

066 Monitoring a Sump
Containing Drilling Mud
with a High Salt Content

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**MONITORING A SUMP CONTAINING
DRILLING MUD WITH A HIGH SALT CONTENT**

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SUMMARY

There is concern that buried sumps containing saltwater drilling fluids in the Northwest Territories may not remain sufficiently frozen to prevent contamination of the surrounding environment, due to freezing point depression by the salt and disturbance of the permafrost. To address this concern, a study was initiated in September, 1985, to monitor a buried salty sump located at the Tweed Lake M-47 wellsite. Fixed-frequency, electromagnetic (EM) surveys were used to locate areas of high conductivity, which, in turn, indicated areas of potential salt seepage and thawed sump fluids. The use of EM surveys for detection of salt in permafrost areas had not been previously documented.

Two potential salt plumes from the Tweed Lake M-47 sump were discovered from the EM surveys--one area at the east corner and another area along the west perimeter. Neither area extended more than 40 m from the sump. In both cases, phenomena other than salt migration likely account for the high conductivity readings. However, to positively determine that a salt plume is not escaping from the sump, periodic EM surveys need to be continued. Intrusive monitoring probes may even have to be installed.

Theoretical calculations were performed to determine the expected conductivity reading at surface if the sump fluids were thawed. Actual conductivity measurements were well below the predicted values, even in the summer. Thus, the sump fluids must be at least partially frozen.

In conclusion, it is recommended that salty drilling fluids that are to be contained on site in a permafrost region should be diluted as much as practical with freshwater to minimize freezing point depression. Salty drilling fluids should not be isolated in a separate sump, since they are less likely to remain frozen and may not even be capable of supporting a sump cap. Furthermore, sumps should be designed so that drilling fluids lie below the active surface layer. A further barrier to thawing of the saltwater fluid might be provided by sealing the drilling fluids with a freshwater layer before the sump is backfilled.

SOMMAIRE

On s'inquiète du fait que, dans les Territoires du Nord-Ouest, les bassins enfouis renfermant des fluides de forage salés ne demeurent peut-être pas suffisamment gelés pour prévenir la contamination de l'environnement, en raison de l'abaissement du point de congélation et des perturbations touchant le pergélisol. Afin d'élucider cette question, la surveillance du bassin du chantier du puits M-47 de Tweed Lake a été entreprise en septembre 1985. On a effectué des relevés électromagnétiques à fréquence invariable afin de dépister les zones à conductivité élevée, ce qui permet de déceler les cas d'infiltration et de dégel possible des fluides dans le bassin. L'utilisation de relevés électromagnétiques pour déceler la présence de sel dans le pergélisol n'avait pas encore été documentée.

Les relevés électromagnétiques ont permis de constater deux infiltrations possibles de sel pour le bassin du puits M-47 de Tweed Lake: une première du côté est, et une deuxième dans la partie ouest du périmètre. Aucune des deux zones infiltrées ne s'étendait à plus de 40 m du bassin. Dans un cas comme dans l'autre, il est probable qu'un autre phénomène que la migration du sel explique la conductivité

élevée qui a été relevée. Toutefois, afin d'éliminer toute possibilité que du sel s'échappe du bassin, il faudra effectuer des relevés électromagnétiques à intervalles réguliers. Il pourra également s'avérer nécessaire d'installer des sondes intrusives.

Des calculs théoriques ont été effectués afin de connaître le niveau prévu de conductivité à la surface du sol en cas de dégel des fluides du bassin. Or, les mesures réelles de conductivité ont été nettement inférieures aux valeurs prévues, même au cours de l'été. Ainsi, les fluides enfouis doivent au moins être partiellement gelés.

En conclusion, nous recommandons, dans la mesure du possible, de diluer avec de l'eau douce les fluides de forage enfouis sur les chantiers des régions gelées en permanence, afin de réduire au minimum les conséquences de l'abaissement du point de congélation. Etant donné qu'il est peu probable qu'ils demeurent gelés et qu'ils puissent supporter le terrain de recouvrement, les fluides de forage salins ne devraient pas être enfouis dans des bassins séparés. De plus, les bassins devraient être conçus de façon que les fluides de forage reposent sous la couche superficielle active. La fait de recouvrir les fluides de forage d'une couche d'eau douce avant de remblayer le bassin pourrait également permettre de contrer les effets de dégel.

INTRODUCTION

Throughout the Northern Interior Plains of the Northwest Territories, there is a significant salt zone that is a member of the Saline River Formation. The top of this zone is found at depths ranging from 700 m in the northern regions of the Northern Interior Plains to over 2000 m at the foot of the Franklin Mountains. The extent and thickness of the Saline River salt member is shown in Figure 1. The thickness ranges anywhere from 0 m in the southeast corner of the Northern Interior Plains to 650 m in nearby Norman Wells.

Oil- and gas-bearing target zones throughout the Northern Interior Plains lie below the Saline River salt member. Salt zones, especially those the size of the Saline River salt member, are difficult to drill through because of hole stability problems. To penetrate the Saline River salt member, some operators in the area use a water-based drilling fluid, saturated with salt (NaCl). By saturating the drilling fluid with salt, salt from the salt zone is prevented from dissolving into the drilling fluid and creating an oversized hole. The use of a saturated salt drilling fluid is only necessary when the salt zone is

exposed. Therefore, drilling and casing programs are designed to minimize the use of salt-saturated fluids.

The accepted practice for the disposal of drilling fluids within the Northwest Territories is total containment on site within a buried sump. Containment is aided by freezing, as mean annual soil temperatures for the Northern Interior Plains are below 0 °C (Judge, 1973).

In 1985, the Department of Indian Affairs and Northern Development (DIAND) expressed concern over the integrity of buried drilling sumps with a high salt content. If a salty sump does not remain frozen sufficiently to contain the drilling fluid, the surrounding area may become contaminated by salt. Two factors may prevent sumps with a high salt content from remaining frozen. The first factor is a reduced freezing point due to the dissolved salt. Pure water freezes at 0 °C. However, with the addition of salt and other dissolved impurities, the freezing point is reduced owing to a phenomenon known as freezing point depression. The degree of the freezing point depression depends on the dissolved salt concentration, as shown in Figure 2 for a pure water-NaCl system. The maximum freezing point depression occurs at a concentration of 270 g/l, when the water is saturated with salt. The freezing point at this concentration is -21 °C (Weast, 1984).

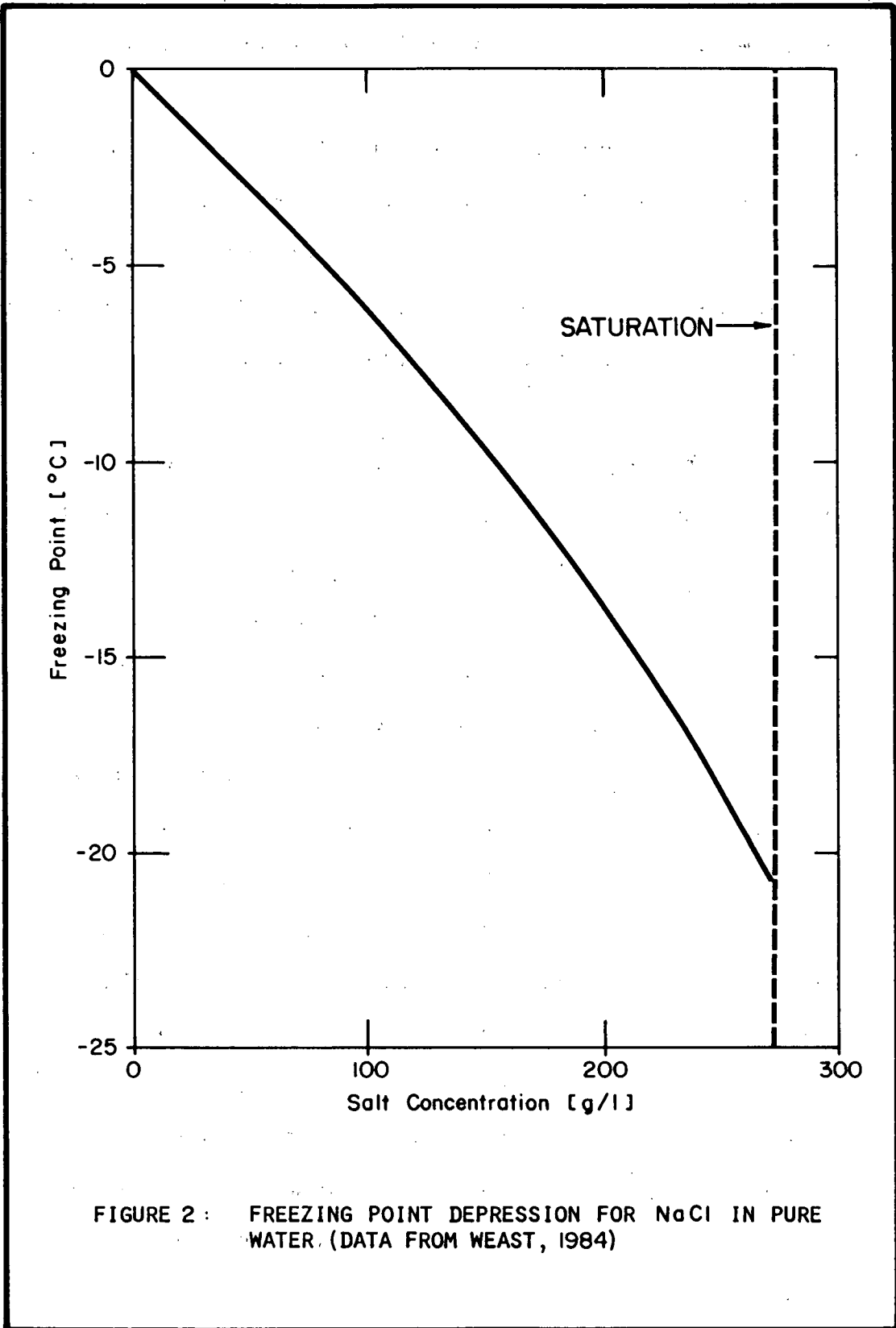


FIGURE 2 : FREEZING POINT DEPRESSION FOR NaCl IN PURE WATER. (DATA FROM WEAST, 1984)

The second factor which may prevent salty sumps in the Northern Interior Plains from remaining frozen is the existence of widespread discontinuous permafrost. Research has shown that after an area of discontinuous permafrost has been cleared, the permafrost layer may never be restored, but continues to recede below the surface (Linell, 1973). In other words, it may be impossible to permanently contain any drilling fluids in an area of discontinuous permafrost.

In May, 1985 DIAND requested that Petro-Canada develop a monitoring program for the buried sump at the Tweed Lake M-47 wellsite. The program was initiated in September, 1985.

OBJECTIVES

There were two main objectives for the Tweed Lake M-47 sump monitoring program:

1. To determine if significant salt seepage into the soil surrounding the sump had occurred, and, if so, to determine the extent and direction; and
2. To determine the extent of unfrozen fluid within the sump.

Both objectives were addressed by fixed-frequency, electromagnetic (EM) surveys. The use of EM surveys for detection of salt in permafrost areas had not been previously documented.

Two sets of land surveys and EM surveys were run to determine changes in characteristics of the sump and the surrounding area over time. The first set of surveys was conducted in December, 1985. The second set of surveys was conducted in August, 1986.

THE TWEED LAKE M-47 SUMP

A sectional view of the Tweed Lake M-47 sump is shown in Figure 3. The wellsite is located at 66°56'47" north latitude and 125°54'09" west longitude (Figure 1). The sump lies across near-surface limestone bedrock. The sump was created by blasting in December, 1984. Drilling of the M-47 well began in January, 1985, and was completed in February. The sump was backfilled April, 1985. Additional backfill was added to the center of the sump in December, 1985. When nearby tank farms were dismantled in March, 1986, material from the berms was spread along the west side of the sump.

The sump is 52 m long and 35 m wide. The deepest point in the sump from the surrounding ground level is 3.5 m. The backfilled cap is mounded approximately 1.2 m above ground level. At the time of backfill, the sump contained approximately 1,200 m³ of frozen freshwater drilling fluid and cuttings at the bottom, covered by approximately 750 m³ of frozen salt-saturated drilling fluid and cuttings. In terms of the fluid level in the sump, these quantities correspond to 1.5 m of freshwater and 0.5 m of saltwater. (The fluid levels are not directly proportional to the fluid volumes because of the concave shape of the sump bottom.)

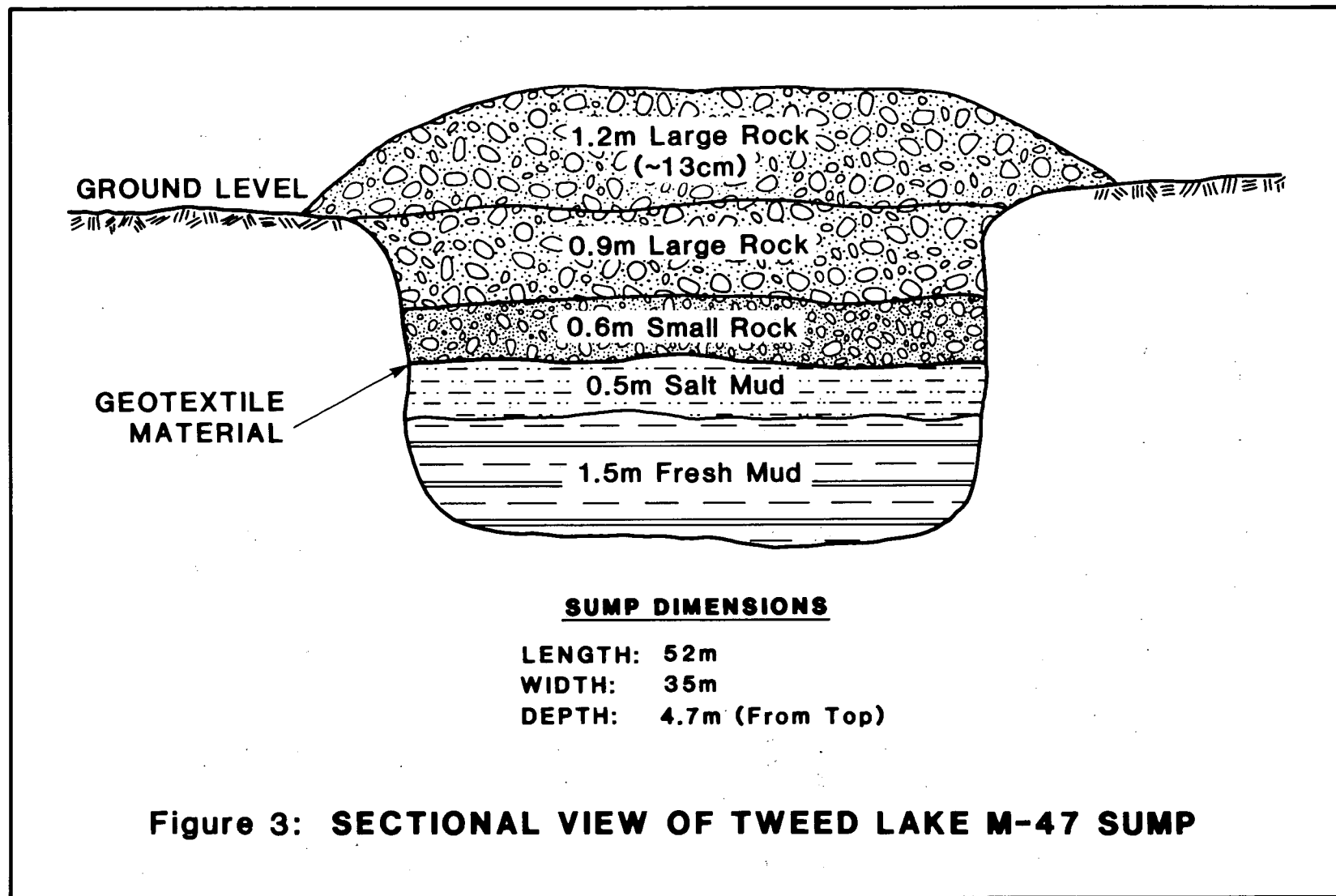


Figure 3: SECTIONAL VIEW OF TWEED LAKE M-47 SUMP

The drilling fluid surface is covered by a layer of permeable geotextile material, followed by 2.1 m of rock originally excavated from the sump. It should be noted that even if the sump fluids have remained frozen since the sump was backfilled, some mixing of the freshwater and saltwater fluids may have occurred, as salt is known to migrate within ice.

METHODOLOGY

BASIS FOR CHOICE

Two general approaches may be taken to determine the salt concentration and thermal state of soils: 1) intrusive sampling, and 2) non-intrusive sampling. An example of an intrusive sampling unit is shown in Figure 4. Typically, an intrusive sampling unit consists of a thermistor string to measure temperature, a conductivity string to measure conductivity, and a cluster of standpipes installed at various depths within the soil to obtain water samples. Salt concentrations may be measured directly from water samples or calculated from the temperature and conductivity measurements. Properly installed, intrusive probes provide unambiguous measurements of the salt concentration and thermal state of soils. However, installation of these units is often hampered in unconsolidated soils (such as might be found within the sump), due to excessive disturbance of the sampling area. In summary, intrusive probes provide good vertical resolution; however, lateral resolution is limited by the number of units installed and their relative positioning.

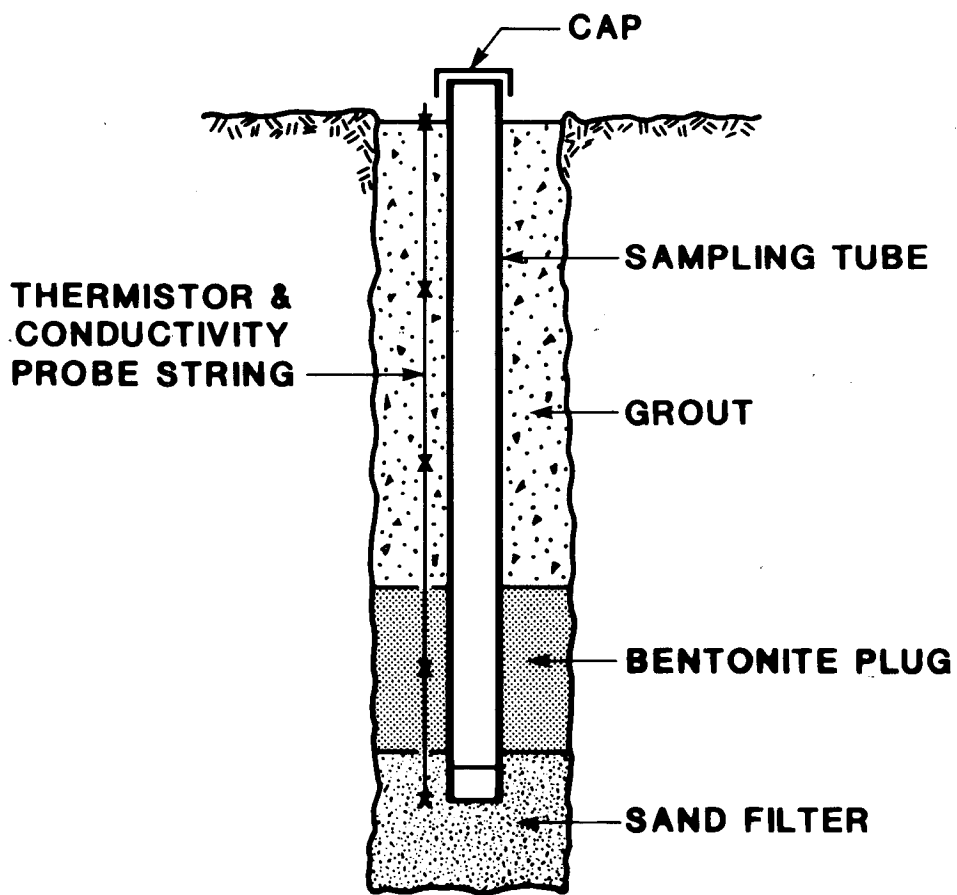


Figure 4: INTRUSIVE SAMPLING UNIT

Non-intrusive sampling can be accomplished with EM surveys. EM surveys are used to measure average terrain conductivity over a given depth. The major factors which influence terrain conductivity are: 1) soil or rock type, 2) moisture content, 3) porosity and drainage characteristics, 4) concentration of ions in the ground water (i.e., dissolved salts) and 5) temperature. Typical conductivities for several types of unfrozen rock are shown in Figure 5. Conductivities are highest for clays and soft shales, and lowest for dense limestone. Conductivity decreases at lower temperatures, particularly once ice forms. See Figures 6 and 7. Conductivity increases dramatically with ion concentration, as shown for a NaCl-water system in Figure 8.

However, because of the dependence on multiple variables, absolute measurements of soil salinity or thermal state are often impossible, based on conductivity measurements alone. Nonetheless, EM surveys are useful to locate areas with high or low conductivity. When EM data is assessed with other geophysical data available for an area (i.e., core and seismic data) or when changes in EM data are monitored over time, it is often possible to deduce what factors are responsible for high or low conductivity readings.

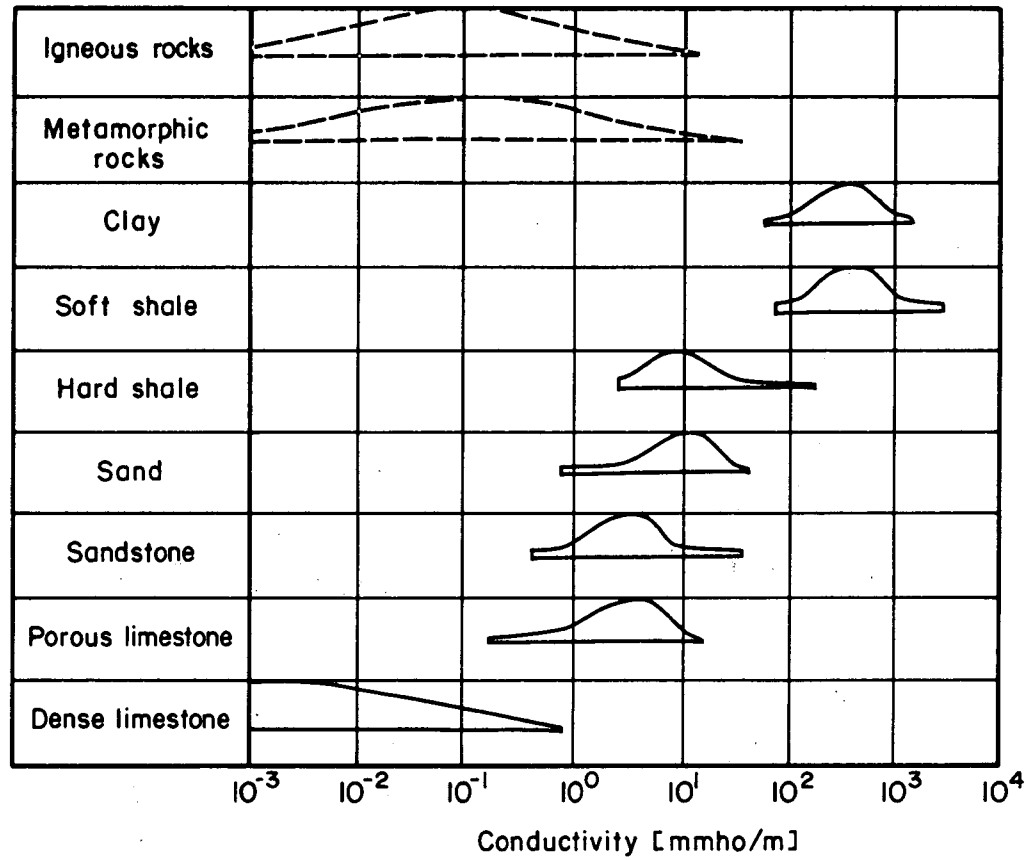


FIGURE 5 : TYPICAL CONDUCTIVITIES FOR VARIOUS ROCK TYPES (GEO-PHYSI-CON)

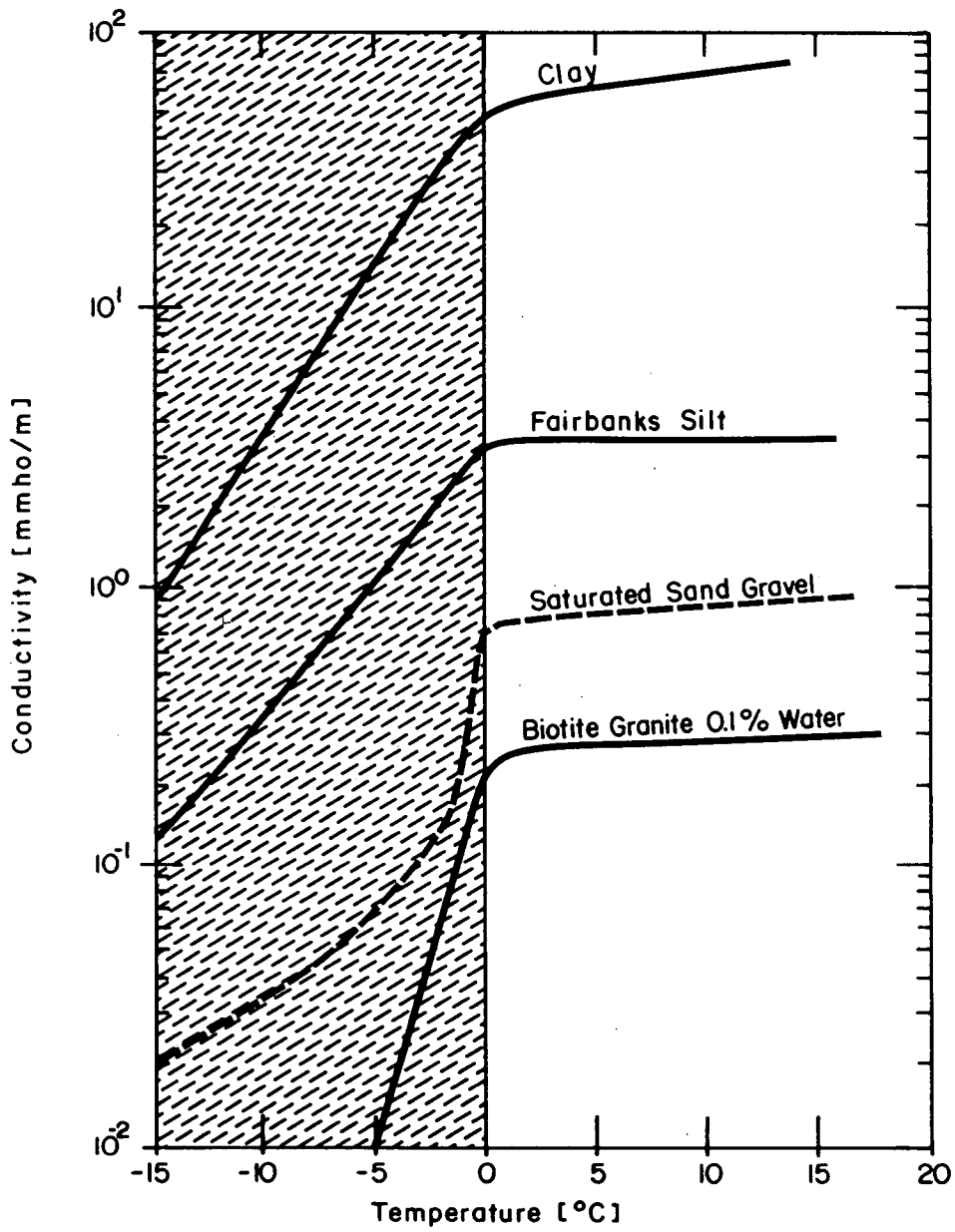


FIGURE 6: EFFECT OF TEMPERATURE ON THE CONDUCTIVITY OF VARIOUS ROCK TYPES (HOEKSTRA AND MCNEILL, 1973)

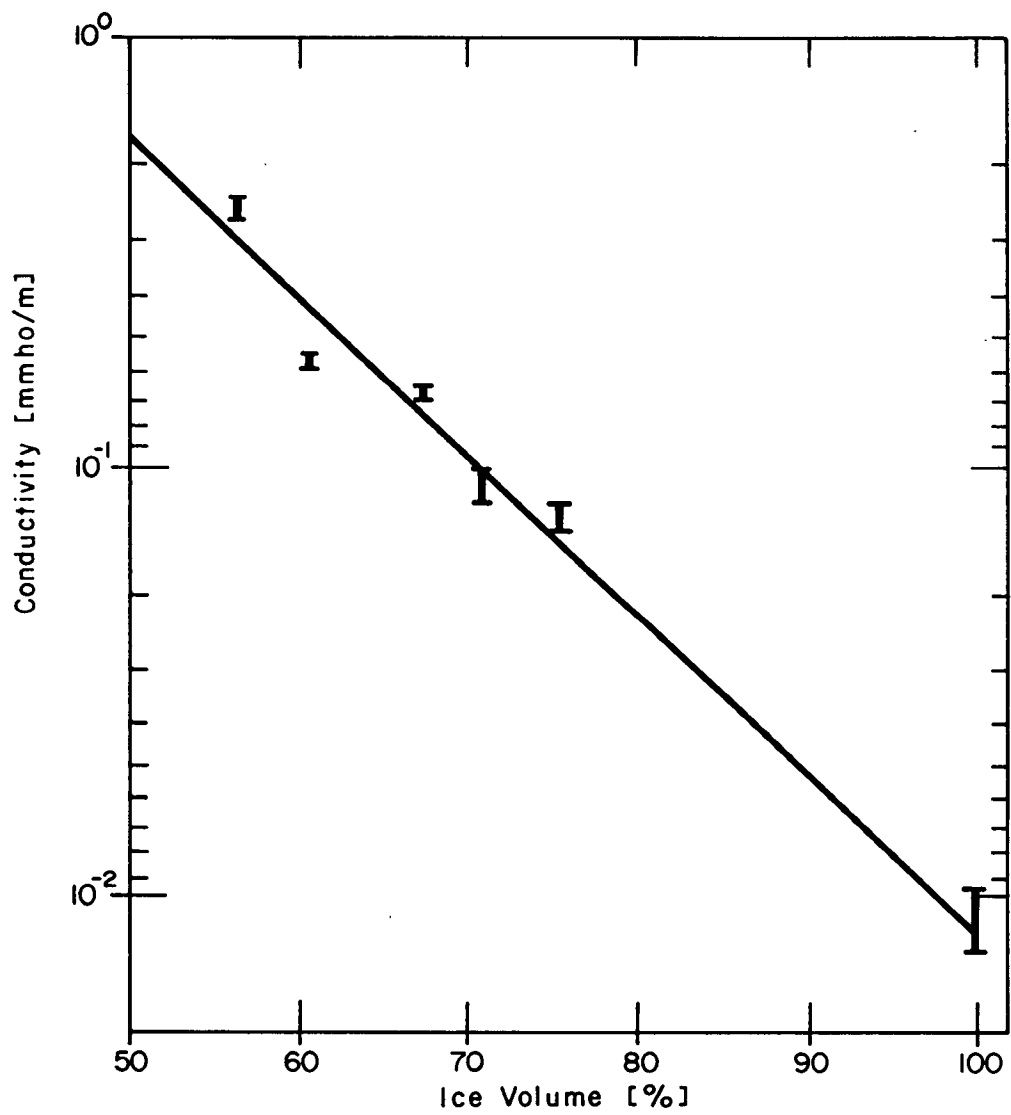


FIGURE 7 : EFFECT OF ICE CONTENT ON WATER CONDUCTIVITY
(HOEKSTRA AND MCNEILL , 1973)

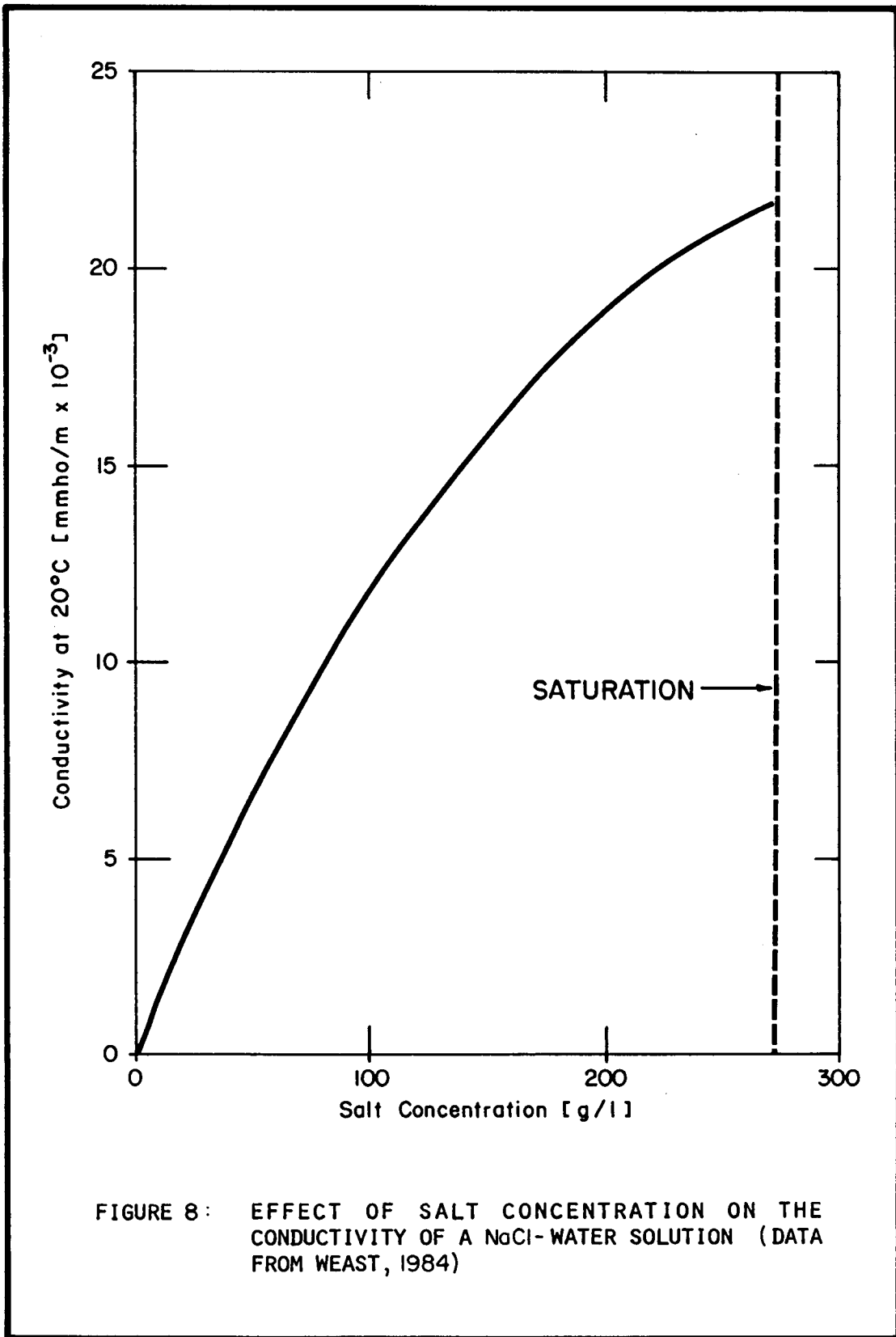


FIGURE 8: EFFECT OF SALT CONCENTRATION ON THE CONDUCTIVITY OF A NaCl-WATER SOLUTION (DATA FROM WEAST, 1984)

In summary, the advantages of EM surveys over intrusive probes are: 1) good lateral resolution, 2) high sampling rates, 3) low cost, and 4) no disturbance of the site. While some ambiguity can arise over the interpretation of EM results, at the very least conductivity mapping is useful to plan a more detailed investigation.

Thus, the approach adopted for the Tweed Lake M-47 sump monitoring study was to first investigate the site by conducting two sets of EM surveys. Based on these initial results, a decision could then be made about the need for further sampling and where it may be required.

OPERATION OF THE EM INSTRUMENT

The basic units of the EM instrument are a transmitter, a receiver, and a readout device. The transmitter generates a magnetic field which induces an eddy current in the ground. The current, in turn, generates a secondary magnetic field, which is sensed by the receiver. The ratio of the primary and secondary magnetic fields is related to the conductivity in the subsurface. The instrument parameters are: 1) frequency, 2) distance between the transmitter and receiver, and 3) orientation of the transmitter and receiver with respect to each other and the ground. These parameters are selected so that the measured conductivity is approximated by the sum of strata conductivities located within the sampling

depth.

EM surveys are conducted by first establishing a grid pattern with a hip chain and flagging. An operator then carries the instrument along the grid lines and measures the terrain conductivity at set intervals. The effective measurement depth is varied by changing the orientation of the instrument relative to the surface. The two EM instruments used in the surveys at the Tweed Lake M-47 site are shown in Figures 9a and 9b. The Geonics EM31 instrument, shown in Figure 9a, can be used to make measurements at depths of 0-2, 0-4, and 0-5 m, and requires only one operator. The Geonics EM34-3 instrument, shown in Figure 9b, can be used to make measurements over depths ranging up to 60 m, depending on the distance between the two hoops (i.e., the transmitter and the detector) and the relative orientation of the two hoops. The EM34-3 instrument requires two operators. For the Tweed Lake sump study, the EM34-3 was used to make measurements at a 0-11 m sampling depth.

It should be noted that effective measurement depths can vary slightly with soil or rock type, and thus are only approximate. For the two instruments used in this study, up to 25 percent of the conductivity signal can originate from materials located at depths greater than the specified sampling depth (McNeill, 1980a). Because the sump is



a) EM 31 INSTRUMENT (0-2 AND 0-5 m SAMPLING DEPTHS)



b) EM 34-3 INSTRUMENT (0-11m SAMPLING DEPTH)

FIGURE 9 : EM INSTRUMENTS USED FOR CONDUCTIVITY MEASUREMENTS AT TWEED LAKE M-47 SITE

contained within limestone, which has a low conductivity, EM conductivity readings may have been overestimated at the 0-2 m sampling depth and underestimated at the 0-5 and 0-11 m sampling depths. However, given the sensitivity of conductivity to salt and thermal state, the uncertainty can be tolerated, as is shown in the theoretical calculations presented in the next section.

RESULTS

The EM results are presented in the form of contours (i.e., points of equal conductivity are connected). Conductivity values are normalized with respect to depth, which allows for direct comparison of readings taken over different depths; the units are mmho/m.

To provide a framework for interpreting the EM results, it is useful to calculate the conductivity that one would expect to measure at surface if the sump contains a significant zone of thawed saltwater. The factors that must be taken into account are salt concentration, temperature, solids loading in the saltwater, depth of the saltwater zone, and conductivity of other materials within the sampling depth. Two cases are considered. In both cases, several assumptions are necessary. However, all of the assumptions are made so that the predicted values are conservative estimates of the expected conductivity.

In the first case, it is assumed, as suggested by Figure 4, that the saltwater zone is saturated and confined to a 0.5 m layer buried 3 m below the sump cap. The conductivity of saturated saltwater at 20 °C is 21,000 mmho/m. (See Figure

8.) To adjust the conductivity to a temperature just above freezing, it is assumed that the conductivity drops by a factor of four to approximately 5,000 mmho/m. If the saltwater contains non-conductive cuttings at 50 percent by volume, then the conductivity is reduced by another factor of three to approximately 1,650 mmho/m (McNeill, 1980b). The contribution to the measured conductivity by layers other than the saltwater zone is assumed to be negligible. An adjustment for depth is made according to the method described by McNeill (1980a). For a sampling depth of 0-5 m, the predicted conductivity reading is approximately 165 mmho/m.

In the second case, it is assumed that the sump fluids are homogenized, so that the salt is evenly distributed in an unfrozen 2 m layer at the bottom of the sump. In this case, the conductivity of the saltwater zone is less than in the first case, but the thickness of the contributing zone is greater. Adjustments for temperature and solids loading are made as before. Likewise, the contribution to conductivity from other materials is ignored. For a sampling depth of 0-5 m, the predicted conductivity reading is approximately 120 mmho/m, slightly less than for the first case.

FIRST SET OF EM SURVEYS, DECEMBER 1985

The first set of EM surveys were run in December, 1985.

The results are shown in Figures 10-12 for approximate measurement depths of 0-2, 0-5, and 0-11 m, respectively. (The three degrees of shading were provided to help distinguish between areas of lowest and highest conductivity.) Measurements made well outside the sump area established the background conductivity at near 3 mmho/m for all sampling depths. This value is characteristic of frozen soil and frozen or resistive limestone. Thus, as a conservative estimate, any area with a conductivity of 4 mmho/m or greater may 1) be influenced by salt or 2) be partially or wholly thawed.

At a sampling depth of 0-2 m (Figure 10), conductivities within the sump ranged from 6-17 mmho/m. The highest conductivities were observed in the east side of the sump. The highest conductivity observed outside of the sump perimeter was 8 mmho/m, although this area was confined near to the sump perimeter. A potential area of salt migration was indicated by conductivity contours of 5-6 mmho/m extending from the southeast corner of the sump. However, these values were only twice the background signal, which is still very low.

At a sampling depth of 0-5 m (Figure 11), trends were similar to those observed at 0-2 m. Again, a potential area of salt migration was indicated at the east corner of the

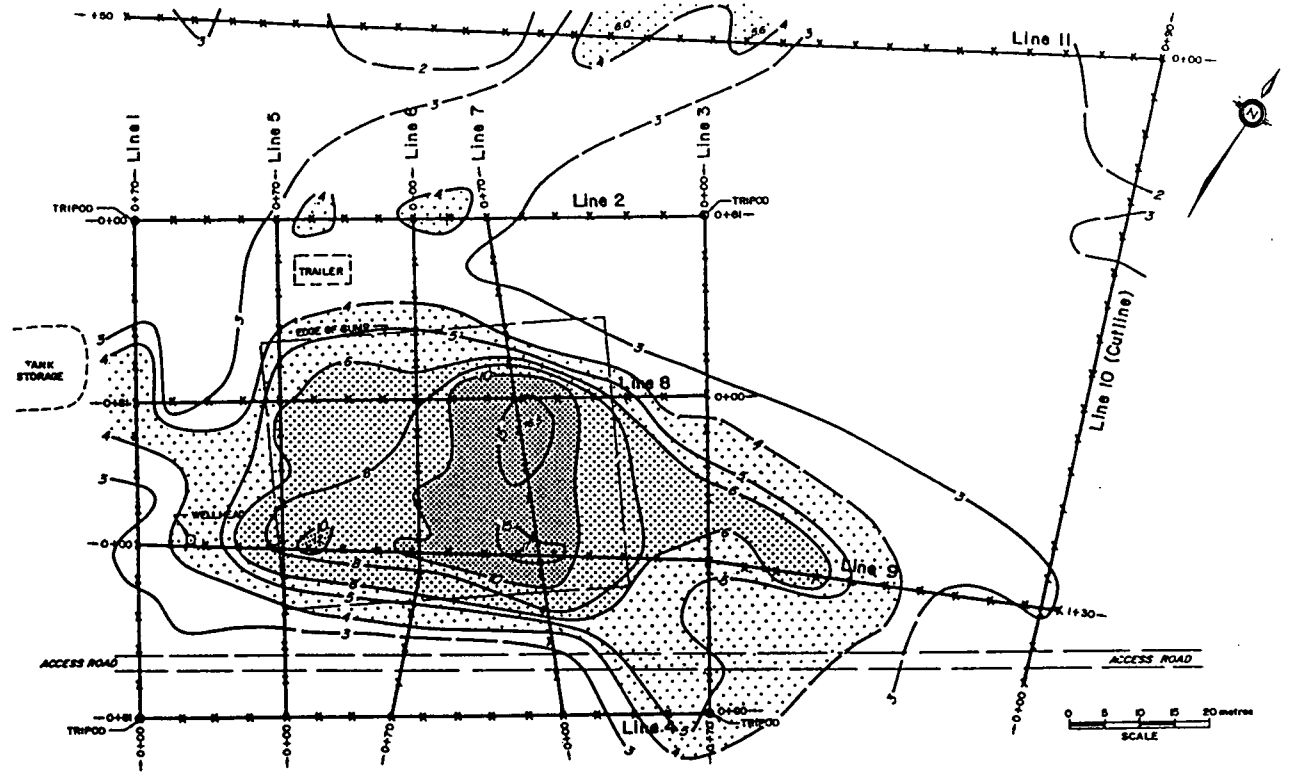


FIGURE 10: CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M-47 SITE AT 0-2 m SAMPLING DEPTH; DECEMBER, 1985 (mmho/m)

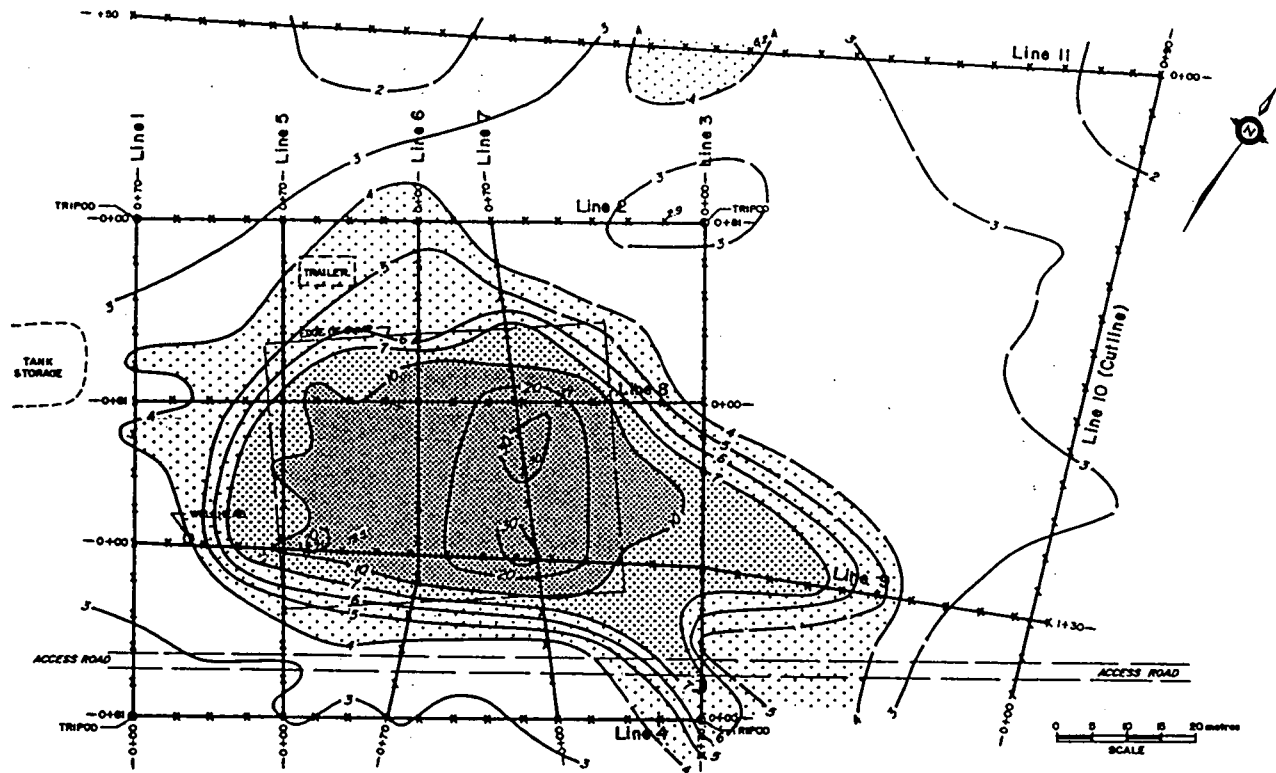


FIGURE 11 : CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M-47 SITE AT 0-5 m SAMPLING DEPTH ; DECEMBER, 1985 (mmho/m)

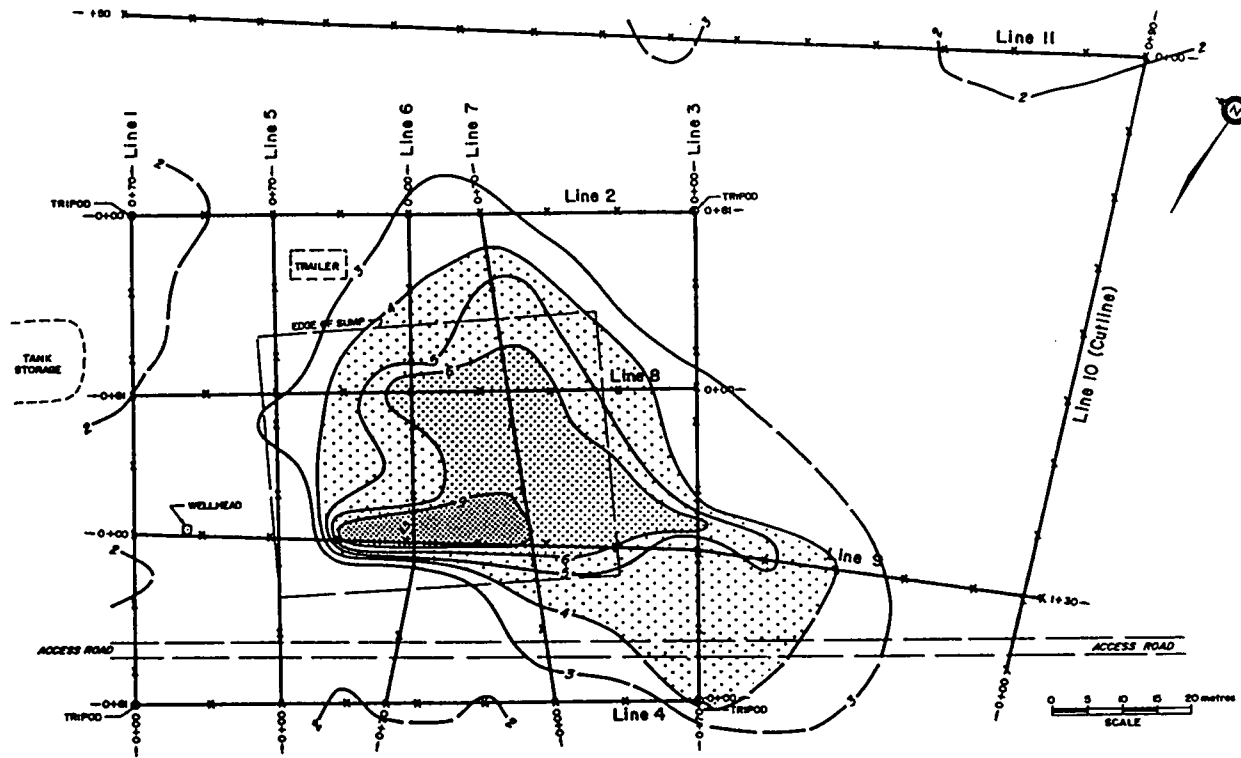


FIGURE 12 : CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M-47 SITE AT 0-11m SAMPLING DEPTH ; DECEMBER , 1985 (mmho/m)

sump. The maximum conductivity within the sump area was 30 mmho/m and the maximum conductivity outside the sump perimeter was 10 mmho/m. Conductivities within the sump area were greater for 0-5 m than for 0-2 m, presumably because more of the salt layer was included in the measurement. Because the actual measured conductivities were only 25 percent of the most conservative value expected for a significant unfrozen salt zone, there is good likelihood that the sump fluids were at least partly frozen.

At a sampling depth of 0-11 m (Figure 12) conductivities were lower than those measured over shallower depths. The lower values are consistent for sump fluids that only extend 3.5 m below the surface. The only substantial difference between the results sampled at 0-11 m and those sampled at shallower depths was that the area of maximum conductivity shifted from the east side of the sump to a more southerly position.

EM measurements were also obtained during December, 1985 for another wellsite in the Tweed Lake area, before the site was prepared for drilling. Some of the results from that site are presented here for comparison with the Tweed Lake M-47 results. EM surveys conducted at 0-2 and 0-5 m on the unprepared site are shown in Figures 13 and 14, respectively. Again, the background conductivity was established at 3

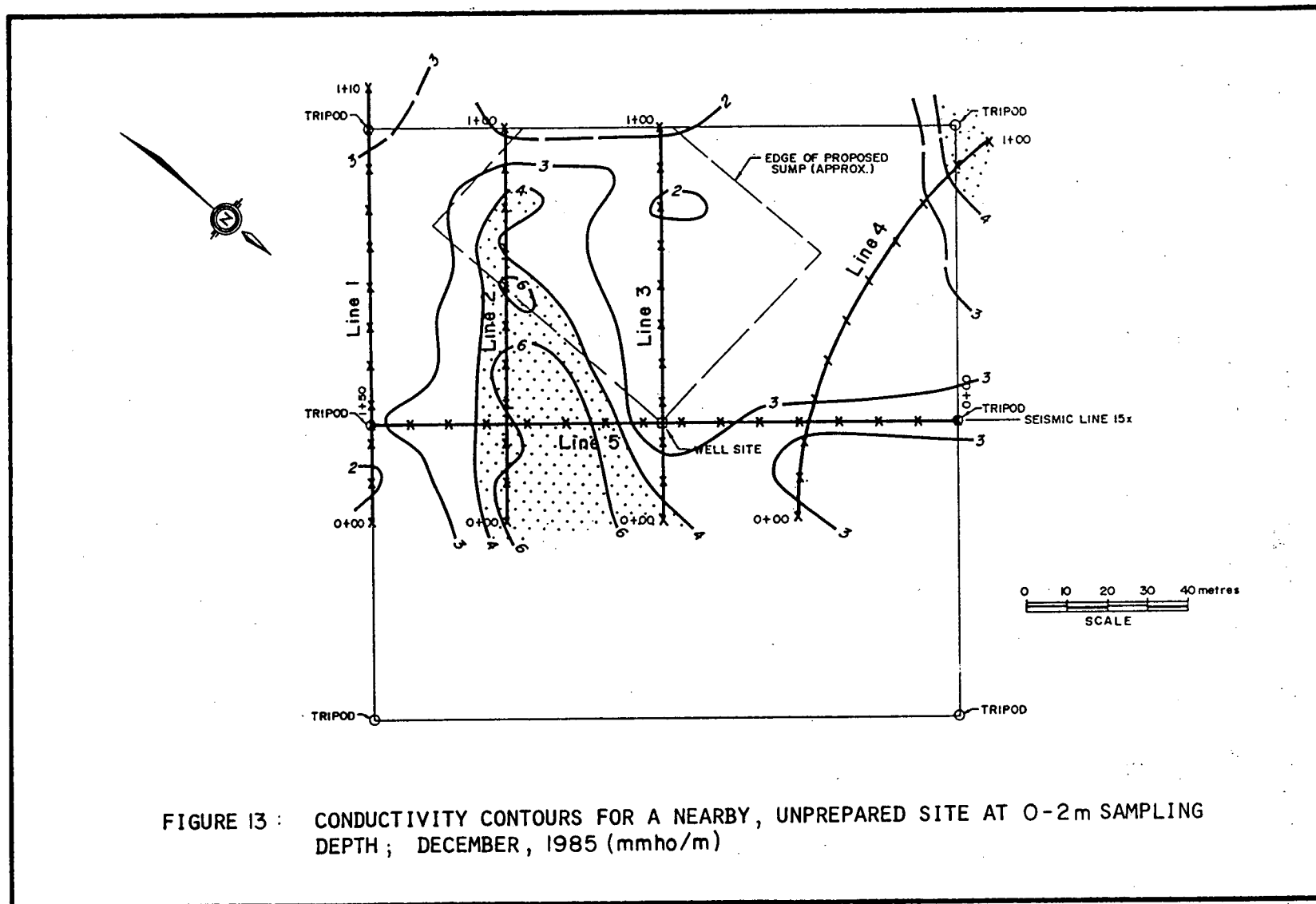


FIGURE 13 : CONDUCTIVITY CONTOURS FOR A NEARBY, UNPREPARED SITE AT 0-2m SAMPLING DEPTH; DECEMBER, 1985 (mmho/m)

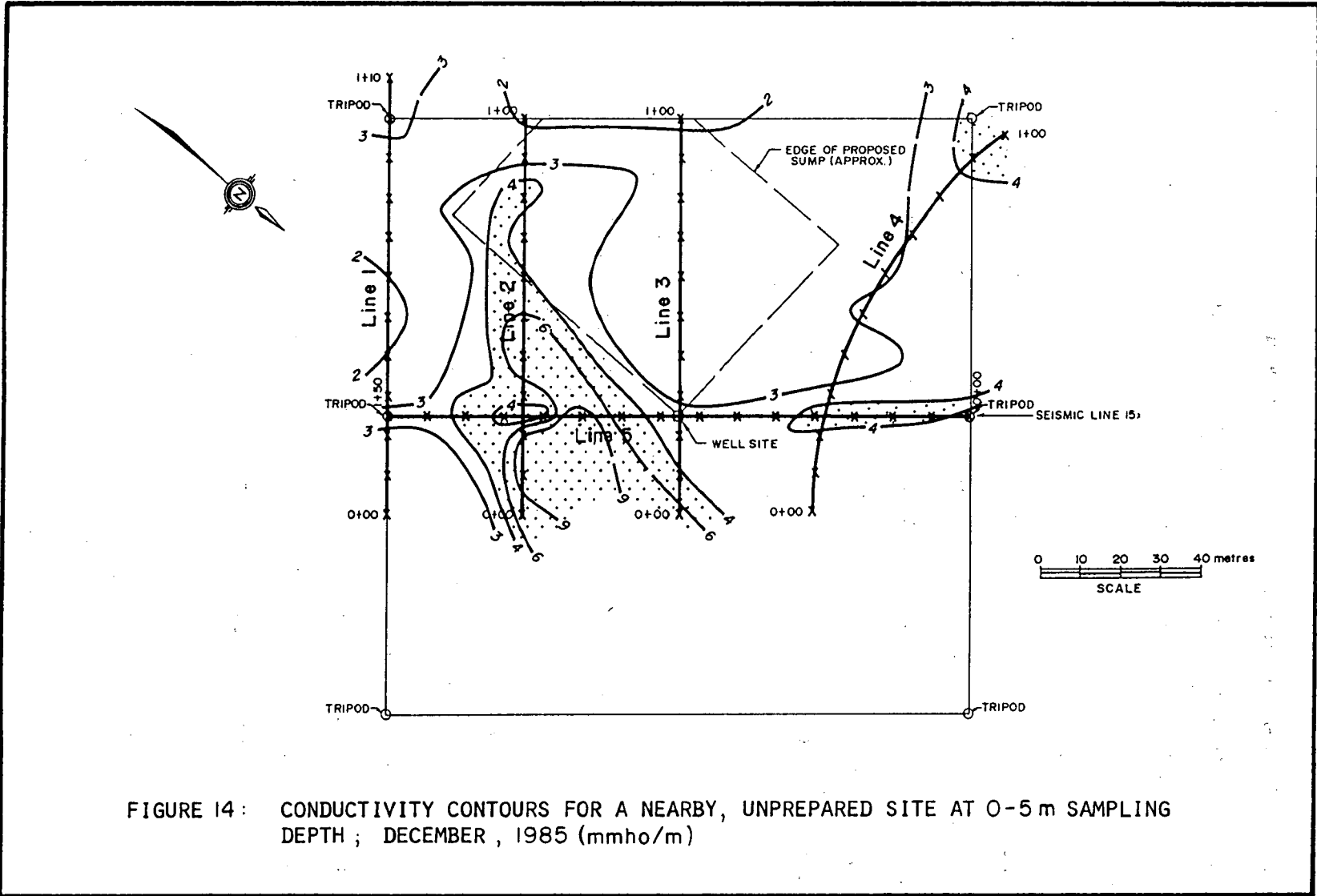


FIGURE 14: CONDUCTIVITY CONTOURS FOR A NEARBY, UNPREPARED SITE AT 0-5 m SAMPLING DEPTH ; DECEMBER , 1985 (mmho/m)

mmho/m. At a sampling depth of 0-2 m (Figure 13), conductivities as high as 6 mmho/m were observed. When the sampling depth was extended to 5 m (Figure 14), even higher values were observed--9 mmho/m. Because the area was not disturbed, these higher conductivities suggest the presence of a naturally-occurring unfrozen or partly frozen area, possibly an underground drainage. This suspicion was confirmed when the sump was blasted shortly after the EM measurements were taken. The west side of the sump was wet. Thus, during the winter months, conductivities as high as 9 mmho/m may be due to unfrozen or partially frozen ground.

The results from the M-47 site and the unprepared site demonstrate the ambiguities that can arise when one attempts to use a single set of EM surveys to distinguish between salt-contaminated soil and unfrozen, uncontaminated soils. The question could, of course, be answered by installing intrusive probes. However, an alternative approach is to monitor the position of conductivity contours over time. If significant salt seepage is occurring, the conductivity contours will continue to expand out from the sump; otherwise they will remain relatively constant.

SECOND SET OF EM SURVEYS, AUGUST, 1986

A second and final set of EM surveys was run in August, 1986. The second set of surveys was scheduled for August

because the potential for salt migration through the thawed surface layer is greatest at this time. For the most part, the survey grid from the first set of surveys was duplicated for the second set. Survey lines along the west side of the sump were extended, in order to survey an area that was previously too close to a tank farm to obtain meaningful measurements. (EM measurements are distorted by metal.) Conductivity contours from the second set of EM surveys are shown in Figures 15-17 for approximate measurement depths of 0-2, 0-5, and 0-11 m, respectively.

Some qualification is necessary before the August, 1986 results can be compared with the December, 1985 results. Because the thickness of the active layer above the permafrost changes seasonally, the background conductivity also changes. As one might expect from Figures 6 and 7, background conductivities are lowest and most uniform during the winter months when the frozen zone extends to the surface. Background conductivities increase during the summer months, depending on the thickness of the thawed surface layer and the amount of retained moisture. Furthermore, during the summer months, background conductivities often decrease with sampling depth, due to temperature gradients in the soil or rock.

At a sampling depth of 0-2 m, the background

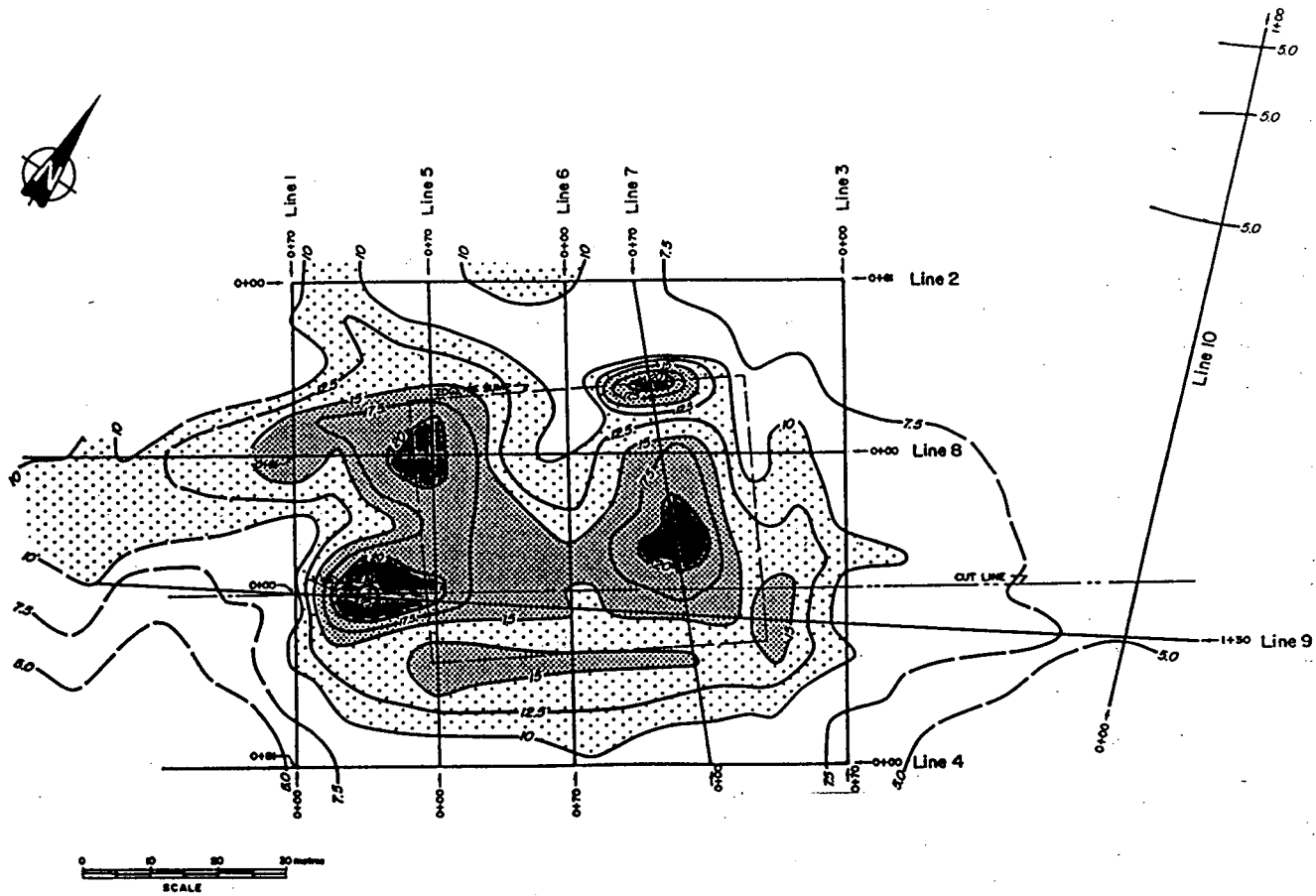


FIGURE 15 : CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M-47 SITE AT 0-2m SAMPLING DEPTH ; AUGUST , 1986 (mmho/m)

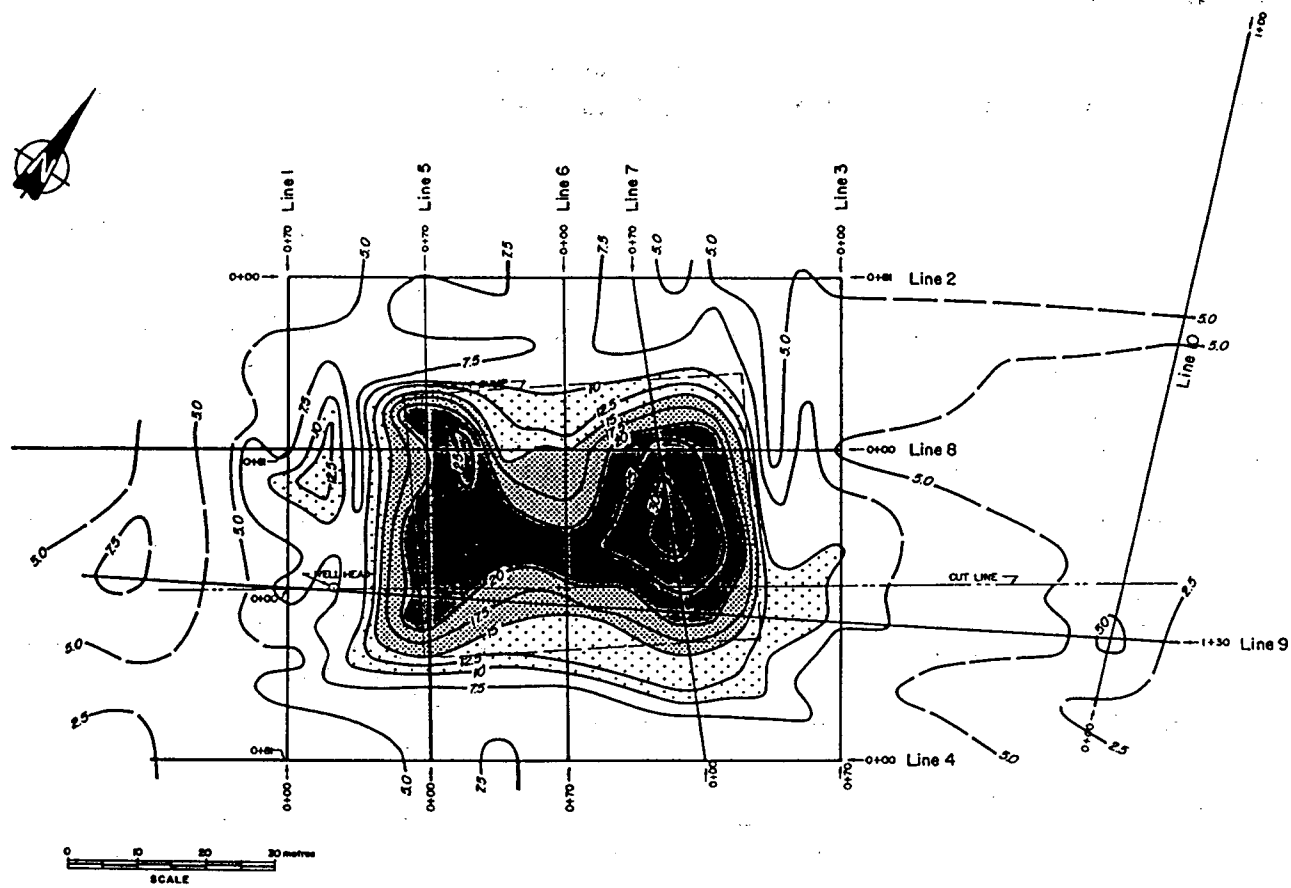


FIGURE 16 : CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M 47 SITE AT 0-5m SAMPLING DEPTH ; AUGUST, 1986 (mmho/m)

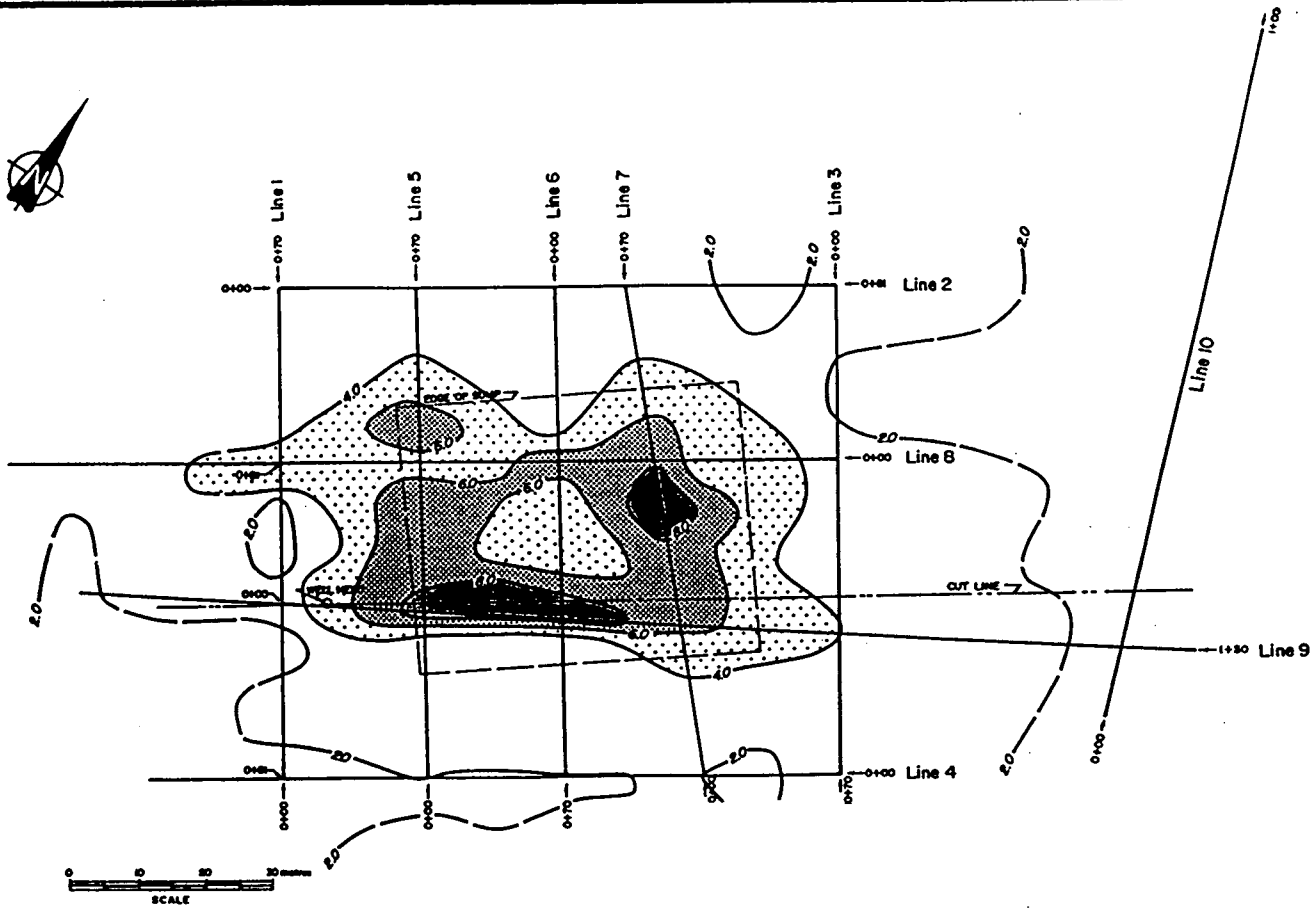


FIGURE 17 : CONDUCTIVITY CONTOURS FOR THE TWEED LAKE M-47 SITE AT 0-11 m SAMPLING DEPTH ; AUGUST , 1986 (mmho/m)

conductivity measured during August, 1986 ranged from 5-12 mmho/m. The higher values were observed in more exposed areas. At a sampling depth of 0-5 m, the background conductivity ranged from 2.5-5 mmho/m. At a sampling depth of 0-11 m the background conductivity was 2 mmho/m. As expected, the August background conductivities were generally higher near the surface and more variable than those observed during the previous December.

The potential plume identified from the December survey at the east corner of the sump was no longer evident from the August results, regardless of sampling depth. Since the conductivities for the east corner area were similar for both December and August, it was concluded that the high conductivity values (4-7 mmho/m) observed during December were probably due to partially frozen terrain, rather than salt. Even if salt is present, no additional salt accumulation occurred.

At a sampling depth of 0-2 m, an area of potential salt migration was detected along the west side of the sump. Conductivities as high as 20 mmho/m were measured outside the sump perimeter. This finding was somewhat surprising, as a potential plume in this area was not identified from the December results. Furthermore, the lay of the land suggests that the near surface-drainage is towards the east, which is

located on the other side of the sump. At a sampling depth of 0-5 m, readings outside of the west perimeter were lower than at 0-2 m. Fluids frozen during the previous winter may have increased fractures and extended channels for salt migration. However, if the high readings were due to salt, one would expect higher conductivities as measurements were extended to depths that include more of the salt layer, not the lower readings that were observed. This discrepancy suggests that the high conductivities were due to a surface phenomenon.

Metal from the wellhead and from a barrel buried in the northwest corner of the sump might account for some of the higher readings along the west side of the sump, but not to the extent indicated by the 15 mmho/m contour in Figure 15. On further investigation, it was discovered that during cleanup operations conducted during March, 1986, the berms from a nearby tank farm were bulldozed over against the west side of the M-47 sump, in essentially the same area as indicated by the 15 mmho/m contour. The tank berms were constructed in early 1985 with gravel from a distant pit and soil removed from the M-47 sump. Soil from the M-47 sump was used because of its "silty clay" characteristics. If clays were concentrated in the berm material, they could easily account for the high conductivities. See Figure 5. However, no analyses were performed to determine the content or type

of clay in the berm material.

Within the sump area, the ranges of conductivities measured in August were similar to those measured in the previous December, regardless of sampling depth. Previously, the higher conductivity contours were concentrated in the east side of the sump. However, in August, the higher conductivity contours had expanded to include parts of the west side as well. Conductivities were higher at 0-5 m than at 0-2 m, which suggests that the increase may be due to increased thawing of sump fluids. However, conductivity values were still well below those expected for extensive thawing of the sump fluids. Some of the increase was no doubt due to thawed surface materials. This contribution was further enhanced by the very wet conditions that existed at the time of the surveys. The closest weather station recorded nearly 3 cm of rain during the week prior to the August surveys. The average annual precipitation is only 33 cm (McDuff, 1986). During the summer months, it is reasonable to expect higher conductivities in the sump area, since the porosity for this area is greater than the background and water can penetrate to a greater extent.

Interpretation of the August EM results was complicated by uncertainties introduced by the March cleanup operations, wet sampling conditions, and variations in the background

conductivity due to surface thawing. Since most of the annual precipitation for the Northern Interior Plains occurs during the summer months (Burns, 1973), it may be preferable to conduct future EM surveys during the winter. Furthermore, if a surface phenomenon is suspected to account for anomalous conductivities, near surface soil samples from the affected area and undisturbed areas should be analyzed for clay and moisture content.

CONCLUSIONS AND RECOMMENDATIONS

EM surveys of the Tweed Lake M-47 sump site were useful to locate areas with anomalous high or low conductivity, which in turn, indicated areas of potential salt seepage and thawed sump fluids. While EM surveys cannot distinguish between salt contamination and thawed terrain, the ambiguities can often be resolved when the results are assessed with other geophysical data or monitoring is continued over time. At the very least, conductivity mapping is useful to plan a more detailed investigation.

A potential salt plume at the east corner of the M-47 sump was detected from the December, 1985 EM surveys. However, measurements from a nearby, undisturbed area showed that unfrozen or partially frozen terrain can account for conductivities as high as 9 mmho/m during the winter. The highest conductivity observed in the potential plume was only 8 mmho/m. Furthermore, the plume was not evident from the August, 1986 EM surveys, conducted nine months later. Since the conductivities in the area were similar for the two sets of surveys, it is concluded that the "plume" identified from the December results was a result of partially frozen terrain, rather than salt. Partially frozen terrain at the

M-47 site may have been caused by natural phenomenon or residual disturbances from the creation and backfilling of the sump. Even if salt is present, the contamination level is very low and no additional salt accumulation has occurred.

A second potential salt plume was detected along the west perimeter of the M-47 sump from the August, 1986 EM surveys. Conductivities within this area were much higher than expected, given the survey results from the previous December. Further investigation showed that the high conductivity readings were probably due to more conductive surface materials that were placed alongside the sump when berms from a nearby tank farm were dismantled in March, 1986.

Except for the area occupied by the dismantled berms, high conductivity readings were confined to areas within the sump. Readings were higher at a 0-5 m sampling depth than at 0-2 m or 0-11 m, which is consistent with the depth and contents of the sump. The highest conductivity reading observed was 35 mmho/m, which is about 25 percent of the most conservative value predicted for unfrozen saltwater. Therefore, the sump fluids must be at least partially frozen.

Conductivity readings within the sump were higher in the summer than in the winter. The higher readings may be due to partial thawing of the sump fluids. However, they may also

be due to thawing of backfill materials and activation of these materials by rain. During the summer, one can expect thawing and activation of the backfill materials to be greater than for background areas, because of the increased porosity of the backfill material.

EM surveys were conducted at the Tweed Lake M-47 site during summer and winter. The measurements were useful to assess conditions at the two extremes. However, confidence in interpretation of the results could be improved if at least two sets of measurements were conducted at the same time of the year. Winter is preferable to summer, since background conductivities are more uniform.

Theoretical calculations provided a conservative estimate of conductivity readings expected for thawed saltwater fluids within the sump. However, confidence in such predictions could be improved if conductivity data on salt solutions at near freezing temperatures were available.

Salty drilling fluids which are to be contained on site in a permafrost region should be diluted as much as practical with freshwater to minimize the freezing point depression. Salty drilling fluids should not be isolated in a separate sump, since such sumps are less likely to remain frozen and may not even be capable of supporting a sump cap.

Given the current technology, the use of synthetic liners is not recommended, since the liners crack and split at the extremely cold temperatures experienced in the Northern Interior Plains. Clay liners are also not recommended, since their effectiveness is greatly reduced in the presence of salt.

Containment of buried sump fluids within a permafrost region could be better assured if sumps were designed so that drilling fluids lie below the active surface layer. For most cases in the Northern Interior Plains, sumps would only need to be slightly deeper than the 3.5 m of the M-47 sump. A further barrier to thawing of the saltwater fluids might be provided by sealing the drilling fluids with a freshwater layer before the sump is backfilled.

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