METHODOLOGY FOR LOCATING AND QUANTIFYING ACID MINE DRAINAGE IN GROUND WATERS ENTERING SURFACE WATERS[1]

David R. Lee and Rob Dal Bianco[2]

Abstract: Subsurface migration of leachate from mining operations to rivers and lakes is now an issue at some sites, particularly where these operations adjoin public waters. Until now there has been no practical method for identifying and quantifying subsurface flows into surface waters. A new method for finding and measuring seepage into surface waters has been evaluated near a mining area in northern Ontario. A bottom-contacting probe was towed behind a slowly moving boat and used to locate areas of leachate discharge. The upward flux of high-dissolved solids ground water in these areas was confirmed (1) by measuring the pore water electrical conductivity 20 to 120 cm below the sediment-water interface, (2) by directly measuring flux using seepage meters or (3) by measuring gradient, hydraulic conductivity and solute chemistry. The discharges ranged from 12,820 to 43 uS/cm and from 6.9 to 4.8 pH. One discharge contributed 12 kg of nickel per annum to the receiving river. Combined with conventional methods, piezometers and seepage meters, the new method forms a methodology that starts with broad reconnaissance to identify potential discharge areas and ends with quantitative measurements in discharge areas.

Additional Key Words: monitoring, electrical conductivity, assessments, offsite migration, contaminant transport.

Introduction

In mining areas, water infiltrating the land surface may contact a large reservoir of noncarbonate, sulfide-bearing soil particles and rocks, become acidic and acquire elevated concentrations of iron and sulfate. These ground waters can also mobilize heavy metals, including radionuclides, and can transport them to points of discharge. There also may be significant attenuation or dilution between source areas and the entry of acid mine drainage (AMD) and metals into surface waters.

Because ground water moves to topographical lows, there is potential for transport of leachates, containing high metal concentrations and depressed pH levels, to aquatic environments. In some settings this may not be obvious because all seepage can move inconspicuously below the waterline to rivers, lakes or their contributing wetlands.

The conventional approach, using piezometers, can approximate the locations of ground water discharge zones, but, because of the heterogeneity of most geologic settings, this can require an enormous number of sampling locations, which are established and monitored at great cost. Data analysis of such point samples would also require a large degree of interpolation between sampling locations. The interpreter must decide whether samples are sufficient and representative. This has an important bearing on the validity of conclusions.

A technique for examining large areas of water-covered terrain was developed to help solve the problem of arbitrary point sampling. The technique involves the towing of a bottom-contacting probe behind a small, outboard-motor boat. This technique provides continuous recordings of electrical conductivity (EC) along bottom sediments while assigning a geographical coordinate to each measurement. This paper describes this technique, its first application to AMD, and shows collection of data and an estimatation of nickel flux to surface waters.

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[2]David R. Lee, Research Officer, Rob Dal Bianco, Technical Officer, AECL Research, Chalk River Laboratories, Chalk River, Ontario, K0J 1J0, Canada

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Under good conditions, a sediment probe survey can cover 10 to 15 line-kilometers of lakebed or riverbed per day. This is intended to provide an accurate and inexpensive identification of locations where environmental impact has occurred or may occur in the future. Discharges, which have been identified with the probe, can then be characterized chemically and hydrogeologically to determine sources and transport times.

Methods

Mapping of Subaqueous Acid Mine Drainage

The presence of a subaqueous, ground water discharge zone was sensed as an increase in sediment EC above the local background using a probe (fig. 1) towed along the riverbed.

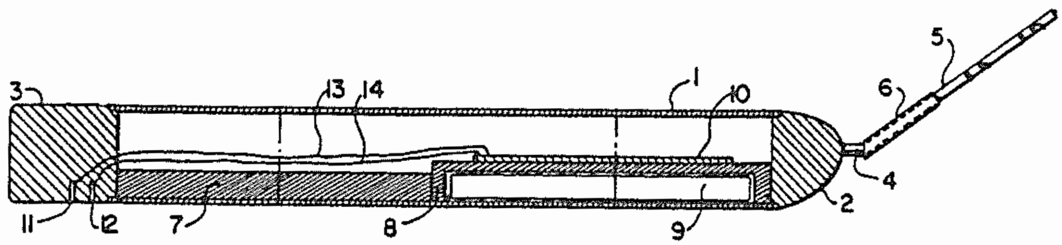

Figure 1. Sediment probe (after Lee and Beattie, 1991) consisting of a slim tubular body or shell **1** closed at one end with a nose cone **2** and at the other end with an end plug **3**. The nose cone has a rounded front which is provided with a waterproof connector **4** to which a towing cable is attached so that the probe can be towed along the bottom of a river or lake bed. A plastic abrasion guard **6** surrounds the lower portion of the cable **5**. One or more lead weights **7**, **8** are located in the bottom portion of the tubular body. A gamma radiation detector **9** may or may not be located in the probe. A ciruit board **10** is located above the lead weight. The end plug contains two or more electro-conductive pins which are flush with the lower surface of the plug and connected to the circuit board. The probe may contain other features (Lee and Beattie, 1991) not used in the present work.

The sediment-probe survey involved three people. The data acquisitions system had readouts for several data channels, so that the two people in the boat could observe data as collected, form mental images of results within the study area, and deploy anchored floats in areas of interest. A portable computer and a paper chart recorder provided visual displays and data logging. Custom software, prepared using LabWindows in C, was used to record input from both the probe and the positioning system.

The positioning system consisted of a shore-based tripod theodolite (for determination of angle and elevation), small computer, a radio telemetry unit and a laser range finder with a maximum range of 15 km. The accuracy was potentially better than plus or minus 0.5 m, but this was compromised to 3 m by the correction of probe position relative to the boat. The shore operator tracked a prism mounted on the boat through a telescope on the laser range finder. The shore-based part of this positioning system supplied the computer in the boat with x and y coordinates relative to the tripod reference point.

In most instances, a sufficient outline of the shoreline of a water body was recorded by tracking the boat as it moved along the edge of the water body as close to shore as possible. The system recorded probe readings every 0.2 to 0.4 s and the boat speed was 0.5 to 1 m/s.

The first step of data processing was conversion of the boat position, boat direction and cable length to the position of the sediment probe corresponding to each probe measurement. The probe was considered to follow the boat by a distance equal to the length of cable.

Data analysis employed software customized and developed by the Environmental Research Branch of AECL Research. Normally colors are used to define ranges of EC along a riverbed or lakebed, using a dot of color for each probe measurement on a map. However, in this paper a shaded gray version of the maps was used.

Confirmation of Sediment-Probe Survey Results

Ground water parameters were measured to quantify and evaluate sediment probe survey results. Harpoon piezometers (Lee and Welch 1989) were used to obtain ground water for EC and chemical analyses, measure hydraulic potentials and estimate hydraulic conductivity. To measure directly the flux of ground water entering surface waters, seepage meters were installed in appropriate locations, such as sandy bottoms in nonflowing waters (Lee and Cherry 1978).

Results and Discussion

Previous monitoring of surface waters had accounted for only 10% of the nickel exported by the Levack portion of the Onaping River (Wiseman, 1993) 40 km northwest of Sudbury, Ontario. In addition to testing the probe, we sought to locate additional sources of nickel loading and provide a basis for future work.

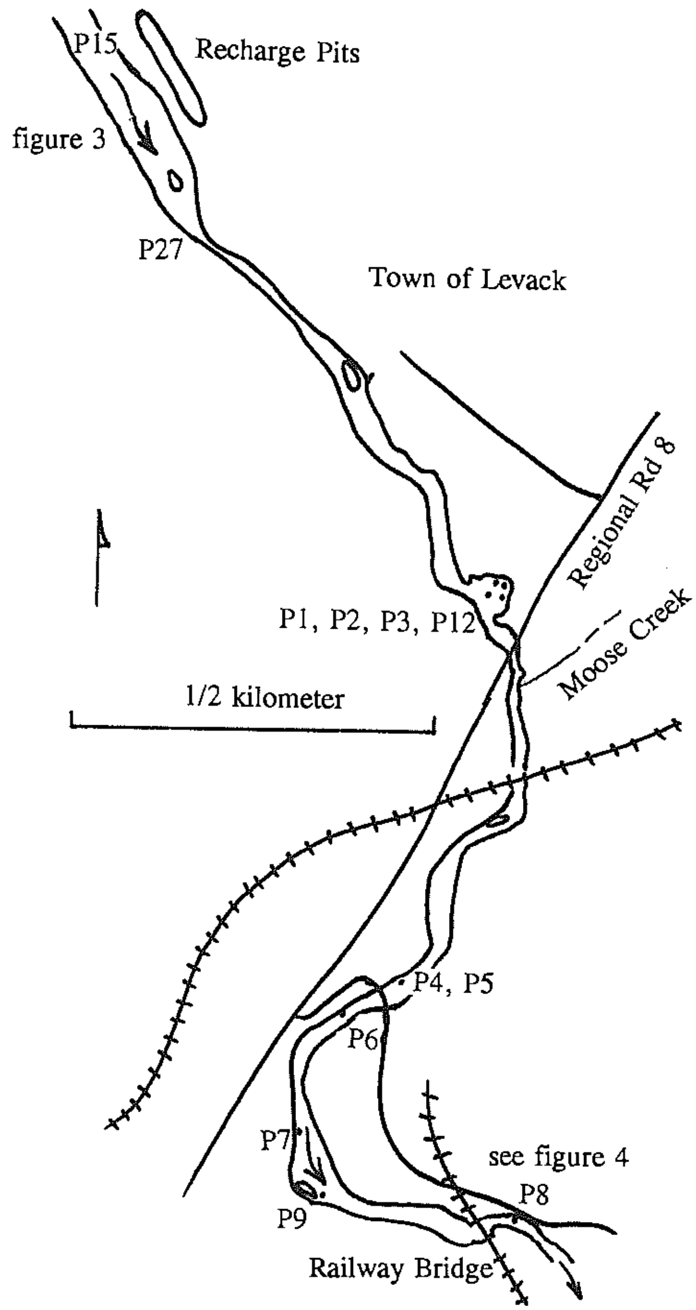

Figure 2. Study area near Levack, Ontario.

Initial survey

Initially the probe was towed up and down a 2 km-long section of river (fig.2). In areas of elevated EC, 12 harpoon piezometers were installed to determine whether high values of EC, identified with the sediment probe, coincided with locations of rapidly flowing, high dissolved solids seepage.

Further delineation of ground water discharge areas was conducted at four sites within this reach of river. Results at all four sites were similar and results at three sites are presented here. The fluxes of water and Ni were calculated from areas of discharge (based on probe survey results), measured seepage rate and pore water solute concentrations.

Samples of sediment pore water were withdrawn from the piezometers for laboratory measurement of EC and pH (table 1). The pore water EC in some of the samples was as much as 100 times greater than that of the river. River values of EC were 46.3 μS/cm at the highway bridge and 228 μS/cm at the rail bridge downstream (fig. 2). Measurements of hydraulic head, relative to the river surface, or measurements of artesian flow confirmed the existence of upward hydraulic potentials.

Table 1. Onaping Riverbed Piezometers

Piezometer Number	Porewater Elect. Cond. μS/cm @ 24-25°C	pH	Depth of Piezometer Screen Below Riverbed cm	Head of Water in Piezometer Above River cm
Piezometers northeast of highway bridge				
P1	1321 [Ni]=2.24	7.00	43	
P2	2160 [Ni]=1.00	6.81	30	
P3	1903	6.42	20	
P4	1075	5.96	75	
P5	1180	6.17	193	
P6	1570	6.55	111	
P7	961	4.91	41	
P8	3910 [Ni]=1.1	4.89	44	
P9	360 [Ni]=2.79	6.47	109	
P12	1869	6.18	30	
Piezometers near Recharge Pits, Fig. 3				
P13	43		108	75 (flowing)
P14			194	52
P15	123	6.49	75	~0
P16	72 [Ni]=≤0.02		79	20 flow=124mL/min
P17	326 [Ni]=2.8	6.05	94	~0
P27	1200	4.83	30	
Piezometers downstream of the RR Bridge, Fig. 4				
P8	1430 field			flow=0.8mL/min
P19	1800 field [Ni]=9.5	5.66	42	1
P20	12820 field	5.44	49	
P21	207			

There was generally excellent agreement of probe values (measured in situ) and the pore water values (collected from piezometers and measured in the laboratory); pH was occasionally depressed where EC was elevated (table 1).

Results at Three Sites

Northwest of the highway bridge (Fig. 2), probe results indicated a 350 m^2 area of elevated EC. While installing piezometers in a surficially sandy bottom, we encountered cobbles and boulders within 50 cm of the sediment-water interface. Due to the shallowness of these piezometers, gradients were too small to measure, except at P1, where the water level stood 0.5 cm above river level and the vertical gradient was 0.01. The piezometer samples (P1, P2, P23, P26) had EC values from 1530 to 2260 μS/cm. The river at this location had an EC of about 50 μS/cm. Nickel in P1 was 2.24 ppm, well above the river background concentration of 0.1 to 0.15 ppm.

Screened just 20 to 30 cm below the riverbed, P2 produced water with an EC of 2160 μS/cm and a nickel concentration of 1 ppm. This EC was 44 times greater than the river value at that location. Considering the proximity to the river and the permeability of the sediments, these water samples provided unequivocal evidence of solute discharge. AMD may enter the river at this site, based on the measured Ni values of 1 to 2.2 ppm in these very shallow piezometers. However, the relative contributions of AMD and road salt will have to be determined by further chemical analysis of water samples from riverbed piezometers.

Hydraulic heads in all the piezometers at P2 were within millimeters of the river level, and considering the currents of 20-30 cm/s, were not suitable for hydraulic potential measurement, except to indicate low or nonexistent gradients. Lack of measurable differences in water levels relative to river level was probably due to the shallow depth of penetration of all the piezometers and the highly permeable bottom materials.

Piezometers near P2 and P12 (fig. 2) also confirmed and quantified discharge of high EC ground waters at locations identified with the probe. Artesian flow of 0.1 mL/min at one peizometer proved upward hydraulic potentials, but the piezometric level could not be distinguished from river level. One piezometer contained 2.8 ppm Ni, which was intriguing, considering its relatively low EC of 360 μS/cm.

An anomaly was noted (fig. 3) in the middle of the river about 150 m below rapids. Here, in water 3.5 m deep, piezometer P15 was screened in gravel 75 cm below the riverbed. While sitting in the boat, we could not see a difference between the water level of this piezometer and the river, so we extended the piezometer tube to shore, 40 m away. The water level in this tube did not differ ($\pm$ 0.2 cm) from the level of the river at the shore, suggesting little or no hydraulic gradient, at least when measured at this location. Pore water pumped to shore from this piezometer had an EC of 123 μS/cm. Although this was three times greater than the river EC at that location, it was lower than expected based on the probe responses nearby. Based on probe response, we expected greater than 123 μS/cm in P15 (table 1). Perhaps the high-EC area was not sampled by P15, which was not installed exactly in the groove formed by the probe where river gravels were too coarse for our installation method. Later, when we visually inspected the bottom, we saw this groove in relation to our piezometer. We also noted a 0.5 to 1-m thick layer of 8°C bottom water, which, considering the overlying river currents, must have been supported by continuous discharge of ground water. The depressed temperature there would have depressed the probe readings by about 16%, not elevated the EC.

Table 2. Onaping River Seepage Meter Data

Seepage meter at piezometer number	*Seepage Flux, μm/s
16	0.8,0.5
8	0.8,0.8

*Seepage flux is equivalent to specific discharge. 1μm/s=31.5 m/yr

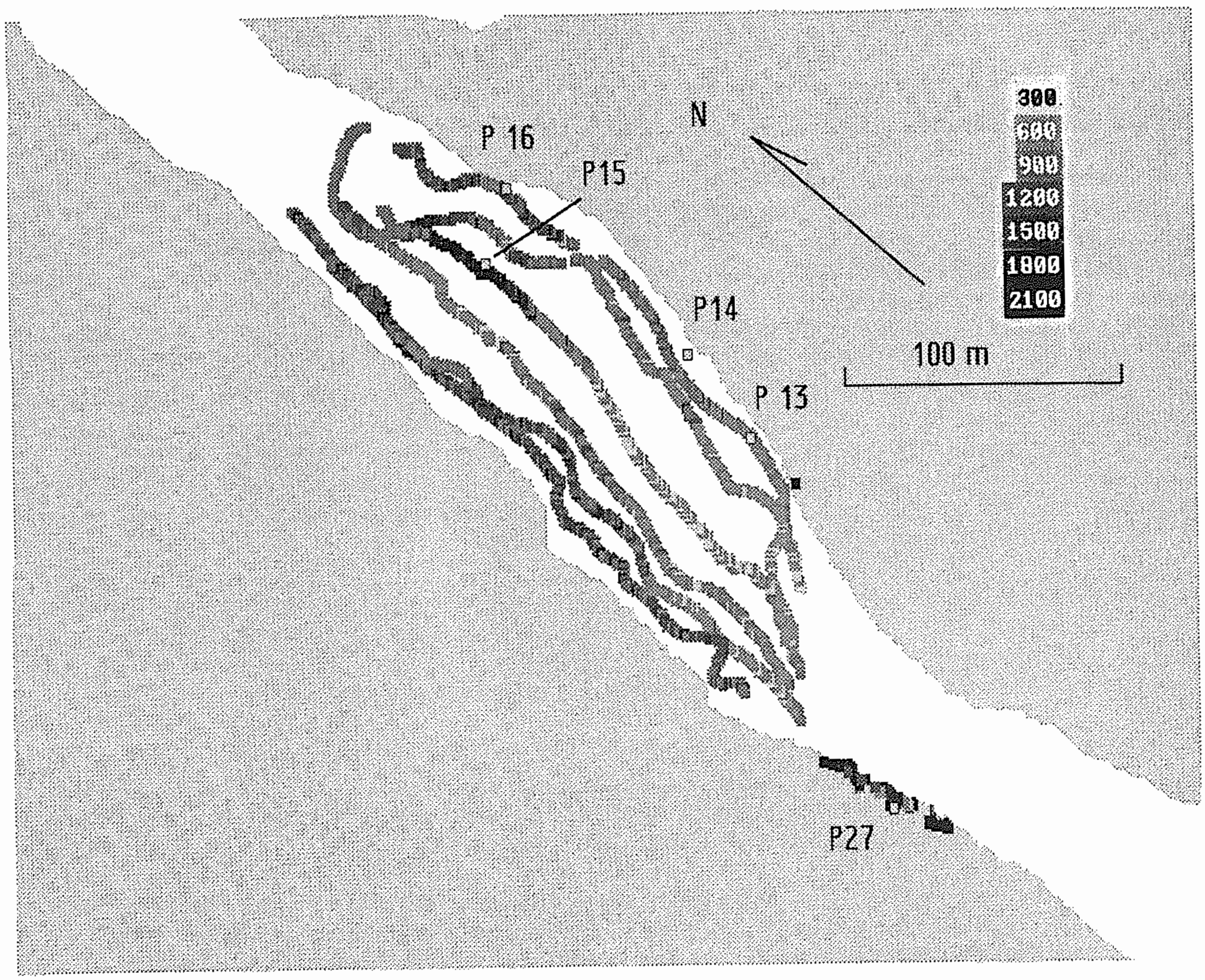

Figure 3. Sediment probe electrical conductivity of the Onaping Riverbed near the Levack, Ontario, municipal well recharge pits. Each dot represents one measurement location and value. The ranges of electrical conductivity from low to high are indicated with shades from white to black.

Where EC was predicted to be high based on the probe results (fig. 3), piezometer samples were correspondingly elevated in EC (table 1). However, along the shoreline adjacent to the recharge pits, the probe did not indicate seepage of high EC ground water. At that location, we observed the discharge of uncontaminated ground water using seepage meters (table 2) and by measuring head, artesian flow and EC in piezometers P13, P14, and P16 (Table 1). Discharge of low-EC water can be attributed to the adjacent pits, which were maintained above river level by pumping from the river with the intention of diverting AMD from municipal wells.

Another anomaly was found along the right bank of the river (P27, fig 4). A piezometer there (P27) yielded water with an EC of 1200 μS/cm, a nickel content of 2.8 ppm and a pH of 4.8 (table 1). Surface water levels in this area were slightly above the level of the adjacent river. The cold water (< 9°C) discharging at this location was visibly pristine and not iron stained.

Two facts indicated that leachate from tailings is diverted from its natural course by a ground water mound produced by the pits, and discharges at locations farther upstream and downstream: a) a plume of tailings-contaminated ground water extends toward the river from tailings 2 to 3 km northeast of the pits (King, 1993), and b) two distinct areas of high EC were found on the river bottom, one above and one below the recharge pits (fig.3, near P15 and P27). To determine solute sources in these zones, it will be necessary to measure sulfate concentrations and environmental isotopes and possibly to install additional piezometers.

At another detailed study site below the railway bridge (fig. 4), the sediment-probe results focused work on an area that yielded pore water of 8,000 to 12,820 μS/cm, 9.5 ppm Ni (table 1) and ground water discharging at a rate of 0.8 μm/s (table 2). Judging by the probe results (fig. 4), the anomaly was 17 m in length. Its width was at least 3 m, based on the distance between piezometers P19 and P20, and seepage meter 8 (at P8). The nickel loading to the river was about 12 kg/yr assuming a rectangular discharge area of 3 m X 17 m, an average seepage rate of 25 m/yr and an average Ni value of 9.5 g/m^3.

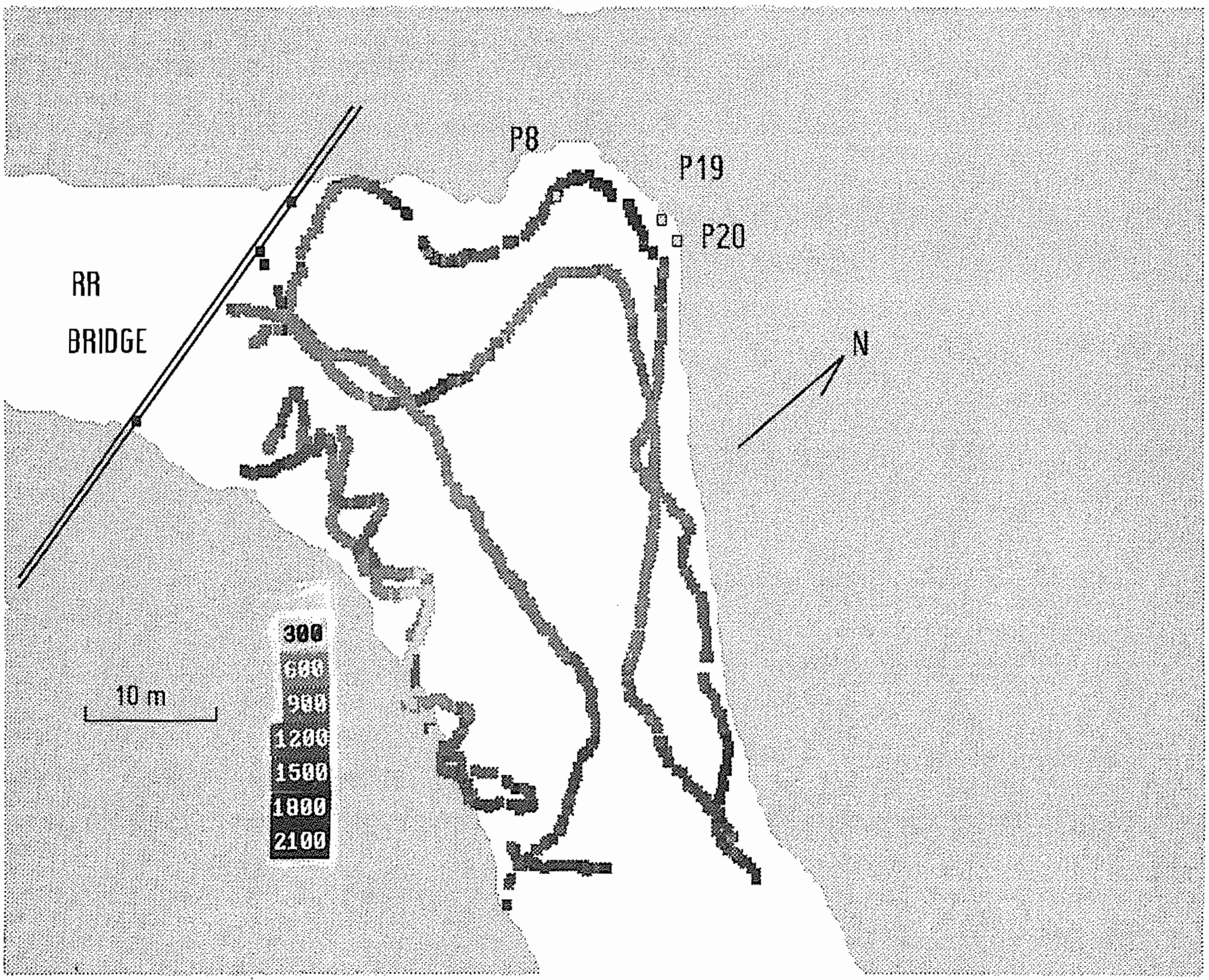

Figure 4. Sediment probe results on the Onaping River one kilometer below Levack near the Inco rail bridge.

Conclusions

1. Sediment probe surveys provided qualitative maps of areas of elevated EC ground water discharge. In every location of high EC identified with the sediment probe, pore water EC was elevated relative to the overlying water. Where the probe registered high values, there was also evidence of upward ground water flow. Pore water EC values were as high as 12,800 μS/cm. Therefore the sediment probe identified ground water discharge areas and these were found to contribute nickel to the Onaping River at concentrations ranging from 1 to 9.5 ppm. Sediment-probe results were used to estimate the size of the discharge area near three piezometers that had elevated EC and a nickel flux of 12 kg/yr was estimated in a 50 m^2 discharge area.

2. Probe performance was unaffected by overhead power lines and other materials that have hampered application of electromagnetic methods. Because the methodology includes quantitative analysis of discharge parameters as an essential part, it yields discharge information in areas of greatest potential contaminant flux. Experience on the Onaping River showed that even in whitewater this methodology can be effective.

3. Now that potential AMD areas have been identified and are known to occupy small areas of river, ground water and contaminant flux may be assessed efficiently. Samples may be collected at existing piezometers, so that additional chemical and isotopic analyses can help determine source areas. Helium-3/tritium analysis using mass spectrometry is recommended to determine ground water age (i.e., underground residence times) for water presently discharging. Some of the suspected AMD may turn out to be natural ground water.

4. In theory, sediment type affects probe response, but in practice did not prevent the identification of ground water discharge areas. Variation of sediment electrical properties was not large enough to interfere with the identification of discharge areas where the contrast in EC between surface and ground water is more than a factor of about 2 or 3. In more homogeneous environments, this contrast may not have to be so large.

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