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BOB BAY STUDY, 1983

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ACKNOWLEDGMENTS

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CONTENTS

ILLUSTRATIONS

TABLES

1. Introduction

Filtered heavy metals have been shown to be toxic at low concentrations (U.S. Environmental Protection Agency, 1980; Johnson and Lieberman, 1979). A large number of studies have examined heavy metal transport and removal in natural waters, as well as the impact of heavy metals on aquatic organisms. Several such studies have focused on metal transport and removal in lake systems (Dolan and Bierman, 1982; Förstner; 1982. Hinkle, 1982; Young and others, 1982; Moore, 1981; Shepard and others, 1980; Förstner, 1976; Håkanson and Ahl, 1975; Hutchinson and others, 1975). These studies have shown significant removal of filtered metals by sediments which, along with dilution, tends to reduce concentrations with distance from the point of contaminant input.

Bob Bay is a shallow bay on Birch Lake in northeastern Minnesota (fig. 1). The bay receives most of its drainage from the Unnamed Creek watershed, part of which is covered by lean ore and waste rock copper-nickel stockpiles (Eger and others, 1981). These stockpiles generate leachate, with elevated levels of Cu, Ni, Co and Zn, that is transported by Unnamed Creek into Bob Bay. This stockpile drainage-stream-bay system may be representative of what could occur on a more widespread scale with copper-nickel mining in the region.

Bob Bay was studied from August 1976 through August 1977 to investigate the effects of the input on water quality (Lapakko and Eger, 1981). The results indicated that filtered copper and nickel concentrations were elevated above background levels, particularly near the bottom ot the bay, and decreased with increasing distance from the mouth of Unnamed Creek. This decrease was a function of both dilution and removal, which were estimated by measuring conservative parameters in the bay.

Since 1977, some changes have taken place in the input to Bob Bay. Trace metal levels in Unnamed Creek near the mouth have fluctuated from year to year, with a general increase observed since 1977 (Eger and others, 1981). This is probably due to a number of factors, including the addition of more waste rock to the watershed and changes in stream discharge. The annual discharge of Unnamed Creek has tended to decrease from 1978 to 1982. The removal of one of the major inflows to the creek, mine dewatering discharge 011, in June 1982 should have accounted for a further reduction in flow. At the same time as these changes in Unnamed Creek have occurred, mine stockpiling has begun to introduce heavy metals to the bay through another, smaller stream, denoted for this study as Flamingo Creek (fig. 1).

The changes in input to Bob Bay called for a reevaluation of heavy metal transport and removal in the bay, with particular attention to those factors influencing toxicity. The study was conducted in two phases, in July and September 1983, in a joint effort by the Minnesota DNR and the Erie Mining Company. In an effort to obtain a more specific estimate of time-of-travel, the July phase of the study utilized both dye and salt tracers.

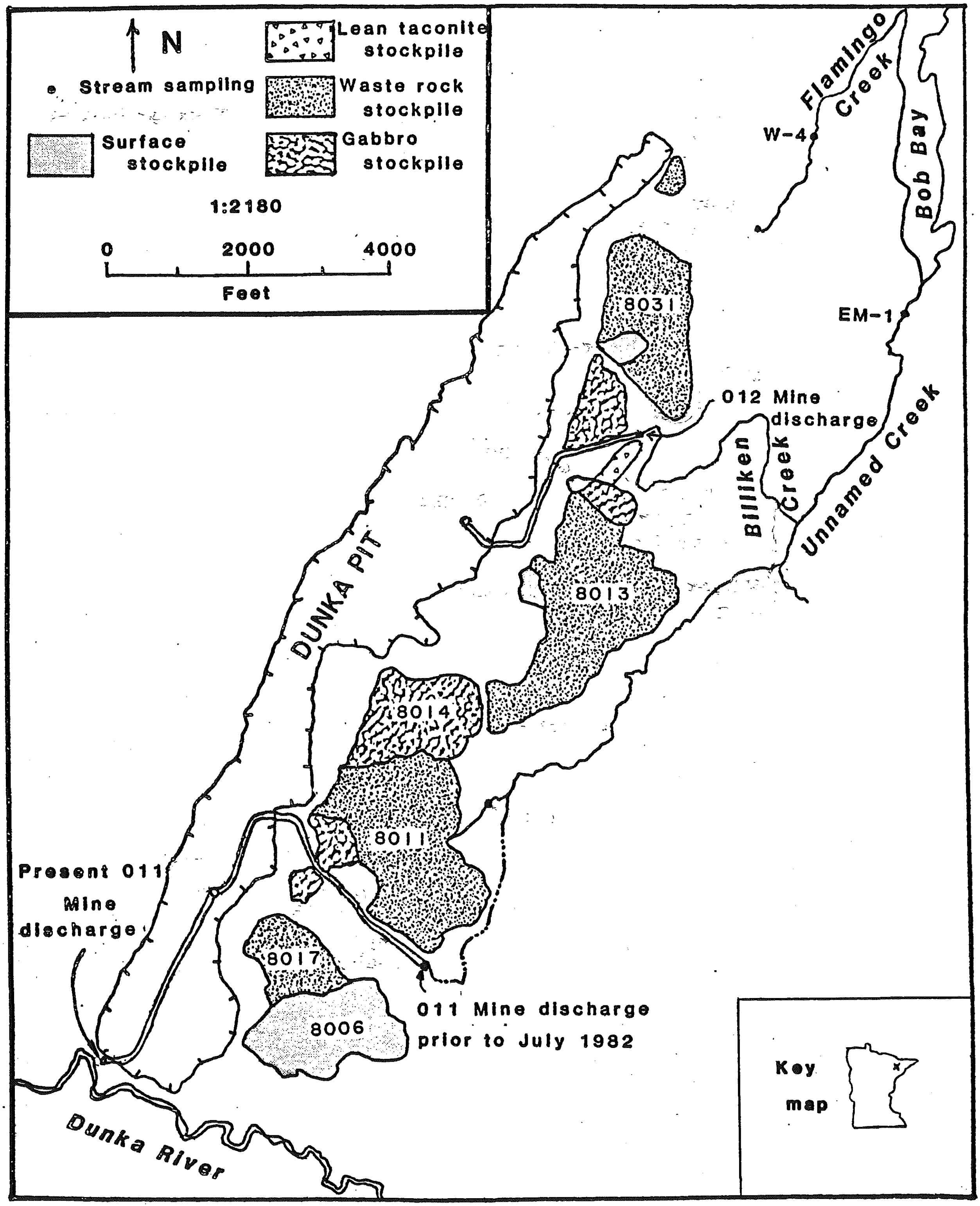


FIGURE 1. Location of Bob Bay.

2. Site description

Birch Lake is a natural reservoir, located in both Lake and St. Louis Counties, near Babbitt, Minnesota. At some time between 1886 and 1905, a logging dam was constructed at the lake outlet, effectively raising the water level about two meters (Frellsen, 1959; Minnesota State Drainage Commission, 1912; Minnesota Surveyor General's Office, 1886). This dam was then taken over and rebuilt in the early 1920's by the Minnesota Power and Light Company, which currently regulates the lake level for its power plant downstream at Winton.

Bob Bay is 20.2-ha in area, 1,400 m long and 20 to 200 m wide, and was created by the damming of the original reservoir (fig. 2). The bay is about two meters deep for most of its length, deepening to about four meters at its junction with the main part of Birch Lake (table 1). A narrow channel runs roughly parallel to the length of the bay in both its northern and southern ends. Many of the monitoring stations were located in this channel, from stations BB-0 to BB-2 and BB-4.5 to BB-6.4 (figs. 2-3).

The water level in the bay fluctuates due to control by Minnesota Power and Light. Water level changes tend to follow those for most lakes in the region, with the lowest levels at the end of winter and in late summer, and the highest during the spring and early summer. Water levels tend to fluctuate within a one meter range (Houtala, 1983). The normal reservoir pool elevation is 465 meters above sea level.

Unnamed Creek, the primary tributary to Bob Bay, drains approximately 770 ha south of the Bay and east of the Erie Mining Company's Dunka Mine (fig. 1). The mine is an open pit taconite mine that is located on the contact of the Giants Range Granite, the Biwabik Iron-formation and the Duluth Gabbro. Some of the gabbro, which has elevated copper-nickel mineralization, has been removed and stockpiled in the watershed of Unnamed Creek since the early 1960's. Much of the water supply of Unnamed Creek since 1966 has come from the 011 (PCA no. 20200) and 012 (PCA no. 20300) mine dewatering discharges. The 011 discharge was relocated outside of the Unnamed Creek watershed in June 1982. Approximately 100 m upstream of the mouth of the creek is monitoring station EM-1, where average monthly flows of 77 to 120 liters/sec were observed from July through September 1983. High flows at EM-1 typically occur during snowmelt in April, and during mid-summer rains, whereas low flows tend to take place in late summer.

The only other significant tributary to Bob Bay is Flamingo Creek, which drains about 80 ha to the west of the bay (fig. 1). Since 1979 waste rock has been stockpiled on a small portion of the Flamingo Creek watershed (Eger and others, 1981). Flamingo Creek outflow is gaged approximately 600 m upstream from the bay at station W-4, where average monthly flows of 5.4 to 18 liters/sec were observed from July through November 1983, with seasonal variations similar to those of Unnamed Creek.

Before the lake level was raised, the area now occupied by the bay was a peatland through which Unnamed Creek flowed. Reedy peat deposits were found beneath an upper layer of lake sediments on the bottom of much of the bay.

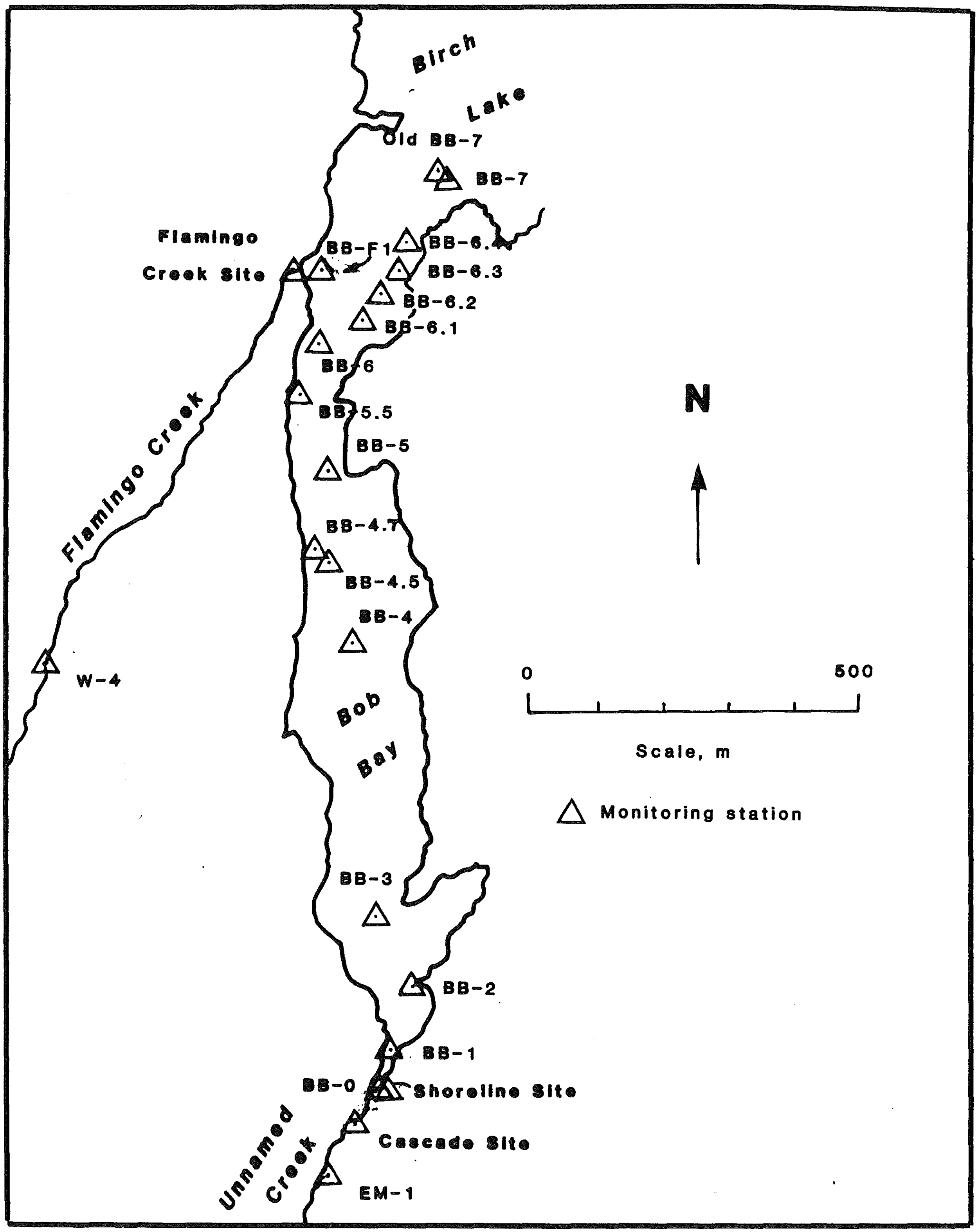


FIGURE 2. Location of monitoring stations.

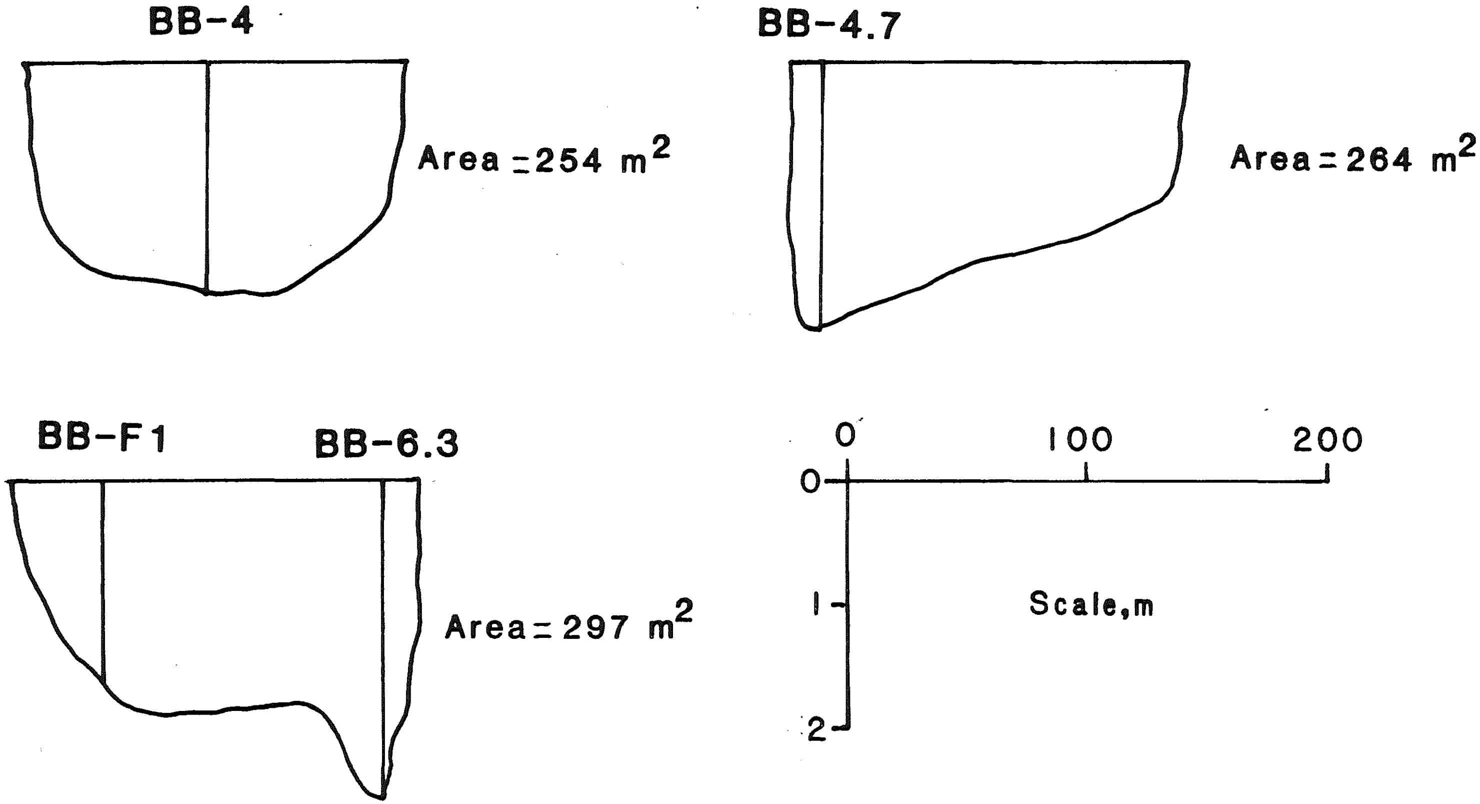


FIGURE 3. Cross-sectional area of Bob Bay perpendicular to tracer flowpath.

The lake sediments are principally organic, gyttja material, about six to eight cm thick. In some near shore areas, however, particularly near the mouths of Unnamed and Flamingo Creeks, the bottom sediments are principally silt and sand over clay with numerous scattered cobbles and boulders. Some of the boulders protrude above the water surface, especially between the mouth of Unnamed Creek and station BB-2 (table 1). The lake sediments, peat and thin glacial deposits in and surrounding Bob Bay overlie the Duluth Gabbro (Stevenson and others, 1979).

3. Materials and methods

The July phase of the bay study utilized two tracers, rhodamine WT and KCl. Rhodamine WT is a fluorescent dye of the xanthene group that is one of the most highly recommended dyes for use in time-of-travel and other tracer studies (Hubbard and others, 1982; Smart and Laidlaw, 1977). The dye was added as a 20 pct solution, while the salt solution was approximately 18 pct KCl. The tracers were added simultaneously to Unnamed Creek at EM-1 over a one-hour period (appendix A). Spigots were used to control the rate of addition of both solutions. Water samples were taken about 50 m downstream of EM-1, at a point referred to as the Cascade site, to determine the distribution of the tracer plume before it entered Bob Bay.

The monitoring carried out in the bay itself was of two types: conductivity/temperature/depth surveys over broad areas of the bay; and water quality sampling that was generally restricted to the designated monitoring sites. An initial survey of the bay was used to help locate the seven original monitoring stations dating from the 1976-77 study. Additional conductivity/temperature/depth surveys resulted in siting eight additional stations (BB-0,-4.5,-4.7,-5.5,-6.1,-6.2,-6.3,-6.4). Most of the conductivity/temperature/depth surveys were taken with a YSI Model 33 S-C-T meter and probe, which was sometimes taped to the bottom of a PVC pipe. Some of the depth surveys also utilized a Lowrance Fish-Lo-K-Tor Model LFP 300D, designed for the 0 to 18 m depth range.

Five methods were used to obtain water quality samples. The first, manual sampling, was used for most of the stream and near surface bay samples. The second method, the PVC-Tygon apparatus, was used in the July phase to collect bay samples below 15 cm depth (fig. 4). The movement of the boat occasionally caused this apparatus to move along the bottom, resulting in higher amounts of suspended sediments in a few samples. The anchor-Tygon apparatus (fig. 4) thus replaced the PVC-Tygon apparatus in the September phase sampling. The sampling inlet of both devices was located 15 cm above the bottom of the pipe or anchor. A guzzler hand pump attached to the Tygon tubing removed samples for both devices. The anchor-Tygon apparatus was allowed to rest on the bottom for five minutes before the near bottom samples were pumped. The two remaining methods of water sampling were the Van Dorn bottle and the ISCO automatic sampler. The Van Dorn was used only at the Old BB-7 site, while the auto-sampler was used at EM-1, the Cascade site, BB-2, BB-4 and BB-6. The plastic Tygon tubing inlet to the auto-sampler was held stationary, typically by taping it to an anchor.

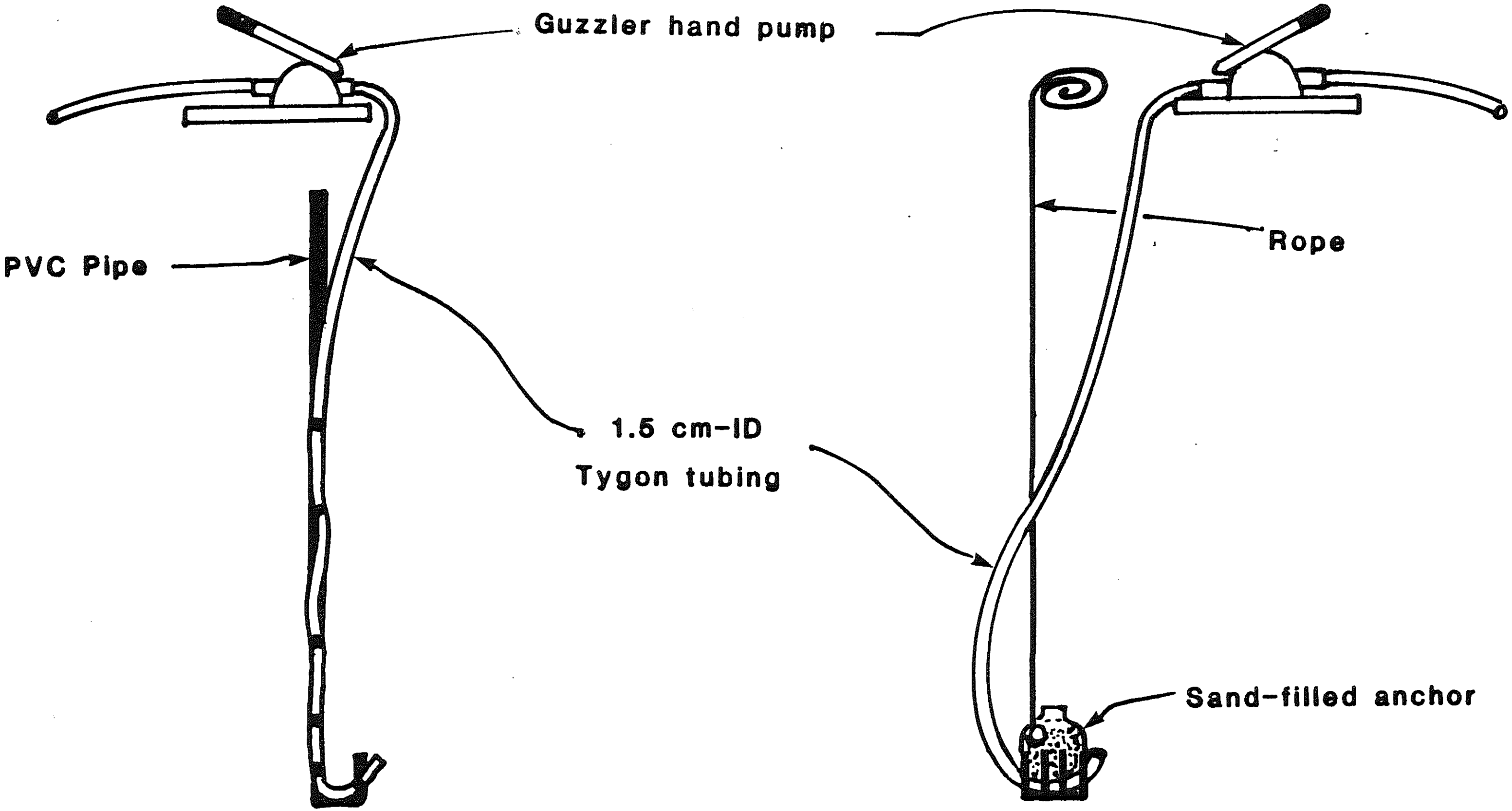
TABLE 1. - Bottom Characteristics and Morphometry at Monitoring Stations

Station	Characteristics of uppermost sediment layer	Depth, m	Cross-sectional area of bay perpendicular to flowpath, m^2	Distance from mouth of Unnamed Creek along tracer flowpath, m
EM-1[1]	Boulders	0.60	NAp	NAp
Cascade[1]	Cobbles	.50	NAp	NAp
BB-0	Sand, scattered cobbles & boulders	1.40	NA	20
Shoreline	sand	.30	NAp	NAp
BB-1	Sand, scattered cobbles & boulders	1.45	NA	57
BB-2	Sand, clay & gyttja	1.50	NA	150
BB-3	Gyttja	1.85	NA	260
BB-4	Gyttja	1.90	254	660
BB-4.5	Gyttja	2.10	NA	800
BB-4.7	Gyttja	2.15	264	830
BB-5	Gyttja	2.20	NA	970
BB-5.5	Gyttja	2.25	NA	1,110
BB-6	Gyttja	2.20	NA	1,190
BB-6.1	Gyttja	2.75	NA	1,240
BB-6.2	Gyttja	2.50	NA	1,290
BB-6.3	Gyttja	2.55	297	1,330
BB-6.4	Gyttja	2.75	NA	1,380
BB-7	Gyttja	4.00	NA	1,480
Old BB-7	Gyttja	4.00	NAp	NAp
Flamingo Creek	Cobbles	.30	NAp	NAp
BB-F1	Gyttja with scattered cobbles	1.50	NAp	NAp

NA = Not available.

NAp = Not applicable.

[1] Measured when EM-1 staff gage read 6.00 ft.



PVC-TYGON APPARATUS

ANCHOR-TYGON APPARATUS

FIGURE 4. Specialized equipment used for deeper bay samples.

Sample filtration and acidification were conducted in the lab for the July phase and in the field for the September phase. Filtered samples were put through 0.45-µm pore diameter filters. The metals and major cation samples were acidified with HNO_3 and the TOC samples with H_2SO_4. All samples were cooled at approximately $5^{o}C$ until lab analysis.

All temperature, conductivity and pH analyses and some dye fluorescence analyses were conducted in the field. The rest of the analyses, including most of those for fluorescence, were carried out in the lab. The fluorescence analyses were performed on a Turner Model 111 fluorometer according to the procedures outlined by Hubbard and others (1982) and Wilson (1968). All other analyses were carried out in accordance with the methods described by the U.S. Environmental Protection Agency (1983). Metal and major cation analyses were conducted by atomic absorption spectrophotometry (AAS). Sample analysis by flame mode was carried out by the Erie Mining Company on an Instrumentation Laboratory 351 AA spectrophotometer. Low concentrations required flameless (graphite furnace) analysis, which was performed on a Perkin-Elmer 603 AA spectrophotometer at the DNR facilities in Hibbing, Minnesota. Sulfate analyses were conducted by Erie using a turbidimetric method. TOC analyses were performed by Aqualab, Inc., of Streamwood, Illinois, using a low level ultraviolet, persulfate oxidation method on a Dohrman DC-10.

The equipment used in the sampling program is listed in appendix B.

4. Results

4.1. Hydrological and meterorological data

Data were collected on hydrological and meterological variables that could influence heavy metal transport and removal in Bob Bay. These included local precipitation, mine dewatering discharge 012, EM-1 discharge, W-4 discharge, lake level and wind velocity.

Precipitation in the Unnamed Creek watershed area was measured on a weekly basis (appendix C). From 26 July to 2 August 1.2 cm of rain fell, mostly after the end of sampling on 28 July. From 19 to 25 September, 0.7 cm of precipitation occurred, followed by 7.0 cm from 26 September to 3 October. Most of the rainfall during this last period occurred after 29 September.

Discharge data from 012, EM-1, and W-4 were compiled on a daily basis. During the period of tracer addition, on 26 July, the 012 discharge was very low, at 0.76 liters/sec (appendix D). This discharge increased to 28.5 liters/sec on 28 July. The 012 discharge remained fairly constant during the late September sampling, at 19.1 liters/sec. The EM-1 discharge at the time of tracer addition, 24 liters/sec (fig. 5), was extremely low in comparison with previous data, possibly representing the lowest Unnamed Creek flow during all of 1983. The EM-1 flow at the start of the September sampling phase was 49 liters/sec, more than double the July value but still low in comparison to flows from previous years. Flow at W-4, in contrast, was higher during the July sampling phase (eight to nine liters/sec) than during the September phase (three to five liters/sec).

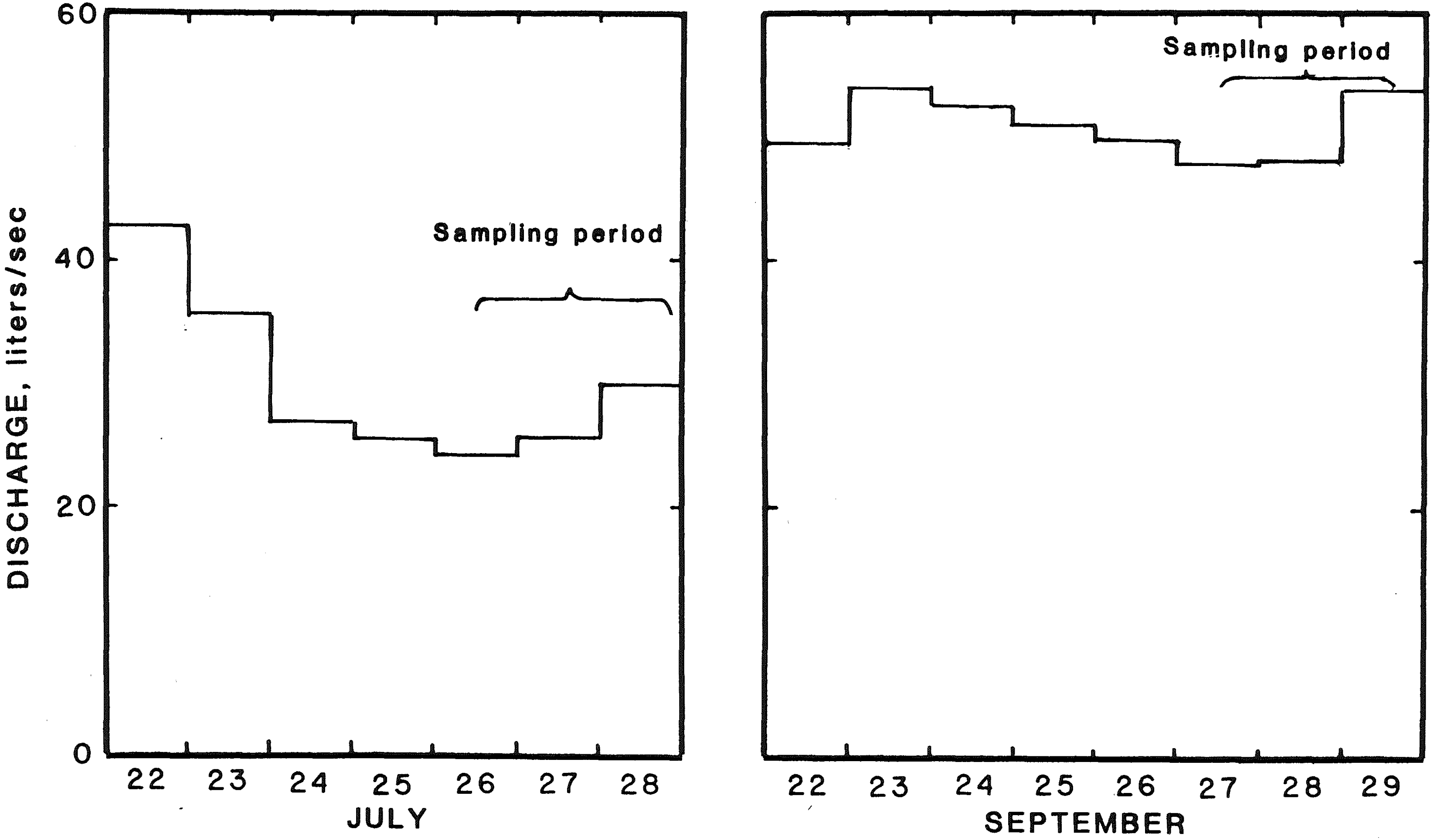


FIGURE 5. Average daily discharge at EM-1 during sampling phases.

Lake level did not vary substantially, either within each sampling phase or between the two phases. Daily lake level elevation data from late July to late September differed 22 cm between the maximum and minimum values (Hautala, 1984). Outside staff gages located near BB-0 and BB-6.1 showed a fluctuation range of 9.4 cm over the time of sampling. It was assumed that these changes did not affect the bay depth measurements.

No instrumentation was available for measuring wind speed and direction, and the only record available was field notes. Wind velocity was highly variable, occasionally even from one hour to another. Winds and the ripples they produced usually moved in north-south direction, due to the north-south orientation of the bay and surrounding ridges. A light to strong breeze from the south-southeast occurred during most of the sampling. The wind and ripples were from the north, however, on 29 September, the last day of sampling. These observations coincide with the wind data taken daily at 14:00 at the U.S. Forest Service station in Ely (appendix E).

4.2. Water quality data

Some deviations were observed for different sampling techniques and methods of sample preparation. At the Cascade site, soon after the passage of the tracer peak, dye concentrations in samples taken by the automatic sampler were more than 10 times those in manual samples. This may have been due to contamination of the sampler inlet tubing by more concentrated samples at the peak (Hubbard and others, 1982). Secondly, a sample taken with the PVC-Tygon sampler had slightly higher specific conductance and sulfate concentration then a sample taken with the PVC-anchor device at the same time. There was, however, no difference in nickel or calcium concentrations between the two samples. Finally, three samples that were filtered and acidified immediately after collection had filtered nickel concentrations which were slightly lower than similar samples which were filtered and acidified the next day. The last two discrepancies were assumed to be inconsequential.

The water quality at EM-1 remained essentially the same during the course of each respective sampling phase, and changed little between phases. Specific conductance was slightly above 1,000 µS/cm and sulfate values were about 700 mg/l during both phases. Calcium and magnesium levels were 120-130 mg/l and 90-100 mg/l, respectively. Trace metal levels were generally observed in the order Ni(0.3-0.5 mg/l)>Zn(0.01-0.06 mg/l)>Cu≈Co(0.004 mg/l). The following differences were observed in EM-1 water quality between July and September: slightly higher nickel and zinc concentrations in September; a fall in temperature from 17°C to 9-13°C from July to September; and an increase in pH from 7.6 to 7.9.

Water quality at the Flamingo Creek site was similar to that at EM-1 during both phases, with the exception of much lower nickel levels and slightly lower pH values. Nickel concentrations at this site were between 0.01 and 0.02 mg/l, while pH ranged from 7.30 to 7.55.

The plumes of both tracers in the July phase appeared to be fairly uniformly distributed in Unnamed Creek as they approached the mouth of the creek (figs. 6-7). The peak tracer concentrations passed the Cascade site

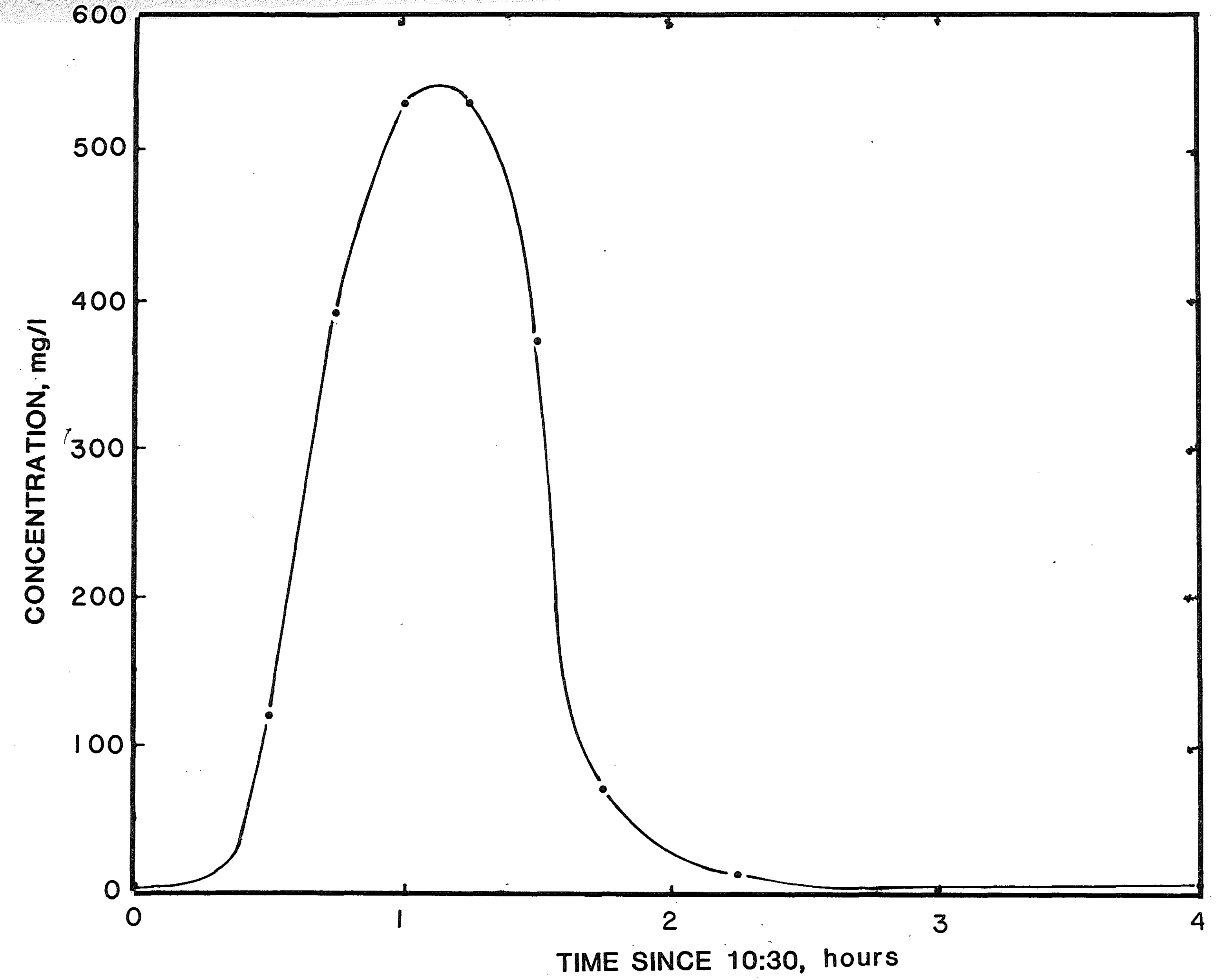


FIGURE 6. Concentration of potassium at Cascade site, 26 July.

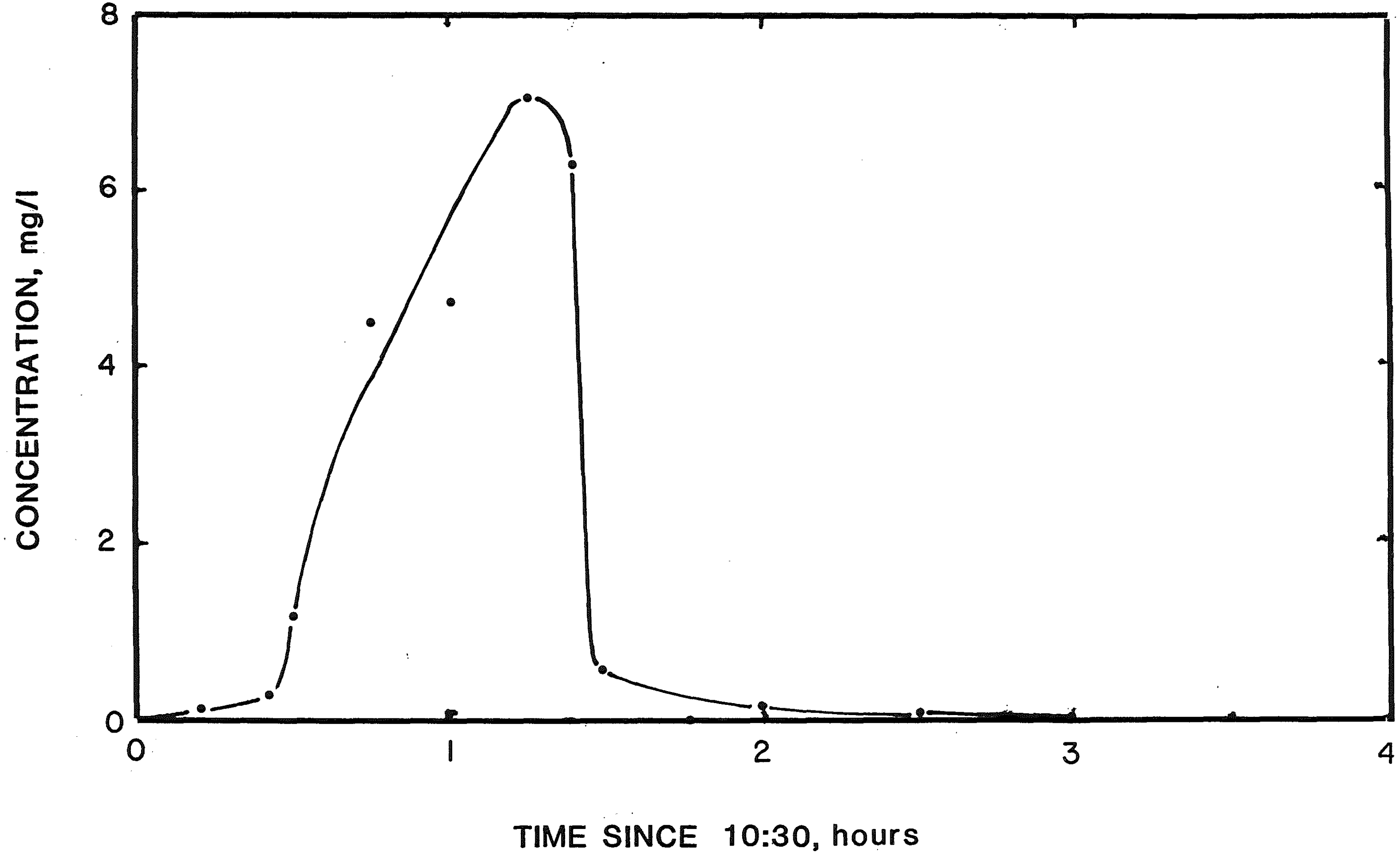


FIGURE 7. Concentration of rhodamine WT at Cascade site, 26 July.

about 30 minutes after the start of tracer addition at EM-1, and entered the bay after another approximately 30 minutes.

The tracers, particularly the dye, were helpful in defining both the flowpath and travel time of the Unnamed Creek discharge through Bob Bay. The most concentrated part of the dye plume followed the bottom of the bay from the mouth of the creek to the main part of Birch Lake. This plume had much higher concentrations and was more easily detected at the southern end of the bay. The plume became more difficult to detect as it moved toward the mouth of the bay and became more dispersed. The passage of the dye peak was observed only as far as BB-2; this took about 4.5 hours from the time of tracer addition. A high dye reading from BB-4.5 30 hours after the addition appeared to be near the dye peak. The dye was detected as far as the last station, BB-7, 56 hours after the tracer addition.

Less data were available for the potassium tracer than for the dye tracer. Potassium concentrations correlated strongly with the dye concentrations at levels above approximately 10 mg/l potassium. Linear regression analysis was applied to the 18 data pairs in this range, giving:

$$K = 75.8R + 27.8, \ r^2 = 0.922 \qquad (1)$$

where K = potassium concentration, mg/l, and
R = rhodamine WT concentration, mg/l.

Potassium concentrations near the background range of 0.7 to 4.0 mg/l did not correlate well with the dye concentrations.

The various conductivity and depth surveys showed that the zone of highest conductivity in any given cross-section perpendicular to the length of the bay was in the deepest part of the cross-section (fig. 8). The width of the high conductivity zone in a given cross-section was a function of channel configuration (fig. 3). The bottom of the bay was relatively broad and shallow in the region between BB-3 and BB-4, and thus the high conductance zone was rather diffuse in this area (fig. 9). Between BB-0 and BB-2 and again from BB-4.5 to BB-6.3, however, the more narrow channel, less than 25 m wide, held a more well defined high conductivity zone. Most of the monitoring stations were located in or near this zone. Conductivity decreased rather steadily within the high conductivity zone with increasing distance from the mouth of Unnamed Creek, along the flowpath defined by the tracers (fig. 10). The thickness of the high conductivity zone also tended to decrease toward the mouth of the bay. The conductivity zone during both phases was about 100 cm thick at BB-1 and less than 40 cm thick at BB-6.

Concentrations of sulfate, trace metals and major cations followed a trend similar to that described for specific conductance. Surface concentrations of SO_4, Ni, Ca and Mg at a particular station were usually about an order of magnitude lower than concentrations at a depth 15 cm above the bottom (table 2). The concentrations of these same four parameters in the near bottom samples generally decreased with distance along the flowpath from the mouth of Unnamed Creek in each sampling phase (fig. 11, table 3). Levels of Cu, Co and Zn also tended to be higher in the samples taken near the bottom

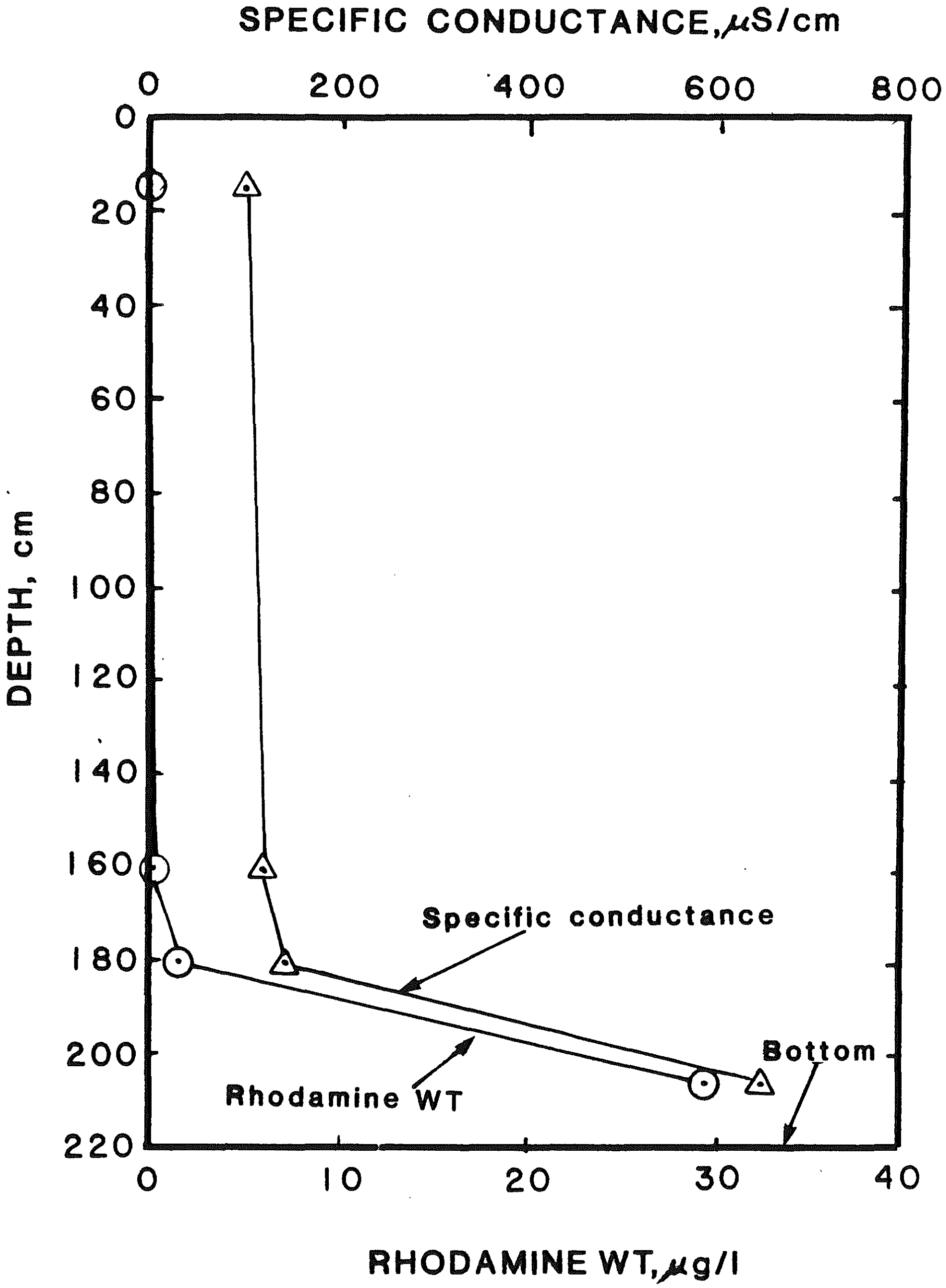


FIGURE 8. Change in dye concentration and specific conductance with depth at BB-6, 10:50, 28 July.

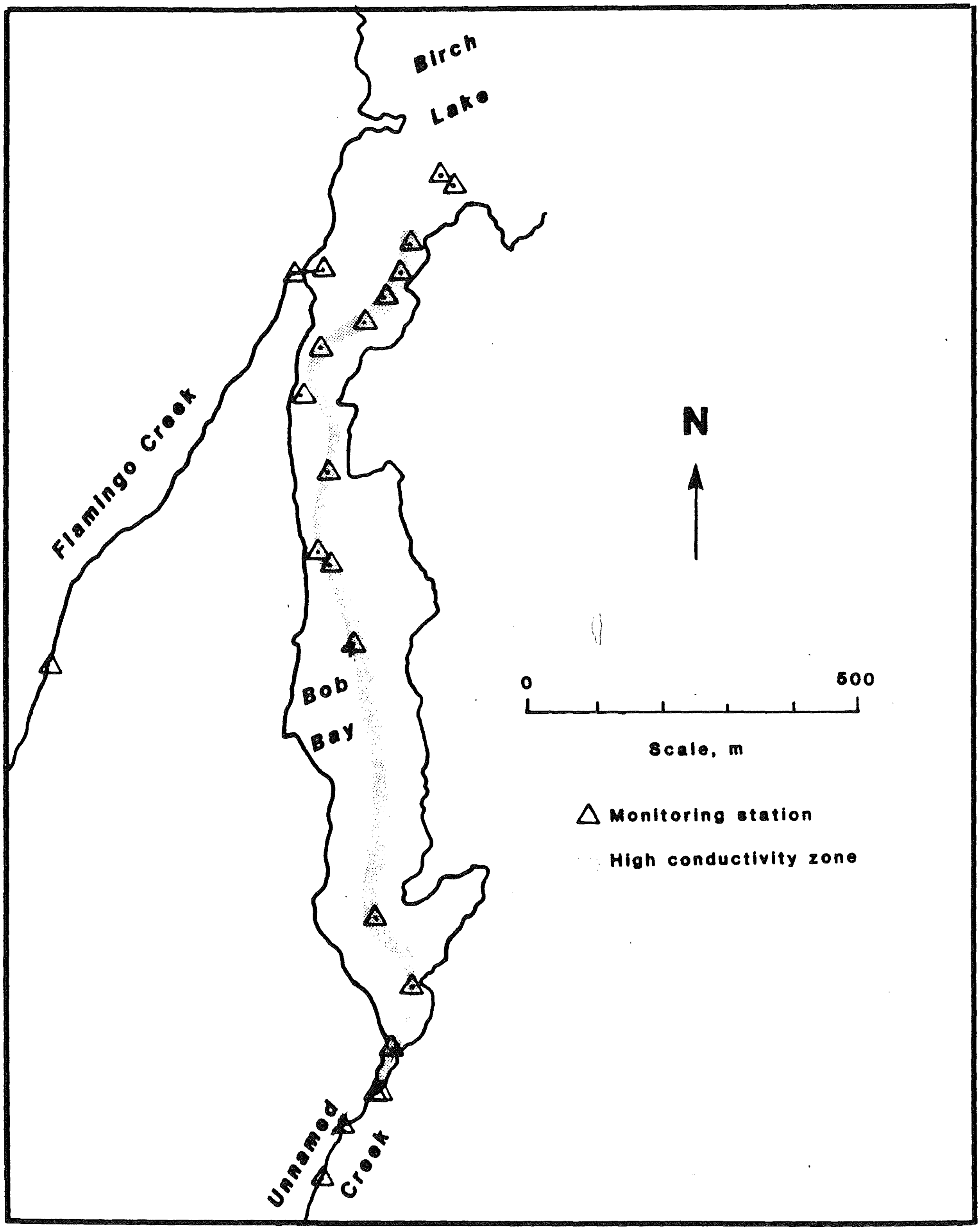


FIGURE 9. Location of high conductivity zones in Bob Bay.

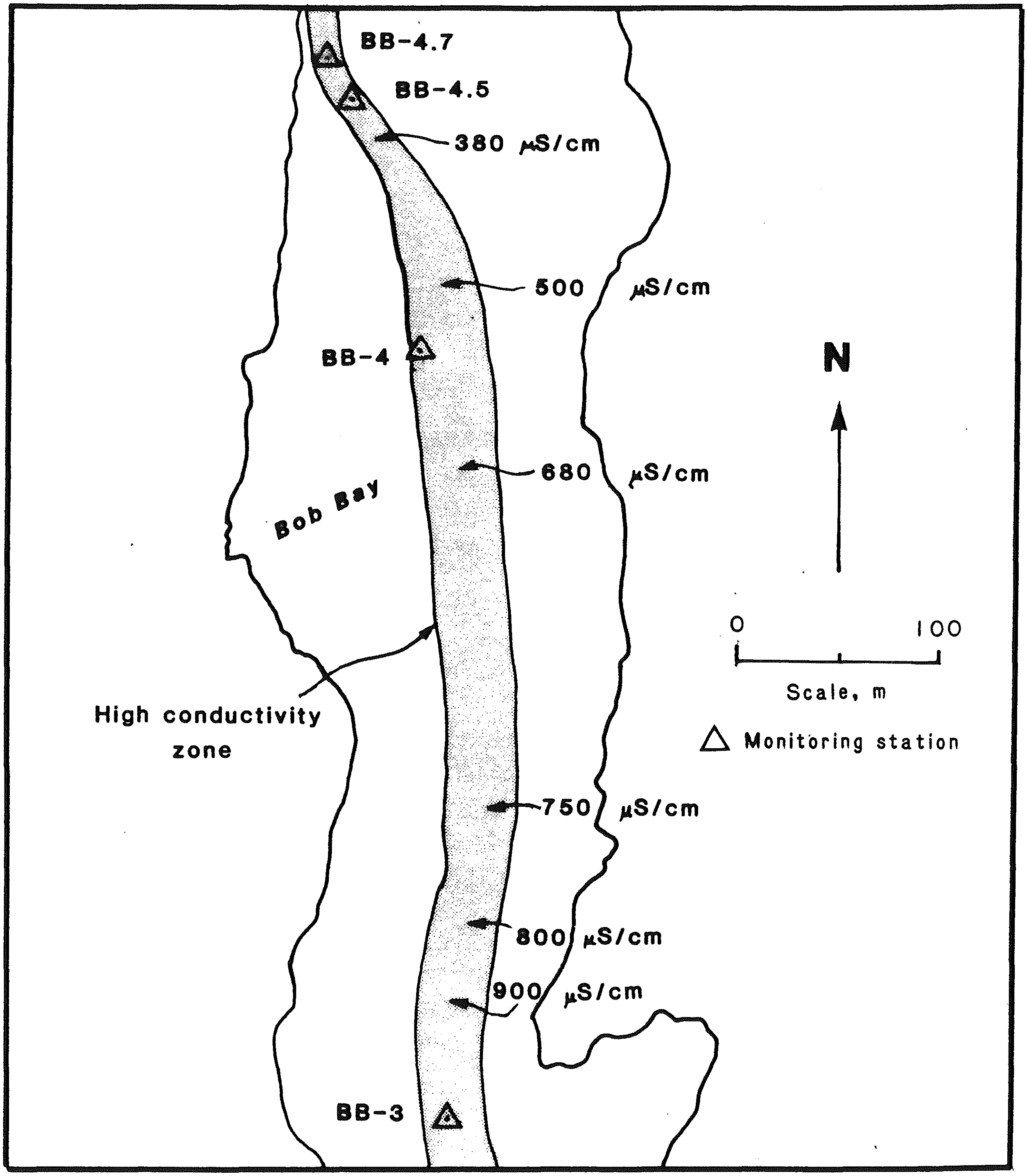


FIGURE 10. Highest conductivity readings between BB-3 and BB-4.5, 12:30 to 14:30, 28 September.

TABLE 2. - Near Surface and Deep Concentrations in Bob Bay

(All chemical data in mg/l)

Site	Date	Depth, cm	SO_4	Filtered Cu	Filtered Ni	Filtered Co	Filtered Zn	Ca	Mg
BB-1	7/26	15	60	<0.001	0.016	0.001	<0.01	15	11
		130	500	.004	.28	.004	.01	84	72
BB-3	7/26	15	39	.003	.018	<.001	<.01	12	8
		170	480[1]	.004[1]	.26[1]	.004[1]	.01[1]	84[1]	69[1]
BB-4	7/27	15	30	.003	.011	.001	<.01	12	7
		175	310[1]	.002	.13[1]	.002	<.01	52	32
BB-6.3	7/28	15	NA	.002	.006	.001	<.01	NA	NA
		240	340	.017	.17	.002	<.01	62	46
BB-6.3	9/29	125	18	NA	.026	NA	NA	8	NA
		240	370[1]	.006[1]	.25[1]	.001[1]	.03[1]	79[1]	57[1]

NA = Not available.

[1] Mean of two or more analyses.

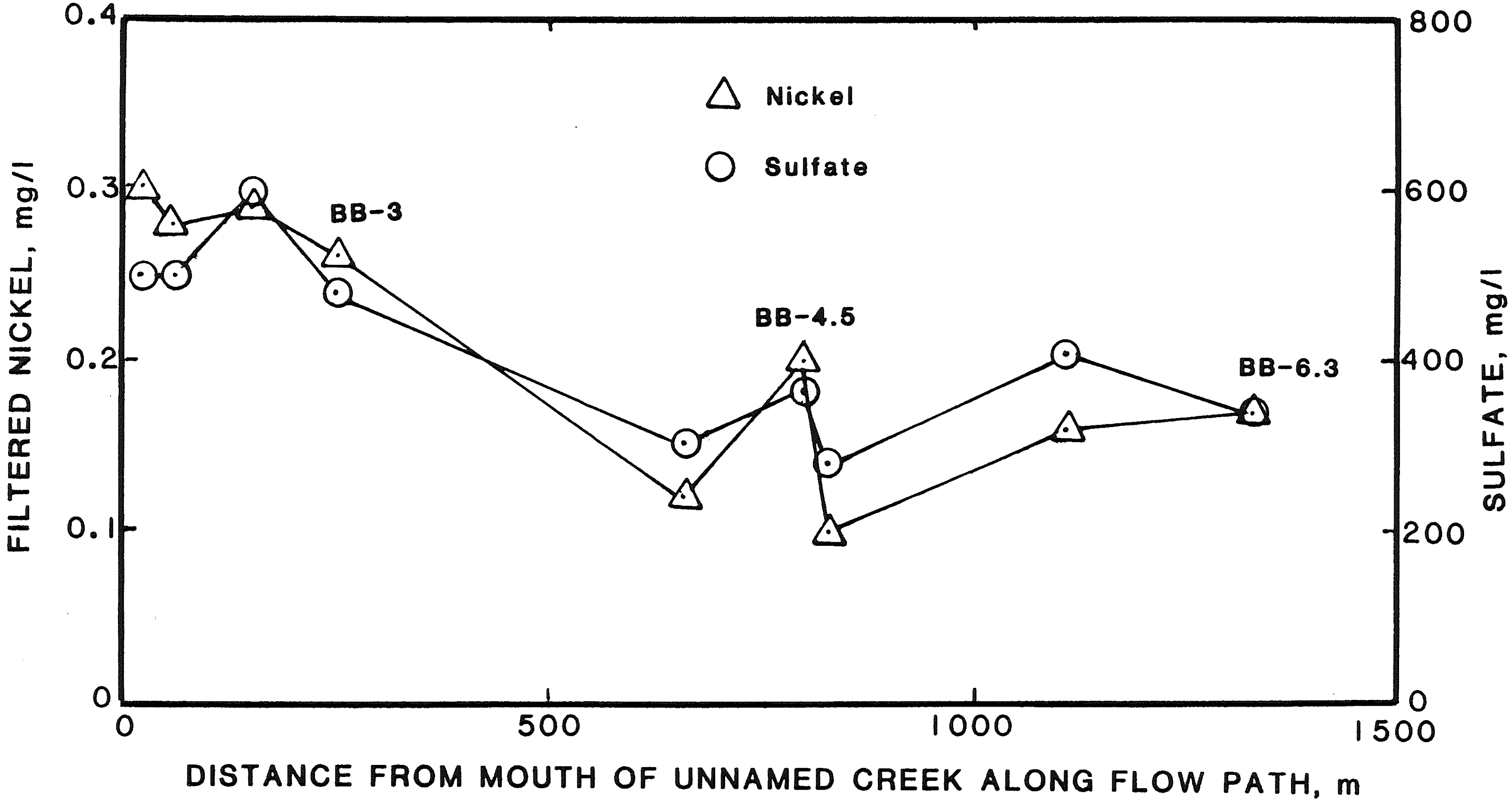


FIGURE 11. Nickel and sulfate concentrations at 15 cm above bottom of bay, 26 to 28 July.

TABLE 3. - Sulfate, Trace Metal, Calcium and Magnesium Concentrations at 15 Cm above Bottom

(All data in mg/l)

Station	SO_4	Cu		Ni		Co		Zn		Ca	Mg
		Total	Filtered	Total	Filtered	Total	Filtered	Total	Filtered		
26-28 July											
EM-1[1]	700	0.004	0.004	0.3	0.3	NA	0.004	0.02	0.01	130	100
BB-1	500	.003	.004	.28	.28	NA	.004	.02	.01	84	72
BB-3[1]	480	.002	.004	.28	.26	NA	.004	.01	.01	84	69
BB-4	310[1]	.006	.002	.16	.13[1]	NA	.002	.01	<.01	52	32
BB-6.3	340	.004	.017	.20	.17	NA	.002	.01	<.01	62	46
27-29 September											
EM-1	660[1]	.007	.004	.49	.45[1]	.004	.004	.07	.06	120	90
BB-1	610[1]	.007	.004	.43	.39	.001	.003	.06	.06	108	84
BB-3[1]	510	.004	.003	.40	.36	.002	.001	.06	.06	100	76
BB-4	<10	NA	NA	NA	.051	NA	NA	NA	NA	16	NA
BB-6.3[1]	370	.003	.006	.26	.25	<.001	.001	.03	.03	79	57

NA = Not available.

[1] Mean of two or more analyses.

and closer to the mouth of the creek, but these differences were much less pronounced than those for SO_4, Ni, Ca and Mg. The Cu, Co and Zn concentrations were also generally much lower than those for the other parameters; filtered Cu and Co levels did not exceed 0.017 mg/l, while filtered Zn levels were less than or equal to 0.06 mg/l. Filtered metal concentrations were generally equal to or slightly less than total metal concentrations; filtered nickel levels, for example, averaged about 90 pct of total nickel levels (table 3).

The pattern of increasing conductivity and metal concentrations with depth was not always found. In particular, a set of samples taken at BB-4.7 on 28 September showed a rather constant distribution of all parameters with depth, with some concentrations even higher in the near surface samples. Conductivity in this particular profile was about 100 µS/cm, while filtered nickel levels ranged from 0.011 to 0.020 mg/l. This pattern at BB-4.7 was detected only on 28 September; the following day, the conductivity profile at BB-4.7 was more like that illustrated by figure 8. This sudden change from one day to another was also noted over the same period at BB-5.

Conductivity stratification was more likely to occur than temperature stratification in the bay near the mouth of Unnamed Creek. The temperature profile changed from a decreasing to a constant profile while the conductivity profile remained unchanged between 27 and 29 September (fig. 12). The temperature of Unnamed Creek rose 3.5^{o}C over this same two-day period.

The part of Bob Bay receiving flow from Flamingo Creek contained a rather high conductivity zone confined to a limited area along the bottom, similar to the high conductivity zone associated with Unnamed Creek. This high conductivity zone could not be traced very far into the bay (fig. 9). The one sample collected from this zone, on 28 September, had a filtered nickel concentration of 0.010 mg/l.

Some minor changes were noted in water quality from the bay stations in the July versus September phases. Temperature declined at all sampling points, by an average of about 10^{o}C. Nickel levels generally increased over the same period, by roughly 20 to 50 pct. Zinc concentrations, which were mostly in the 0 to 0.02 mg/l range in July, increased to as high as 0.06 to 0.07 mg/l in September.

The water quality data is tabulated in appendix F.

5. Discussion

The Unnamed Creek inflow to Bob Bay appeared to follow a path corresponding to the high conductivity zone (fig. 9). The higher density of the creek inflow compared to the bay water accounted for the presence of this zone. The increased density was due to higher dissolved solids concentrations and colder temperatures in the inflow (fig. 12). Such density currents are often generated by stream inflow to lakes (Wetzel, 1975). The density current occupied the deepest channel in the bay, which may have aided in physically confining the flow. This channel probably represented the old path of Unnamed Creek before the lake level was raised.

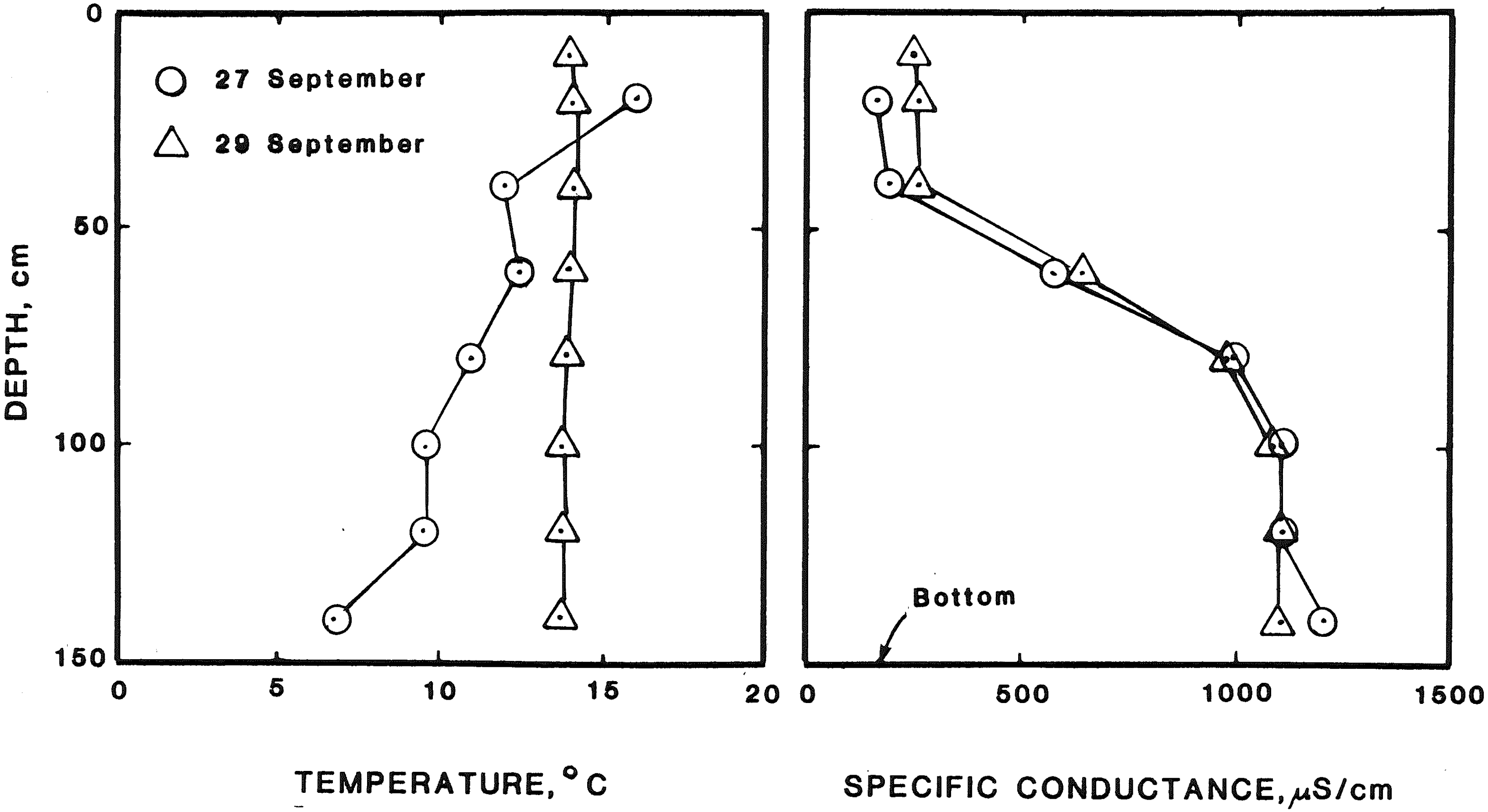


FIGURE 12. Change in temperature and specific conductance profiles at BB-1, 27 to 29 September.

The dye tracer plume appeared to have moved through Bob Bay in a period of one to three days, when Unnamed Creek inflow was 24 to 30 liters/sec. The precise travel time could not be determined because the peak concentration of the tracers was not determined near the mouth of the bay. Estimates were made, however, based on the travel time required for the peak to have reached various monitoring stations before station BB-7:

$$t_7 = d_7 t_i / d_i, \tag{2}$$

where t = travel time, and
d = distance from mouth of Unnamed Creek along tracer flowpath, and subscript denotes monitoring station.

The travel times to BB-7 calculated by this method with data from BB-2 and BB-4.5 were 34 and 54 hours, respectively. The cross-sectional area of the flowpath between the mouth of the creek and BB-4.5 was probably more representative of that for the bay as a whole than was that between the creek mouth and BB-2. Thus, the 54-hour value would appear to be more accurate than the 34-hour value.

Higher Unnamed Creek flows, such as the 49 to 54 liters/sec discharge during the September phase sampling, would most likely result in shorter travel times. In the extreme case that the cross-sectional area of flow does not vary with discharge level, doubling the creek inflow would halve the travel time.

The samples taken from the density flow, at 15 cm above the bottom, were collected successively from BB-0 to the mouth of the bay over two-to three-day periods. The set of density flow samples from each phase were taken in an attempt to sample the same creek inflow parcel at each station.

Since metal concentrations increased with specific conductance, they were highest along the flow path of the density current. The highest trace metal values, in the range of 0.04 to 0.05 copper equivalent units (CEU), were measured in the flowpath at those stations closest to the mouth of Unnamed Creek (table 3). The CEU was developed by Johnson and Lieberman (1979) to normalize the toxic effects of Ni, Co and Zn to those of Cu, as follows:

$$[Cu] + 0.1\,[Ni] + [Co] + 0.1\,[Zn] = CEU, \tag{3}$$

where [ ] represents the aqueous concentration.

Hardness and TOC are presented along with metal levels in table 4, since both parameters have been shown to reduce trace metal toxicity (U.S. Environmental Protection Agency, 1980a, 1980b, 1980c; Lind and others, 1978). Hardness ranged from 900 mg/l as $CaCO_3$ in Flamingo Creek to 220 mg/l as $CaCO_3$ in the density current at BB-7, while TOC values were from 22 to 24 mg/l. Figure 13 plots nickel versus hardness levels for several of the samples listed in table 4 in comparison with the U.S. Environmental Protection Agency (EPA) ambient water quality criteria for freshwater aquatic life (U.S. Environmental

TABLE 4. - CEU, Hardness and TOC Values for Samples with High Trace Metal Concentrations

(All bay samples taken at depths 15 cm above bottom unless noted)

Station	Date	Filtered concentration, mg/l					Hardness (Ca, Mg), mg/l as $CaCO_3$	TOC, mg/l
		Cu	Ni	Co	Zn	CEU		
EM-1[1]	7/26	0.004	0.36	0.004	0.002	0.044	720	NA
EM-1[1]	9/27	.007	.46	.004	.06	.063	670	NA
Flamingo Creek	9/28	.005	.013	.004	.03	.013	900	NA
BB-0	7/26	.003	.3	.004	.01	.04	610	22.9
BB-0	9/27	.004	.40	.001	.06	.051	660	NA
BB-1	7/26	.004	.28	.004	.01	.037	510	23.3
BB-1	9/27	.004	.39	.003	.06	.052	610	NA
BB-2	7/26	.003	.4	.003	.01	.05	560	23.6
BB-3	7/26	.004	.26	.004	.01	.035	490	22.0
BB-3	9/27	.003	.36	.001	.06	.046	560	NA
BB-4	7/27	.002	.12	.002	<.01	.016	260	NA
BB-5.5	7/28	.003	.16	.003	<.01	.022	410	NA
BB-6.3	7/28	.017[2]	.17	.002	<.01	.036[2]	340	NA
BB-6.3	9/29	.006	.25	.001	.03	.035	430	NA
BB-7[3]	7/28	.003	.14	<.001	.01	.018	220	NA

NA = Not available.

[1] Mean of two or more samples.

[2] Anomalous value.

[3] Sampled at 10 cm above bottom.

Protection Agency, 1980b). These criteria were developed for waters of hardness less than 350 mg/l as $CaCO_3$, which is below the values typically observed in the density current. The curve is presented as the best available method of approximating toxicity as a function of hardness. Based on the EPA criteria, nickel appeared to be present at more toxic levels than the other three trace metals analyzed. All samples had trace metal concentrations below the acute toxicity level, although several from stations near the mouth of Unnamed Creek exceeded the chronic toxicity level.

The EPA ambient water quality criteria are based on total recoverable metals, whose value lies between those of filtered and total metals; since the filtered and total metal values from Bob Bay were similar, however, the total recoverable metal values would not be expected to have been much higher than those given for filtered metals in table 3 and figure 13.

Nickel concentrations in the density current were not only higher than those of the other three trace metals, but also accounted for 70 to 80 pct of the CEU value in the samples with high metal levels (table 4). At increasing height above the density current, Ni levels dropped more rapidly than those of Cu, Co and Zn; this was probably due to a greater difference between creek and background bay concentrations for Ni than for Cu, Co and Zn. The background concentrations of all four metals were less than 0.002 mg/l. The confinement of high trace metal levels to the density flow zone was also noted in the 1976-77 bay study (Lap-Eg, 1981).

Some estimates were made to determine what percentage of the total bay volume was occupied by the density current/high metals concentration zone. The initial calculations used the July phase creek discharge and travel time values, as follows:

$$A = (Q/d_7)t_7 \qquad (4)$$

$$V_7 = Ad_7 \qquad (5)$$

$$V_7 = Qt_7, \qquad (6)$$

where A = average cross-sectional area of density current,
Q = density current discharge, and
V_7 = density current volume from mouth of Unnamed Creek to BB-7.

The maximum value of the density current discharge was assumed to be the creek discharge at EM-1. This value was taken as 24 liters/sec for the July phase with t_7 as 54 hours, by equation (2). The maximum volume of the density current during the July phase was thus 4,700 m^3. When the average cross-sectional area of the bay was taken to be the area at BB-4, 254 m^2, then this density current volume represented 1.2 pct of the total bay volume.

Higher creek inflows, such as during the September phase, would be expected to increase the cross-sectional area of flow as well as shorten travel time. Increases in the cross-sectional area of the density current at higher creek inflows were observed in the 1976-77 study (Johnson, 1984). An increased cross-sectional area of flow would result in a proportionately larger percentage of the bay being occupied by water with high heavy metal levels. One can examine the extreme case in which increased discharge does

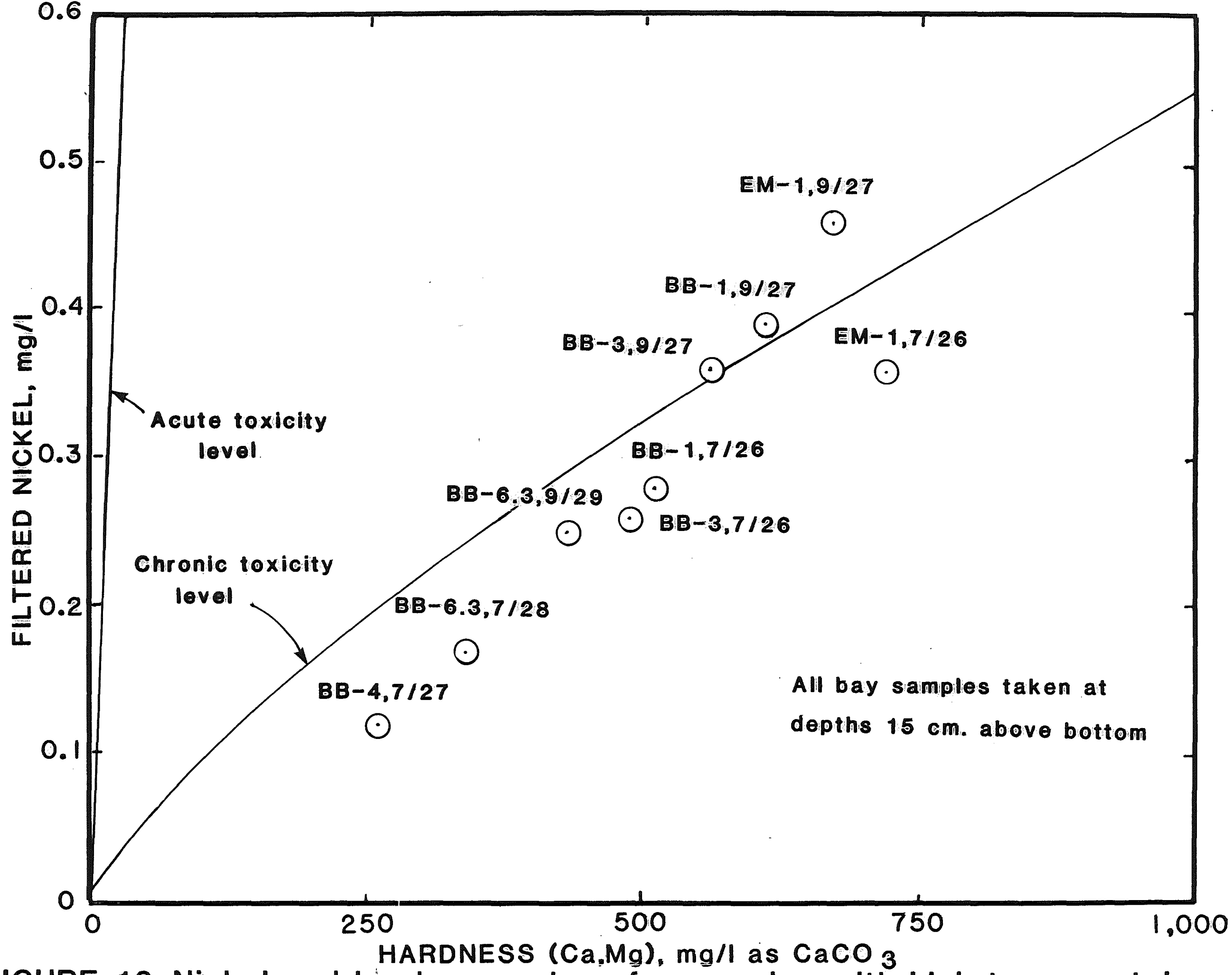


FIGURE 13. Nickel and hardness values for samples with high trace metal concentrations, as compared to EPA ambient water quality criteria for freshwater aquatic life (U.S. Environmental Protection Agency, 1980b)

not increase travel time but only cross-sectional flow area. Had this occurred in the September phase, with a discharge of 49 liters/sec, the density current would have occupied 2.5 pct of the bay volume. Similarly, for one of the highest recorded EM-1 daily discharges, at 740 liters/sec in 1982, 38 pct of the bay would be occupied by the zone with high metal levels.

In addition to determining the distribution of metal levels in Bob Bay, one major purpose of the 1983 study was to better assess the dilution and removal of these metals. Of the four trace metals monitored, only nickel was present at levels sufficiently above background to make a valid assessment. Nickel concentrations were compared to those of sulfate, both at EM-1 and in the density current. Sulfate was assumed to be conserved, as was the case in the Unnamed Creek watershed (Eger and Lapakko, 1980).

Nickel concentrations in the density current varied in roughly the same ratios as sulfate concentrations (fig. 11). The linear plot of sulfate versus nickel (fig. 14) seems to indicate that both parameters were being diluted at the same ratios, and that little if any nickel was being removed. The slightly lower sulfate/nickel ratio in September versus July simply reflects the lower sulfate/nickel ratio in the source water of Unnamed Creek.

The regression equations presented on figure 14 can be compared to a steady-state conservative mass transport model, based on the following equations:

$$Q_i = Q_x - Q_o \qquad (7)$$

$$Q_x[\mathrm{Ni}]_x = Q_i[\mathrm{Ni}]_i + Q_o[\mathrm{Ni}]_o \qquad (8)$$

$$Q_x[\mathrm{SO_4}]_x = Q_i[\mathrm{SO_4}]_i + Q_o[\mathrm{SO_4}]_o \qquad (9)$$

where Q_i = Unnamed Creek inflow,
Q_x = flow at point x in density current,
Q_o = flow of bay water with background levels into density current, and
$[\mathrm{Ni}]$, $[\mathrm{SO_4}]$ = nickel and sulfate concentrations of i, x and o.

These equations can be combined to give:

$$[\mathrm{SO_4}]_x = a[\mathrm{Ni}]_x + b \qquad (10)$$

where $a = ([\mathrm{SO_4}]_o - [\mathrm{SO_4}]_i)/([\mathrm{Ni}]_o - [\mathrm{Ni}]_i)$, and
$b = -a[\mathrm{Ni}]_i + [\mathrm{SO_4}]_i$.

With $[\mathrm{Ni}]_o = 0.015$ mg/l, $[\mathrm{SO_4}]_o = 25$ mg/l, and the influent filtered Ni and $\mathrm{SO_4}$ values listed in table 2, the following relations were obtained:

$$\text{for July, } [\mathrm{SO_4}]_x = 2{,}250\ [\mathrm{Ni}]_x + 0 \qquad (11)$$

$$\text{and for September, } [\mathrm{SO_4}]_x = 1{,}440\ [\mathrm{Ni}]_x + 10.6. \qquad (12)$$

Both (11) and (12) are similar to the regressions obtained in figure 14, further substantiating that nickel behaved as a conservative parameter. The above determinations, both in figure 14 and equations (11) and (12), used filtered nickel data because these were more available than total nickel data; the coefficient "a" should be multiplied by a factor of approximately 0.9 to

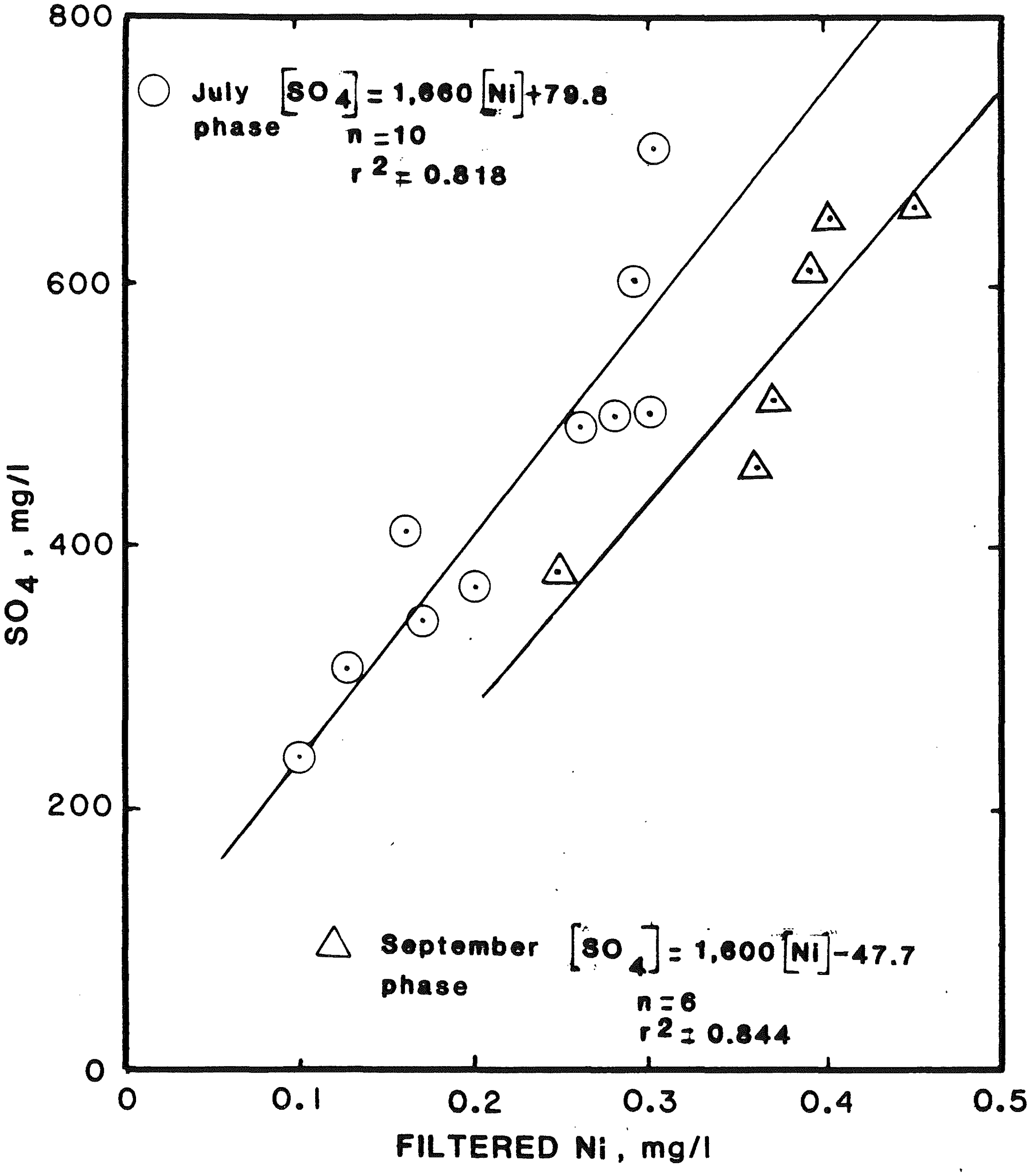


FIGURE 14. Sulfate versus nickel concentrations from EM-1 and bottom samples.

estimate similar relations between sulfate and total nickel.

Sediment analyses from the 1976-77 study seemed to indicate that lake sediments had removed some nickel from the density current inflow (Lapakko and Eger, 1981). The 1983 water quality data suggest either that this removal rate is extremely slow, that it has essentially stopped, or that the sensitivity of measurement is not great enough to detect any removal, at least at those influent nickel levels examined in 1983 (0.3 to 0.5 mg/l).

No nickel removal in the bay indicates that mass nickel transport is thus solely a function of Unnamed Creek mass transport. The mass transport in the creek is in turn a function of creek discharge and metal concentrations. These variables are discussed in more detail below.

The discharge of Unnamed Creek is ultimately a function of precipitation in the mine area. There are several responses, with varying lag times, to precipitation events in the watershed. Stormflow produces a short-term response. It is difficult to analyze the effect of direct stormflow on creek discharge since no major precipitation events occurred just before or during the two sampling phases. The 012 mine dewatering discharge also represents a short-term response to precipitation. A sharp increase in 012 discharge occurred from zero to three days after rainfalls of greater than 1.5 cm in 1981 and 1982. EM-1 discharge generally increased sharply one day after large storm events; this increase was probably a combination of both stormflow and higher 012 discharge. The 012 discharge was manually controlled, and its fluctuations were thus sometimes not directly linked to rainfall patterns. Such was the case on 26 and 27 July, when mechanical problems resulted in low 012 discharges which in turn lowered the discharge of the creek (fig. 5). Mine stockpile seepage is a long-term response to precipitation that should also be noted, particularly as the main contributor of heavy metals to Unnamed Creek (Eger and others, 1981).

Higher creek discharges would produce greater metal transport into the bay if metal concentrations remained constant. Metal levels in Unnamed Creek, however, have varied significantly. Both EM-1 discharge and nickel and zinc concentrations increased from the July to the September sampling phases. A general though not well pronounced pattern of seasonal changes in metal levels at EM-1 is evident from the data of previous years. Concentrations were generally lowest during the winter months and higher, often by twice as much, in the late summer and fall. High metal levels were occasionally encountered in the spring and early summer.

Higher metal levels in Unnamed Creek are to be reflected in higher levels within the density current in Bob Bay. The increase in nickel and zinc levels from July to September was in roughly the same proportion at both EM-1 and within the density flow. A similar, though more generalized, proportional change in nickel and zinc concentrations can be found in comparing the EM-1/density current data from the 1983 to the 1976-77 studies (table 5).

The density current in Bob Bay was usually quite obvious in the 1983 surveys, just as it had been during the 1976-77 surveys (Lapakko and Eger, 1981). The data from the middle of the bay on 28 September, where no density

TABLE 5. - Comparison of 1976-77 and 1983 Bob Bay Survey Data

(All samples from 15 cm above bottom)

Date	Site	Flow, liters/sec	pH	Specific conductance, µS/cm	Temperature, °C	SO_4, mg/l	Total metals, mg/l				Ca, mg/l	Mg, mg/l
							Cu	Ni	Co	Zn		
8/26-8/27/76	EM-1	83	7.36	694	19.1	243	0.003	0.105	NA	NA	42	NA
	BB-1	NA	7.18	435	21	NA	NA	NA	NA	NA	NA	NA
	BB-3	NA	7.56	390	21.4	165	.003	.068	NA	NA	37	NA
	BB-4	NA	6.62	225	23.6	NA	NA	NA	NA	NA	NA	NA
1/31/77	EM-1	0	7.30	389	NA	53	.007	.056	0	0.01	27	20
	BB-1	NA	7.30	395	0.2	49	NA	NA	NA	NA	NA	NA
	BB-3	NA	7.32	395	0.2	59	NA	NA	NA	NA	NA	NA
	BB-4	NA	7.04	155	0.2	20	.0028	.010	0.0005	.004	12.4	8.4
5/5/77	EM-1	204	7.61	510	NA	125	.002	.038	NA	NA	NA	NA
	BB-1	NA	7.65	520	11	61	.011	.043	.001	.0011	40	26
	BB-3	NA	7.90	455	13.6	71	.0057	.038	.0006	.0018	32	21
	BB-4	NA	7.92	320	14.2	62	.0038	.023	<.0005	.0016	23	15
8/17/77	EM-1	167	7.65	725	14.5	208	.002	.126	NA	NA	NA	NA
	BB-1	NA	7.70	725	15.5	210	.0082	.110	.0028	.0041	60	43
	BB-3	NA	8.60	283	18.3	62	.0042	.041	.0010	.012	29	20
	BB-4	NA	8.30	327	17.7	73	.0039	.041	<.0005	.0048	24	16
7/26-7/28/83	EM-1	27	7.55	1,210	17.2	700	.004	.3	NA	.02	130	100
	BB-1	NA	NA	NA	NA	500	.003	.28	NA	.02	84	72
	BB-3	NA	7.58	1,000[1]	NA	480	.002	.28	NA	.01	84	69
	BB-4	NA	6.65	750[1]	23	310	.006	.16	NA	.01	52	32
9/27-9/29/83	EM-1	52	7.9	1,050	11	660	.007	.49	.004	.07	120	90
	BB-1	NA	7.6	920	11	610	.007	.43	.001	.06	108	84
	BB-3	NA	8.00	920	14	510	.004	.40	.002	.06	100	76
	BB-4	NA	7.45	202	NA	<10	NA	NA	NA	NA	16	NA

NA = Not available.

[1] Higher value due to KCl tracer plume.

current could be found, were thus anomalous. It is possible that on that day the principal density current may have migrated in a transverse direction from its usual location through BB-4.7 and BB-5. A transverse survey of the bay at BB-4.7, however, could detect no high conductivity zone and furthermore, it is difficult to imagine how a density current could move out of the deeper channel present at BB-4.7 (fig. 3). Wind-induced currents in the middle of the bay might have dispersed the density current on that particular day. Had wind-driven currents been responsible, there may also have been some resuspension of sediments with subsequent effects on metal transport and removal, as discussed for Saginaw Bay by Dolan and Bierman (1982). Care should be taken, however, in extrapolating too far from these data for one portion of Bob Bay on one day alone.

The 1983 study examined the inflow from Flamingo Creek in addition to that from Unnamed Creek. The mass transport of metals to Bob Bay from the former was considerably less than that contributed by the latter. For Cu, Co and Zn this was principally due to the lower flow of Flamingo Creek. The mass transport of nickel by Flamingo Creek was one to three orders of magnitude below that of Unnamed Creek, due to both lower discharge and lower concentrations.

The inflow from Flamingo Creek could not be traced far into the bay (fig. 9). This was due to both the relatively low discharge of the creek and the lack of a well defined channel at the bottom of the bay near the mouth of the creek. The bottom of the bay near the creek mouth sloped down gradually past BB-F1 and then flattened out at about two meters depth (fig. 3). Inflow from the creek passing through this part of the bay appeared to have been well mixed before it reached either the channel occupied by BB-6.3 or the open part of Birch Lake.

Comparison of the 1983 survey data to those from 1976-77 is complicated by the location of the sampling stations and depths. These were probably not exactly the same in both surveys, even though the 1983 study tried to site the stations at the same locations. This is significant in that concentrations can change markedly as one moves toward the center or the edge of the density current. Despite the siting differences, it is clear that specific conductance, sulfate, nickel, calcium and magnesium (and thus hardness) levels were notably higher in bay samples from 1983 as compared to those in 1976-77. This appears to be due more to increased levels of the same parameters in the Unnamed Creek discharge than to any long term changes in the bay itself. Table 5 presents a comparison of water quality at EM-1, BB-1, BB-3 and BB-4 during both studies. The four 1976-77 sets of samples presented were selected from the nine sets taken. These four sets of samples were taken when the EM-1 flow was sampled at a time when it could be correlated with the timing of the samples at the bay sites, no more than two days later.

6. Conclusions

High Cu, Ni, Co and Zn concentrations in Bob Bay were restricted to a rather narrow density flow along the bottom of the bay. This density current carried inflow from Unnamed Creek northward through the bay to the main part of Birch Lake, and occupied no more than five pct of the bay volume during the

1983 study periods. The highest trace metal concentrations in this density flow were found nearest the mouth of the creek, and ranged from 0.035 to 0.052 copper equivalent units (CEU). Nickel concentrations in the density current were one to two orders of magnitude greater than those of the other three metals. No significant nickel removal was observed in the density current during the one to three days required for it to pass through Bob Bay. The observed decrease in nickel concentrations along the flow path was the result of dilution. Metal concentrations in the density current appeared to be controlled mainly by the water quality of Unnamed Creek. The input of metals from Flamingo Creek was much smaller and could not be traced very far into the bay. Differences in metal concentrations in the bay between 1976-77 and 1983 appeared to be more due to changing water quality in the creek inflow than any long-term changes in the bay itself. Metal concentrations were higher in this study than the previous study due to increased concentrations in streamflow from the mining watershed.

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