Improved Near Surface Mapping in Groundwater Studies: Application of Fast-Sampling Time-Domain EM Surveying Methods

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Introduction

There are a limited number of methods currently in use to gather information on the various hydrogeological/environmental problems that are part of "everyday" life. Traditionally, groundwater problems have been evaluated and then monitored using a carefully designed network of wells where water depth and quality are measured on a regular basis. In recent years, some of the various mining and petroleum oriented geophysical techniques have been modified from their deeper applications to sample at shallower depths (Poeter et al., 1997). Often the goal of these surveys is to help geologists and engineers determine whether their assumptions on well location and water flow are correct. Techniques that have been used include shallow seismics (Bachrach and Nur, 1998), DC resistivity (Benson et al., 1997), ground penetrating radar (Hagrey and Muller, 2000), frequency domain electromagnetics (FDEM) (Acworth, 2001), and time domain electromagnetics (TEM) (Yang et al., 1999).

Recent advances in sampling speed, circuitry speed, and data recording have allowed the development of TEM techniques where data can be taken faster (and therefore start closer to the surface), and with better resolution of the top 15-50 m. These techniques include the Zonge Engineering NanoTEM system and the fast sampling modifications to the SIROTEM-3 system.

This paper briefly summarises the TEM results from three separate study areas encompassing a range of hydrogeological and environmental problems, each of some immediate importance in Australia at this time. The first study, at the Stockyard Plain Disposal Basin (SPDB) near Waikerie, South Australia, examines the changing hydrological environment around a groundwater disposal basin in the Murray-Darling system. The second study, in the Willaura Catchment in Victoria, examines water mobility in an evolving dryland salinity system. The third study, at an abandoned mine site in New South Wales, attempts to delineate the extent of acid-mine drainage in the area around the mine.

Aims

Some of the long-term aims of these types of geophysical surveys are to:

(a) Develop relationships between downhole geophysics and revised, local stratigraphy, so that downhole methods can be used to "map" the occurrence or absence of formations on a broader, regional scale. Regional mapping may help in borehole site selection.

(b) Use geophysical techniques to map the spread of groundwater mounds beneath irrigation areas, the alluvial groundwater quality, the water quality within mounds (variation of salinity with depth), and revise/expand the hydrostratigraphy based on the results of this type of work.

(c) Use geophysics to monitor the efficiency of various schemes that are aimed at improving water quality to help determine their effectiveness.

Methods

All of the time domain data in this paper were taken using a Zonge Engineering and Research Organization NanoTEM system. In each case the transmitter loop had 20 m sides, with a centrally placed horizontal receiver loop of 5 m sides. For each study the transmitter turn-off time was approximately 2 μs, while the turn-on time was less than 2 μs. The sampling rate was set either to 1.2 or 1.6 μs (depending on the depth and resolution desired). Assuming a 5 O.m ground, and the first sample taken within 4 μs of the top of transmitter turn-off ramp, information for the first data window is shallower than 4 m.

Although field-data acquisition is not as fast as some FDEM techniques (such as Geonics EM34), several line-km of TEM data can be collected in a day. For example, in the Willaura survey 120 measurement sites separated by 20 m were obtained in less than 15 hr (i.e. 1 line-km of data in 6.25 hr). Data quality for all of the sites reviewed here was exceptionally good. As with most electrical geophysical surveys, larger distances from roads, powerlines and urbanisation leads to better data quality. Both the Stockyard Plains data set and the Acid-mine Drainage data set were taken at remote locations, fairly distant from noise sources. Although half of the Willaura data were collected within 50 m of a small powerline, they were also of very good quality.

All the data displayed in this paper were inverted using Zonge Engineering's smooth-model inversion program STEMINV. Smooth-model inversion is a robust method for converting TEM measurements to profiles of resistivity versus depth. Observed TEM dB/dt magnitude data as a function of time for each station were used to determine the parameters of a 1-D layered-earth model. Layer resistivities were then adjusted iteratively until the model TEM response was as close as possible to the observed data, consistent with smoothness constraints. Lateral variations in resistivity were determined by "stitching" together inverted 1-D profiles from successive stations along a survey line to create a 2-D section (MacInnes, 2000). Results were contoured using the Geosoft geophysical contouring package: warm colours in the NanoTEM sections displayed below indicate conductors and cold colours indicate resistors.

Stockyard Plain Disposal Basin

Background: Intercepted saline groundwater and drainage-effluent from irrigation are commonly stored in both natural and artificial saline disposal basins throughout the Murray-Darling Basin. Concerns have been expressed about the possible environmental impacts these disposal basins

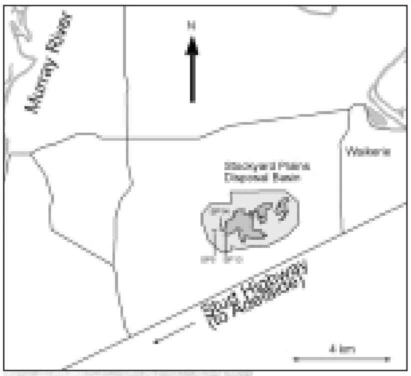


Fig. 1. (Top) Approximate location of Stockyard Plain Disposal Basin, near Waikerie, South Australia (Australian Water Environments).

Fig. 2. (Above) Location of Stockyard Plain Disposal Basin, and traverse. Note that Waikerie (and therefore the source wells for the water dumped here) is approximately 15 km to the northeast of the traverse (modified from Australian Water Environments). The boreholes MW2 and SP14 are situated within a few cm of each other.

may have, particularly on underlying groundwater systems and subsequently on surrounding low-lying land and river systems. Their continued use as wastewater evaporation sites therefore requires a detailed understanding of the groundwater dynamics beneath them. Of critical importance is leakage into underlying aquifers and the potential for salinisation of surrounding land, groundwater, streams and rivers. This study examined the use of non-invasive geophysical techniques to determine extent of saline plume migration and efficacy of saline groundwater disposal at Waikerie, South Australia.

Saline groundwater interception schemes have been in place along the River Murray at Waikerie and Woolpunda since the late 1980's. Saline ground water is intercepted before it enters the river and is then pumped to a natural depression approximately 15 km southwest of Waikerie, known as Stockyard Plains. Figures 1 and 2 are maps that show the approximate location of the field area.

Early in 2001, Adelaide University approached Australian Water Environments to test whether geophysical techniques could be used to help monitor the flow of groundwater in the area. A 500 m transect on the western side of the lake was run as a pilot study. A number of methods were tested at that time including TEM, FDEM, GPR and DC Resistivity. This paper concentrates only on the results of the TEM; full results of the study are provided in Barrett (2001).

NanoTEM Results and Discussion: Figure 3 shows inverted 1-D models contoured as a 2-D section of all data to the limit of data resolution between 45-70 m depth. Resistivities vary from > 50 O.m at the westernmost site (next to borehole SP5), to < 1 O.m adjacent to the lake (next to borehole SP13). The approximate water table depth (from boreholes SP13, SP14, MW2 and SP5) is shown by the solid black line. The prominent low resistivity layer is most likely clay.

Figure 4 shows the inversion for the top 15 m from the surface. The approximate water table depth (from boreholes SP13, SP14, MW2 and SP5) is shown by the solid black line. A thin clay layer (of resistivity < 2 O.m) is evident in the eastern section over depth range 3-8 m beneath SP13, SP14 and MW2. It is interesting to note how the shallow resistive layer in the east deepens to the west, apparently following a perched water table.

Willaura Catchment

Background: The Willaura catchment is located on the southeastern side of the Grampians Ranges in western Victoria (Figure 5). Much has been learned about the Willaura catchment from a series of investigations carried out starting in the early 1990s. It is clear that there is much more surface and sub-surface water now mobile within the Willaura catchment. Such increase in water prominence has major implications to landholders who depend on the land for their livelihoods. It is not only the obvious increase in water that is important, but also the serious implications as to the mobility of salt in the near-surface that is critical. The quantification of the mechanisms giving rise to this increase in water-flow is still a significant challenge. A number of scenarios have been put forward that act individually or in combination.

These include:

- Altered drainage and lake management practices,
- Excessive recharge occurring on the Grampians colluvial slopes,
- Increased local rainfall since the 1940s,
- Increased runoff and recharge across the landscape generally, and
- Increased runoff and recharge concentrated in the cleared Stavely Hills,

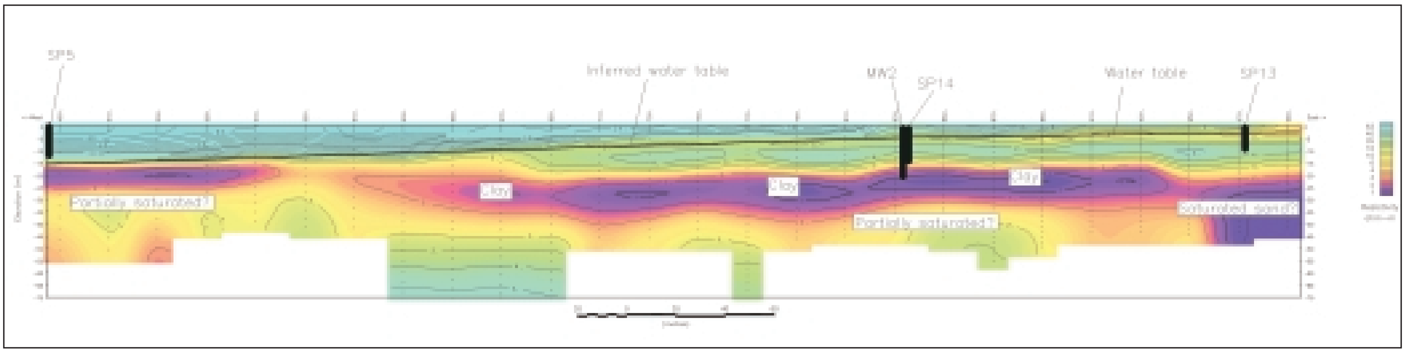
The survey transect reported in this paper follows Helens Rd (approximately 5 km west of Willaura Township) along gently sloping topography from north to south.

For most of the area there is a shallow layer of Pleistocene basalt quite close to the surface (within 4 m at Bore 103350). North of Wedding Lane three basalt flows are evident in bore logs and are inferred from airborne magnetic data. South of Wedding Lane the airborne magnetics indicate that a thin flow is present (Street et al., 1998). Below the basalt, at approximately 65 m depth, are Ordovician sandstones and shales. Soils are noted to be ~3 m thick. Figure 6 shows a schematic view of the interpretation of the area based on evidence available before 2001.

Strong features in airborne magnetics on the southwestern margin of Lake Muirhead have been interpreted as greenstone axes with associated bedrock faulting (Street et al., 1998). Heislers (1998) suggested that although such greenstones structures usually act as a barrier to groundwater flow from the north, they can also act as a conduit for preferential groundwater flow (e.g. leakage from Lake Muirhead) that may ultimately seep into underlying basalt aquifers (and therefore mix with surface waters in local creeks). Strontium and tritium isotope analyses reveal that younger, fresher basaltic water is mixing with older, more saline Ordovician sandstone and shale water (Bennetts, 2001).

NanoTEM Results and Discussion: Figure 7 shows inverted 1-D models contoured as a 2-D section for the top 100 m of ground. Resistivities vary from > 25 O.m to < 1 O.m adjacent to Boggy Creek and other saline features.

Deeper resistive units have been interpreted from aeromagnetic data as linear greenstone units (Street et al., 1998). The resistive unit labeled as fresh basalt matches well with occurrence of basalt in Bore 327 and Bore 103350. There is water in Bore 103350 at <2m depth, suggesting the existence of a perched water table over the fresh basalt (correlating with the slightly more conductive unit apparent above the basalt). Resistivity of this unit decreases markedly at 15 to 30 m depth, suggesting that this is the "true" water table over the northern half of the survey area.



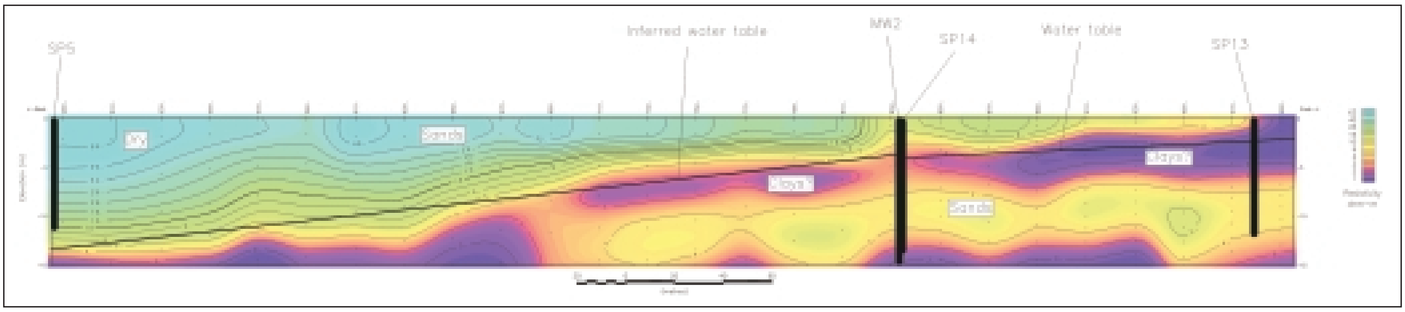


Fig. 3. (Top) Two-dimensional section (from 1-D inversions stitched together) of all data to the limit of data resolution between 45 and 70 m depth. The solid black line shows the approximate water-table depth. The prominent low resistivity layer is probably a clay region. Resistivities vary from > 50 O.m to < 1 O.m adjacent to the lake.

Fig. 4. (Above) Two-dimensional section (from 1-D inversions stitched together) for the top 15 m below the surface (note that the vertical scale has been exaggerated by a factor of four). The solid black line shows the approximate water-table depth. Note how resistivities increase to the west near the surface of the inverted section, apparently following a perched water table.

Fig. 5. (Right) Approximate location of Willaura Catchment study area (Bennetts, 2001).

Examination of Figure 8 suggests that the more resistive (greenstone?) unit is acting as a barrier to deeper flow in the area, forcing deeper water toward the surface to mix with the shallower perched water. It is interesting to note that Boggy Creek (further to the south - see Figure 7) occurs over one of these resistive units, and that a similar zone (although less intense) occurs south of Blue Gum Road. On Figure 8 it is also interesting to note the shallow resistive zone associated with the tree line. Which came first - the trees or the resistive zone? Does the resistive zone reflect the presence of less saline ground water? In this scenario NanoTEM can provide a pinpoint location for groundtruthing this feature, and may in fact help reveal the influence of trees on groundwater movement and salinity.

Acid-mine Drainage

Background: Acid-mine drainage in older mine sites around the country poses a significant threat as a potential groundwater pollution source that can extend for many kilometres beyond the mine sites. It is believed these fluids are more conductive than surrounding geology, and therefore may be detectable with shallow sounding EM techniques.

The study area is an acid-mine drainage site in central New South Wales . At this site 3500 t of copper were recovered from strongly pyritic ore in the early 1900's. A heap leach plant operated intermittently from the 1950's to the 1970's and recovered a further 500 t of copper (Craig Roberts, Personal Comm., 2001).

This field area slopes slightly to the south and east (suggesting that the groundwater gradient is similar). The topography on each line is generally gentle, although on most of the lines, at the edge of the waste dump, the topography can drop nearly 10 m vertically over a distance of 20 m horizontally.

In an effort to track drainage from the mine site, TEM measurements were made along five east-west lines across the site.

NanoTEM Results and Discussion: Two figures are shown here to summarise the results from the five lines of data. Figure 9 shows the results of the inversion of line 53210N. This line is located over the waste dump, extending past their western margin. Note the shallow conductive zone at the west end of the line, apparently extending to depth. We have interpreted this as possible acid runoff. The survey line was extended to the west in an attempt to

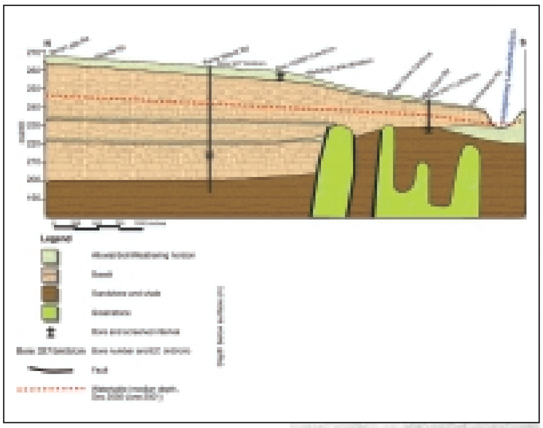
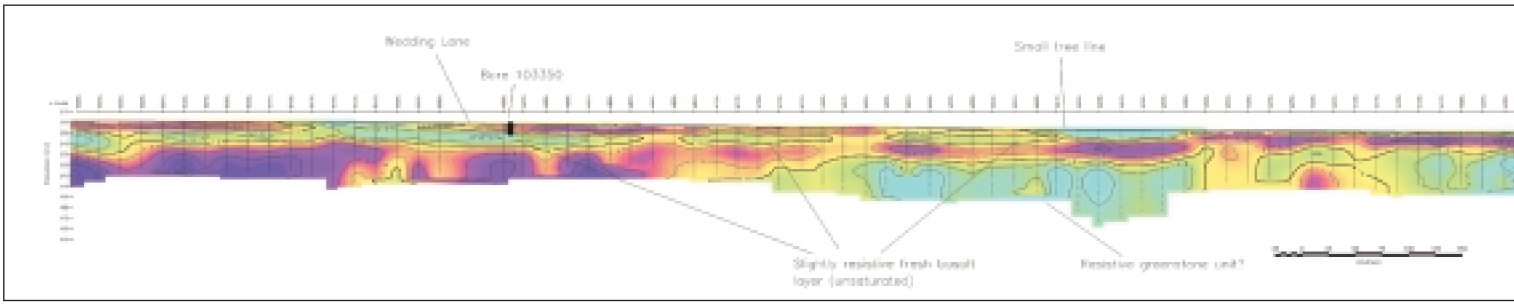


Fig. 6. Schematic interpretation of the Helen's Road transect in the Willaura catchment. This interpretation is based on information available before 2001 (Bennetts, 2001).



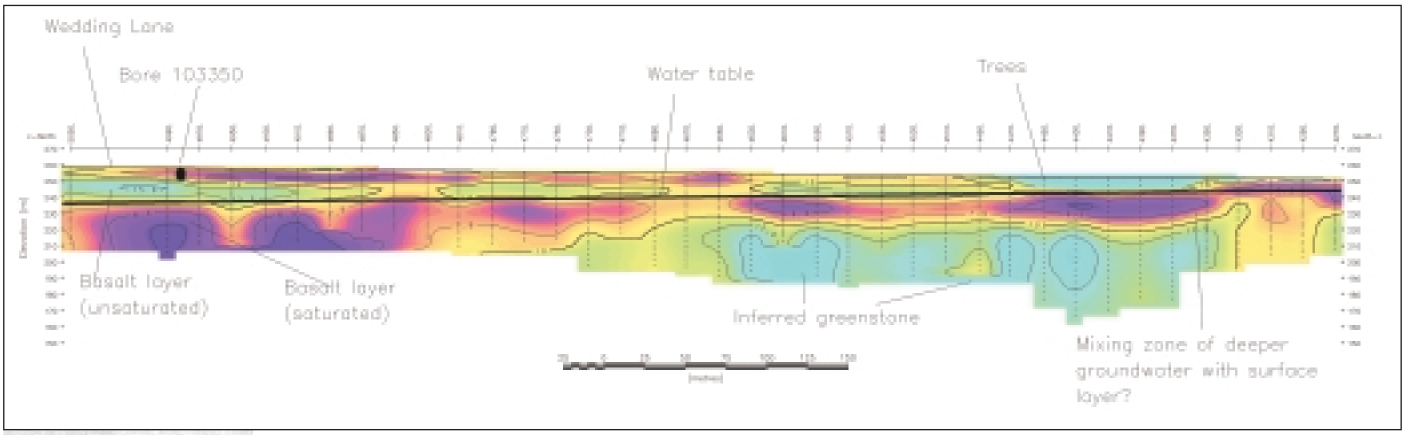


Fig. 7. (Top) Two-dimensional section for the top 100 m of ground along Helen's Road, Willaura Catchment. Resistivities vary from > 25 Ω.m to less than <1 Ω.m.

Fig. 8. (Above) Two-dimensional section along Helen's Road, looking with more detail from Wedding Lane to south of the small tree line. The more resistive (greenstone?) unit appears to be acting as a barrier to deeper water flow in the area, forcing this deeper water toward the surface to mix with the shallower perched water.

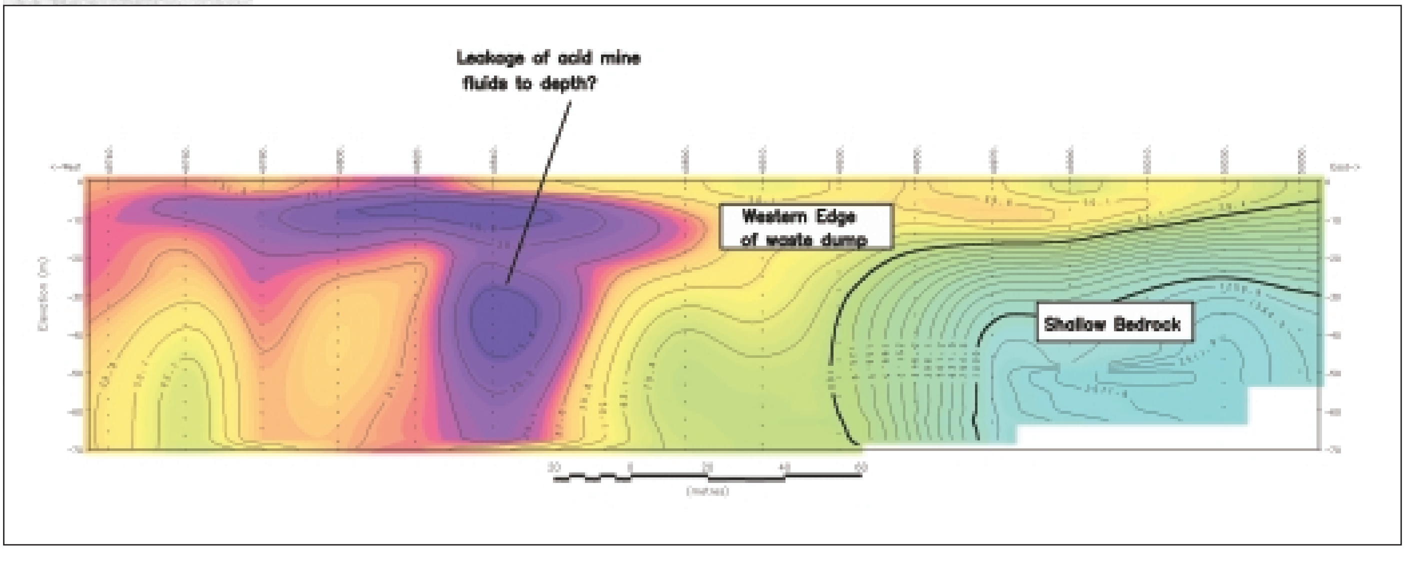
quantify the extent of the runoff, and as contours appear to close, it suggests that leakage is limited.

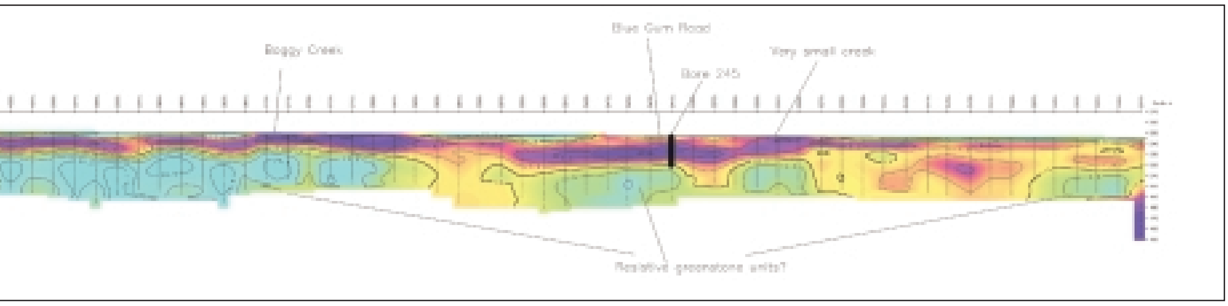
Figure 10 is a contoured "depth slice" created from the inversions of all of the lines. This plot was "cut" at a depth of 30 m. Again, it is worth noting the more conductive zone extending to the west and south of the waste dump. We have interpreted this as acid-mine runoff. A quick summary of the five lines follows.

- Line 53410N was located ~70 m north of the waste dump. It is believed that this is minimally affected by runoff from the mine.
- Line 53350N was located over the waste dump, extending west past the western margin of the dump.
- Line 53290N was located over the waste dump, extending west past their western margin. Note that an old mineshaft has disrupted readings at station 49930E.
- Line 53210N is presented in this paper in Figure 9.
- Line 53110N is located just to the south of the waste dump, running approximately through a small drainage along the south edge of the waste dump.

We believe that the thin, near-surface conductive zone extending over the west end of the four southern lines, at a depth of 10-25 m is partially related to the acid-mine drainage from this old mine site. Local topography suggests

Fig. 9. (Below) Two-dimensional section along line 53210N. This line starts in the waste dump, extending to the west well past their western margin. Note the shallow conductive zone at the west end of the line, apparently extending to depth - possible acid-mine runoff. This line was extended to the west in an attempt to quantify the extent of the runoff. The contours appear to close, suggesting that the lateral extent is limited.





that groundwater movement in this area should increase to the south and west. This correlates well with the apparent thickening of the inferred acid-mine drainage layer in the NanoTEM cross-sections also to the south and west. It is interesting to note that on Line 53110N at station 49830E and Line 53210N at station 49840E this conductive zone appears to extend to depth, suggesting a possible accumulation of the acid waters along fractured rock.

Conclusions

Fast sampling, fast turn-off EM methods (such as NanoTEM) are highly effective at mapping small-scale (<100 m) changes in shallow conductivity. Studies suggest that these changes are related to changes in lithology and fluid composition. Surveys can be carried out rapidly, about 500 m in just over three hours at 20 m station spacing.

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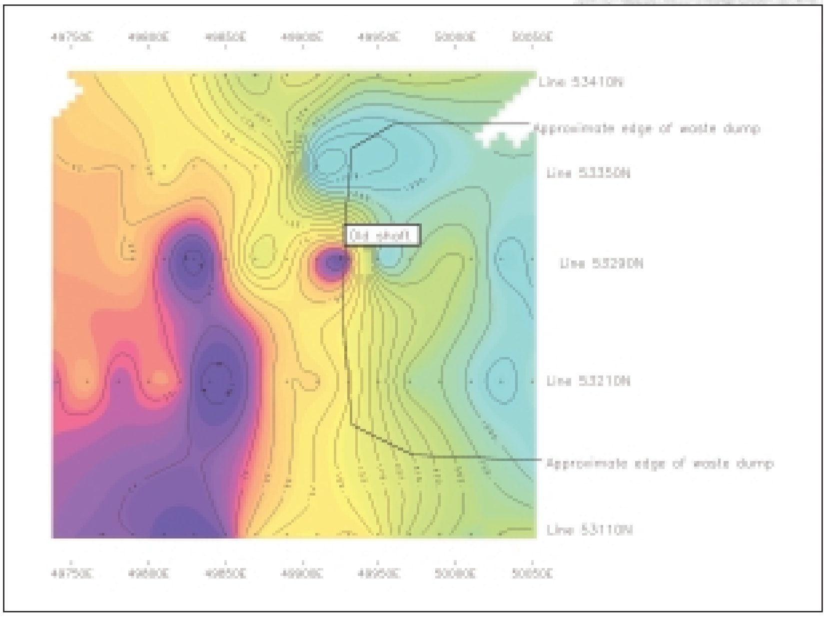

Fig. 10. (Right) Contoured "depth slice" at 30 m depth created from the one-dimensional inverted sections of all five lines. Note the more conductive zone extending to the west and south of the waste dump possibly acid-mine runoff.