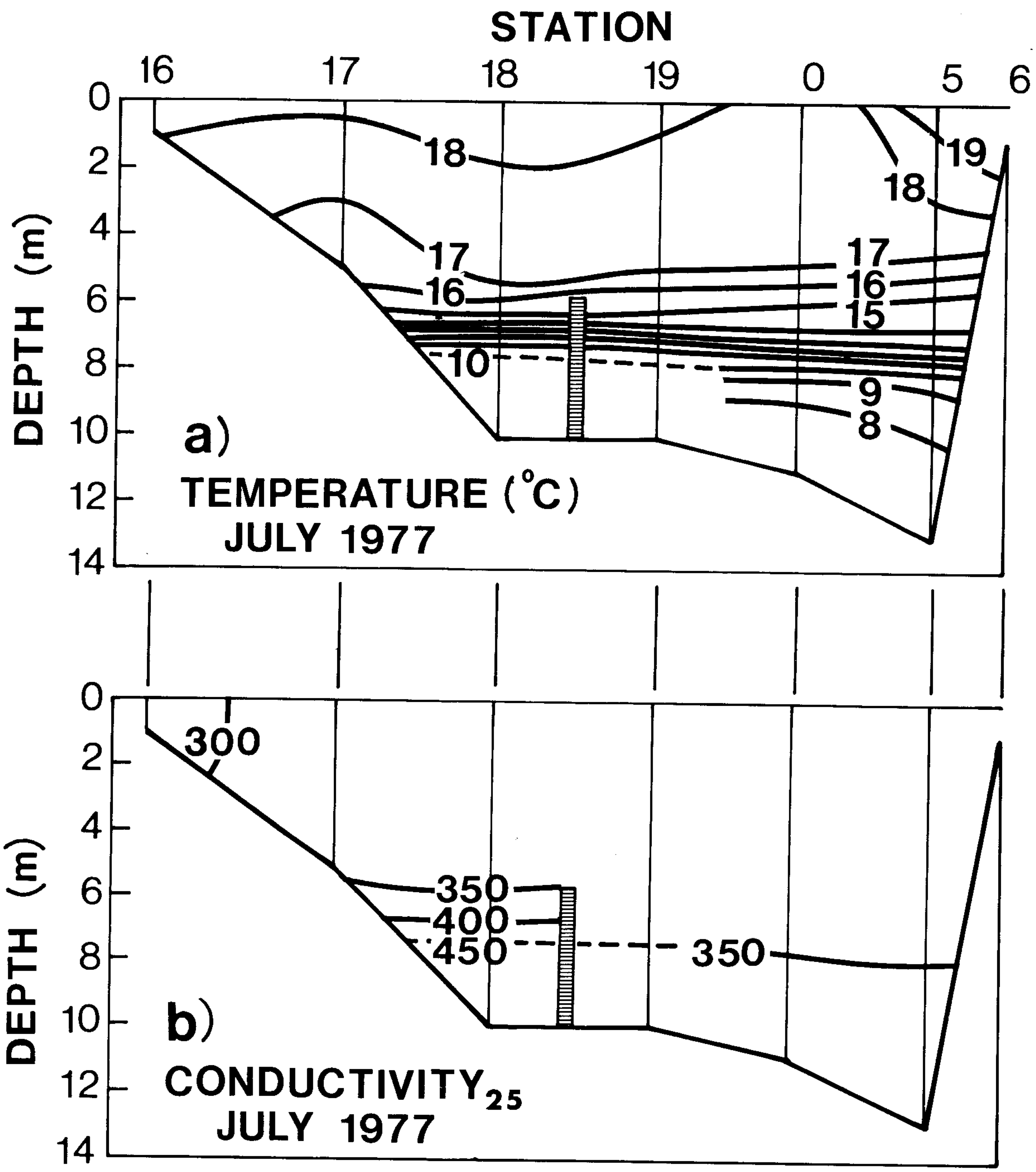
21: Longitudinal sections of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, August 1977.



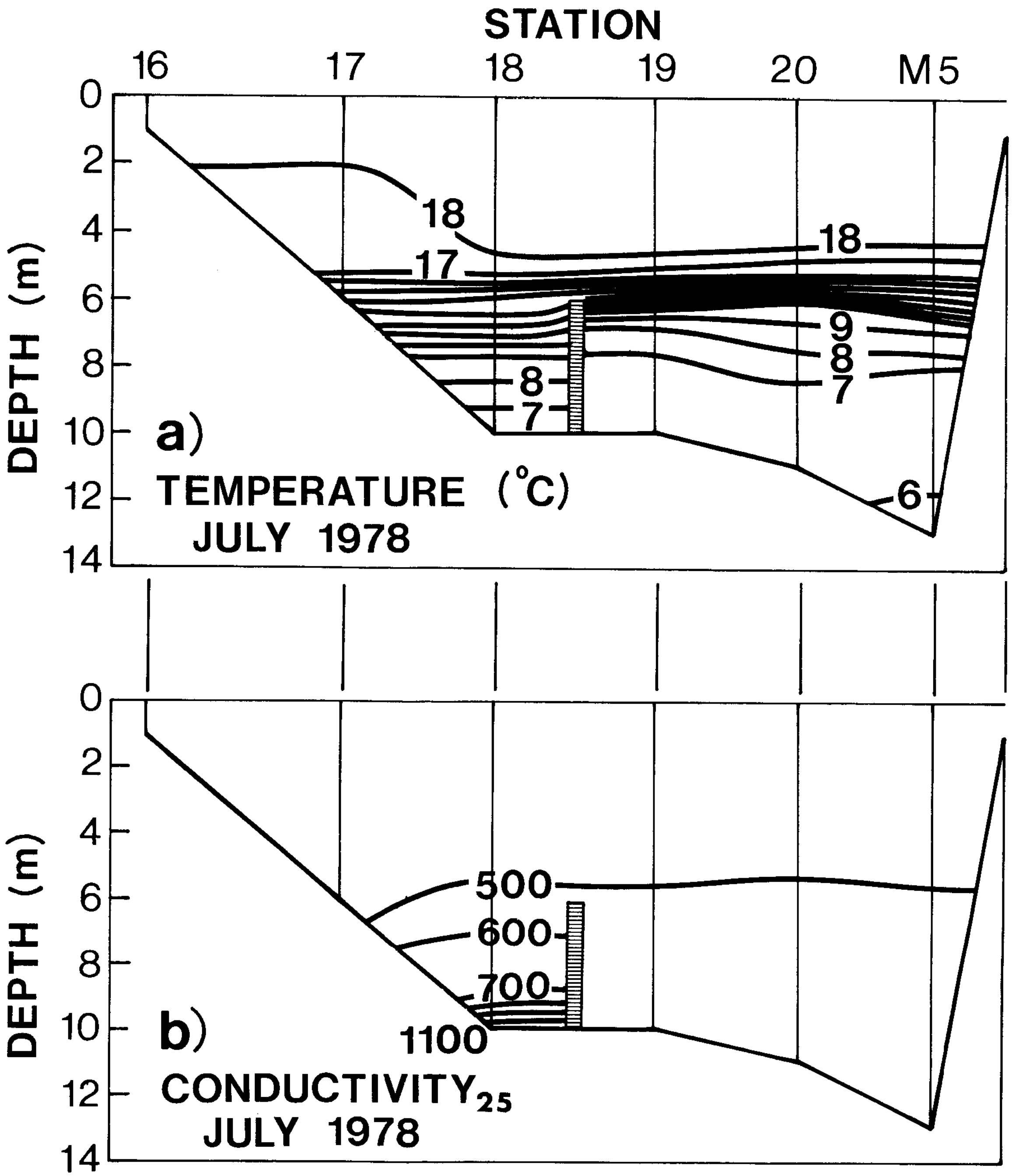
22: Longitudinal sections of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, July 1978.



23: Longitudinal sections of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, August 1978.



24: Longitudinal sections of (a) temperature and (b) conductivity-25 in Spillway Basin, July 1977.



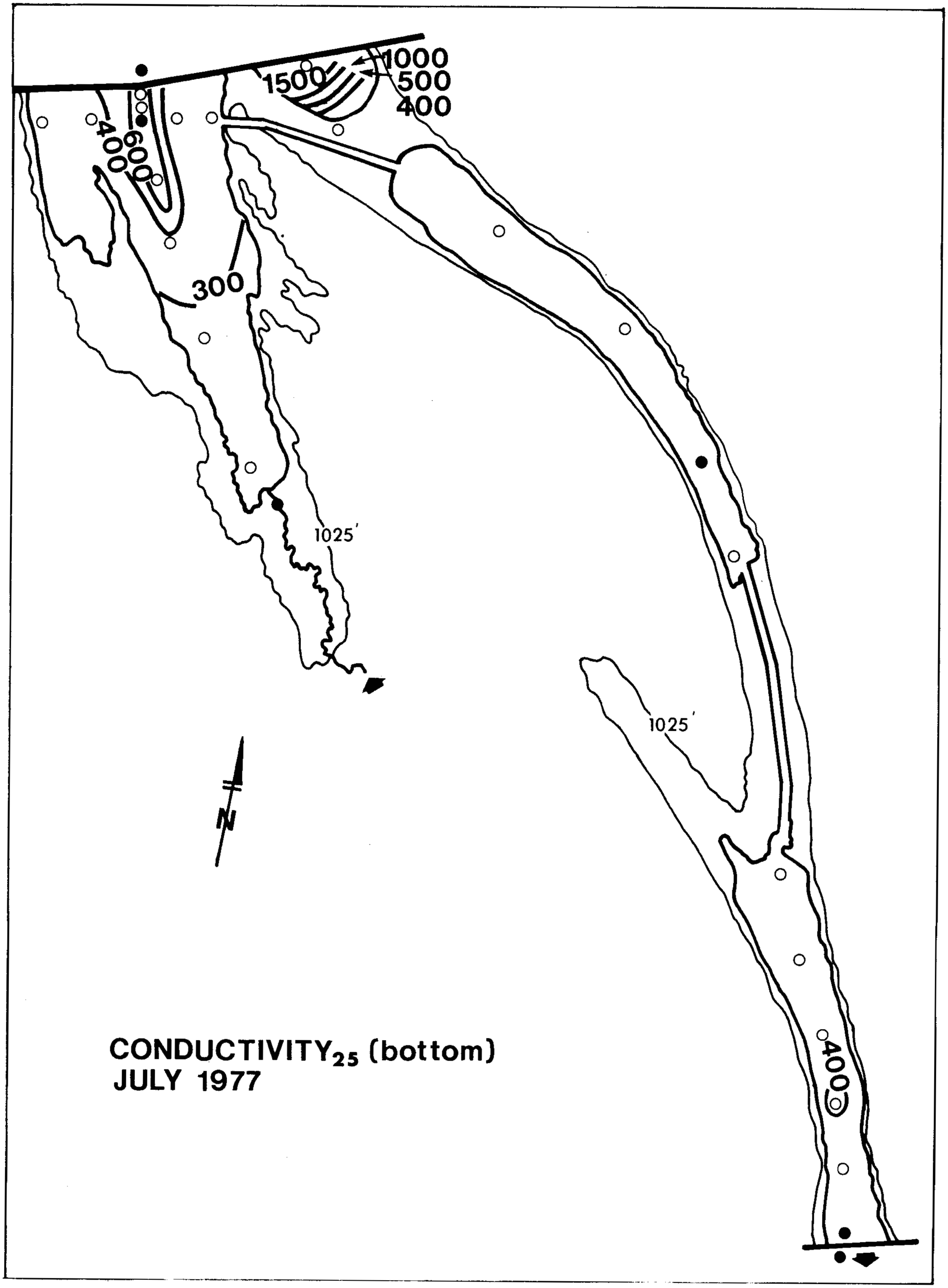
25: Longitudinal sections of (a) temperature and (b) conductivity-25 in Spillway Basin, July 1978.

irregular.) Of immediate interest here is the isopleths of C_{25} in Beaver Creek Basin which are not horizontal but rather embank against the dam structure near the source of mine water. Some freshening due to natural inflows is also evident in the southern half of the basin. Although we cannot say for certain (cf. Section 2), salinity and chlorinity likely show similar distributions. Temperature, too, is typically non-uniform in the horizontal suggesting either internal wave motions or, more likely, localized heating/cooling from input waters.

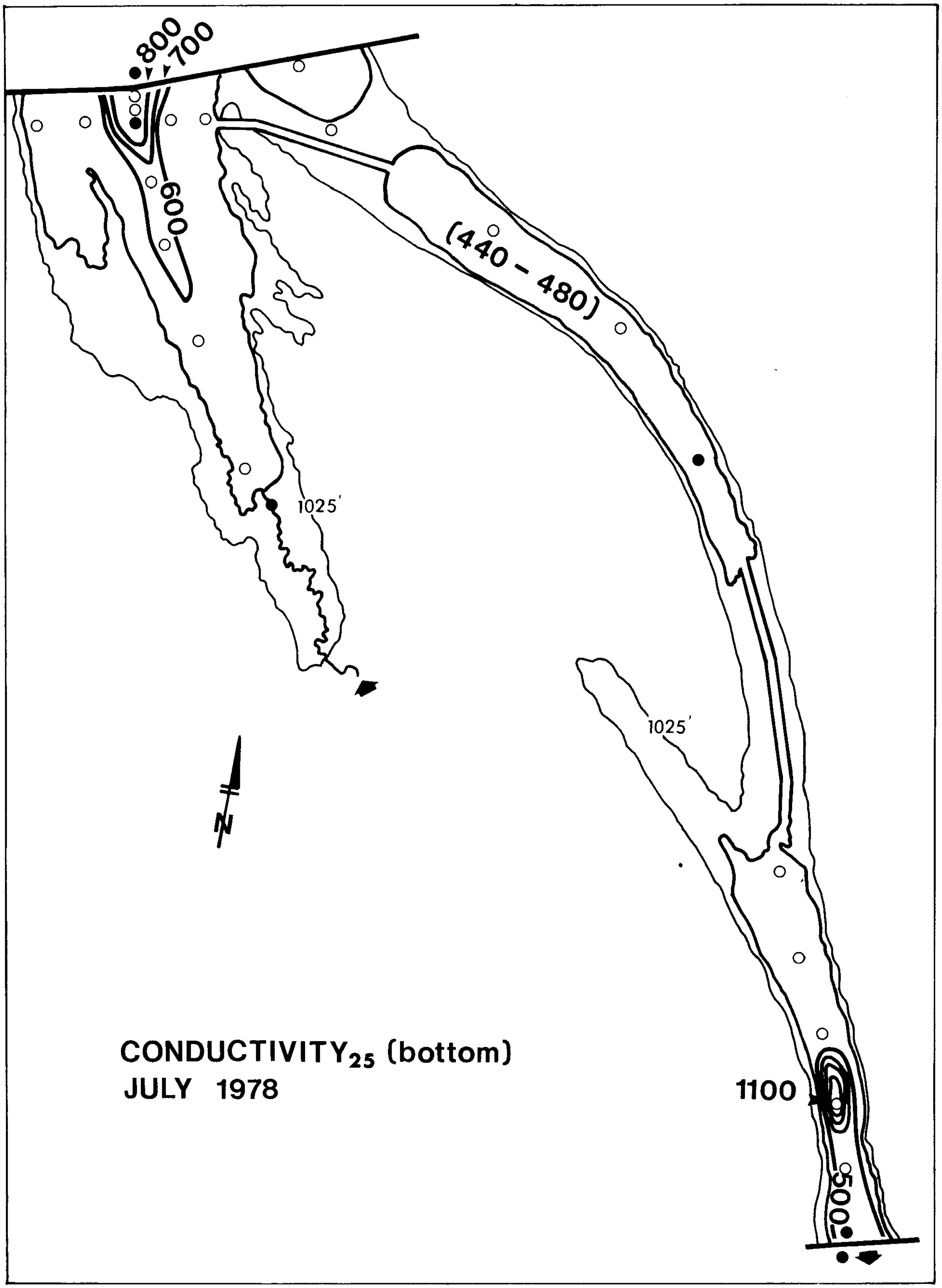
Sections for Spillway Basin typically show much flatter isopleths; however, there is a distinct change in stratification characteristics between Stations S18 and S19, the location of the road causeway. Above ≈6 m depth the isopleths of T and C_{25} are uniform and continuous; below ≈6 m (the apparent sill depth) they are not, with the northern part of the basin exhibiting much higher C_{25} values. Now, since the bottom waters at S18 typically show C_{25} higher than that of water entering from Ruth Lake, we interpret this to be evidence of local groundwater seepage.

A view of spatial heterogeneity may also be obtained from horizontal property maps; shown here are bottom C_{25} maps for July, 1977 (Figure 26) and July, 1978 (Figure 27). These representations clearly show the tendency of high conductivity water to collect in the deepest portions of each major basin.

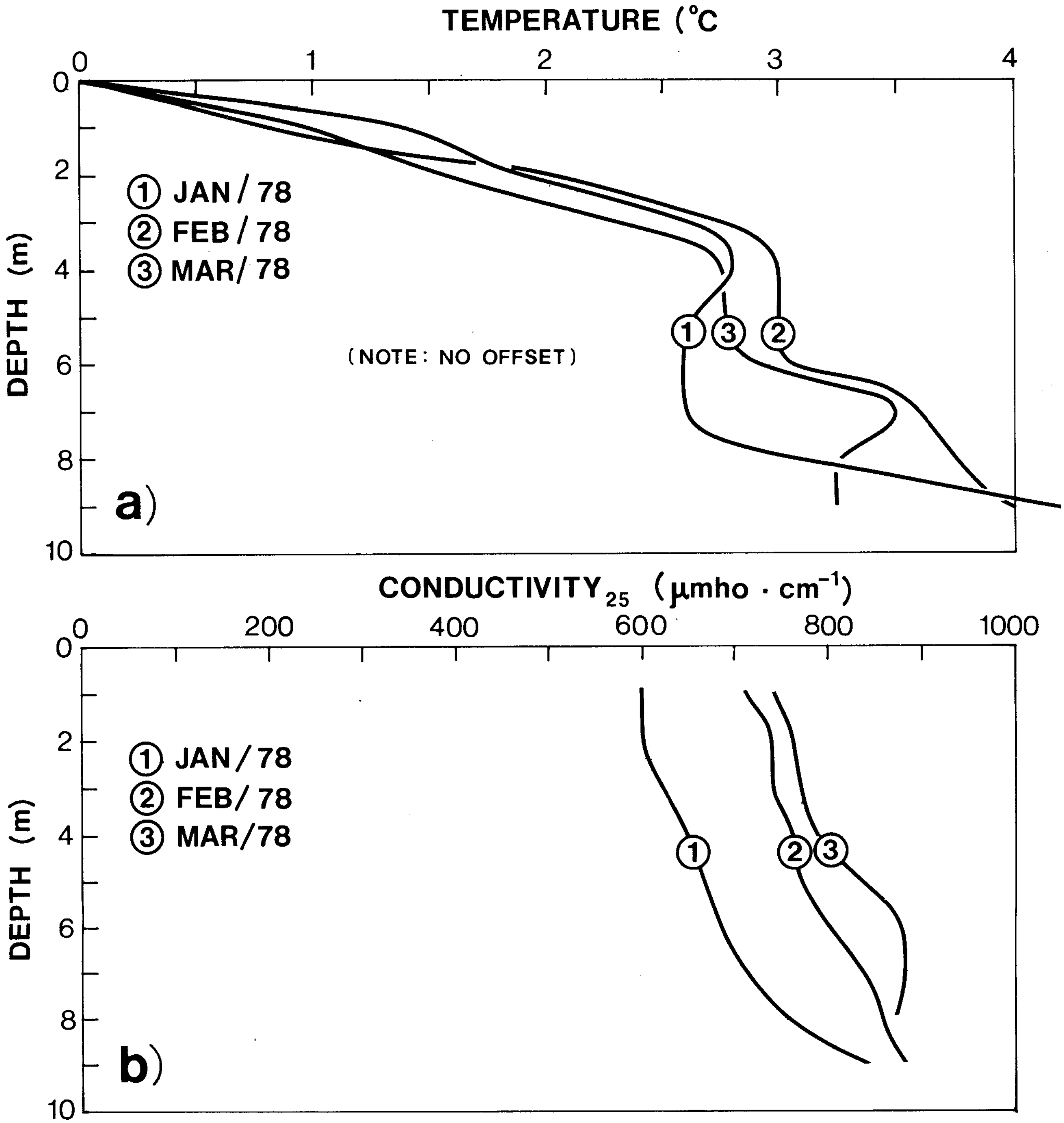
Winter. Vertical profiles of T and C_{25} during winter, 1978, are shown for Beaver Creek Basin (Figure 28) and Spillway Basin (Figure 29). Again, the effects of salt stratification are of interest. In both systems, the January profiles of temperature increase rapidly from 0°C at the ice-water interface to an intermediate-depth temperature maximum (T_{max}), decrease to a minimum (T_{min}), and finally increase again near the bottom. On the basis of temperature considerations alone this structure appears unstable; however,



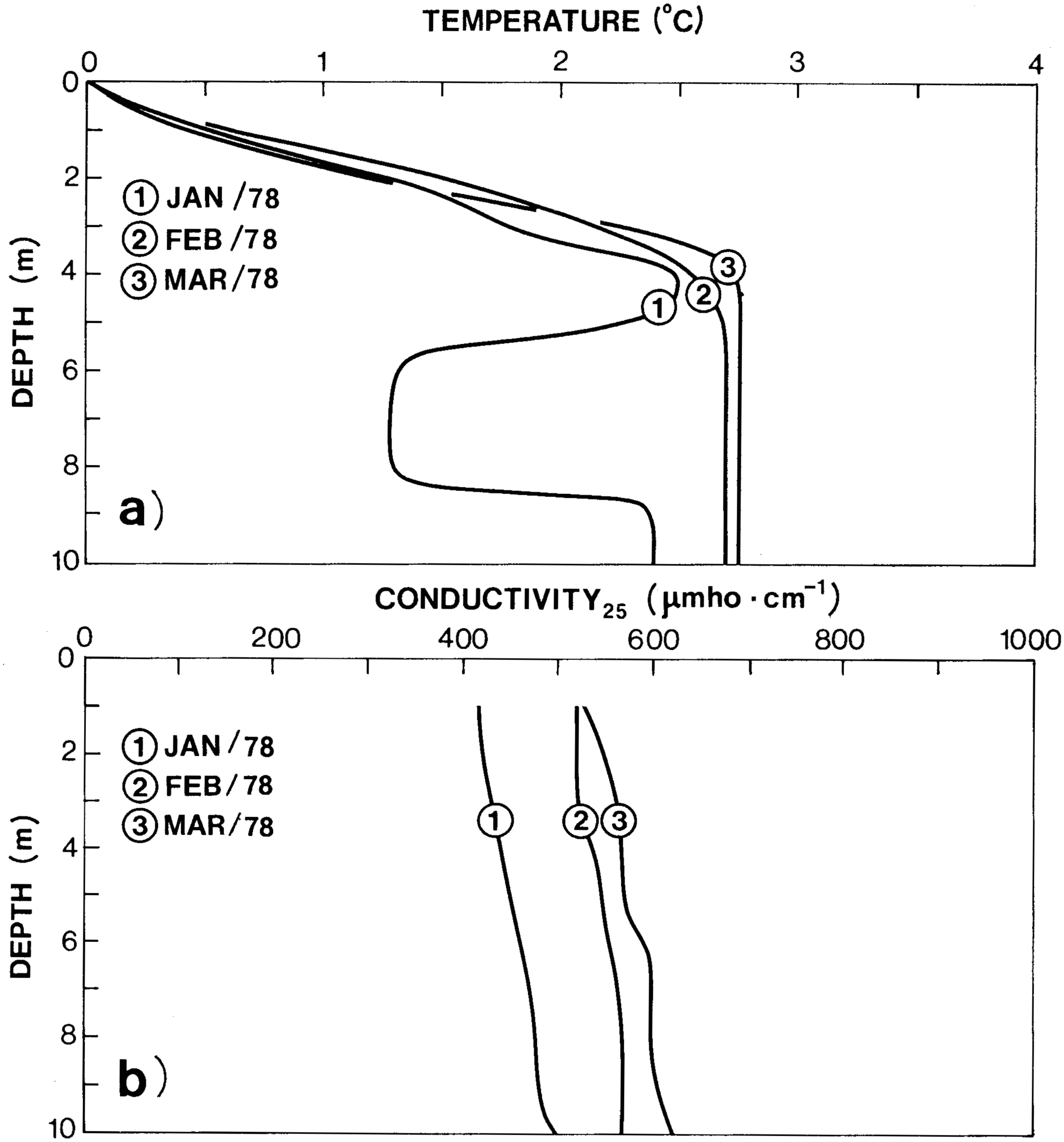
26: Horizontal map of conductivity-25 (bottom) in July 1977.



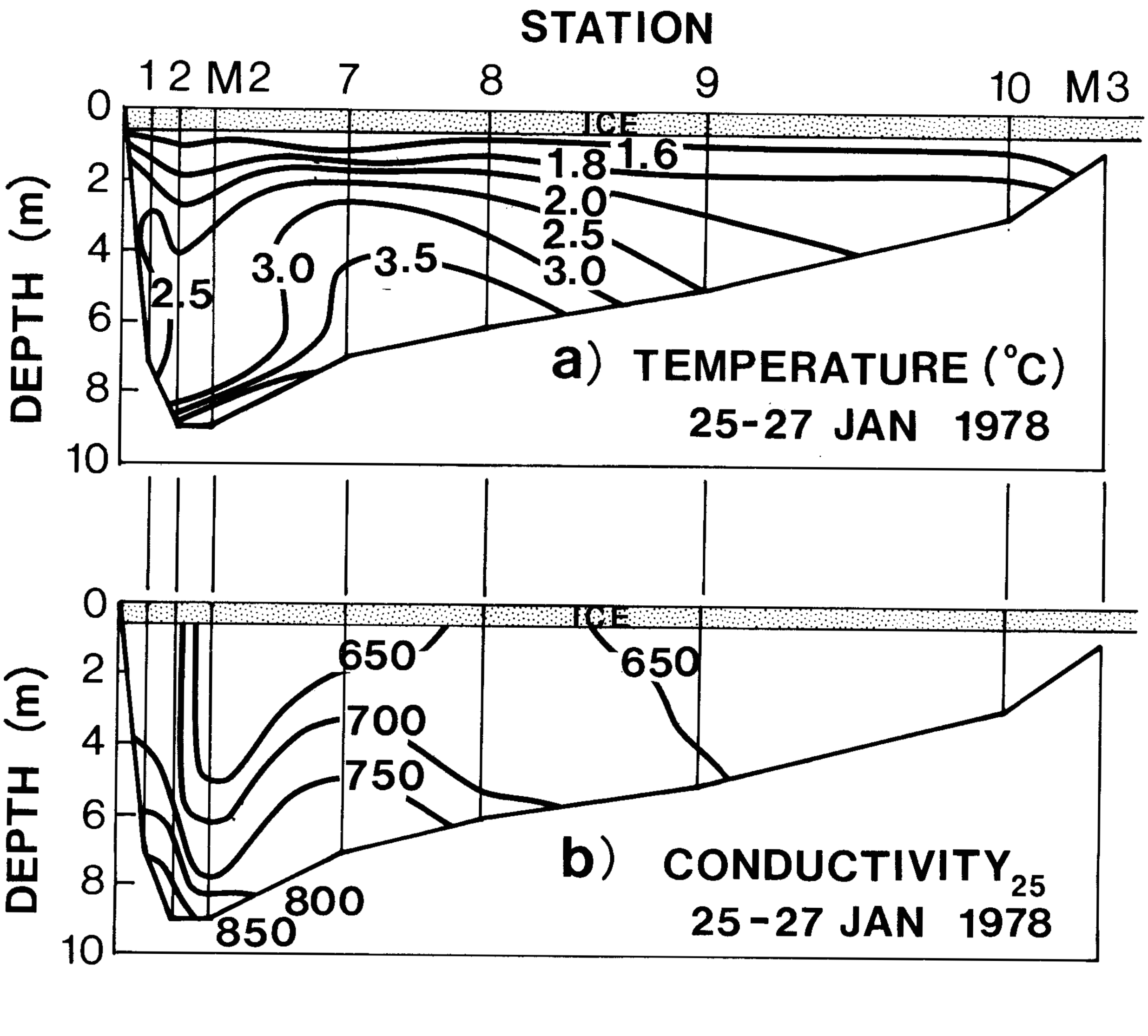
27: Horizontal map of conductivity-25 (bottom) in July 1978.



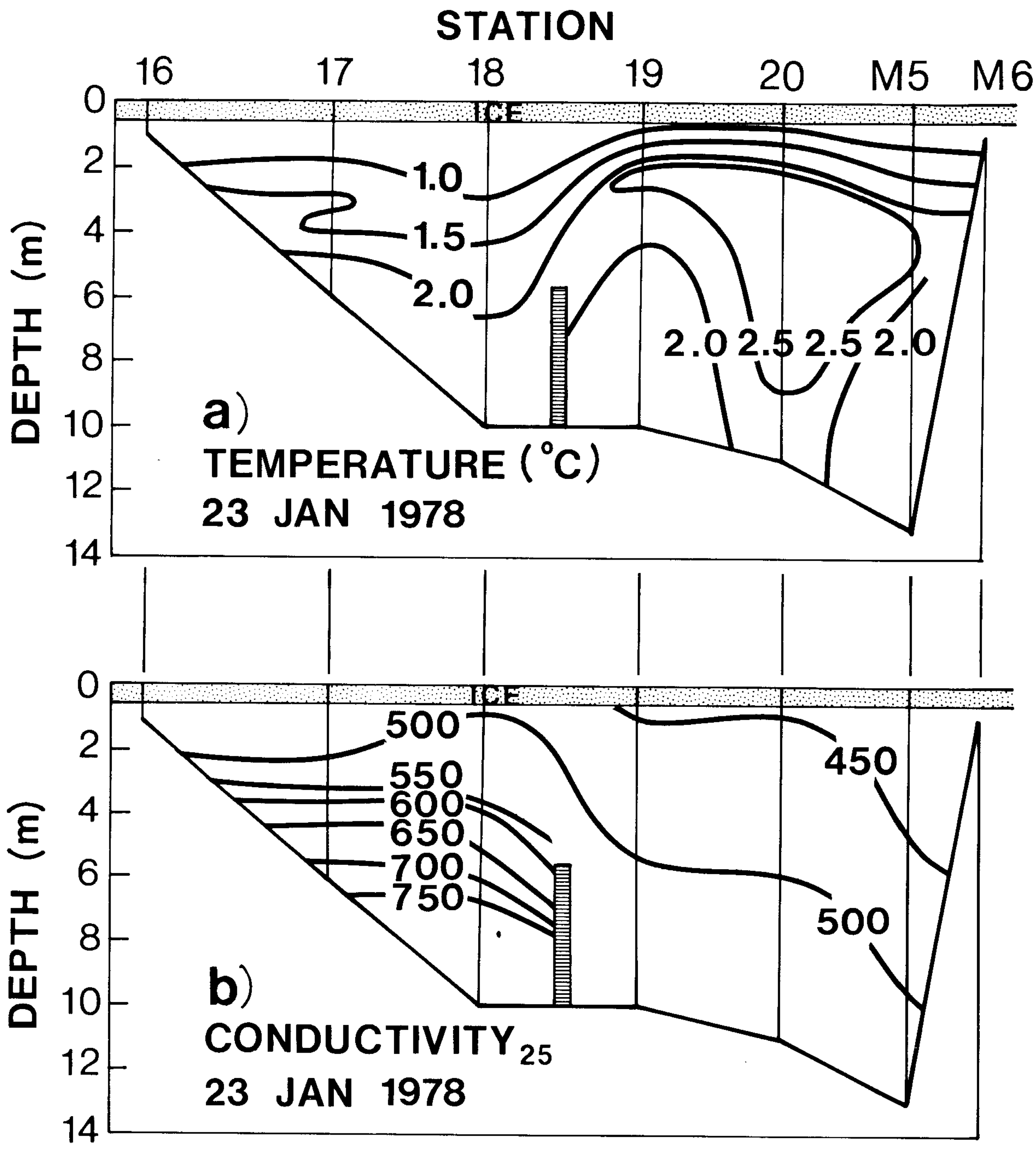
28: Vertical profiles of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, Winter 1978.



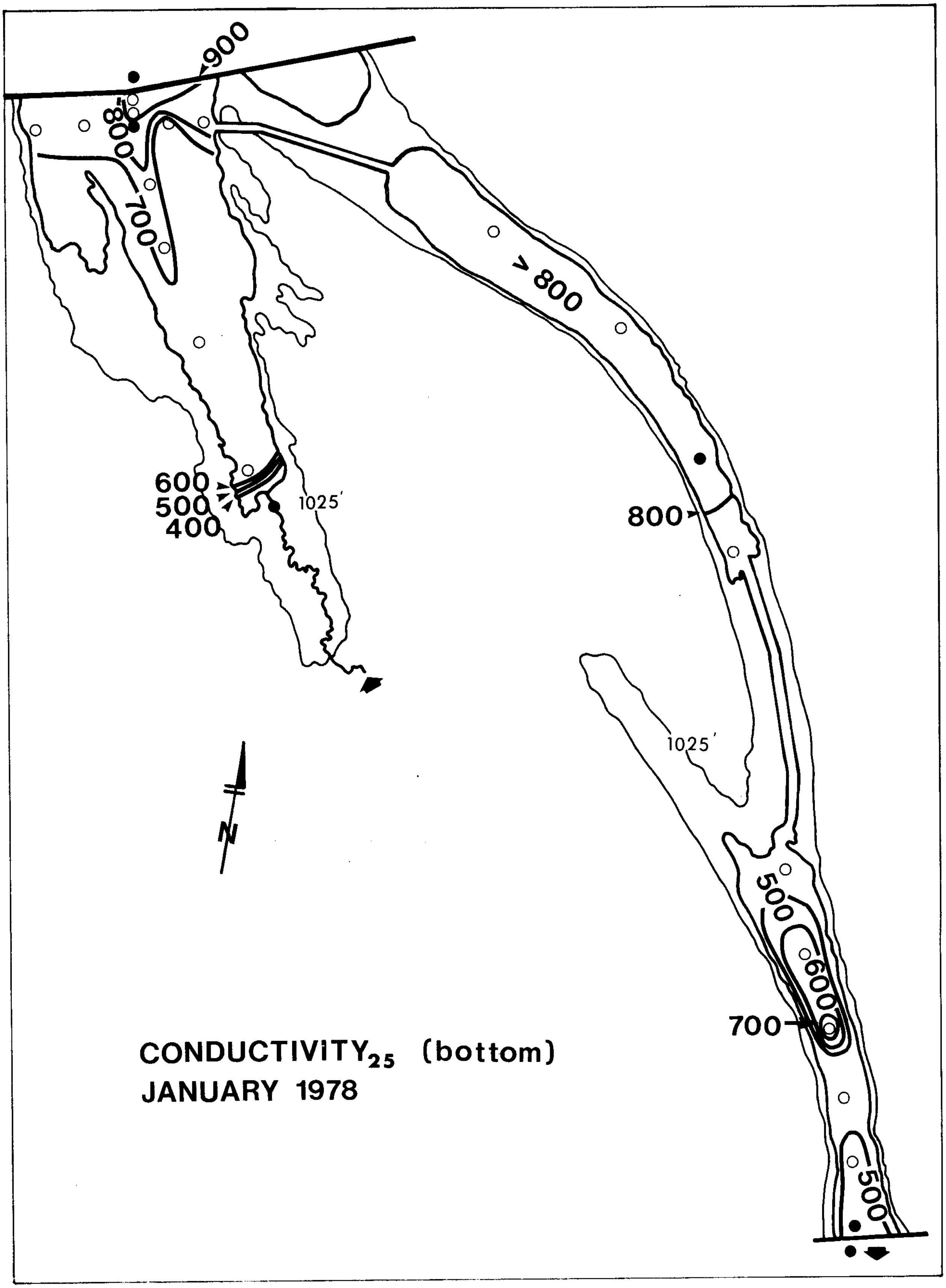
29: Vertical profiles of (a) temperature and (b) conductivity-25 in Spillway Basin, Winter 1978.



30: Longitudinal sections of (a) temperature and (b) conductivity-25 in Beaver Creek Basin, January 1978.



31: Longitudinal sections of (a) temperature and (b) conductivity-25 in Spillway Basin, January 1978.



32: Horizontal map of bottom conductivity-25 measurements in January 1978.

at low temperatures, water density is a very weak function of temperature (Hutchinson, 1957) and only a small salinity gradient is required to offset the destabilizing temperature distribution. Both basins show winter haloclines separating the intermediate-depth T_{max} and T_{min} layers.

One explanation for the unusual temperature structure noted above is that solar radiation penetrating the snow/ice acts to warm the underlying water toward the temperature of maximum density, particularly at shallow depths and near the lake bottom (Hutchinson, 1957; Hoare, 1968). In the absence of salt stratification this water would then sink; however, salt stratification is apparently sufficient to prevent sinking. If, on the other hand, solar radiation were to penetrate below halocline depth, then convective flow and warming of the lower water column may result (Ragotzkie and Likens, 1964). Some support for the notion of radiative warming lies in the fact that deep temperatures are sometimes observed to increase between January and March. Discounting any input of warm saline water this warming must be due to solar radiation (cf. Farmer, 1974 for theoretical treatment).

For completeness we have included winter sections of T and C_{25} (Figures 30-31) as well as a bottom C_{25} map for the system (Figure 32). Again, the effects of salt stratification and impoundment are evident. Since most of the salient features have already been noted, no further description is presented.

4. MASS BUDGET CONSIDERATIONS

In this section an attempt is made to formalize mass budget calculations for Beaver Creek Basin. The major aim is to estimate the flux of chloride into and out of the system at any one time (month) and on average (pumping season) in comparison to the observed change in content (cf. Dyer, 1973; Walin, 1977; Gardner and Kitchens, 1974, for discussions). This calculation is useful for two reasons. First, it provides a test of experimental design and/or data quality. For example, the experimental design provides no direct measurements of groundwater seepage - if this is significant in Beaver Creek Basin then any attempt to derive a mass balance should fail. The same is true if the surveillance cruises are too widely spaced in time to describe temporal changes, or if there is technical error in the data. Second, such calculations are a prerequisite for predictive numerical models; that is, if basic budgets - which are essentially zero-dimensional models - fail, then there is little hope for successful numerical modelling of the system.

Before describing the formulation, a basic goal should be set. Based on existing methodologies, mass balances for any material substance are difficult to obtain due to the difficulty in collecting reliable flow and ionic concentration measurements. Even when relatively uniform bodies of water are present, and a high density of flow measurements are made (i.e. current meters), precision greater than ±20% can rarely be achieved (Imberger et al, in press). In the present case (i.e. monthly time intervals, weak spatial coverage, indirect flow measurements, and sometimes questionable data), some error must be expected.

With the above limitations in mind we will proceed with the simplest possible chloride balance calculation. First, we consider Beaver Creek

Basin only. If the budget fails here, it is unlikely that it will hold for the whole system; besides, we have evidence that groundwater seeps into Spillway Basin. Second, we consider only the 1978 data owing to its overall higher quality. Third, we consider only the period subsequent to freshet (April-November). Finally, we assume the pumping rates reported by Syncrude represent the only inputs of chloride-rich water to the system.

Consider the chloride contained in Beaver Creek Basin and its concentration C^c at some time, t. The total mass of chloride M^c is then

$$M^c = \iiint_{V(t)} C^c(x,y,z,t)$$

where x, y, z are position co-ordinates. This mass may change with time due to inputs from Beaver Creek (F^c_{BC}), inputs from mine water (F^c_{MW}), and outflow via Ruth Lake Basin (F^c_{RL}). Hence, the mass balance can be written

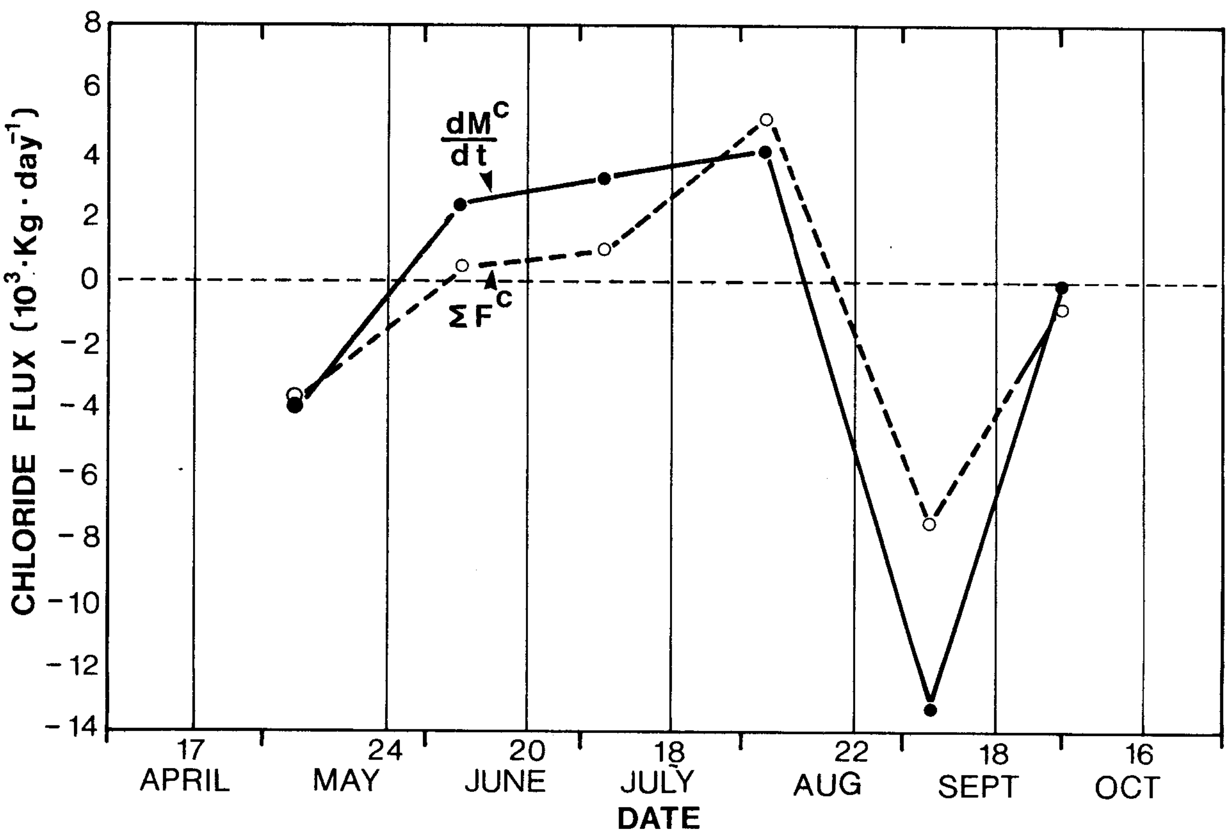
$$\frac{dM^c}{dt} = F^c_{MW} + F^c_{BC} - F^c_{RL}$$

Each individual flux F^c can be estimated as an integral value

$$F^c_i = \iint_{A(t)} U_i C^c_i dA_i$$

where U_i represents flow velocity and A_i the cross-sectional area of the inflow. In practice the integral of $U_i dA_i$ can be replaced by the flow rate (volume per unit time). In the present application, bi-monthly values of Beaver Creek streamflow and mine water discharge were used. In turn, these values are multiplied by the corresponding chlorinity levels interpolated from the monthly observations to yield the required flux estimate.

Independently, dM^c/dt can be calculated <u>internal</u> to the system by volumetrically integrating the monthly profiles and comparing one month to the next. This is done by multiplying the chloride content at each one metre interval by the volume of water contained in the corresponding interval, and then summing the contents. This assumes, of course, that chlorinity



33: Chloride budget calculations for Beaver Creek Basin.

Table 5. Chloride Budget Calculations - Summer 1978

Cruise Date	M^C (10^3 kg)	ΔM^C (10^3 kg)	Δt (days)	$\Delta M^C/\Delta t$ (10^3 kilogram per day)	F^C_{BC}	F^C_{MW}	F^C_0	ΣF^C
17 APR	325							
		-138	35	-3.94	0.60	0.38	-4.82	-3.84
24 MAY	187							
		63	26	2.42	0.33	2.36	-2.20	0.50
20 JUN	250							
		88	27	3.26	0.30	2.06	-1.35	1.01
18 JUL	338							
		134	33	4.06	0.18	7.39	-2.44	5.13
22 AUG	472							
		-344	26	-13.23	0.43	2.21*	-10.12	-7.48
18 SEP	128							
		-5	28	-0.18	0.43	4.43	-5.71	-0.85
16 OCT	123							
MEAN	260	-34	-	-1.27	0.38	3.14	-4.44	-0.92

isopleths are horizontal everywhere within the system and there is no volume change due to water level fluctuations. The test for the present formulation is that the sum of the fluxes for a given time period (ΣF_i^c) be equal to the change in content for that same period (dM^c/dt).

The results of this calculation (Figure 33, Table 5) are relatively good. Although individual values show some disagreement, the general trends for 1978 are very well depicted. For example, both curves model the spring dilution concurrent with freshet, the summer build-up following mine water discharge, and the sudden freshening due to runoff in autumn.

One may complain that the absolute values for individual months are not well represented. This is likely due not only to uncertainties in the data base but also the assumption that isopleths of chloride are everywhere horizontal. If chloride concentrations at a given depth near Station M2 were, in reality, higher than at corresponding depths further south, then this would suggest that the present estimates of dM^c/dt are too high. Indeed, this seems to be the case in Figure 33.

Integrated over the entire pumping season, the above agree to within 35%. This agreement is encouraging and leads one to suspect that the mass balance approach may prove useful in monitoring the reservoir system.

5. A FILLING-BOX MODEL OF CHLORIDE DISPERSION

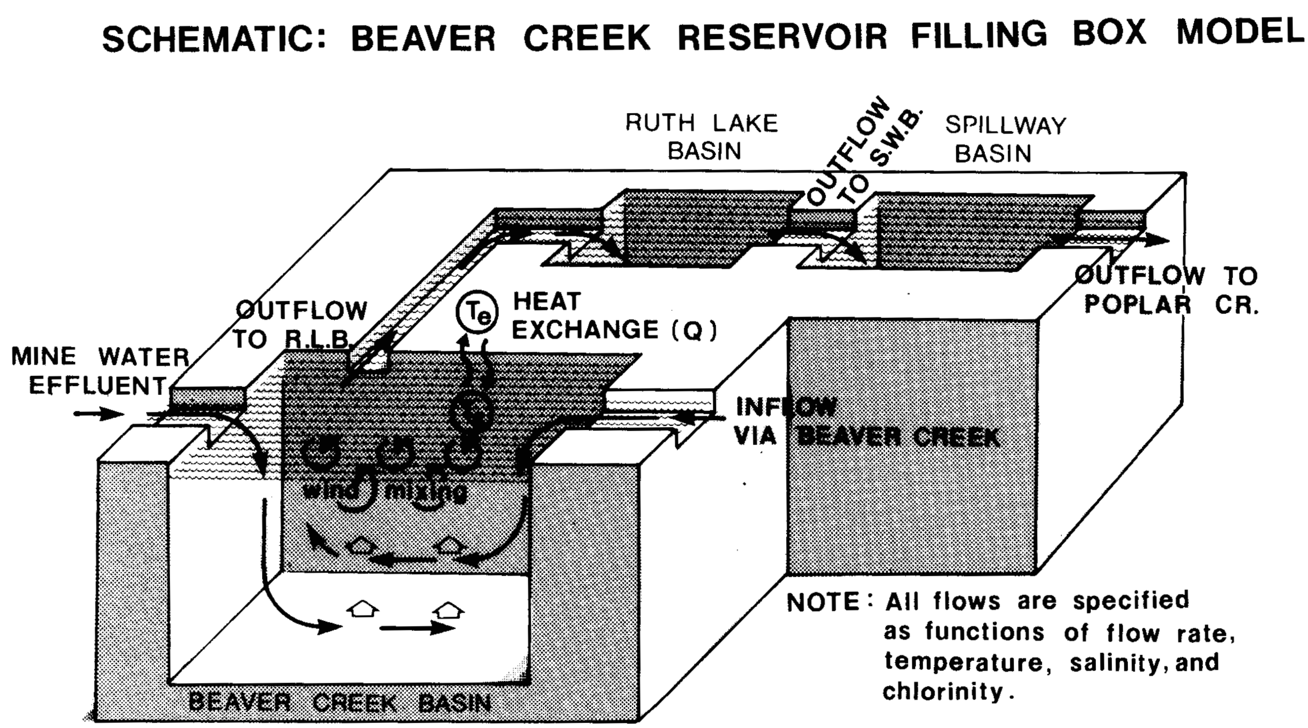
5.1 Rationale

We now turn to the problem of modelling - for predictive purposes- the dispersion of chloride-rich water within the diversion system. The previous report (Carmack, 1976) considered two extreme-case models of chloride dispersion: complete mixing and zero mixing. The truth must lie somewhere between these extremes (Fischer, 1976; Rumer, 1977). If we are to predict chloride values with any degree of accuracy, account must be made of the way properties vary in each basin, especially in the vertical. This will require the inclusion of some simplified dynamical considerations.

A model well suited to the present purpose is the so-called "filling-box" model (Manins, 1973; Killworth and Carmack, 1979). Its structure is summarized in Figure 34. Each basin is considered as a container of fluid fed by one or more sources. In Beaver Creek Reservoir, these sources take the form of the Beaver Creek diversion (relatively fresh water) and the input of saline groundwater. In Ruth Lake and Spillway Basins, the sources are the outflows from Beaver Creek Reservoir and Ruth Lake, respectively.

These sources enter as dense plumes or gravity currents, and are assumed to fall vertically at one end of the basin (both ends in the case of Beaver Creek Reservoir). They fall to a depth determined by the dynamics and then spread out horizontally at that depth (Hamblin and Carmack, 1978) forcing the lake water above them to upwell, and eventually to leave at the lake's outflow.

To our knowledge, the present formulation is quite unique in reservoir dispersion applications. The model requires only field measurements of input characteristics (flow rate, temperature, salinity, and chlorinity) and



34: Schematic of the filling-box model.

reservoir surface temperature. It requires no measurements internal to the system (other than for verification), no estimates of turbulent diffusion coefficients, and no meteorological (wind stress of heat flux) measurements. All of the above are eliminated by the use of simple physical assumptions based on the observations described earlier in this report.

5.2 Model Assumptions

Based on data described earlier, we make the following physical assumptions:

1. Within each basin, and within each plume, all properties are considered only as functions of the downward co-ordinate, z, and time, t. All horizontal variation is averaged out. This approximation implies that plumes spread out horizontally in a time shorter than the natural time scale of the lake. Estimates of spreading rates based on Froude number criteria (cf. Orbob, 1969) confirm this assumption.
2. Each plume is in steady equilibrium with ambient basin water. This is justified, as a plume falls vertically in about one hour, compared with the longer time scales of the basins.
3. The plumes experience no turbulent entrainment or drag. Laboratory simulations, large lakes, and oceanic observations all confirm that low entrainment and friction coefficients are applicable to such plumes (Killworth, 1977). This, together with the small depths involved, confirms this assumption.
4. Mixing within each basin is due to two independent sources: static instability (when water of a greater density overlies water of a lesser) and wind stirring near the surface (cf. Imberger et al, 1978; for discussion of mixing effects). This greatly simplifies

the problem, at the cost of producing somewhat more jagged profiles than would be obtained using (guessed) turbulent mixing coefficients.

5. The density ρ of the water depends on salinity S and temperature T, and is given by

$$\rho = \rho_o[1 + \beta S - \alpha(T - 4)^2] \tag{1}$$

where

$$\beta = 7.5 \times 10^{-7} \ (\text{ppm})^{-1} \tag{2}$$

$$\alpha = 6.94 \times 10^{-6} \ (°\text{C})^{-2} \tag{3}$$

and ρ_o is a reference density, equal to 1 g cm^{-3}. Although chloride content C is needed for predictive purposes, it is treated in this model as a passive contaminant (but because ρ depends on T and S, these too must be predicted by the model).

6. Ice exists at the surface when the lake's temperature drops below 0°C at the surface.

7. Groundwater seepage effects are neglected.

5.3 Model Formulation

The Plumes. The equations describing the descent of each plume are those of conservation of mass, momentum, heat, chloride and salinity (Turner, 1973) and may be written under the above assumptions as:

$$\frac{\delta}{\delta z}(aw) = 0 \tag{4}$$

$$\frac{\delta}{\delta z}(aw^2) = \frac{ga}{\rho_o}(\rho - \rho_\ell) \tag{5}$$

$$\frac{\delta}{\delta z}(awT) = 0 \tag{6}$$

$$\frac{\delta}{\delta z}(awC) = 0 \tag{7}$$

$$\frac{\delta}{\delta z}(awS) = 0 \tag{8}$$

where the local cross-sectional area of the plume is $a(z,t)$, its downward velocity $w(z,t)$, g is the acceleration due to gravity, and $\rho_\ell(z,t)$ the lake density at that depth. These equations may be integrated to yield

$$aw = F(t) \tag{9}$$

$$\frac{\delta}{\delta z}(w^2) = 2g\{\beta(S - S_\ell) - \alpha[(T - 4)^2 - (T_\ell - 4)^2]\} \tag{10}$$

$$T = T_s \tag{11}$$

$$C = C_s \tag{12}$$

$$S = S_s \tag{13}$$

where $F(t)$ is the volume flow rate of the plume, and T_s, C_s, S_s are the inflow values of T, C, S, respectively. If w is specified at the surface (because a_s is known), (10) may be integrated downwards until the value of z where w vanishes is found. At this level, the plume spreads out. Alternatively, w may still be non-zero at the bottom (if the plume is denser than its surroundings, or if it possessed enough momentum initially). In this case, the plume spreads out at the bottom. Below any plume, its velocity is defined to be zero.

The Basins. The equations describing lake quantities are now straightforward. At a depth z, there can be no net flux of water downwards, thus

$$\Sigma aw + AW = 0 \tag{14}$$

where Σ denotes a sum over all plumes in the basin (two for Beaver Creek, only one elsewhere), $A(z)$ is the lake area at that depth, and $W(z,t)$ is the vertical velocity (actually upward) in the basin. Below the lowest plume, then, all w's are zero and hence W vanishes also (the water is quiescent). Equation (14) still holds at the surface: $A(0,t)W(0,t)$ represents the outflow to the next basin, to keep the filling-box from overfilling.

Conservation of heat, chloride and salinity within the basins then yields (except at plume outflows, for which see below)

$$\frac{\delta T_\ell}{\delta t} = -W\frac{\delta T_\ell}{\delta z} + \sigma_T + q \tag{15}$$

$$\frac{\delta C_\ell}{\delta t} = -W\frac{\delta T_\ell}{\delta z} + \sigma_c \qquad (16)$$

$$\frac{\delta S_\ell}{\delta t} = -W\frac{\delta S_\ell}{\delta z} + \sigma_s \qquad (17)$$

where the terms in W represent upward advection by the vertical velocity and the σ terms represent vertical mixing. q is a surface heating or cooling in the top metre by atmospheric processes, equal to Q(t)/1 m; Q(t) is a surface heat flux per unit area, divided by the specific heat of water. Below the lowest plume, then, lake variables only change due to mixing.

Mixing in the vertical occurs when the wind blows and stirs the top five metres. It occurs year-round except under ice conditions. Mixing also occurs when the vertical density gradient ρ_ℓ becomes negative (recall z is downward). In both cases, mixing is accomplished by replacing T_ℓ, C_ℓ and S_ℓ over the mixing region by their area-weighted averages. This is done automatically for wind-mixing, whereas the areas of static instability must be examined at every time step.

At the level where a plume spreads out, (15)-(17) must be modified. The plume is assumed to spread out uniformly in a layer of thickness Δz equal to 0.5 m. Conservation of heat over this layer then gives

$$\frac{\delta T_\ell}{\delta t} = -W'\frac{\delta T_\ell}{\delta z} + \frac{F(T-T_\ell)}{A\Delta z} \qquad (18)$$

where W' is the vertical velocity due to other plumes in the basin, and F is the relevent plume flux. Similar expressions hold for C_ℓ and S_ℓ.

5.4 Running the Model

The above equations may be integrated straightforwardly via a finite-difference formulation in z and t (a 0.5 m vertical resolution and a 0.5 day time step are adequate). A year's integration takes only 10-15 seconds on modern computors.

Initial conditions must be supplied. The initial conditions are straightforward: T_ℓ, S_ℓ and C_ℓ must be given as functions of depth for each lake at time zero (usually set to zero for long integrations).

Boundary conditions must also be supplied. For Ruth Lake and Spillway Basin, the plume inflow quantities are given by the (calculated) outflow from the previous basin. For Beaver Creek, the inflow quantities (mine outflow and river) must be given as functions of time. Additionally, Q(t) must be specified. Lacking any meteorological data regarding heat transfer, Q(t) is taken for each basin as

$$Q(t) = 5 \times 10^{-4} \, [T_e - T_\ell(0,t)] \qquad (19)$$

in (°C) cm sec^{-1}. T_e, the equilibrium temperature, is assumed to be

$$T_e = [10 - 12\cos(2\pi t/12)]°C \qquad (20)$$

where t is measured in months from January 1. If T_ℓ is less than 0°C, not only is there no mixing (except for static instability) but also the ice is assumed a perfect insulator (so Q(t) = 0). This crude assumption is obviously poor for long periods of time, but we have no data to improve it.

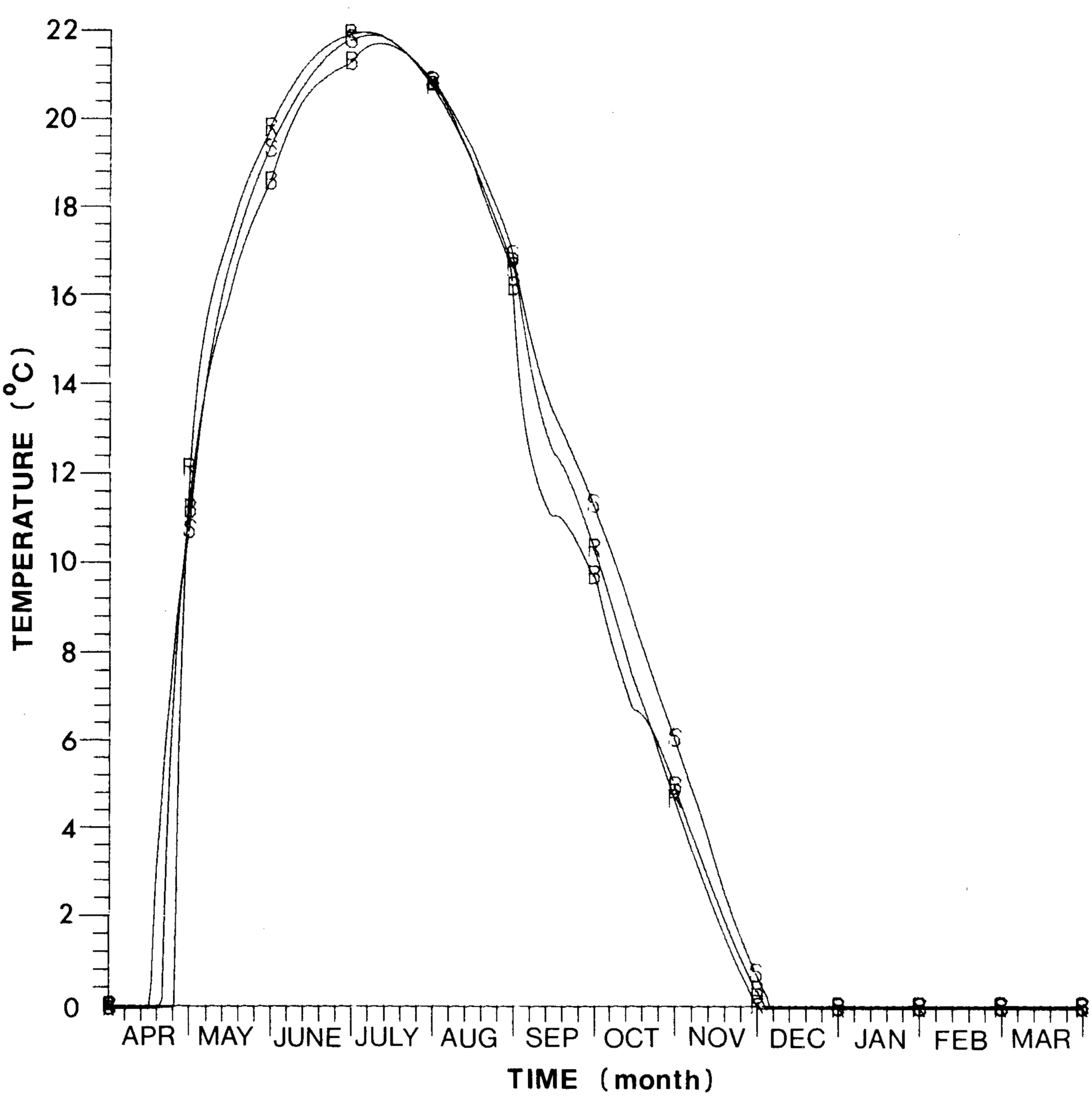
5.5 Model Calculations

Two sets of calculations have been performed as a test of the model. The first attempts a simulation of 1978 while the second is based on longer term values; only the 1978 is described in this report. Input conditions were taken as 1978 values, either monthly or semi-monthly, with mean values taken where the 1978 values were dubious or missing. Instead of starting the calculation with observed values (which requires field measurements), the initial conditions were zero T, C and S in all basins; the model was then run for one year. At this stage, at the beginning of April, the output is then used to initialize the model. Thus, the simulation is that of a cyclic situation in which every year is 1978.

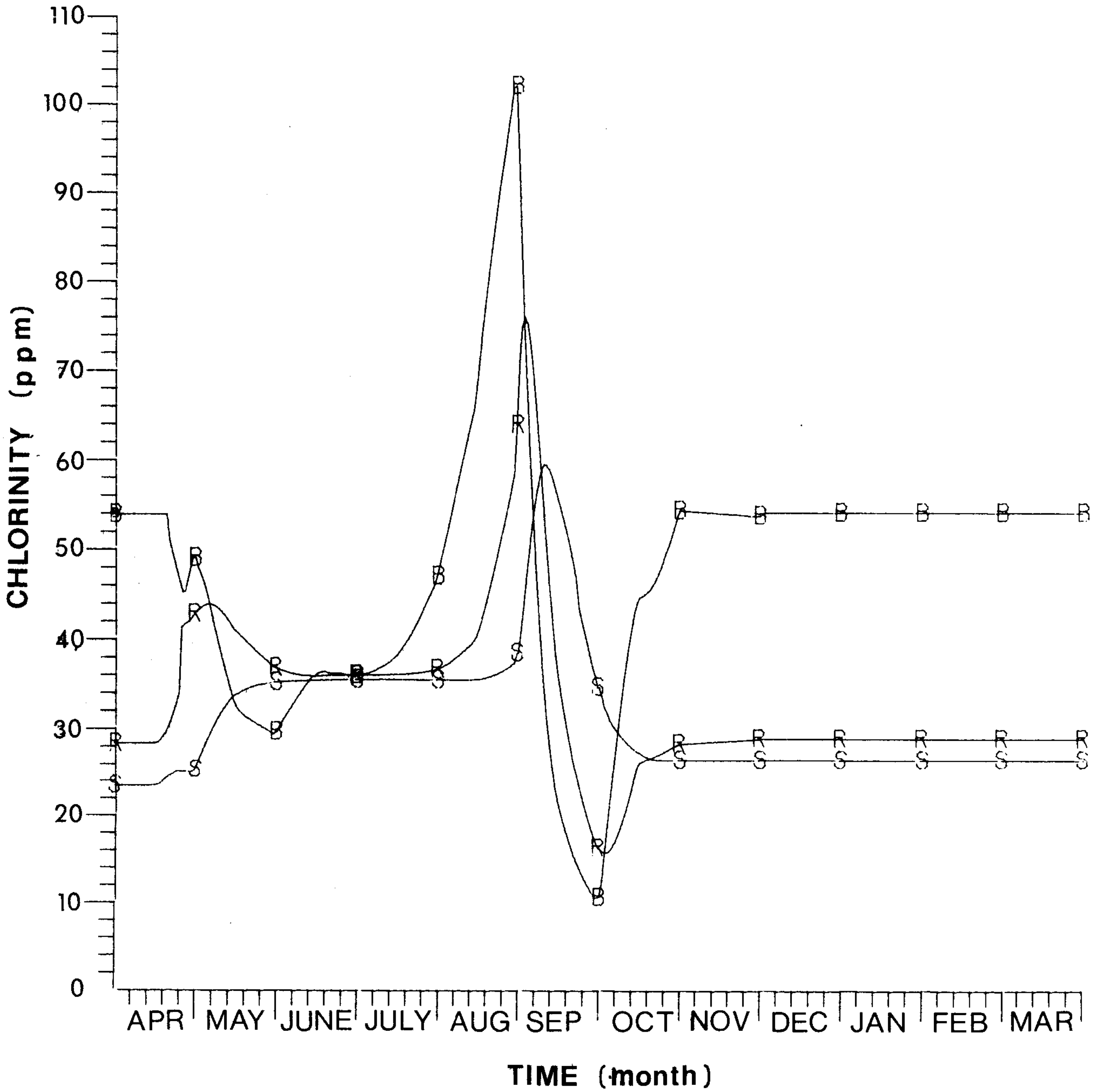
The results are shown in Figures 35 to 38. The "jagged" behaviour is due to the lack of turbulent diffusion and the one-month means used in the calculation.

The surface temperatures of all three basins are similar throughout the year, reaching just short of 22°C in July. Freezing (ice) occurs from December to April. In April, there is warm (6°C) water at depth in Beaver Creek Basin (unlike the data, which show colder values - a fault again of the guessed values for surface heating). By May, however, the basin heats up (to 11°C) leaving cold, dense water at depth. Throughout summer, the trend of weak top-to-bottom temperature differences observed in Beaver Creek Basin is well reproduced: on July 1, for example, the surface and bottom temperatures are 21 and 13°C, respectively, compared with 21 and 5°C for Spillway Basin. During autumn, there is rapid cooling: by November 1, the temperature is nearly 5°C at the surface, 6-7°C at depth. The latter water remains through winter, while the surface freezes.

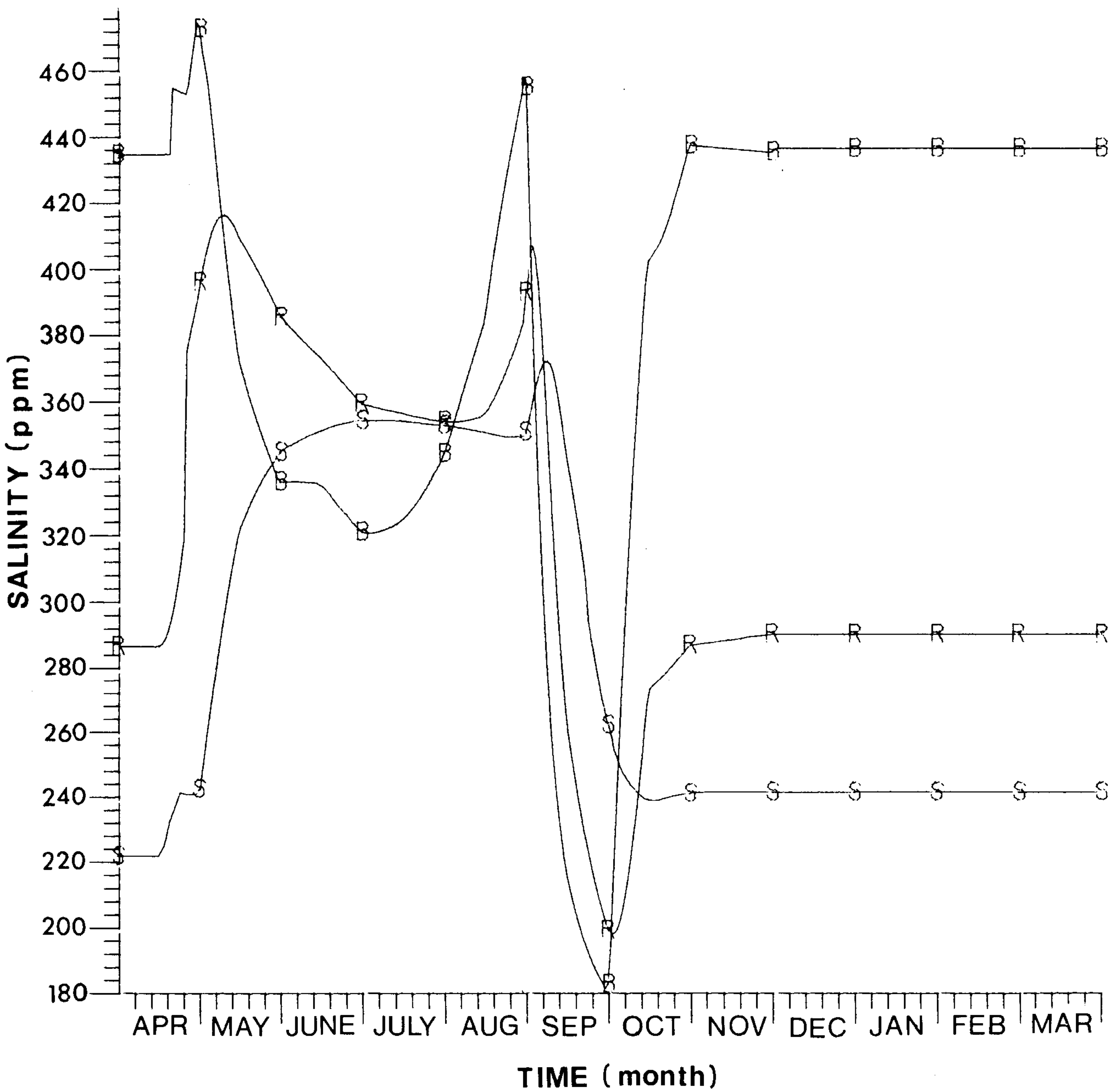
Of interest is the chloride distribution. Beaver Creek Basin begins with a strong vertical gradient of chloride, from 54 ppm at the surface to 600 ppm at the bottom. This value is higher than that observed in April, 1978; it results from the (mean) November mine input used to generate the cyclic solution, and is actually a prediction of late winter, 1979. The comparison between modelled and observed chloride values improves as the



35: Numerical simulations of the Beaver Creek Diversion System showing predicted outflow properties for Beaver Creek (B), Ruth Lake (R) and Spillway (S) Basins for 1978; (a) temperature, (b) chlorinity and (c) salinity. Time (in months) is shown on the lower axis beginning April 1.


110
100
90
80
70
60
50
40
30
20
10
0
CHLORINITY (ppm)
APR
MAY
JUNE
JULY
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
TIME (month)

35 (b)


SALINITY (ppm)
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
APR MAY JUNE JULY AUG SEP OCT NOV DEC JAN FEB MAR
TIME (month)

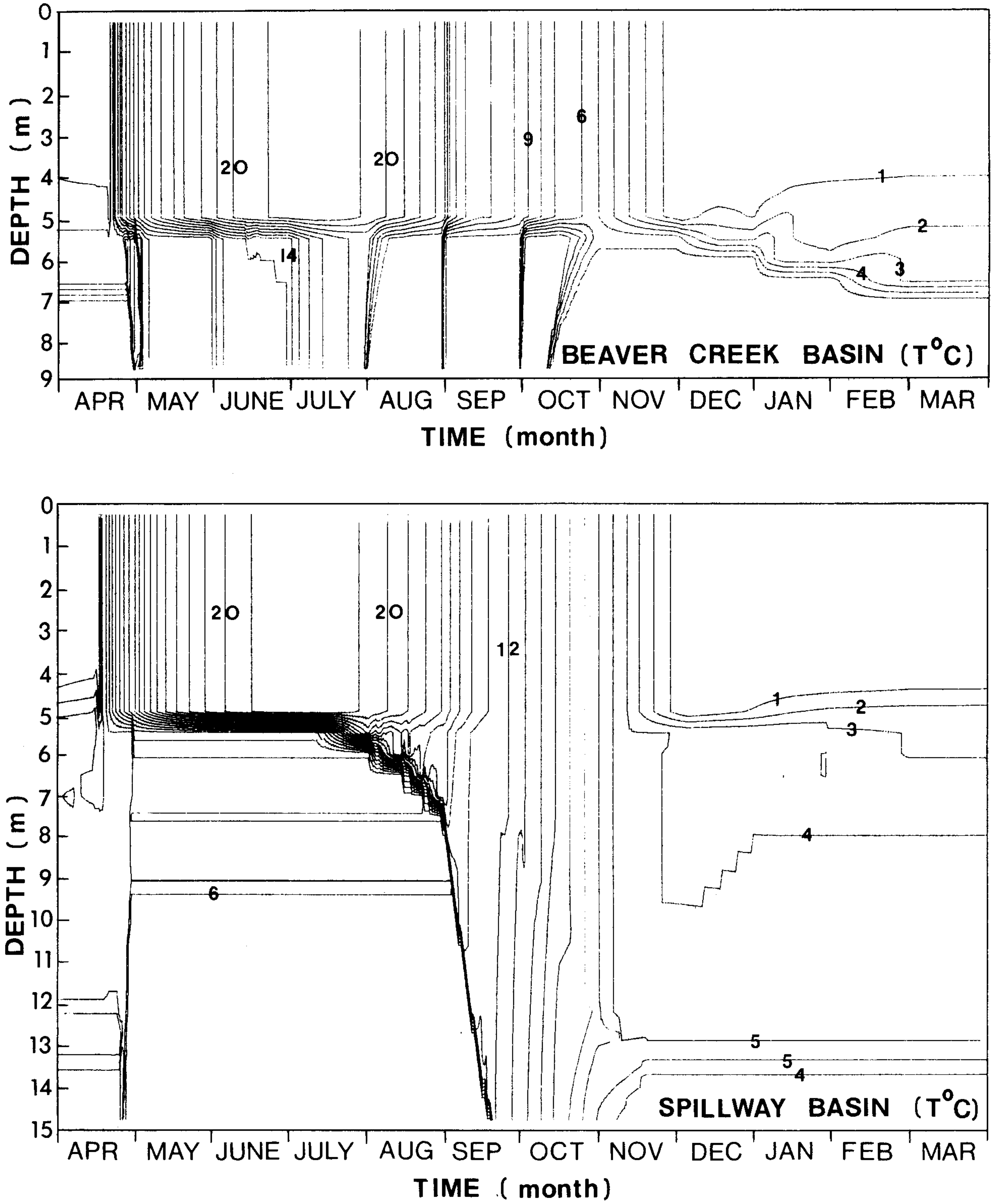
35 (c)

much fresher spring inputs from the river reduce chloride levels at the bottom to less than 100 ppm by May 1.

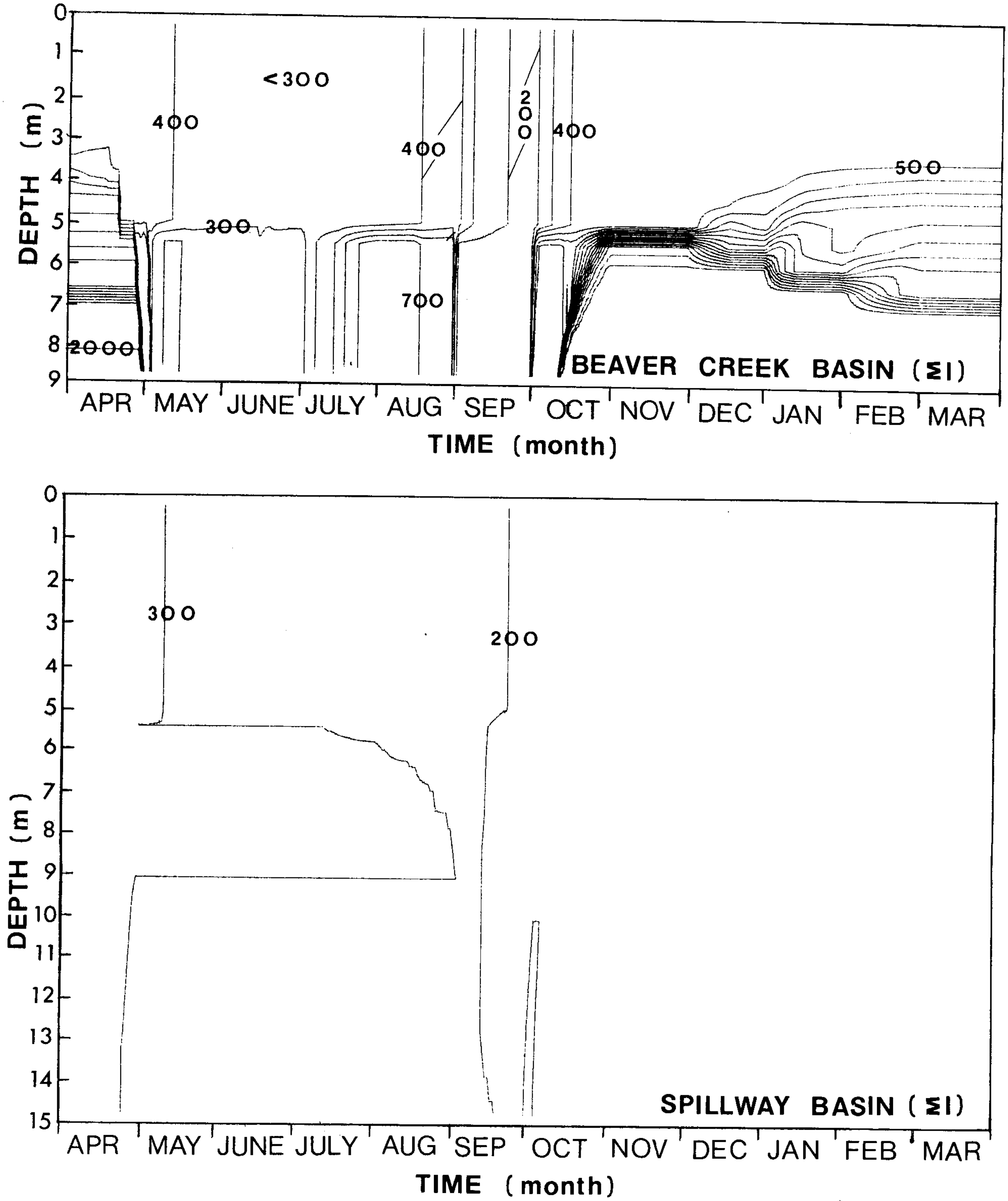
The mine input now rises, to 286 ppm, but the rapid increase in lake temperature means that the cold river water sinks to the bottom (because it is denser than the lake) and flushes the mine effluent away. Comparison with data shows that this did not occur in reality. This discrepancy results from the necessity of guessing the lake's surface heat input. Were the lake cooler (as was the case in reality), the flushing action would not have occurred, because the river plume would tend to remain nearer the surface, due to its density being similar to that of the lake. It is thus essential that the thermal structure be obtained correctly, as it has important implications on the system's response. Still, the overall chloride content is fairly well represented.

The increase in surface and bottom chloride values during summer is well modelled (bottom values of more than 250 ppm, surface values of 100 ppm) until September 1. The decrease in near-bottom chloride levels just before September is due to flushing by the cold (11.5°C) river inflow. The large rainfall in September now acts to flush the entire basin, although towards October (based on our limited data for this period), chloride begins to build up at depth. This increases to the 600ppm value in November which remains throughout the winter. Surface values remain below 100 ppm.

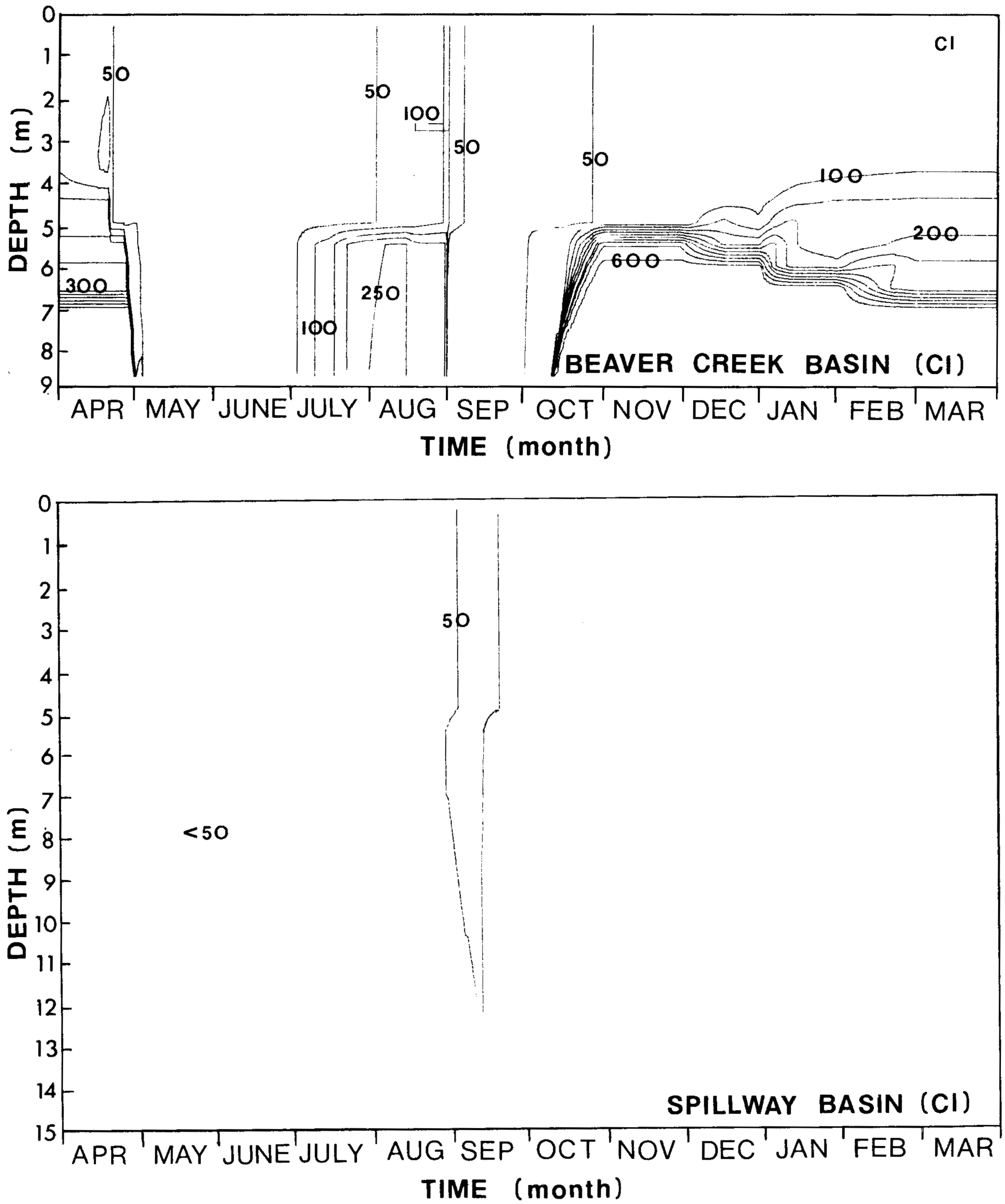
In contrast, the variation within Spillway Basin is much weaker. In April, surface values are 23 ppm, at depth 28 ppm. Bottom values increase to 40 ppm, surface to 35, then 38 ppm (a little less than observed) during summer. Between September and October, the rainfall flushing reduces bottom values to 16 ppm, followed by an increase into winter, giving surface and bottom values of 26 ppm and 28 ppm, respectively.



36: Numerical time-depth diagram for temperature in (a) Beaver Creek Basin and (b) Spillway Basin.



37: Numerical time-depth diagram for chlorinity in (a) Beaver Creek Basin and (b) Spillway Basin.



38: Numerical time-depth diagram for salinity in (a) Beaver Creek Basin and (b) Spillway Basin.

The salinity picture is also quite reasonable. In Beaver Creek Basin, bottom values begin high in April (a left-over from November) and then decrease rapidly to 600 ppm in May (surface level, 400 ppm). During summer, surface levels increase and bottom levels decrease (this discrepancy occurring uniformly in T, C and S). A build-up to over 700 ppm (cf. 1000 ppm observed) occurs in August with large mine outflows. This drops to 250 ppm by September, although the flushing by rainfall is then countered by 2000 ppm mine outflow in October, producing surface values of 400 ppm and bottom values of 2000 ppm during winter.

Again the variation is less in Spillway Basin. In April, values are 220 ppm at the surface, 280 ppm at depth. These increase during summer to 350 ppm at the surface and 370 ppm at depth, very much as observed. By October 1, there is a reversal; 260 ppm at surface, 200 ppm at depth (due to outflow from Ruth Lake reaching the bottom). By winter, surface and floor values are 240 ppm and 280 ppm as before.

Thus - within the limitations imposed by our lack of knowledge of meteorological conditons - the fit to data is quite reasonable and supports the hypothesis that the model can be used as a predictive tool.

6. SUMMARY AND CONCLUSIONS

In this two-year study of the dispersal of saline groundwater in the Beaver Creek Diversion System, we have attempted to: a) critically evaluate the overall quality and usefulness of the physical and chemical data base; b) describe the salient trends in stratification and mixing; and c) model, via mass budget and numerical simulation, the dispersion of chloride-rich mine water within the system.

With regards to mixing, the reservoir has behaved much as predicted by Carmack (1976, section headed 'Hypothetical mixing history'). That is, mixing appears to be dominated either by the stirring action of the wind (upper 4-5 m) or by convective flow. The dense, saline mine water effluent generally sinks rapidly to depth and settles in depressions in the pre-impoundment stream channel. Owing to the depth and sheltered nature of water within these depressions, the effects of wind stirring are significantly reduced allowing halocline development. However, convective flows during periods of overturn (especially in autumn) are effective in reducing vertical stratification.

Based on available information, we can formulate a reasonable pattern of effluent dispersion during a so-called typical year. Bear in mind, however, that these views are based on only two years of observations, and that one of these years (1978) was highly atypical.

Late Winter. Prior to ice break-up and convective overturn, there is a build-up of high salinity water, probably due to groundwater seepage. This water may be either low (i.e. 1976) or high (i.e. 1978) in chlorinity. The high salinity water imponds at depth in Beaver Creek Basin. There is very little vertical mixing of this water into the surface layer since the ice cover prevents wind mixing. Subsequently, this water does not appear to spread into Ruth Lake Basin and Spillway Basin.

Spring. Three sequential processes affect the dispersal of saline groundwater in spring: loss of ice cover exposes the surface layers to wind-mixing; convective overturn effectively mixes the entire water column; and increased streamflow serves to flush the reservoir and lower the overall concentration of salt. This trend is observed throughout the reservoir, but is most dramatic in Beaver Creek Basin.

Summer. The onset of temperature stratification acts to inhibit vertical mixing. The natural streamflows enter above the pycnocline leading to increased flushing of the surface layer (i.e. decreased residence time), and vice versa below the pycnocline. Owing to its density, saline groundwater tends to impond in the deepest portions of the basin leading to buildups at depth of chlorinity and salinity. The spread of mine effluent through the system is generally slow, since interbasin exchange takes place via surface flows from one basin to another.

Autumn. Hydrological and limnological conditions in autumn play an important role in mine effluent dispersal. For example, Carmack (1976) called attention to the possibility of a gradual, saw-tooth build-up of chlorinity from one year to the next. This pattern appears to have been realized up until September, 1978, when the system was effectively flushed by high runoff combined with convective overturn. We must conclude from this experience that interannual variations may completely overwhelm any established long term trends.

To date, the diversion system appears to have served as a 'mixing machine' for mine water effluent without serious threat to the aquatic environment, either in terms of outflow chlorinity levels or on the basis of temporal and spatial distributions within the system. In terms of long-range conditions, however, we cannot say whether or not a gradual "sawtooth' build-up will occur (cf. Carmack, 1976) since interannual variations in streamflow are capable of disrupting long term trends. It is obvious that the reservoir is most efficient as a mixing machine during periods of high runoff, especially if such periods coincide with convective overturn.

Certain questions remain unanswered. How important is groundwater seepage? There is evidence to suggest that seepage occurs but we have no information on the quantity of water involved. What causes the late winter salinity increase in Beaver Creek Basin? Thus far our data yields conflicting reasons for the observed build-up. What are the effects of intermittent pumping operations on chloride distributions? Here we lack adequate temporal coverage to discuss this problem; however, since no 'overall' problems have been observed, we must assume intermittent pumping is not a serious concern to water quality. Finally, how important are interannual fluctuations in surface runoff to safe disposal operations? Certainly we have seen that 1978 was a "good" year for the disposal of mine water - would effects be equally dramatic (in a negative sense) during a particularly dry year? Such questions as this could be probed with further field and/or modelling efforts, but are beyond the scope of this report.

REFERENCES

BOYLE, E., R. Collier, A. T. Dengler, J. M. Edmond, A. C. Ng, and R. F. Stallard. 1974. On the chemical mass balance in estuaries. *Geochimica et Cosmochimica Acta,* 38:1719-1728.

CARMACK, E. 1976. Physical limnology of saline water disposal in the Beaver Creek Diversion. *Unpublished report to Syncrude Canada Ltd.*

CARMACK, E. C. 1979. Combined influence of inflow and lake temperatures on spring circulation in a riverine lake. *Journal of Physical Oceanography* 9:422-434.

CARMACK, E. C., C. B. J. Gray, C. H. Pharo, and R. J. Daley. 1979. Importance of lake-river interaction on seasonal patterns in the general circulation of Kamloops Lake, British Columbia. *Limnology and Oceanography* 24:634-644.

COWARD, J. M. and D. Crawford. 1977. Surface Water Hydrology of the Syncrude Mine Area. *Syncrude Canada Ltd.* 133 p.

DYER, K. R. 1973. Estuaries: a physical introduction. *Wiley* 140 p.

FARMER, D. M. 1975. Penetrative convection in the absence of mean shear. *Quarterly Journal of the Royal Meteorological Society* 101:869-891.

FISCHER, H.B. 1976. Mixing and dispersion in estuaries. *Annual Review of Fluid Mechanics* 8:107-133.

GARDNER, L. R. and W. Kitchens. 1978. Sediment and chemical exchanges between salt marshes and coastal waters. *In*: B. Kierfve (ed.) Estuarine Transport Processes. *Wiley* 191-208p.

HAMBLIN, P. F. and E. C. Carmack. 1978. River-induced currents in a fjord lake. *Journal of Geophysical Research* 83:885-899.

HEBBERT, B., J. Imberger, I. Loh, and J. Patterson. 1979. Collie River underflow into the Wellington Reservoir. *J. of Hydraulics Div., ASCE*

HOARE, R. A. 1968. Thermohaline convection in Lake Vanda, Antarctica. *Journal of Geophysical Research* 73:607-612.

HUTCHINSON, G. E. 1957. A treatise on limnology, Volume I. *Wiley* 1075 p.

IMBERGER, J., J. Patterson, B. Hebbert, and I. Loh. 1978. Dynamics of a reservoir of medium size. *Journal of the Hydraulics Division, ASCE,* 104:725-743.

IMBERGER, J., T. Berman, R. Christian, E. Haines, R. Hanson, L. Pomeroy, D. Whitney, W. Wiebe, and R. Wiegert. In press. The influence of water motion on the spatial and temporal variability of chemical and biological substances in a salt marsh estuary.

KILLWORTH, P. D. 1977. Mixing on the Weddell Sea continental slope. *Deep-Sea Research* 26:427-448.

KILLWORTH, P. D. and E. C. Carmack. 1979. A filling-box model of river dominated lakes. *Limnology and Oceanography* 24:201-217.

KOH, R. C. and N. H. Brooks. 1975. Fluid mechanics of waste-water disposal in the ocean. *Annual Review of Fluid Mechanics* 7:187-211.

MANINS, P. C. 1973. A filling-box model of the Red Sea. *Mem. Soc. Roy. Sci. Liege* 6:153-166.

ORLOB, G. T. 1969. Mathematical models for prediction of thermal energy changes in impoundments. Water Resources Engineers, Inc.

RAGOTZKIE, R. A. and G. E. Likens. 1964. The heat balance of two antarctic lakes. *Limnology and Oceanography* 9:412.

RUMER, R. R. 1977. Physical processes for pollutant transport in the water environment. *In*: I. H. Suffet (ed.) Fate of Pollutants in the Air and Water Environments. *Wiley* 297-322p.

SMITH, S. A. and D. A. Bella. 1973. Dissolved oxygen and temperature in a stratified lake. *Journal of the Water Pollution Control Federation* 45:119-133.

TURNER, J. S. 1973. Buoyancy effects in fluids. *Cambridge University* 367 p.

WALIN, G. 1977. A theoretical framework for the description of estuaries. *Tellus* 29:128-136.

Conditions of Use

Carmack, E.C. and P.D. Killworth, 1979. Observations on the dispersal of saline groundwater in the Beaver Creek Diversion system, 1976-1978. Syncrude Canada Ltd., Edmonton, Alberta. Environmental Research Monograph 1979-2. 83 pp.