EVALUATION OF AN UNDERWATER MONITORING PROBE FOR LOCATING AND ESTIMATING THE IMPACT OF GROUNDWATER DISCHARGES TO SURFACE WATERS ADJACENT TO POTENTIAL SOURCES OF AMD

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EVALUATION OF AN UNDERWATER MONITORING PROBE FOR LOCATING AND ESTIMATING THE IMPACT OF GROUNDWATER DISCHARGES TO SURFACE WATERS ADJACENT TO POTENTIAL SOURCES OF ACID MINE DRAINAGE [NORTHERN ONTARIO DEVELOPMENT AGREEMENT]

by

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EXECUTIVE SUMMARY

The migration of leachate from mining operations through the ground is an issue of concern to the mining industry, regulators, and public, particularly where leachate constituents may be moving into surface waters. In many geologic settings, seepage enters surface water invisibly through submerged fractures and bottom sediments. Until now there were no practical methods for identifying these subsurface flows. Knowing the location and contaminant flux of offsite seepage can be important in estimating the degree of contamination in an area, and in designing programs for useful monitoring, remediation and reclamation. By identifying and quantifying subaqueous seeps, it should be possible to reduce costs of hydrogeological investigation and monitoring.

A new reconnaissance method for detection of acid mine drainge (AMD) has been evaluated near mine operations near Sudbury and Timmins, Ontario. An electrical-conductance, bottom-contacting probe (known as the sediment probe) was towed behind a slowly moving boat over more than 21 line-kilometres of lake and river bottom.

The evaluation has been successful, both as a test of the method and as a preliminary identification of groundwater discharge areas at the two study sites. The method effectively solves the problem of identifying discharge of AMD in surface waters and, by quantifying the groundwater and solute-transport, it has provided estimates of impact at points of discharge.

The sediment-probe method depends on two conditions: 1) groundwater-contaminant plumes and surface waters differ in electrical conductivity, and 2) upward advection moves the groundwater signatures within centimetres of receiving surface waters.

The method was used to locate eight areas of leachate discharge. These were studied quantitatively, to evaluate the utility of the probe and provide site-specific information. Some targets were confirmed by measuring the porewater electrical conductivity 20 to 120 cm below the sediment/water interface. Other targets were confirmed using direct measurements of flux, using seepage meters. Still others were confirmed by measuring upward gradient, moderately high hydraulic conductivity and solute chemistry.

The discharge conductivities ranged from l2 820 to 43 µS/cm and from 6.9 to 4.8 pH. Some discharges contributed nickel in concentration ranging as high as 9.5 ppm to the surface waters.

In order to attribute many of the discharges to leachate from mine tailings, waste rock, septic tanks or road salt, it will be necessary to do additional chemical and isotopic work using the existing piezometers. The authors and industrial partners hope to conduct major-ion, metal and isotopic analyses, to distinguish sources and provide contaminant concentrations for better flux estimates.

Specific findings:

1. Sediment-probe results, supported by quantitative measurements, show that groundwater of elevated electrical conductivity is entering Lake Kamiskotia along two-thirds, or 1.5 km, of the northeastern shoreline. This shoreline discharge could contain AMD, road salt, septic-tank effluent or waters that are naturally high in dissolved solids.

2. Bottom-water samples below the outlet of Lake Kamiskotia in the Little Kamiskotia River indicate that AMD may be entering the river 300 m upstream of any obvious damage to the terrestrial environment.

3. Several sources of nickel input to the Onaping River were identified on the river bed. At one location, a crude but illustrative calculation showed that 12 kilograms of nickel enter the river each year over a 50 m^2 bottom area.

4. Recommendations for further work include: (a) analysis of existing samples to determine sources of high dissolved solids water entering the studied surface waters, and (b) collection of additional samples for chemical and isotopic analyses. Helium-3/tritium analysis using mass spectrometry should be used to determine the groundwater residence time for the discharging waters. Some of the suspected AMD may, in fact, be natural discharge.

RÉSUMÉ

La migration de lixiviats provenant de travaux d'exploitation minière est un problème pour l'industrie minière, les organismes de réglementation, et le public, en particulier dans le cas où les constituants du lixiviat peuvent se déplacer du site d'exploitation vers les eaux de surface. Jusqu'à maintenant, il n'existait aucune méthode pratique pour identifier les écoulements souterrains dans les eaux. La connaissance du point et du débit des contaminants se déplaçant hors du site peut être importante pour estimer le degré de contamination d'une région, et également pour concevoir des programmes de surveillance, d'assainissement et de remise en état.

Dans de nombreux milieux géologiques, le lixiviat pénètre invisiblement dans les eaux de surface par les fractures submergées et les sédiments de fond. En identifiant et en quantifiant les infiltrations subaquatiques, on pourrait réduire les frais d'étude et de surveillance hydrogéologiques.

Une nouvelle méthode d'exploration pour la détection du drainage minier acide (DMA) a été évaluée près d'une exploitation minière aux environs de Sudbury et de Timmins, en Ontario. Une sonde à conductivité électrique, se déplaçant au ras des sédiments (appelée subséquemment "sonde à sédiments"), a été remorquée derrière un canot se déplaçant lentement sur une distance totalisant 21 km de lignes balisées sur des lacs et rivières.

L'évaluation a été réussie aux deux lieux d'étude en tant qu'essai de la méthode, et également pour l'identification préliminaire des principales aires d'émergence des eaux souterraines. La méthode résout efficacement le problème de l'identification des rejets du DMA dans les eaux de surface et, en quantifiant les apports en eaux souterraines et la migration des solutés, elle a fourni des mesures de l'impact aux points de rejet.

La méthode de la sonde à sédiments dépend de deux conditions : 1) les panaches de contaminants des eaux souterraines et les eaux de surface doivent avoir une différente conductivité électrique, et 2) le déplacement vers le haut des eaux souterraines contaminées doit se faire dans les quelques centimètres des eaux de surface réceptrices.

On a employé cette méthode pour localiser huit points de rejet de lixiviats. Ces points ont été étudiés quantitativement pour évaluer l'utilité de la sonde et fournir des renseignements particuliers sur ces points de rejet.

Certains points de rejets ont été confirmés en mesurant la conductivité électrique de l'eau de pores à une profondeur de 20 à 120 cm sous l'interface eau-sédiment. D'autres points de rejets ont été confirmés en mesurant directement les débits à l'aide d'un appareil de mesure d'infiltrations. D'autres encore ont été confirmés en mesurant le gradient ascendant, la conductivité hydraulique moyennement élevée et les propriétés chimiques des solutés. La conductivité des rejet s'est échelonnée de 12,820 à 43 µS/cm et le pH de 6,9 à 4,8. Quelques rejets exportent jusqu'à 9,5 ppm de nickel aux eaux de surface.

Pour attribuer un bon nombre de ces rejets au lixiviat des résidus miniers, des stériles, des fosses septiques et du sel de déneigement de routes, il faudra effectuer d'autres travaux de recherche sur les contenus chimiques et les isotopes à l'aide de piézomètres déjà existants. Les auteurs et partenaires industriels espèrent mener des analyses d'ions dominants, de métaux et d'isotopes pour distinguer les sources et déterminer la concentration de contaminants pour mieux en estimer les débits.

Résultats particuliers :

1. Les résultats obtenus à l'aide de la sonde à sédiments, soutenus par les résultats des mesures quantitatives, montrent que des eaux souterraines de conductivité électrique élevée pénètrent dans le lac Kamiskotia, sur les deux-tiers de la rive nord-est, dont la longueur totale est 1,5 km. Le rejet le long de cette rive pourrait contenir du DMA, du sel de déneigement de routes, des effluents de fosses septiques out des eaux naturelle à forte teneur eu solides dissous.

2. Les échantillons d'eau de fond prélevés sous l'exutoire du lac Kamiskotia vers la rivière Little Kamiskotia indiquent que du DMA pénètrent dans la rivière à 300 m en amont de toute dégradation évidente du milieu terrestre.

3. Plusieurs sources potentiellement importantes d'apport de nickel ont été identifiées dans le lit de la rivière Onaping. En un point, un calcul grossier mais illustratif a montré que 12 kilogrammes de nickel pénètrent dans la rivière chaque année, sur une surface de lit de 50 m^2.

4. Des travaux additionnels sont recommandés, dont entre autres : (a) l'analyse des échantillons existants pour déterminer les sources d'eaux à forte teneur en solides dissous pénétrant dans les eaux de surface étudiées, et
(b) le recueil additionnel d'échantillons pour les analyses en espèces chimiques et en isotopes. On devrait effectuer l'analyse du mélange hélium-3/tritium par spectrométrie de masse pour déterminer le temps de séjour des eaux rejetées dans les eaux souterraines. Il se pourrait que certains rejets qu'on a soupçonnés être des rejets du DMA sont en fait d'origine naturelle.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

This study was designed to evaluate AECL's sediment-probe technology for an application to another industry: the identification of groundwater discharge points of acid mine drainage (AMD) to surface water. The approach used was to apply this technology at sites where AMD discharge to surface water was suspected, and then test anomalous areas for groundwater parameters and constituents of mine leachate. This report discusses field applications and evaluates the technology. For a limited number of locations, we have quantified the discharge of groundwater. At one location we have estimated the nickel loading of the receiving river.

Because groundwater generally moves to rivers and lakes in topographical lows, there is potential for transport of leachate, containing metals and depressed pH levels, to aquatic environments. In some settings there may be no obvious signs of discharge and no visible overland seepage. All seepage may move inconspicuously below the waterline to rivers and lakes. In earlier studies, groundwater discharging directly through bottoms of surface-water bodies was detected by measuring electrical conductance (EC) of sediments using a probe dragged across submerged sediments (Lee, in preparation).

The term "sediment-probe survey" is used here to mean a coarse-grid, broad-area reconnaissance that uses a boat-towed sediment probe to locate areas where groundwater may be entering a water body through its bottom from a contiguous aquifer or permeable fracture zone. The presence of a groundwater discharge zone is sensed by measuring changes in sediment EC from the local background. Areas of elevated EC need to be verified using simple follow-up methods and, if possible, quantified for potential contaminant flux.

The survey and the confirmation methods can be performed in lakes and rivers. Under good conditions, a survey can cover 10 to 15 line-kilometres of lake- or river-bed per day. These advantages allow accurate and inexpensive identification of locations where environmental impact has occurred or is likely to occur in the future. Then, contaminant discharges can be characterized as to their sources, transport times and actual detriment. With respect to mining development, the following specific applications of sediment-probe technology were identified at the proposal stage:

1. Pre-operational surveys could be conducted, to locate potential points-of-impact prior to making critical monitoring and/or development decisions.

2. Surveys at operational sites would help to identify where and to what extent off-site migration occurs, while providing information on point-of-impact locations that need to be monitored on a continual basis. With this information, decisions could be made that would result in more efficiently managed mine and mill wastes, with less cost and less impact on the environment.

3. Surveys at post-operational sites would provide information that could limit the

number of boreholes and piezometer installations during a hydrogeologic investigation, and thus reduce the expense of remedial action.

BACKGROUND

Submerged groundwater discharge zones can be located and mapped with the sediment probe because groundwater EC usually differs from the EC of surface waters. This is particularly true where the groundwater contains additional ions originating from road salt or leaching of waste rock and the groundwater is seeping into a surface freshwater environment.

A traditional method for locating submerged groundwater discharge zones would require a vast number of piezometers at individual point locations. Because of the heterogeneity of the geologic environment at most sites, a conventional point-sampling approach could require an enormous number of sampling locations that would be expensive and extremely time-consuming. Data analysis of such point samples requires a large degree of interpolation between sampling locations. The interpreter must decide whether samples are representative. This has an important bearing on the credibility of results.

As a result of deficiencies in point-sampling approaches, a new technique of towing a compact, cylindrical sediment probe behind a small boat was developed, to cover the greatest territory possible in a shorter time period and in a more cost effective manner. This technique, with the aid of a hydrographic positioning system, allows the probe to take continuous recordings of EC along the bottom sediments while assigning a geographical coordinate to each measurement.

Waters in contact with non-carbonate, sulfide-bearing rocks are usually acidic and contain elevated concentrations of iron and sulphate. These waters can mobilize heavy metals, including radionuclides, and can transport them to points of groundwater discharge.

Before starting this work, we installed a pH electrode in a prototype sediment probe, so that we could attempt simultaneous measurement of pH and EC. It was hoped that this would complement the EC measurements and provide better, more definitive targeting of acidic groundwater discharge.

SCOPE OF WORK

Following discussions with Falconbridge Limited and Ministry of Northern Development and Mines in the summer of 1992, we proposed to conduct sediment probe surveys at the Kam-Kotia Mine Tailings Rehabilitation Area near Timmins, Ontario and in the Onaping River near Levack, Ontario. Levack is about 30 km northwest of Sudbury, Ontario. The surveys were to use a sediment probe capable of detecting changes in pH and EC. After each survey, a "ground-truthing" investigation using harpoon piezometers (Lee and Welch, 1989) and/or seepage meters (Lee and Cherry, 1978) was conducted.

The objectives of this project were:

1. To conduct a broad (coarse-grid) reconnaissance for acid leachate seepage using the sediment probe on the Onaping River and on surface waters near the Kam-Kotia Mine Tailings Rehabilitation Area. The study sites were moderately accessible, they had a high probability of having groundwater discharge zones and were known to have potential sources of AMD.

2. If identified, to measure and quantify groundwater discharge at a minimum of four locations per area, where sediment survey results appeared interesting or anomalous. This was intended to allow us to test the probe's ability to identify acidic seepage. Samples were to be collected, field-filtered and preserved for possible chemical analyses.

3. To evaluate the use of the sediment probe as a method for determining the location of submerged acidified groundwater discharge zones and to discuss in report form recommendations for this application, including improvements and limitations.

METHODS

Mapping of Subaqueous AMD

The sediment probe (Figure 1) comprised a tubular shell, brass nose cone, tail piece with electrodes and tow cable. The patent is held by AECL (Lee and Beattie, 1991) and other patents are pending. For the AMD work, the radiation detector was omitted. For the measurement of pH, a combination electrode was incorporated within the probe body.

The standard setup was similar for all types of sediment probe surveys: radiation, EC, pH or other parameters. Three people were involved: one person was on shore operating the laser positioning system and two were in a small boat (of the latter, one person operated the on-board electronic instruments and one drove the boat and handled the tow cable). The probe was dragged along the bottom behind the boat at an optimum speed of about 1 m/s. The tow cable, between 5 and 50 m in length, contained wires connecting the probe sensors to a custom data acquisition system aboard the boat. This system had readouts for several data channels, so that the people in the boat could observe data as it was collected, to verify operation, form mental images of results within the study area, and deploy anchored floats in areas of interest. The two visual displays and loggers were a portable computer and a paper chart recorder. Custom software, prepared using Labwindows in the computer language C, recorded input from both the probe and the positioning system on the computer.

The laser positioning system consisted of a shore-based tripod theodolite (for determination of angle and elevation), laser range finder, small computer and radio telemetry unit. The maximum range was 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 motor 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 Cartesian coordinates relative to the tripod reference point.

In most instances, a crude but 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 0.3 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. The calculation involved both direction of travel and the boat position. Calculation of probe position may be in error by as much as 3 m (for a 50 m cable), because probe path is not identical to boat path. The boat probably followed a more zigzag course than the probe, which tended to average out small course adjustments made by the boat operator.

Data analysis on the computer employed software customized and developed by Jeff Cheung of the Environmental Research Branch, AECL Research. Seven colours were used to define seven ranges of EC along the river- or lake-bed, a coloured dot for each probe measurement on a map. In some areas the laser positioning system was useless, due to narrow, winding waterways and vegetation that interfered with line of sight. In these areas we noted our approximate
location on the strip-chart record of probe response.

Confirmation of Sediment-Probe Survey Results

Direct measurements of groundwater parameters were used to quantify and evaluate sediment-probe survey results. Harpoon piezometers (Lee and Welch, 1989) were used to obtain groundwater for EC and chemical analyses, measure hydraulic potentials and estimate hydraulic conductivity. To measure directly the flux of groundwater entering surface waters, seepage meters were installed in appropriate locations, such as sandy bottoms in non-flowing waters (Lee and Cherry, 1978). Although it was outside the scope of this study, it would be possible to use these methods to quantify groundwater and contaminant flux over large areas after using the sediment probe to define areas of flux.

RESULTS

Progress Against Objectives

The first objective was:

> To conduct a broad (coarse-grid) reconnaissance for acid leachate seepage using the sediment probe on the Onaping River and on surface waters near the Kam-Kotia Mine Tailings Rehabilitation Area.

The reconnaissance work began on the Onaping River in 1992 October. Approximately 1.5 km of river was surveyed with about 5 km of total survey lines. A preliminary progress report was submitted in 1993 January and those results are included here.

In 1993 June, reconnaissance surveys were performed on four lines on Kamiskotia Lake, for a total distance of about 6 km, and on two lines on the Little Kamiskotia River, over a distance of 6 km.

In 1993 July, reconnaissance surveys were performed on the Onaping River within four detailed study sites, covering a distance of 4 km.

The second objective was:

> To measure and quantify groundwater discharge at a minimum of four locations per area where survey results appeared interesting or anomalous. Samples were to be collected, field-filtered and preserved for possible chemical analyses.

Groundwater discharge was quantified using 27 piezometers and two seepage meters at four locations on the Onaping River near Levack. Groundwater discharge was quantified using nine piezometers and nine seepage meters at three locations in Kamiskotia Lake. Low permeability sediments were encountered while attempting to install piezometers in the Little Kamiskotia River. At one site (Number 6, Figure 2), bottom waters/sediment porewaters were collected through a tube and a screen was attached to the sediment probe.

Seven samples were field-filtered, acidified and submitted to Falconbridge Ltd. for analysis. Additional samples of bottom sediments and waters, using time and materials outside the scope of this project, were also collected for future research or as reference materials.

The third and final objective was:

> To evaluate the use of the sediment probe as a method for determining the location of submerged acidified groundwater discharge and to discuss in report form recommendations for this application, including improvements and limitations.

The remainder of this report presents results and discussions intended to meet the third objective.

Kamiskotia Area

Electrical conductance surveys were conducted during 1993 June 21-25 in two general areas: 1) between the public access and the lake outlet of Kamiskotia Lake, and 2) in the Little Kamiskotia River from the lake outlet to the power transmission line about 3 km downstream (Figure 2). Kamiskotia Lake is about 25 km northwest of Timmins, Ontario. A laser positioning system (International Measurements Inc.) was used on the lake, but it could not be used on the river due to the winding, forested nature of the banks of the river and adjoining swamps.

Walking surveys allowed access in areas of water less than 0.3 m deep, where proximity to the large area of no living vegetation warranted detailed coverage. This area appeared to be on the groundwater flow path leading to the Lake; it was a few hundred metres across Highway 576 from the lake and just north of the outlet. These shoreline surveys, using a "conductivity walking stick" connected to a portable conductivity meter, were performed along the eastern lakeshore from the outlet, northward about 400 m to the rocky point labelled "R" in Figure 2. The stick was pushed 2 to 5 cm into the sediment to make point measurements while walking in shallow water.

Probe Survey and Groundwater Measurements on Kamiskotia Lake

Figures 3a to 3d show 7 km of probe survey lines on Kamiskotia Lake. A few interesting high values (P1-3) were noted near the public access on the north end of the lake. Seepage-meter and mini-piezometer data were collected in a few of these anomalous areas (Tables 1 and 2). At site 3 the measured seepage ranged from 1.0 to 1.9 μm/s (32 to 60 m/a). These flows are at the high end of typical discharge rates for sandy lakeshores. Piezometers provided water with EC as high as 1638 μS/cm. Solute sources could be road salt, septic-tank effluent from nearby cottages or leachate from tailings situated 1.5 km north. Further chemical analysis can distinguish among those three possible sources.

The EC walking-stick survey identified one high-EC anomaly at site 7, far from any known septic tanks. This anomaly was confirmed when piezometer P7 (Figure 2, site 7) furnished groundwater having an EC of 1083 μS/cm, which is approximately ten times more conductive than the lake.

Sediment Probe Survey and Groundwater Measurements on the Little Kamiskotia River

Sediment probe results on this small river revealed numerous high EC areas from the lake outlet to a point just downstream of KZ pond (Figure 2). From KZ pond, one can see northward several hundred metres through a forest of dead trees, roots and organic soils stained orange by iron oxyhydroxide. Beginning at the culverts at the highway and extending downstream several kilometres, iron appears to be staining below the high water mark.

We installed piezometers in areas of anomalously high EC in KZ pond. But because the maximum yield from these piezometers was less than 10 mL per hour, we did not have time to obtain porewater samples. Such low yield is indicative of hydraulic conductivity less than 10^{-7} m/s.

About five metres below the culvert at the outlet of the lake, at the head of the Little Kamiskotia River, the sediment probe provided indications of high EC. Piezometers installed there (Figure 2, site 6) again indicated that the bottom material was low in permeability; porewater could not be obtained by pumping, within the time-scale of our investigation. Instead, we obtained water from the sediment anomaly at site 6 using a length of 25-mm diameter polyethylene tubing fitted at its lower end with a screen. The screen was attached to the sediment probe and the tubing was taped to the towing cable. The probe was drawn slowly across the area of interest until high EC values were relocated. Then, with the probe lying stationary in the bottom muck, the screen was cleared by pumping the tubing for a few seconds in both directions. In three of four attempts, this surging yielded water that exhibited EC values of 677, 2830, and 3080 μS/cm. The overlying river water was much less conductive, at about 120 μS/cm.

Onaping River Area

Preliminary Results

An initial EC survey was performed near Levack, Ontario, in 1992 October 13-16, on the Onaping River from 100 m above the bridge at Levack (Regional Road 8 Bridge) downstream to about 50 m below the Inco railroad bridge, for a total river length of 1.3 km (Figure 5).

By towing the probe up and down the river several times, we found several areas of elevated EC. Twelve harpoon piezometers were installed in the riverbed to determine whether high values of EC identified with the sediment probe would reveal locations of rapid seepage and high values of porewater EC measured in the laboratory. If so, then we would attempt to delineate areas of groundwater discharge in the river. The fluxes (of water, hydrogen ion, and Ni, for example) could then be calculated from porewater solute concentrations, area of discharge (based on survey results) and measured seepage rate.

Samples of sediment porewater were withdrawn from the piezometers for laboratory measurement of EC and pH (Table 1). The porewater EC in some of the samples was as much as 100 times greater than that of the river. River (surface-water) values of EC were 46.3 μS/cm at the Regional Road bridge and 228 μS/cm at the Inco rail bridge downstream (Figure 5). Measurements of hydraulic head relative to the river surface or measurements of artesian flow confirmed the existence of upward hydraulic potentials at some piezometers.

Figure 6 shows a composite of sediment-probe, strip-chart and porewater results from above piezometer P7 to just downstream of piezometer P8 (Figure 5) along the right bank of the river. There was excellent agreement of probe values (measured in situ) and the porewater values (collected from the piezometer and measured in the laboratory). Values of pH were depressed where EC was elevated (Table 3).

Detailed Reconnaissance at Four Sites on the Onaping River

On 1993 July 5-8, a more detailed EC survey was conducted on the Onaping River at four sites (Figure 5):

1. Northwest of the bridge on Regional Road 8 leading into Levack (Figure 7).

2. Near the Levack Well Recharge Pits, about 0.6 km to 0.9 km north-west of the bridge on Regional Road 8 (Figure 8).
3. South of Regional Road 8 from the Falconbridge-Onaping Area Gatehouse to the Inco Railway Bridge (Figure 9).
4. Downstream of the Inco Railway Bridge (Figure 10).

These figures display results as lines of coloured dots. Each dot represents one measurement recorded from the sediment probe. The ranges of electrical conductivity from low to high (black to white in photocopies) are indicated with the colours black, dark blue, blue, green, purple, pink, orange and yellow. The shoreline position is approximate. All locations are related to the position of the laser telescope tripod, which was at x = 1000 m and y = 1000 m. "Grid north" was not necessarily magnetic north.

Northwest of the bridge on Regional Road 8 leading to Levack (Figure 5), probe results indicated a 350 m^2 area of elevated EC. While installing piezometers there, we encountered cobbles and boulders within 50 cm of the sediment-water interface. The piezometer samples (P1,P2,P23,P26) had EC values from 1530 to 2260 μS/cm. 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. Nickel in P1 was 2.24 ppm.

One of the most interesting locations near the Levack Recharge Pits (Figure 8) was at P15 in the middle of the river about 150 m below the next set of rapids. Here, in 3.5 m of water, a piezometer, P15, was installed 75 cm into the riverbed gravels. A pocket of cold water was noticed on the bottom. Apparently, groundwater discharge was fast enough there to maintain this pocket, despite the mixing effects of the river current. A difference between the water level of this piezometer and the river could not be observed while sitting in the boat, so the piezometer tube was extended to shore, 40 m away. Even there, the water level in this tube did not differ (plus/minus 0.2 cm) from the level of the river at the shore. Porewater pumped to shore from this piezometer had an EC of 123 μS/cm. Although this was 3 times greater than the river EC at that location, it was lower than expected based on the probe responses nearby.

DISCUSSION

Experience has shown that the variation of sediment-electrical properties is often not large enough to interfere with the identification of discharge areas where the contrast in EC between surface and groundwater is more than a factor of about 2 or 3. This factor may, in some environments, be as low as 1.1; it depends upon the magnitude of the matrix variations, the depth of travel of the probe, dispersion at the interface and the rate of groundwater advection. The probe, therefore, is a targetting tool and quantitative point measurements are essential.

Measurement of pH

During the field portion of this work, it was not possible to experiment with the pH-equipped sediment probe. However, later in the summer the pH probe was tested elsewhere. The flow-through cell functioned properly during travel over non-cohesive sediments such as sand and gravel, but it became clogged while sliding through soft bottoms like soupy peats and organic muds. Possible solutions to the clogging problem, which will also address the inherent tendency of electrode liquid junctions to become plugged, will be explored in the future. There is also a problem with response time, the desired rate of travel with the probe being fast enough that pH anomalies could be averaged over distances larger than they may exist in a bottom sediment.

Interpretation of Results

Kamiskotia Lake

Seepage at P1 (Figure 2) was about 1 μm/s (n=10, x=1.14 μm/s, sd=0.65), measured 1.5, 5.1 and 7.7 m from the shoreline in water depths of 21, 39 and 60 cm, respectively (Table 2). A seepage rate or specific discharge of 1 μm/s is 32 m/a. For the seepage flux within 8 m of shore at this site, each metre-wide strip contributes 32 m/a X 8 m X 1 m wide = 250 m^3/a of groundwater to Lake Kamiskotia. There was no apparent change in seepage rate related to distance from the shoreline. There was, however, a striking decrease in lake-water EC with distance from shore: 133, 118 and 107 μS/cm at 1.5, 5.1 and 7.7 m from the shoreline, respectively. This pattern existed in the presence of onshore waves 10 to 15 cm high and occurred on several transects near the public access (Figure 1, tripod location). These results support the conclusion that groundwater contributes significantly to the dissolved solids load of the lake along this shore. The porewater EC values were 577 to 1130 in piezometer nest 1 (Table 1). We do not know the thickness of permeable sand at location 1, but it was at least 1.89 m, the depth of the deepest piezometer screen. A core there to 1.12 m was entirely sand.

Seepage flux at P3 was 1.3 μm/s (x =1.3, sd =0.35, n = 3) 5 m offshore. The range of EC for the porewaters at location 3 was 850 to 1638 μS/cm, compared with the lake at 118 μS/cm.

Seepage was not measured at P4. However, water levels in the piezometers screened 0.36 and 1.11 m below the lakebed responded quickly, as if in sand, and were virtually at lake level, indicating little or no potential for flow into the lake. The lakebed sand appeared to be continuous to a depth of 1.11 m because: (1) the pumping rate from piezometers at location 4 was comparable to that at location 3, and (2) during installation of these piezometers, the drive pipe felt and sounded like it was going through sand. The presence of water 6 to 8 times more conductive than the lake only 0.36 m and 1.11 m beneath the lake at P4 (Table 1) and the low sediment probe readings there (Figure 3, Panel C) indicate that groundwater is entering the lake much more slowly than at locations 1 and 3. *SLOWLY* flowing groundwater, even highly conductive electrically-conductive groundwater, would not produce a sediment-probe anomaly at the sediment water interface, particularly along this shore, where waves would tend to mix lakewater into the upper few centimetres of sandy lakebed.

Examination of the sediment-probe results shown on the coloured map (Figure 3, panels A-D) supports the hypothesis that groundwater enters the lake, near the shore, along the eastern two-thirds of the 1.5 km-long surveyed area. The main overburden unit is a thick clay (Ferguson, 1992). Yet a 1 to 2 m thick veneer of beach sand could provide a permeable connection between the lake and the leachate-affected land north and east of the highway, within a few hundred metres of that shore. The line closest to shore was obtained by pulling the boat along the shore in about 30 cm of water. Here the action of waves had created a visibly-homogeneous sand beach free of silt or clay. In the absence of clay, the elevated readings near the shore and the quantitative measures of groundwater were interpreted as a reliable indication of shoreline seepage of high-conductivity water.

Piezometer P7 was installed along the shoreline just north of the culvert/outlet of Kamiskotia Lake, where elevated EC was identified with the "conductivity walking stick". The porewater EC at this location was 1083 μS/cm. This value signified seepage of high EC water at this location. And nearby there were several other locations of elevated conductivity observed with the probe just south of P7 in the lake near the outlet culvert (Figure 3, Panel A).

Little Kamiskotia River

Anomalously high EC values below the outlet of the lake and within most of the pond 500 m downstream (Figure 4) could not be confirmed in the usual way, because of the difficulty encountered in obtaining water from four piezometers installed there. Fine-grained sediments were collected from the pond and may later be centrifuged and analyzed.

Sediment porewater at location 6 (Table 1) was collected by attaching a screen to the probe and then drawing it across the bottom until high EC readings were obtained. Then the screen was pumped to the surface, providing samples of water for testing. The values were in excess of 3000 μS/cm, nearly 30 times the EC value of the overlying water.

In a riverine system such as this, brackish bottom-waters are not likely to exist as stagnant pools. High EC water is probably groundwater emanating from the tailings 2 km to the north.

When we were there, values as high as 1200 μS/cm were being found by Ministry of

Northern Development and Mines staff (Ferguson, 1992) in ditches on the up-gradient side of the highway. In the future, it will be important to measure sulfate in the water samples from our location 6, to help distinguish among the three possible sources of elevated EC: road salt, septic-tank effluent, naturally occurring mineralized waters or AMD.

In summary, the sediment probe was used along the shore of Kamiskotia Lake to target sampling for high-dissolved-solids porewater and measurement of seepage flux, the results of which confirmed the movement of groundwater into the lake. In the Little Kamiskotia River, where water could not be drawn from piezometers, one "hot area" was confirmed by measuring
the EC of water drawn from a screen fixed to the sediment probe.

Onaping River

Previous work had shown that approximately 10% of the nickel in the Onaping River could be accounted for from known point discharge treatment systems (Wiseman, 1993). Both Inco Ltd. and Falconbridge Ltd., would like to develop a cost effective tool to help locate previously unidentified sources of nickel loading to the river and this site was a good location as 90% of the Ni load came from, as yet, unidentified sources. While not a specific objective of this work, guidance for future work for locating and quantifying these sources was implicit.

The preliminary survey of 1992 October identified and confirmed several conductivity targets. This work was conducted with the paper chart recorder (analog) and without the positioning system. In every instance of high response by the sediment probe, the porewater was found, using standard laboratory EC analysis, to agree with the sediment probe. Northwest of the bridge (Regional Road 8) leading to Levack, probe results revealed a large area of high EC water (2160 to 1075 µS/cm) beneath the riverbed. Nickel concentrations in these waters were elevated (1.0 to 2.8 ppm), suggesting that a component of this water may be AMD. The river itself in this location had an EC of about 50 µS/cm.

Further surveys were conducted with the sediment probe and the positioning system to collect digital records of probe response and location. Harpoon piezometers were installed and sampled to further test the ability of the method to locate AMD. The following discusses the findings at the four study sites, beginning upstream and moving downstream.

Near the Levack recharge pits, where EC was predicted to be high based on the probe results (Figure 7), piezometer samples were correspondingly high (Table 3). Discharge of uncontaminated groundwater was found along the shoreline adjacent to the recharge pit. This was shown by the seepage rates (Table 4, 0.8 and 0.5 µm/s) and by the measurements of head, artesian flow and EC in piezometers P13, P14, and P16. This was attributed to the adjacent pits, where the water level is maintained above the level of the river by pumping water into the pits from the river. Also, the material between the pits and the river appears to be esker sands and gravels, which intersect the river in that area.

Two facts led to the hypothesis that leachate from tailings is diverted from its natural course into the river by the pit-groundwater mound, and discharges further upstream and downstream (Figure 7, P15, P27):

a) a plume of tailings-contaminated groundwater extends toward the river from tailings 2-3 km northeast of the pits (King, 1993), and
b) two distinct areas of high EC were found on the river bottom, above and below the recharge pit near P15 and P27 (Figure 7).

Water levels in the river-bank discharge or spring area near P27 were, at the time of our work, slightly above the river level. Pockets of spring water were 9 to 11°C on an afternoon when the air temperature reached 27°C and the river temperature was 22-23°C. During a low river stage, discharge from this seepage area could be gauged using appropriate tracers. Under normal conditions, most of the area would be submerged.

Piezometer P15, screened 65 to 75 cm in coarse, gravelly sediments, contained water with an EC of 123 µS/cm, 3 times the river value at that location. The other area (P27, Figure 8) yielded water with an EC of 1200 µS/cm, a nickel content of 2.8 ppm and a pH of 4.8 (Table 3).

To determine the origins of these groundwaters, it will be necessary to measure sulphate concentrations, install additional piezometers near P15 and determine the subsurface residence time of the waters. Based on probe response, we expected more than 123 µS/cm in P15. Perhaps the high-EC area was not sampled by P15. We examined the gravelly riverbed, felt a 0.5 to 1-m thick layer of icy water on the bottom, and saw the groove formed by the probe. Piezometer P15 was not installed exactly on the groove, where we wanted it, because the gravels there were too coarse for our installation method. The bottom water, colder by about 8°C, could have depressed the probe readings by about 16%, and therefore cannot account for the elevated EC measurements.

Measurements of the EC of porewater from piezometers NW of the bridge to Levack substantiated the high-conductivity probe results near several small islands (Figure 7; Table 3 P1, P2, P3, P23). 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.

The riverbed at this site was a 20 to 43 cm thick layer of medium coarse sand over cobbles and boulders. Hydraulic heads in all the piezometers at this site were within millimetres 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 non-existent gradients. A gasoline-powered hammer was used to vibrate piezometer P23 into the cobble layer, but this penetrated only 121 cm, not deep enough to indicate hydraulic potentials. 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. As at several other sites, the contribution of AMD, road salt, etc., will have to be determined by further analysis of water samples from riverbed piezometers. 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.

At the next area downstream, piezometers at four locations--P7, P9, P18 and P22 (Figure 4, Figure 8 and Table 3)--confirmed the probe results. Artesian flow of 0.1 mL/min at P22 proved upward hydraulic potentials, but the piezometric level could not be distinguished from river level. P9 contained 2.8 ppm Ni, which was intriguing, considering its relatively low EC of 360 µS/cm (Table 3).

Below the Inco railway bridge, results with the sediment probe focused attention on an area that yielded porewater with EC of 8 000 to 12 820 µS/cm, Ni at 9.5 pm (Figure 9, Table 3) and groundwater discharging at a rate of 0.8 µm/s (25 m/a). Judging by the probe-survey results (Figure 9), 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). Crudely, then, the nickel loading to the river was 12 kg/a based on these assumptions: a rectangular discharge area of 50 m^2 (i.e. 3m X 17m), one measured seepage rate of 25 m/yr and one measured Ni value of 9.5 ppm (9.5 g/m^3). This is far less than the 50 000 kg of nickel exported yearly by this river.

CONCLUSIONS

1. Sediment-probe surveys provide qualitative maps of EC discharge. Porewater EC values were as high as 12 800 µS/cm. Where the probe registered high values, there was high-conductivity porewater and evidence of upward groundwater flux. Results were unaffected by overhead power lines and other materials that have hampered application of airborne or ground electromagnetic methods. Because the methodology includes, as an essential part, quantitative analysis of discharge parameters, it yields discharge information in areas of greatest potential contaminant flux.

2. The sediment probe identified groundwater discharge areas that contribute nickel to the Onaping River at concentrations in the range 1 to 9.5 ppm. For illustrative purposes, a nickel flux of 12 kg/a through a 50 m^2 discharge area was estimated below the Inco railway bridge. For this calculation, sediment-probe results were used to estimate the length of the discharge area near three piezometers that have elevated EC water.

3. The sediment probe and harpoon piezometers were used to identify two areas of groundwater and solute flux to the Onaping River near the Levack Recharge Pits. AMD or natural seepage contributes groundwater to the river at P27, 250 m south of the pits, where pH was 4.8 and Ni content was 2.8 ppm.

4. Nickel in the range of 2 to 3 ppm enters the river in groundwater discharge areas 50 m northeast of the Levack bridge and 50 to 200 m south of the Falconbridge-Onaping-Area Gatehouse. Whether those areas account for the nickel loading of the river can be estimated with further work.

5. Based on sediment-probe results and hydraulic measurements at three locations,

groundwater with elevated EC was entering Lake Kamiskotia along the eastern two-thirds of the 1.5-km-long study area. Until chemical analyses are done, the sources of solutes (natural, AMD, road salt or septic effluents) will be unknown. Seepage measurements near the shore of Lake Kamiskotia ranged from 0.3 to 2.1 μm/s (9 to 66 m/a) in areas of elevated EC (577 to 1 638 μS/cm).

6. Based on the EC of collected waters, seepage enters the lake above the outlet culvert (P7) and also enters the Little Kamiskotia River below the culvert.

7. In theory, sediment type affects probe response, but in practice it did not prevent the identification of groundwater discharge areas having elevated electrical conductivity.

8. A prototype sediment probe for continuous measurement of pH was not successful, because of clogging of the inlet ports by soft bottom sediments.

9. Regarding the sediment probe system, seasonal limitations restrict use to ice-free periods. Work on large bodies of water like Lake Ontario can be conducted only 20% of the days of summer and early autumn, for safety reasons. Yet working from small boats can be an advantage. Our experience on the Onaping River showed that applications in whitewater are possible.

RECOMMENDATIONS

1. Water samples stored from this study should be analyzed for major ions so that sources of contaminants can be identified. This could be attempted, at low cost, using the unacidified samples that were collected. We have barely begun to assess the fluxes in the studied areas. Now that targets have been identified, they may be assessed efficiently.

2. Samples should be collected by mining company staff at existing piezometers, so that additional chemical and isotopic analyses can be conducted. Specific isotopic work recommended is helium-3/tritium analysis using mass spectrometry to determine the groundwater age (i.e., underground residence times) for the waters presently discharging. This may show that some of the suspected AMD is actually natural groundwater and solute flow. If so, it may be economical to show that some perceived "environmental contamination" is, in fact, related to the occurrance of ore bodies in this area.

3. The sensitivity of the probe needs to be evaluated for locating highly diluted leachates entering surface waters through clayey bottoms, where there is minimal contrast in EC between overlying open water and moving groundwater and

maximum interference from sediment-matrix conductivity. This can be done in the laboratory using samples of bottom materials and standard solutions from a variety of field sites. Additional work is also needed to test sensitivity to groundwater upwellings where the probe slides over cobbles in whitewater.

4. The probe should be adapted to measure specific contaminants. Readers with suggestions are invited to contact us.

5. Additional areas of the river should be studied. We still do not know where the missing 90% of the nickel originates.

ACKNOWLEDGEMENTS

Mark Wiseman recognized the potential of this method and arranged partnerships for financial support: Inco Ltd., Falconbridge Ltd. (both Sudbury and Kidd Creek operations), MEND, and the Northern Ontario Development Agreement. He also directed us to questions on the Onaping River and provided analysis for water samples.

Bruce Mikila suggested access and study sites along the Onaping River and provided general familiarization with the area. Rob Ferguson showed us the Kam-Kotia Mine Rehabilitation Area, pointed us to areas of interest, explored local rivers in advance to determine areas that we would be able to navigate with our boat and outboard motor, and provided an introduction to the surficial geology.

Marcia Blanchette set up the research contract within the MEND program and Department of Supply and Services Canada.

Carl Weatherell gave us technical-contractual supervision.

Within AECL, Rick Janzen looked after administrative details, especially those involved in amending the contract to allow us to do field work in the summer of 1993. Jeff Cheung developed the software to compile data in the field, process it in the office and display it in the report. Mark Ungrin, a Co-op student with us for the summer from the University of Waterloo, assisted in the field with the ground-truthing methods and with the laser positioning system. Ken Whitlock helped design the sediment probe and manufactured harpoon piezometer drive tips. Mark St.Aubin provided essential electronic support.

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TABLE 1. Piezometer and Other Data - Kamiskotia Are

Number	Elect. Cond. Sediment Porewater µS/cm @ 24-25°C	pH	Depth of Piezometer Screen Below Riverbed, cm	Head of Water in Piezometer above river, c
P1d	577		189	
P1m	1130		98	
P1	705		24	
CORE2	676			
P3.1s	908		26	
P3.1d	1265	6.90	108	
			15	
P3.2s	1638			
P3.2d				
P4s	693		36	
P4d	850	7.00	111	~0
SITE6				
A	677			
B	1200-3500			
6B2	2830			
6B4	3080			
KZPOND WATER	325	7.19		

TABLE 2. Seepage Meter Data - Kamiskotia Lake

Seepage meter at piezometer number		Distance offshore, m	*Seepage Flux, µm/s
Loc. P1:	1A	1.5	2.1,0.9
	1B		0.3, 0.1
	2A	5.1	1.6,0.8
	2B		1.5
	3A	7.7	1.9
	3B		1.2,1.0
Loc. P3:	1B	5.0	1.3
	2A		0.9
	2B		1.6

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

The mean of ten seepage measurements at P1 was 1.14 µm/s (sd=0.65). For the three measurements at P3 the mean was 1.3 (sd=0.35). Letters A and B denote pairs of seepage meters placed a metre apart but equidistant from shore.

TABLE 3. Riverbed Piezometers - Onaping River

Number	Elect. Cond. Sediment Porewater µS/cm @ 24-25°C	pH	Depth of Piezometer Screen Below Riverbed, cm	Head of Water in Piezometer above river, cm	General Notes
P1	1321	7.00	43		P1[Ni]=2.24 ppm
P2	2160	6.81	30		P2[Ni]=1.00 ppm
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	4.89	44		P8[Ni]=1.1 ppm
P9	360	6.47	109		P8[Ni]=2.79 ppm
P12	1869	6.18	30		
<u>Piezometers near Levack Recharge Pits, Fig. 7</u>					
P13	43		108	75	flowing
P14			194	52	(amorph)-FeOOH(s)
P15	123	6.49	75+10	~0	
P16	72		79	20	flow=920mL/5 min
P17	326	6.05	94	~0	P16[Ni]≤0.02 ppm
P27	1200	4.83	0.3		P27[Ni]=2.8 ppm
<u>Piezometers east of Reg. Rd. 8, Fig. 8</u>					
P18	525		200	~0	flow=20mL/210 min
P22	260				flowing slowly
River values: 49-51					
<u>Piezometers downstream of Inco RR Bridge, Fig. 9</u>					
P8	1430 field				flow=65mL/85 min
P19	8000 field	5.66	42	1	P19[Ni]=9.5 ppm
P20	12820 field	5.44	49		
P21	207				
<u>Piezometers west of bridge on Reg. Rd. 8, Fig. 6</u>					
P23	1530	6.14field	121	~0	
P24	225		55		
P25			49	~0	
P26		6.36	49	~0	

TABLE 4. Seepage Meter Data - Onaping River

Seepage meter at piezometer number	*Seepage Flux, µm/s
P16	0.8,0.5
P8	0.8,0.8

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

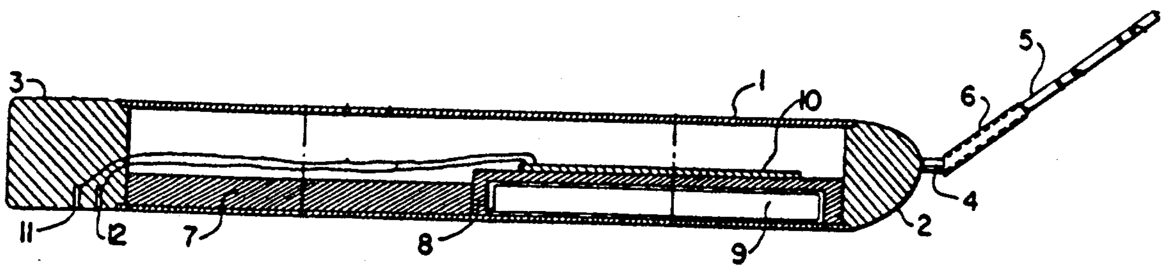


Figure 1. Sediment probe (after Lee and Beattie, 1991) consisting of a slim tubular body or shell **1** closed at one end with a nose cone **2** and at the other end with an end plug **3**. The nose cone has a rounded front which is provided with a waterproof connector **4** to which a towing cable is 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.

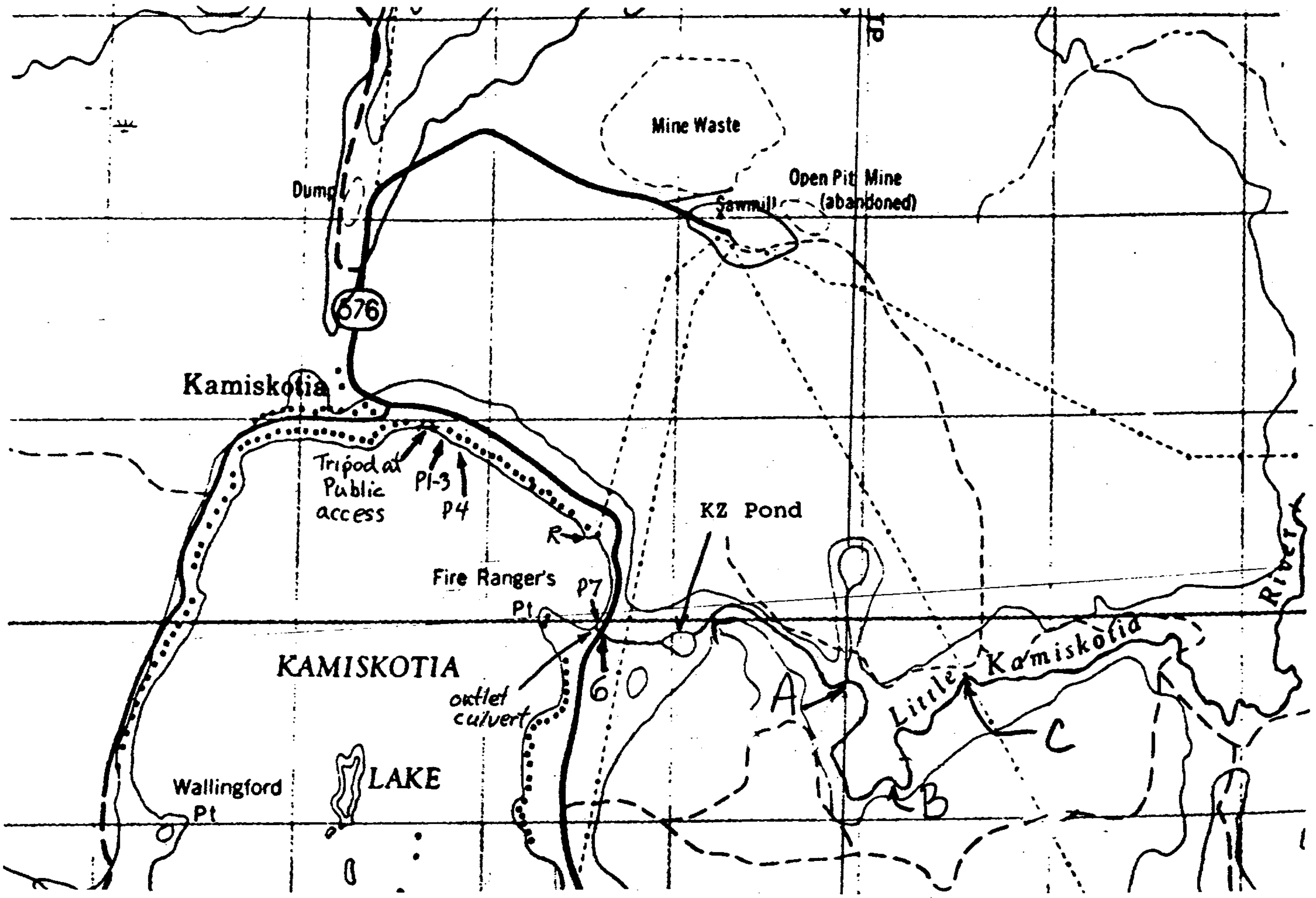


Figure 2. Kamiskotia Lake and Little Kamiskotia River.

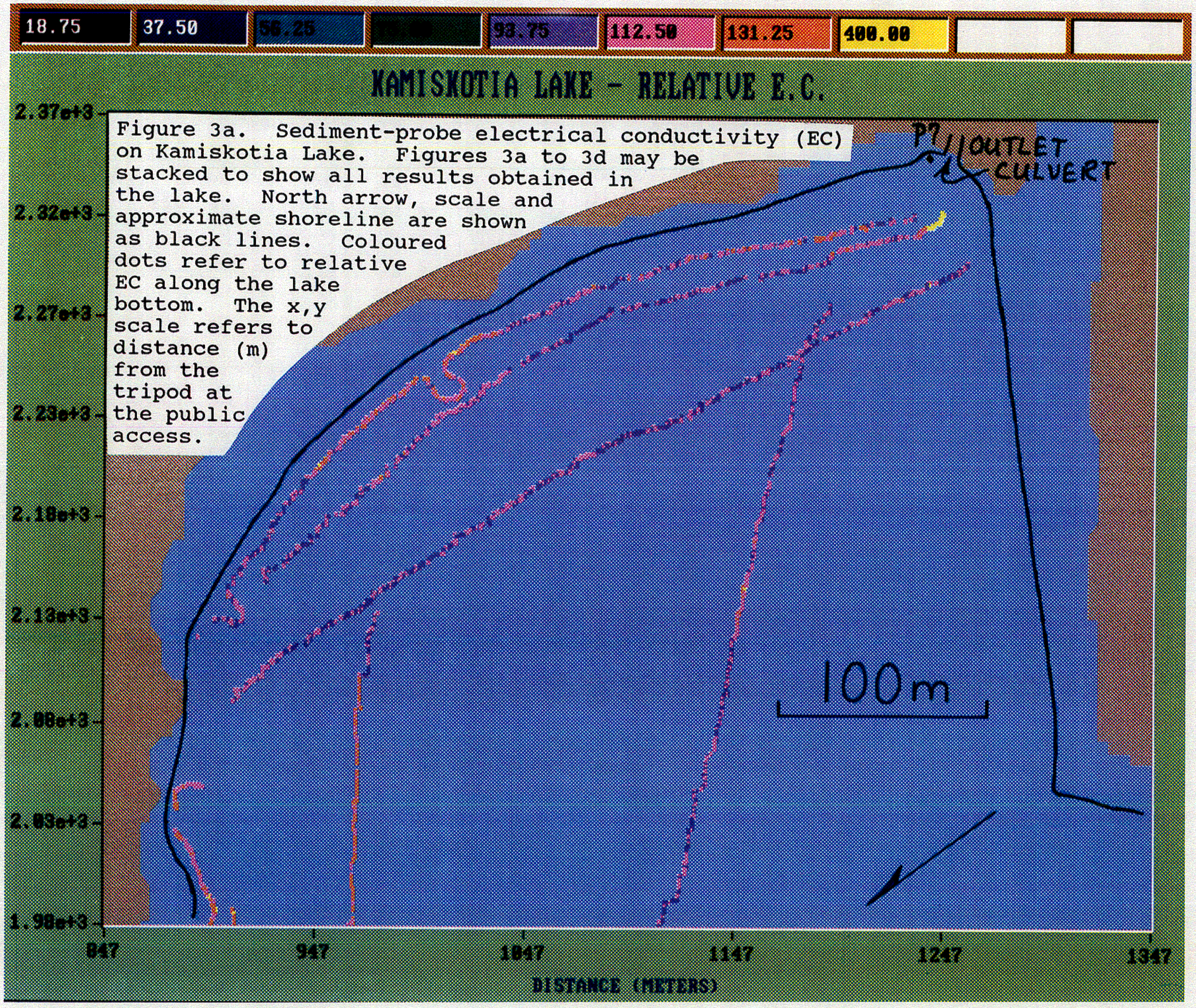


Figure 3a. Sediment-probe electrical conductivity (EC) on Kamiskotia Lake. Figures 3a to 3d may be stacked to show all results obtained in the lake. North arrow, scale and approximate shoreline are shown as black lines. Coloured dots refer to relative EC along the lake bottom. The x,y scale refers to distance (m) from the tripod at the public access.

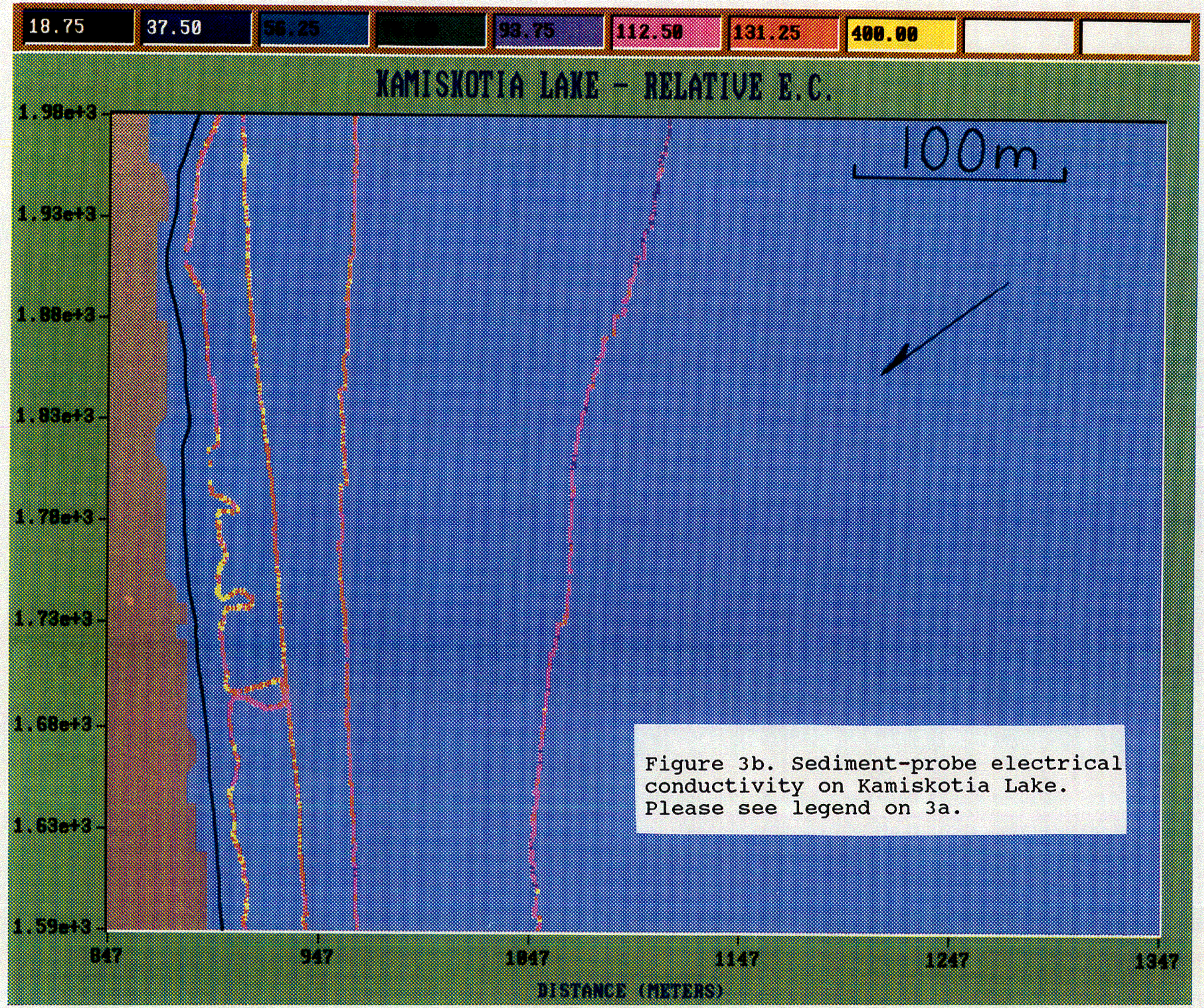


Figure 3b. Sediment-probe electrical conductivity on Kamiskotia Lake. Please see legend on 3a.

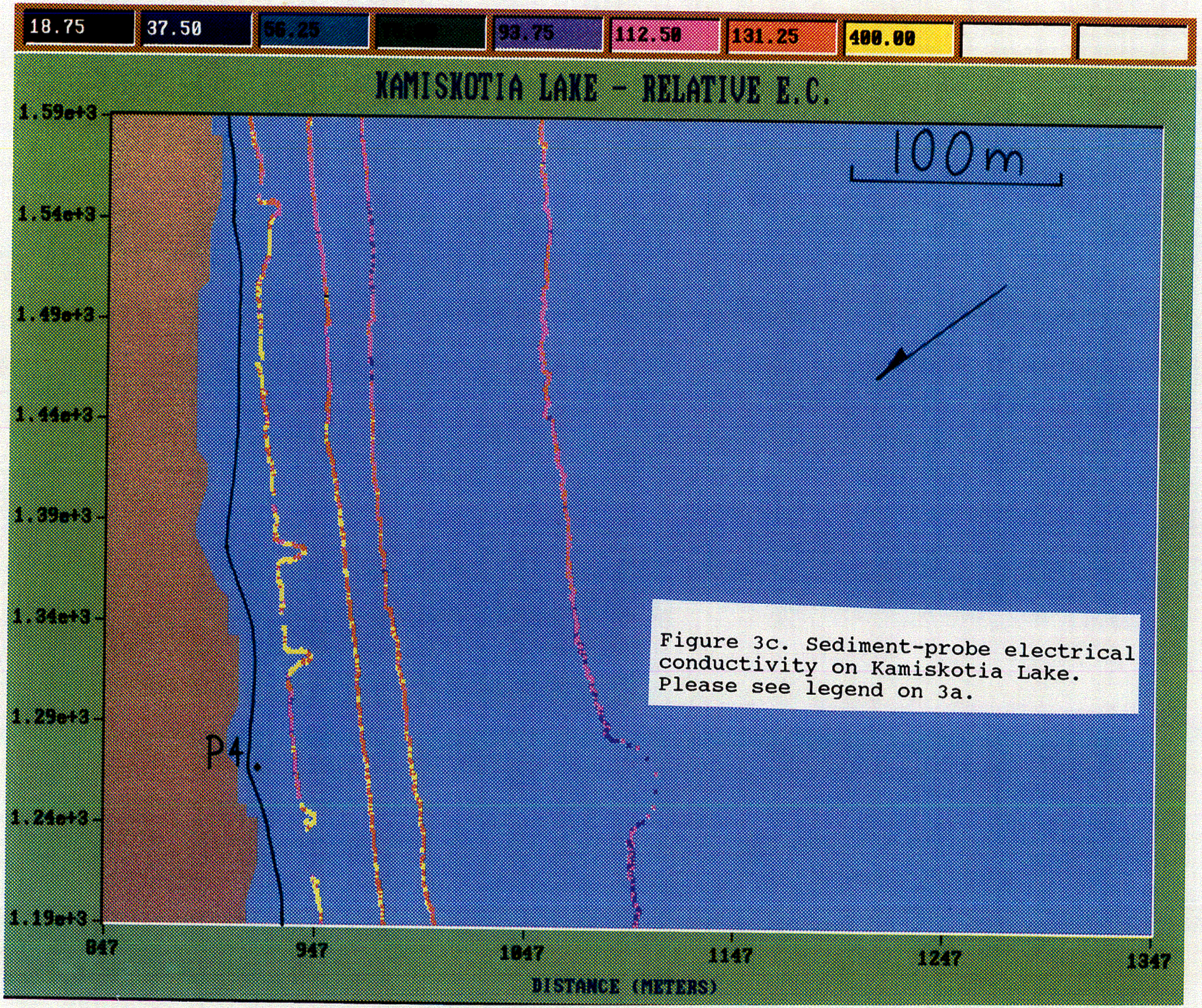


Figure 3c. Sediment-probe electrical conductivity on Kamiskotia Lake. Please see legend on 3a.

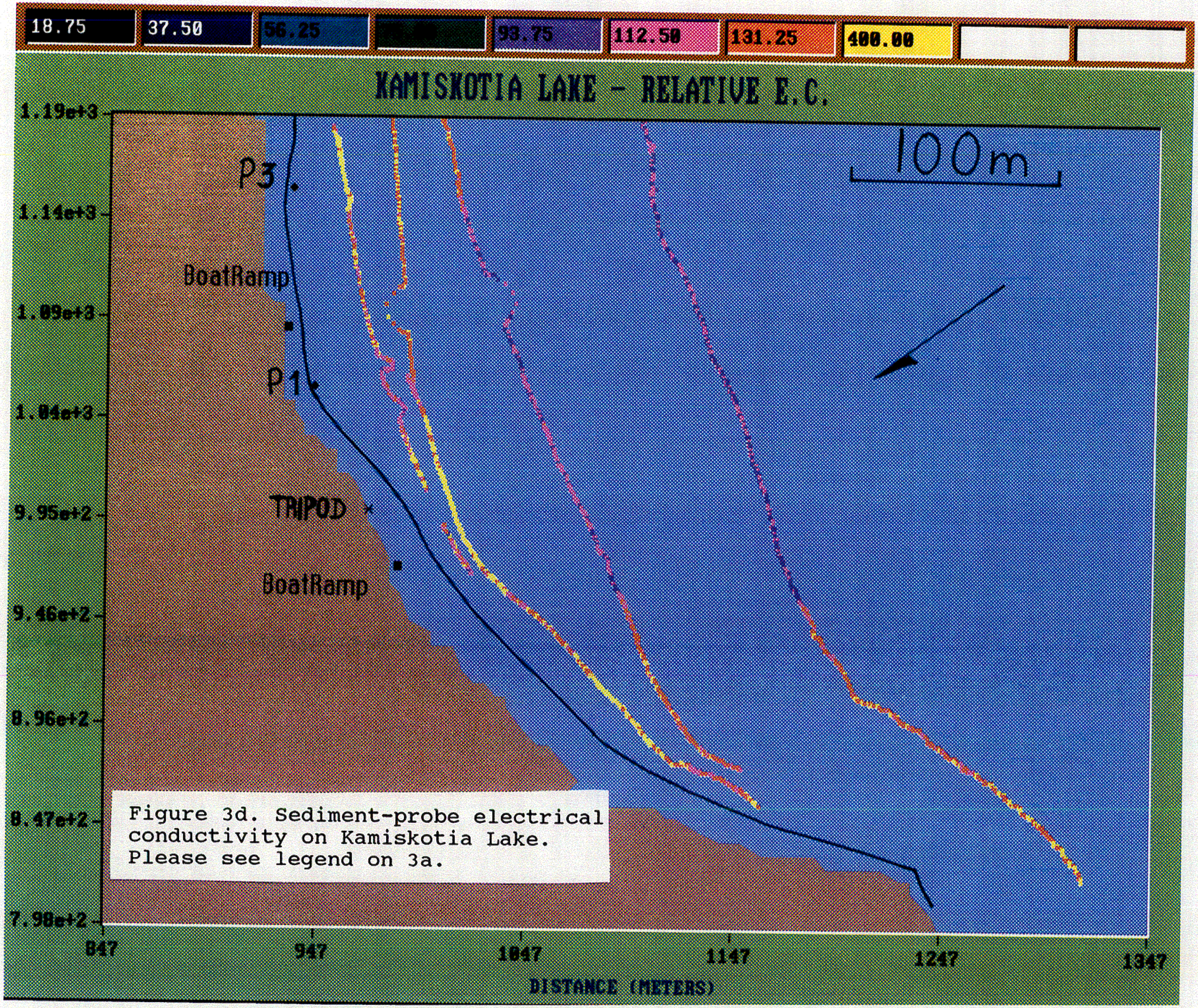


Figure 3d. Sediment-probe electrical conductivity on Kamiskotia Lake. Please see legend on 3a.

Figure 4a. Strip-chart record of electrical conductivity down the Little Kamiskotia River from Kamiskotia Lake about 500 m downstream. Upper panel shows upstream section and others follow in a downstream direction.

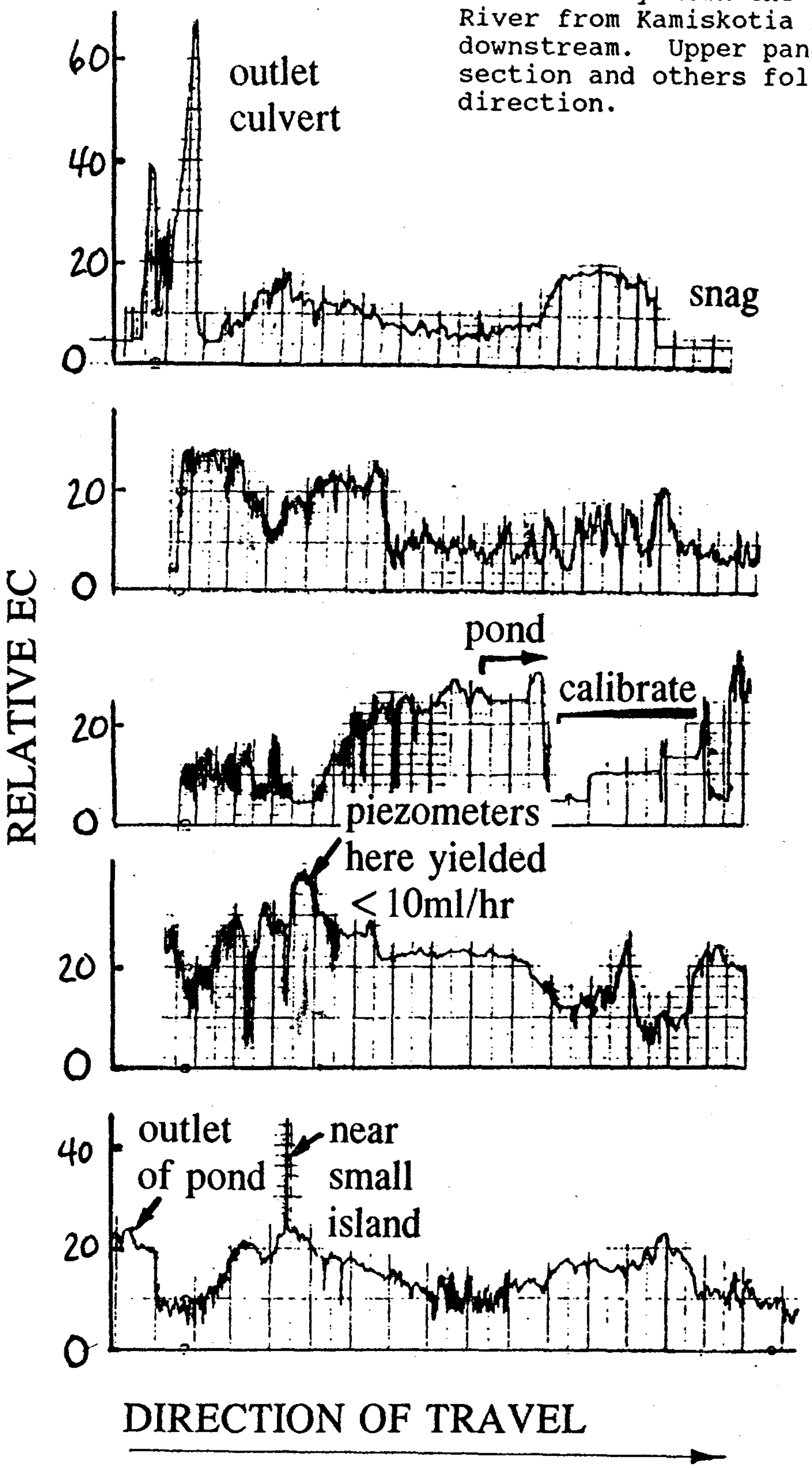
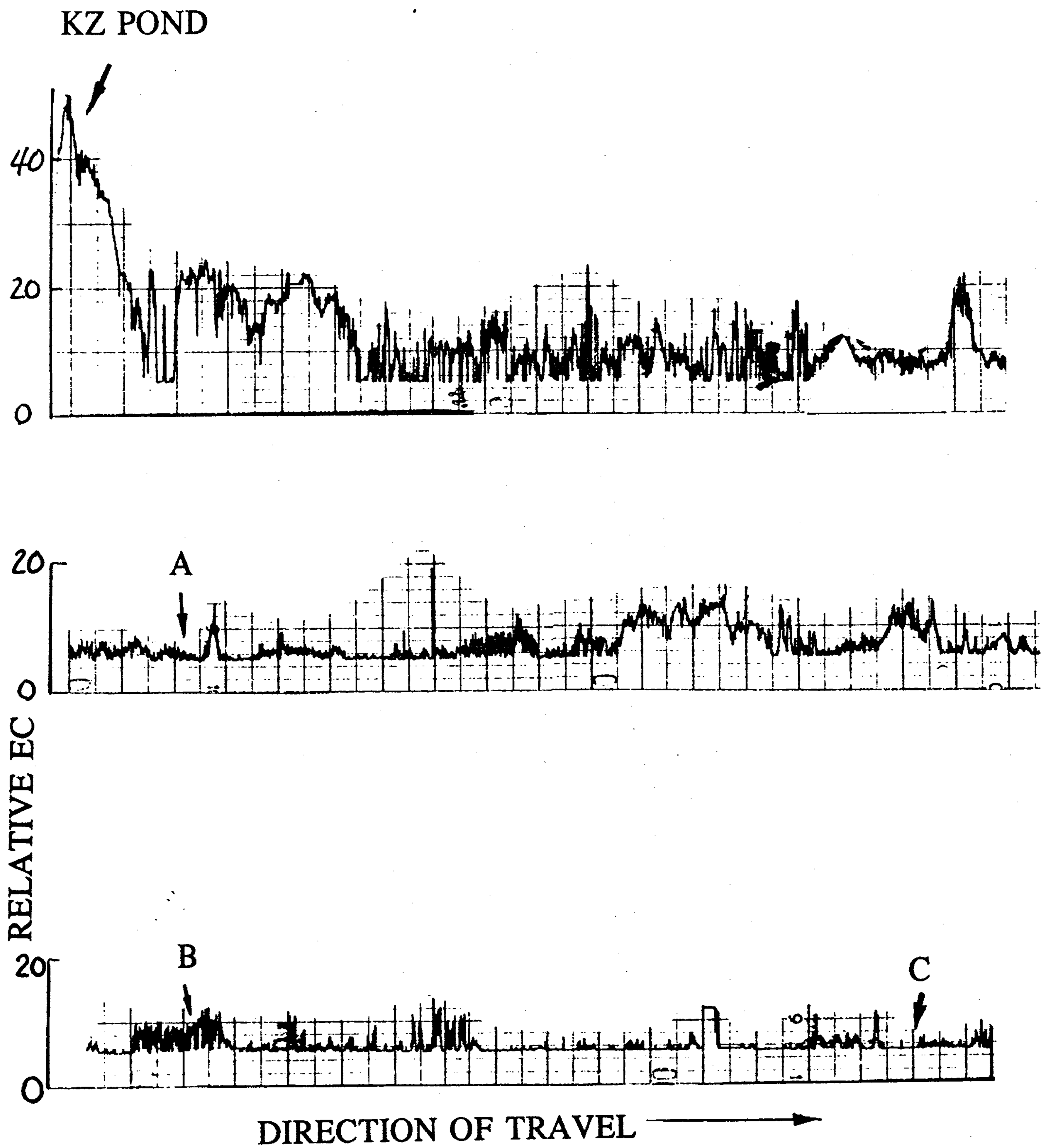


Figure 4b. Strip-chart record of electrical conductivity down the Little Kamiskotia River from KZ Pond to the power transmission line 3 km from Kamiskotia Lake. Reference points A, B and C are shown on Figure 2.



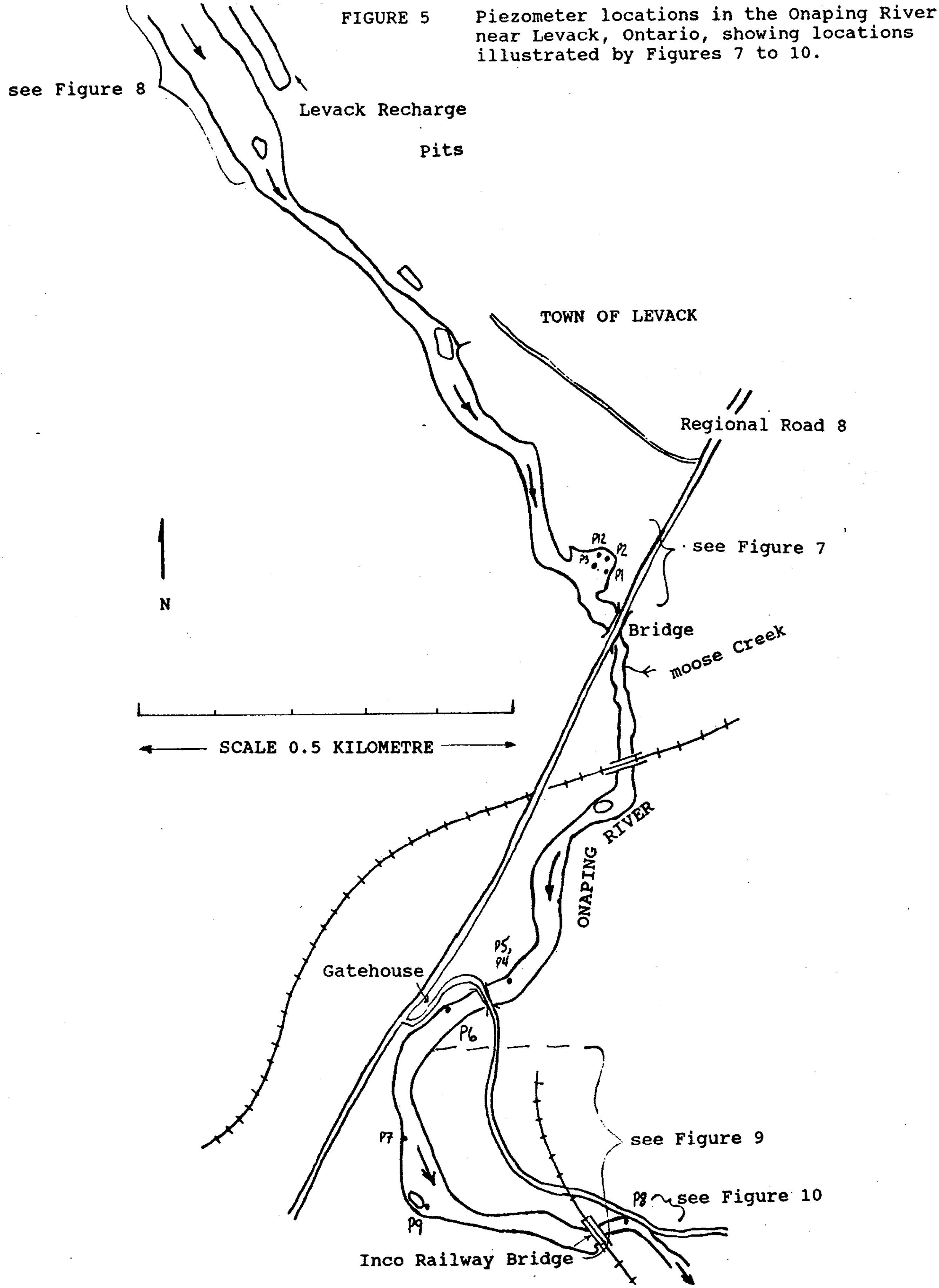
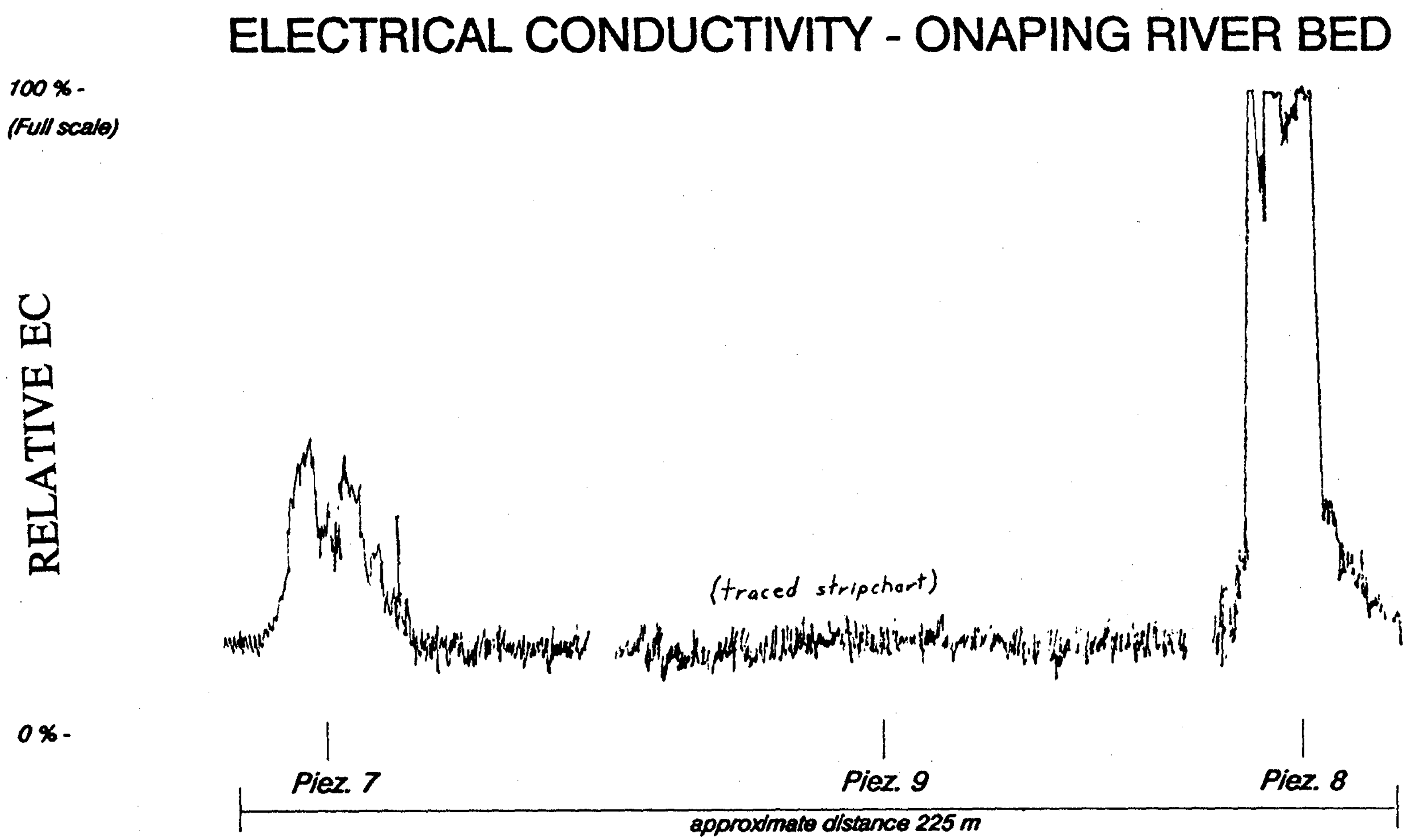


FIGURE 5 Piezometer locations in the Onaping River near Levack, Ontario, showing locations illustrated by Figures 7 to 10.



EC (uS/cm)	961	360	3910
pH	4.91	6.47	4.86

River Water = 228 uS/cm

Figure 6. Sediment-probe results in the Onaping River showing values of electrical conductivity (EC) and pH in water from riverbed piezometers P7 to P9.

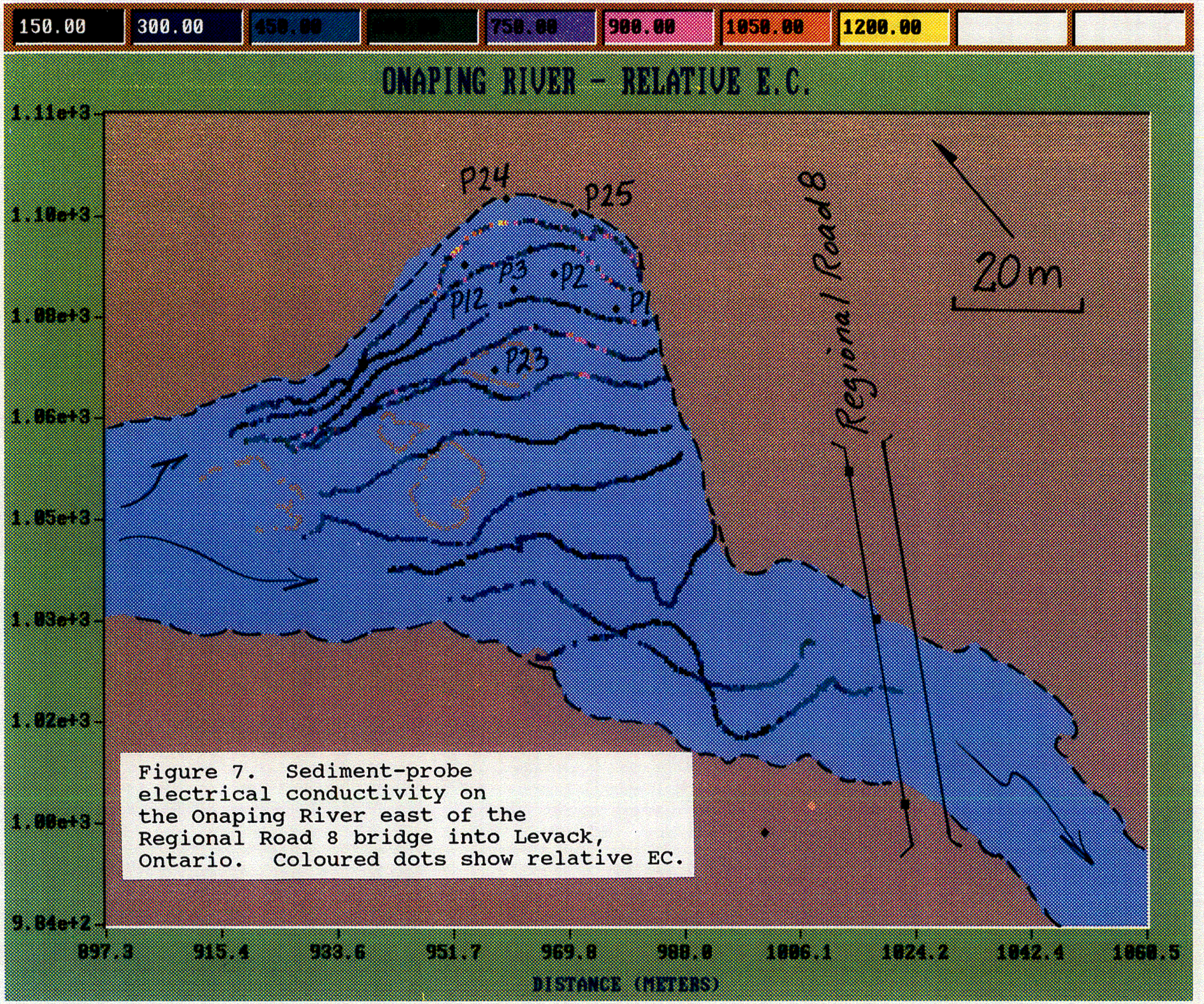


Figure 7. Sediment-probe electrical conductivity on the Onaping River east of the Regional Road 8 bridge into Levack, Ontario. Coloured dots show relative EC.

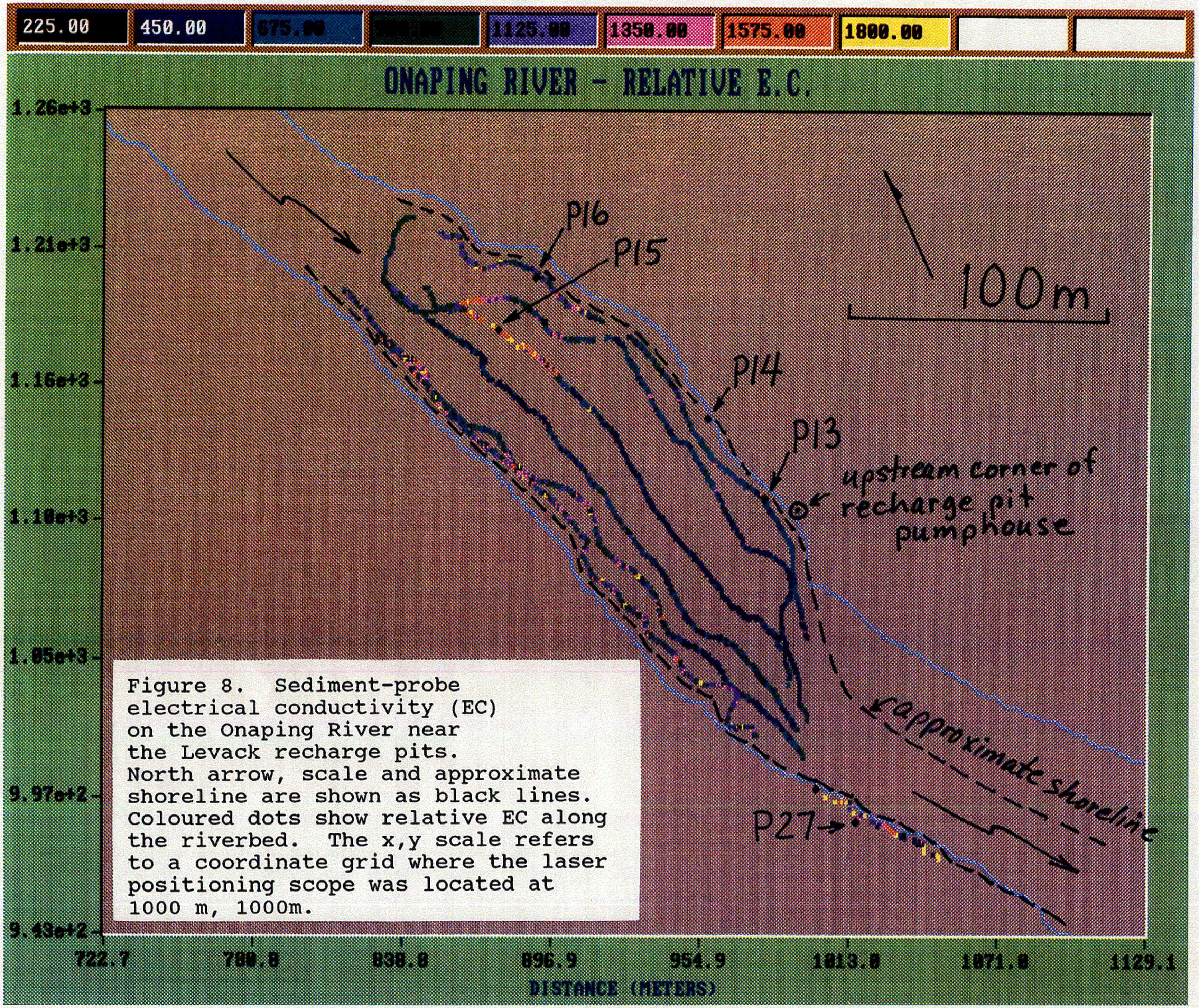


Figure 8. Sediment-probe electrical conductivity (EC) on the Onaping River near the Levack recharge pits. North arrow, scale and approximate shoreline are shown as black lines. Coloured dots show relative EC along the riverbed. The x,y scale refers to a coordinate grid where the laser positioning scope was located at 1000 m, 1000m.

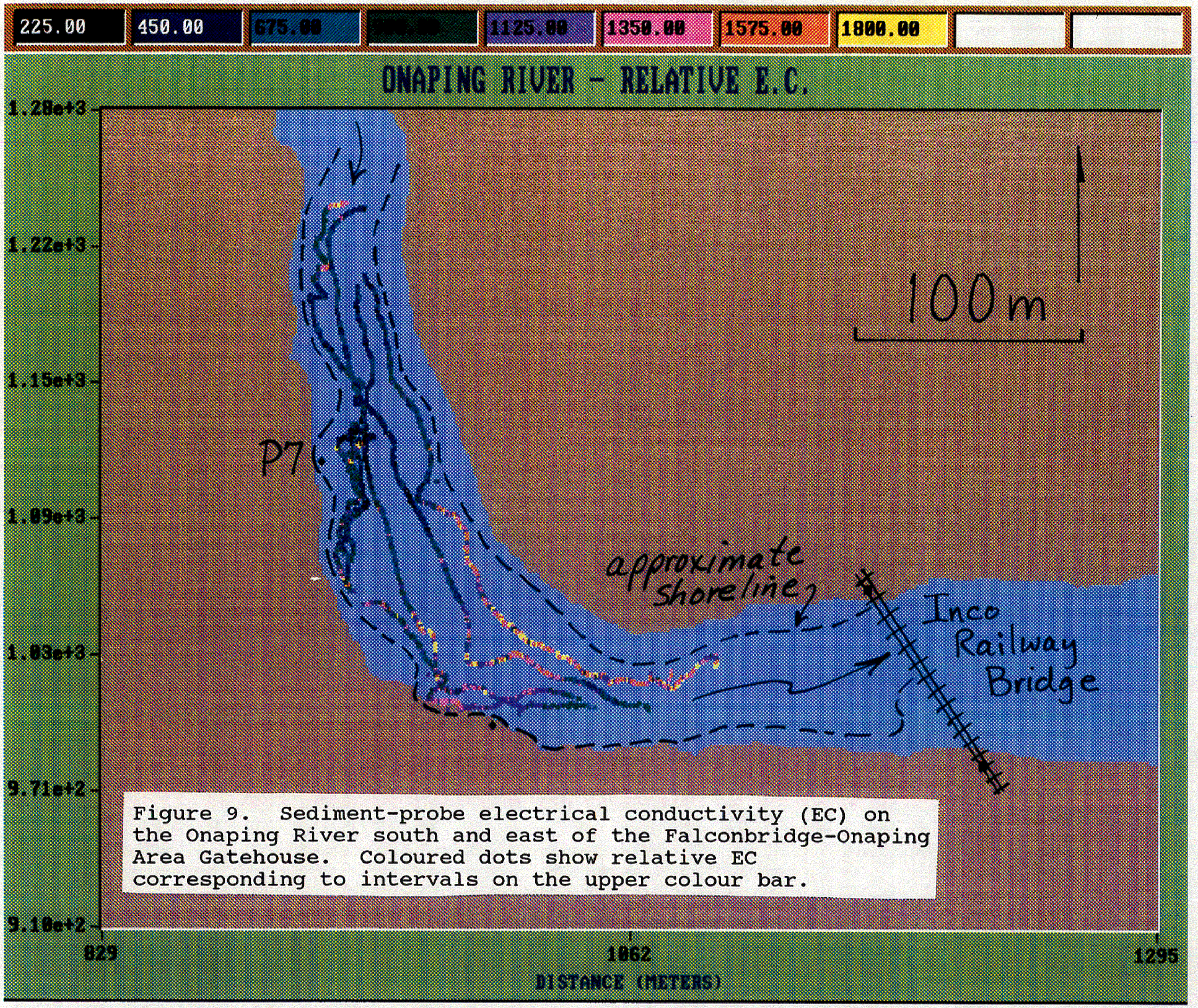


Figure 9. Sediment-probe electrical conductivity (EC) on the Onaping River south and east of the Falconbridge-Onaping Area Gatehouse. Coloured dots show relative EC corresponding to intervals on the upper colour bar.

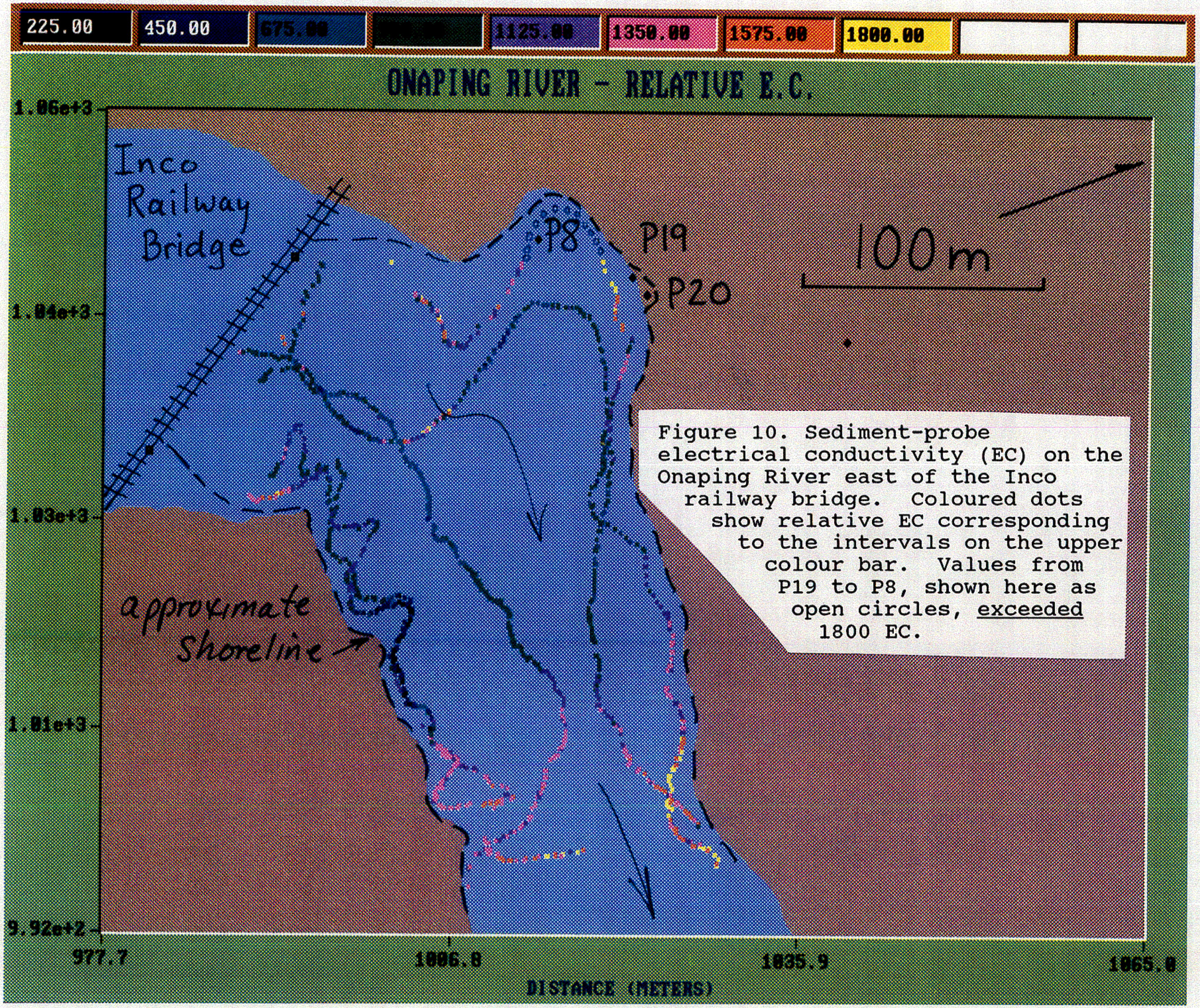


Figure 10. Sediment-probe electrical conductivity (EC) on the Onaping River east of the Inco railway bridge. Coloured dots show relative EC corresponding to the intervals on the upper colour bar. Values from P19 to P8, shown here as open circles, exceeded 1800 EC.