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GROUND PENETRATING RADAR – THE PROS AND CONS OF IDENTIFYING PHYSICAL FEATURES IN ALLUVIAL SOILS

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Abstract

Predicting soil drainage and zones where denitrification occurs requires knowledge of the spatially varying subsurface features, for example depth to gravel, soil thickness and water table fluctuations. Soil physical characteristics and depth to gravel play a vital role in water and nutrient movement through the soil profile. Although surface topography may give an indication of overland flow, the flow of water and nutrients through the soil profile may alter extensively from that at the surface.

Gathering data relating to the subsurface is becoming essential to understand flow pathways, potential zones of denitrification and nutrient loss. Identifying physical features that contribute to soil water flow pathways has not only been time consuming and labour intensive but is also limited to the immediate area of observation. The use of ground penetrating radar (GPR), a proximal sensing method can minimise the use of time-consuming methods such as pit excavations for identifying subsurface factors, enabling extrapolation of these observations to a wider area.

This research integrated the use of GPR, ground-truthing and a geographical information system (GIS) software package to produce a 2-D view of the change in gravel contours and soil thickness over two 0.4 ha plots at Dairy 1 farm, Massey University, Palmerston North. Additionally, water table depth was assessed between spring (September) and summer (February). On inspection of radargrams, gravel contours were more easily detected when soil moisture conditions were drier, likewise textural changes were more easily detected in these drier conditions. Water table depth fluctuated from 4 m to 5 m depth between spring and summer respectively, but was only identified in some radargram images. Change in soil moisture conditions between spring and summer had an overall effect on the quality of images collected, likewise antenna radio frequencies presented varying degrees of clarity in the radargram images.

GPR has the ability to efficiently identify soil physical characteristics, depth to gravel and water table under appropriate conditions. Therefore, the use of GPR has the potential to assist in future research projects that aim to understand nutrient movement and zones of potential denitrification in alluvial soils.

Introduction

Identifying physical features that contribute to soil water flow pathways has not only been time consuming and labour intensive, for example, pit excavations, installation of piezometers and observation wells, but is also limited to the immediate area of observation (Doolittle et al., 2006). Proximal sensing methods provide a more rapid and intensive data collection of subsurface factors over a larger area and without significant ground disturbance (Adamchuk et al., 2004).

A proximal sensing method used to survey the subsurface to greater depths is ground penetrating radar (GPR). This geophysical tool provides an approach for detecting rapidly and non-invasively the subsurface factors such as soil horizons, the depth to gravels, or the depth to groundwater (Adamchuk et al., 2004). Delineating features that affect soil drainage pathways with the assistance of GPR could effectively result in improved irrigation and farming practices, thereby minimising the loss of water and nutrients via subsurface drainage. However, GPR does not perform equally in all soils, and therefore its effective application may be limited to certain soil types. For instance, soils with high electrical conductivity such as some clays (smectite and vermiculite), will attenuate the radar signal more strongly than non-clay, dry granular materials such as sand or gravel (Doolittle & Collins, 1995).

The purpose of this research is to test the ability of GPR to map subsurface physical features thought to control soil water flow pathways in alluvial soils. The ability to efficiently map subsurface features using a non-invasive technique would be highly desirable to those who need to understand the movement of nutrients and water through alluvial soils.

Materials and Methods

Study Site

Figure 1: Site 1 – Pasture Plot: Rangitikei silt loam over sand & Manawatu fine sandy loam. Site 2 – Arable Plot: Manawatu silt loam over sand & Manawatu sandy loam

The study area is located on the upper alluvial terraces of Massey Dairy 1 farm adjacent to the Manawatu River, approximately 2 km east of Palmerston North. Two 0.4 ha (40 x 100 m) study sites were used; a pasture plot (1) (24.8 – 23.9 m above sea level (ASL)) and an arable plot (2) (26.7 – 25.2 m ASL) (Fig 1). Soil types include the Manawatu fine sandy loam and Rangitikei silt loam over sand present at the pasture plot and Manawatu silt loam over sand and Manawatu sandy loam present at the arable plot.

Introduction to the Experiment

The study site consisted of two plots, arable and pasture. These plots were chosen to show a comparison between land use and soil type. Within both plots, GPR grid surveys and associated soil measurements were conducted. These soil measurements focused on soil physical attributes that affected soil water flow and were used to ground truth GPR imagery (radargrams). Surveys were conducted in September 2015 (increased soil moisture conditions and higher water table) over both plots and February 2016 (decreased soil moisture conditions and a lower water table) on the pasture plot only as access to the arable plot was limited due to an established cropping rotation.

Grid Setup

Seventy-two GPR lines were collected at each plot to form a grid pattern (black lines in Fig 2). This totalled 21 long lines (100 m length) and 51 short lines (40 m length). Lines were labelled according to distance along the short or long GPR lines axes. For example, Long_12 refers to a long 100 m GPR line, located 12 m along the Long GPR Lines axis and Short_92 refers to a short 40 m GPR line, located 92 m along the Short GPR line axis (blue lines in Fig 2).

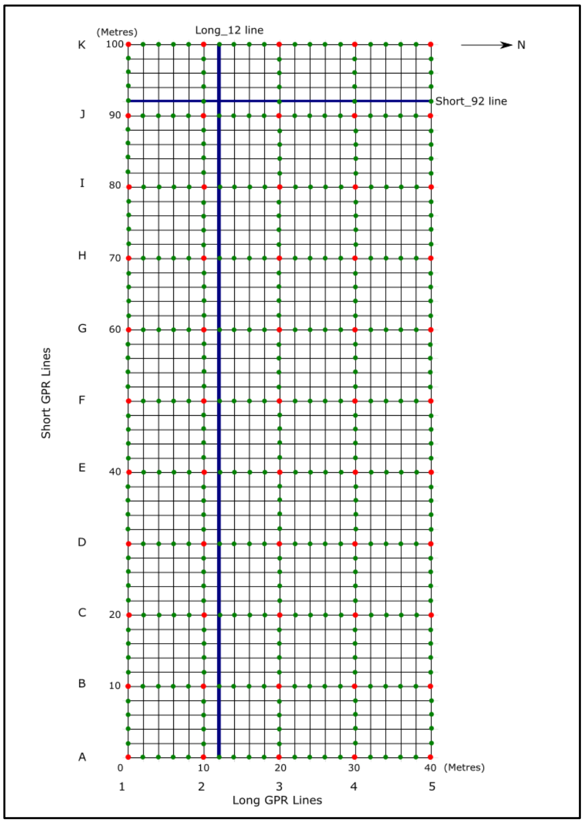

Figure 2: Grid setup, 10 m markers (red dots), 2 m markers (green dots), GPS points were recorded at each red marker. GPR lines (black lines) are spaced every 2 m. Example GPR names of two lines (blue).

Ground Penetrating Radar

The GPR system used for this research was a Sensors & Software Pulse EKKO Pro ground penetrating radar. In September 2015, the 200 MHz antennas were used to collect line data over both the arable and pasture plots, and repeated in February 2016 for the pasture plot. It was not possible to resurvey the arable plot in February, due to land use restrictions. While the results of the 200 MHz antennas surveys in September 2015 provided good resolution information of the top few metres of soil, it was decided that 100 MHz antennas would be required for imaging the base of the soils (i.e. the soil-gravel interface) and the water table. These were then used in conjunction with the 200 MHz antennas in the February 2016 survey.

Displaying Grid Data in EKKO Project 4

EKKO Project 4 software was used to display individual radargrams. Converting the two-way travel time of the radar waves to a corresponding depth involved an estimation of the average radar wave velocities. The velocity between different radargrams was very similar, and as a result an average velocity of 0.09 m/ns was chosen and applied to all of the data. The February 100 MHz surveys were adjusted to 0.1m/ns to show an accurate depth scale when soil moisture conditions were drier as this resulted in a faster radar wave velocity penetrating the subsurface.

Soil and Piezometer Measurements

Physical soil measurements were made to ground truth the GPR data and assess the ability of the GPR to detect differences in various soil properties. Thirteen sites (five from arable plot and eight from pasture plot) were chosen for soil coring (i.e. recovery of soil for logging and measurement) and 29 sites (21 from arable plot and eight from pasture plot) were selected for soil augering (Fig 3) to establish the depth to the gravel layer below the soils. The sites for soil coring and augering were chosen to intercept strong reflections and anomalies noted in the radargram images. Soil sample locations were numbered 1 through 13 for ease of reference, where cores 1 – 5 and 6 -13 were located in the arable and pasture plot respectively (Fig 3). Measurements of water table depth were recorded at the pasture plot with an electronic dip-meter. An average depth to the water table was recorded from four piezometers. Measurements were collected after each GPR survey performed at the pasture plot (i.e. 30 September 2015, 26 November 2015 and 24 February 2016), to help to identify the water table in the radargrams.

Surface and Subsurface Contour and Soil Thickness

To capture the spatial variation of surface elevation and the depth to the gravel surface, geographic coordinate points including elevation, were used to produce raster's using a Natural Neighbour interpolation method in the geographic information system (GIS) ArcMap 10. By subtracting the elevation of the gravel layer from the ground surface elevation using Raster Math, a soil thickness raster was created.

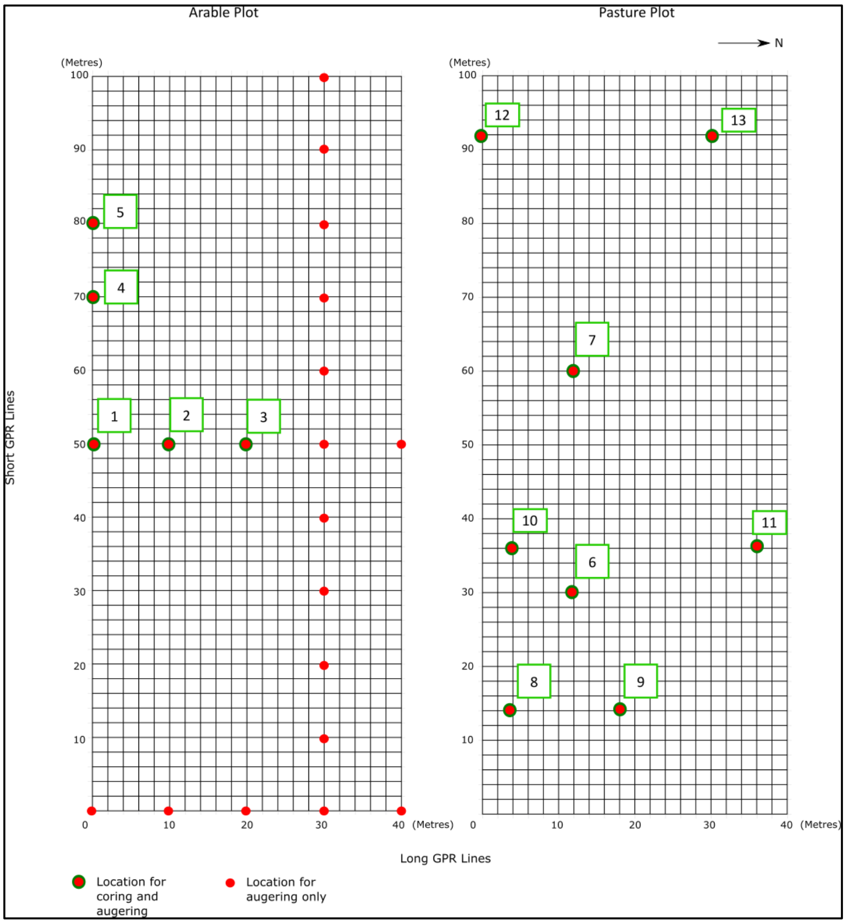

Figure 3: Soil core and auger locations across the two plots.

Results

The Relationships of Radargrams to Field Measurements

Soil Physical Properties

Across all radargrams, an interface or contrasting boundary layer (i.e. a sharp change in moisture content due to a change in grain size or wetting front positioned across a homogenous layer) appears as a continuous line of two to three bands (triple banding) (Doolittle et al., 2006; Shih & Doolittle, 1984). This is due to the oscillations in the radar signal. These bands limit the ability of GPR to detect shallow or closely spaced interfaces when using radar frequencies < 250 MHz, like that used for this research. The thickness of the bands are directly related to the dielectric constant of the material and are inversely related to the antenna frequency (i.e. a high dielectric constant and low frequency antennas will produce a thick band) (Shih & Doolittle, 1984). Finer features tend to be concealed when thicker layers of high dielectric constant material (i.e. wet sand) produce a strong reflective signal. Thus, distinguishing finer features using 200 MHz or 100 MHz antennas is limited by the strength of the radar signal and the reflective nature of the material being surveyed. Although the depth profile of a radargram can give an overall picture of the subsurface, depth should not be relied on for accurate interpretation of closely spaced interfaces.

Figure 4 shows the internal structure of the arable Long 0 line. There are three identifiable layers that have been ground-truthed with soil cores and auger samples. The simple to complex layered patterns at the eastern end of the radargram are interpreted as medium sand. Towards the western end of the radargram, the reflection patterns become wavy and are interpreted as very coarse silt and medium sand. Decreasing signal strength from 1.5 m to 2 m depth suggests attenuation due to the presence of gravel. The depth to gravel was identified along this attenuated zone with auger samples (green stars) and generally follow the reflection configuration.

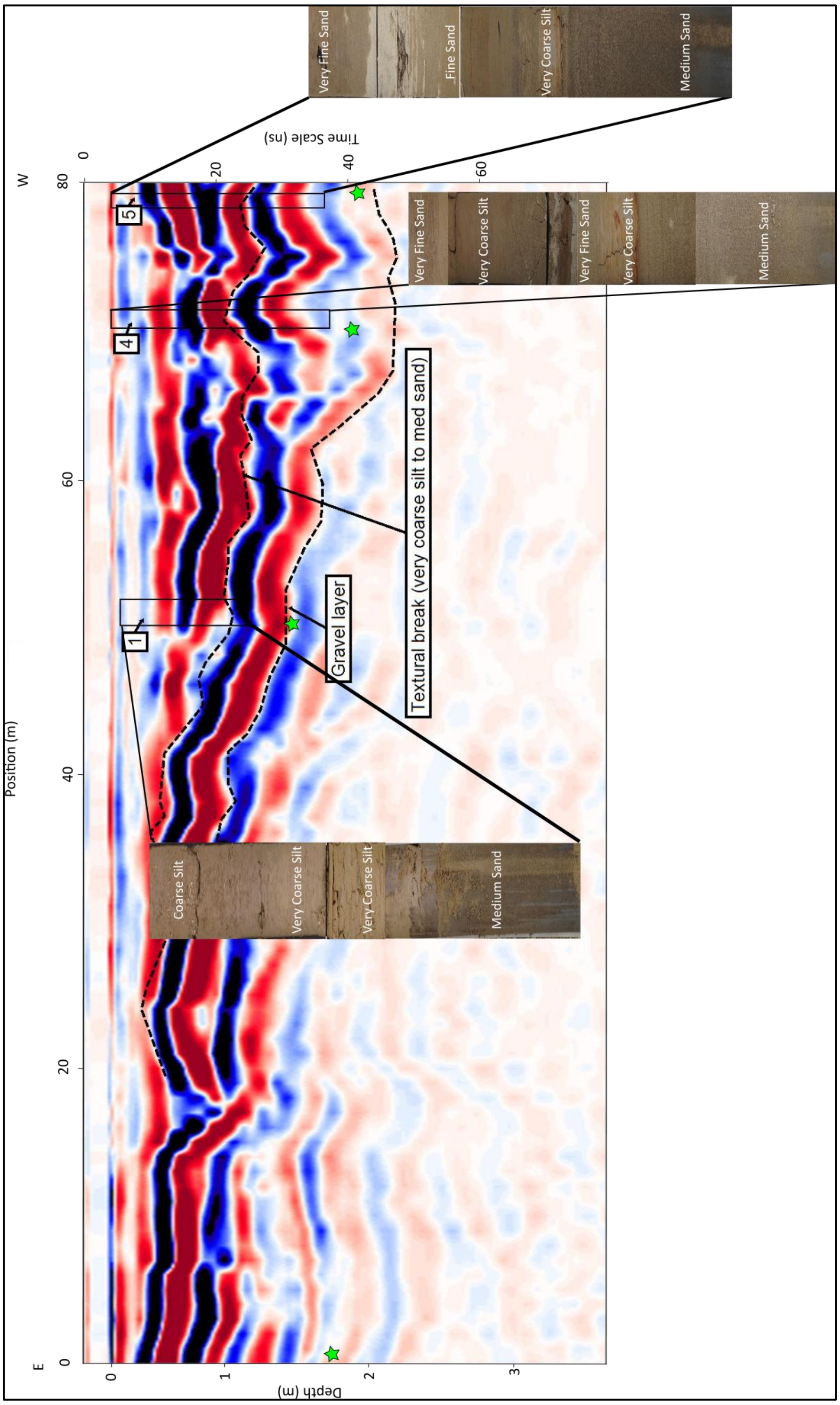

Figure 4: Interpreted 200 MHz radargram of arable Long 0 line, with soil Cores 1, 4 and 5. Auger samples assessed depth to gravel (green stars).

Depth to Gravel

Radargrams from the arable plot generally correlated well with the ground-truthed measurements of augered gravel depths (e.g. Short 50, Fig 5) where depth to gravel was identified as a triple band feature. However, gravel features in the pasture plot were not as obvious (e.g. Long 12, Fig 6). Although there are some reflections, a distinguished triple band feature is not seen across the majority of the radargrams. Other subsurface features, such as finer silt layers or a thick sand band may impact on the identification of a defined gravel layer.

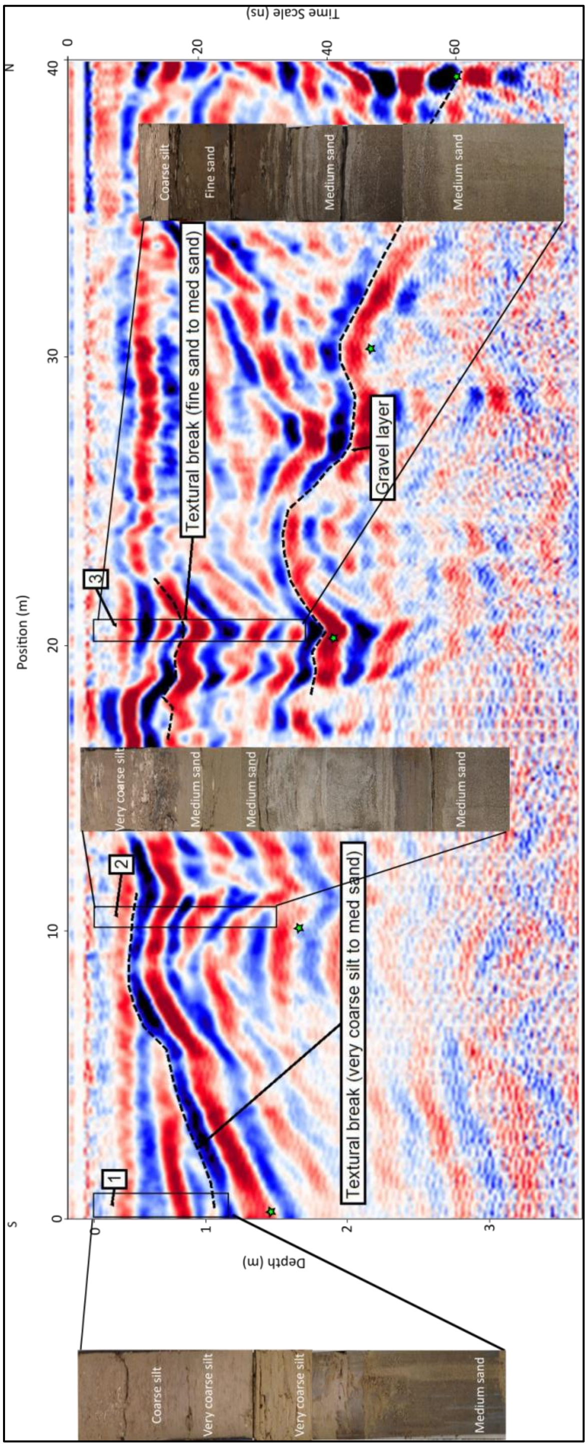

Figure 5: Interpreted radargram of the arable Short 50 line, with soil Cores 1, 2 and 3. Auger samples assessed depth to gravel (green stars).

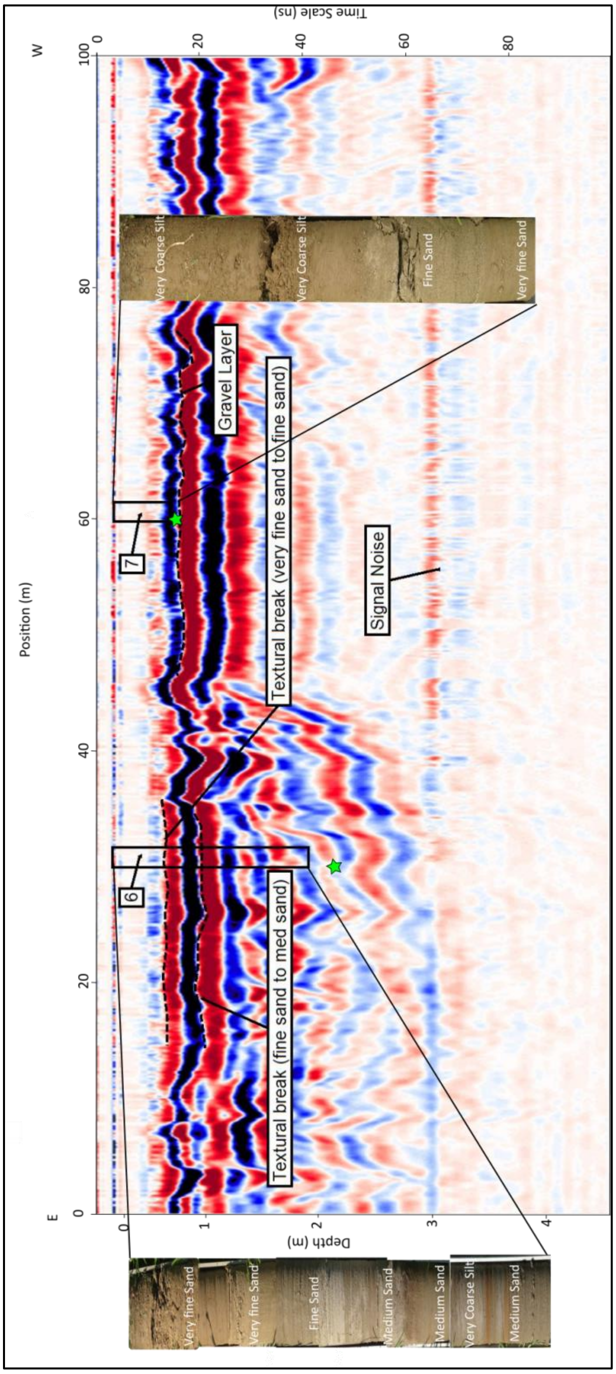

Figure 6: Interpreted 200 MHz radargram of the pasture plot Long 12 line, with soil Cores 6 and 7. Depth to gravel (green stars).

Depth to Groundwater

To identify features (e.g. water table) at depths beyond the top of the gravels, the 100 MHz antennas were deployed over the pasture plot. The longer wavelength allowed a deeper penetration of the subsurface to depths up to 182 ns (two-way travel time) or ~9.6 m (v= 0.09 m/ns). A radargram of the pasture plot Long 12 line (Fig 7) has detected the water table at 5 m depth. This is indicated by the triple band feature and has been correlated with the piezometer measurements taken in conjunction with the February surveys. Hyperbolic reflectors are indicative of gravel present at the water table depth.

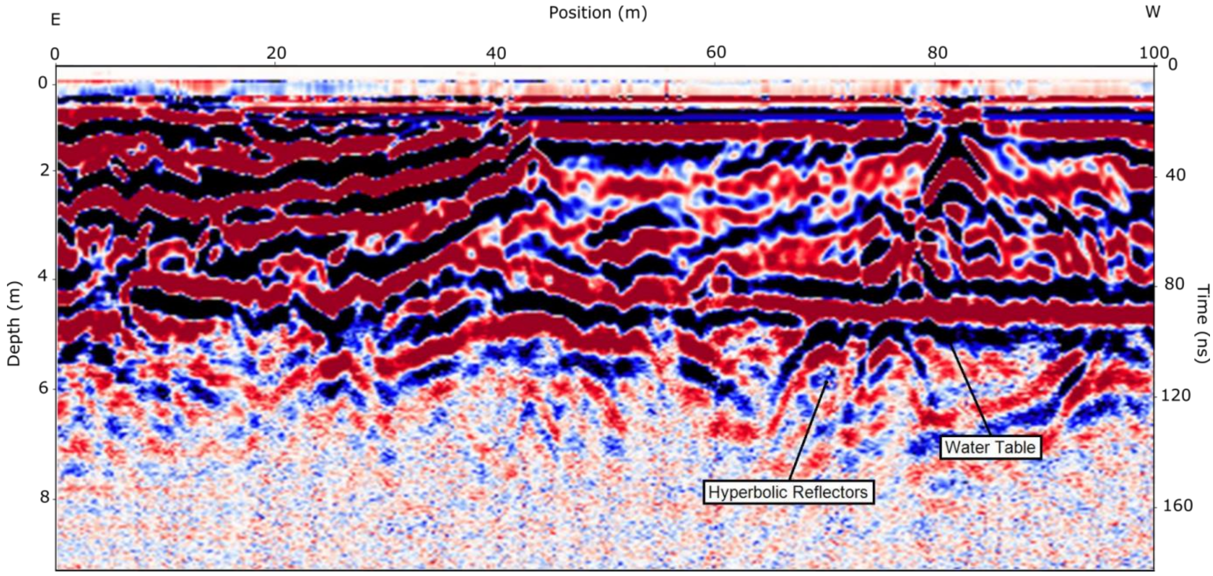

Figure 7: Interpretation of the 100 MHz survey of the pasture plot Long 12 line showing the groundwater reflector (triple band) within the Manawatu fine sandy loam (60-100 m) and a distorted reflection within the Rangitikei silt loam over sand (0-60 m).

Surface and Subsurface Contour and Soil Thickness

Using GPR, depth to gravel and associated soil thickness were determined from interpretation of radargrams from comparison with soil augering data. Data was extrapolated in ArcGIS to produce the associated images in Figure 8.

In relation to the arable plot, unlike the surface contour, gravel contour has the highest elevation points located along the north-western and south-eastern sides of the plot and the lowest elevation points are at the north-eastern and south-western sides of the plot, suggesting that this relates to the location of an infilled pool. The soil thickness map (Fig 9, C, arable plot), calculated as the difference between the gravel surface elevation and the ground surface elevation, highlights a deeper soil present over the infilled pool at the north-eastern end of the plot. Within the pasture plot (Fig 9, C, pasture plot), soil thickness increases from west to east at a depth of 0.6 m to 2.8 m. This area could be representative of an infilled channel.

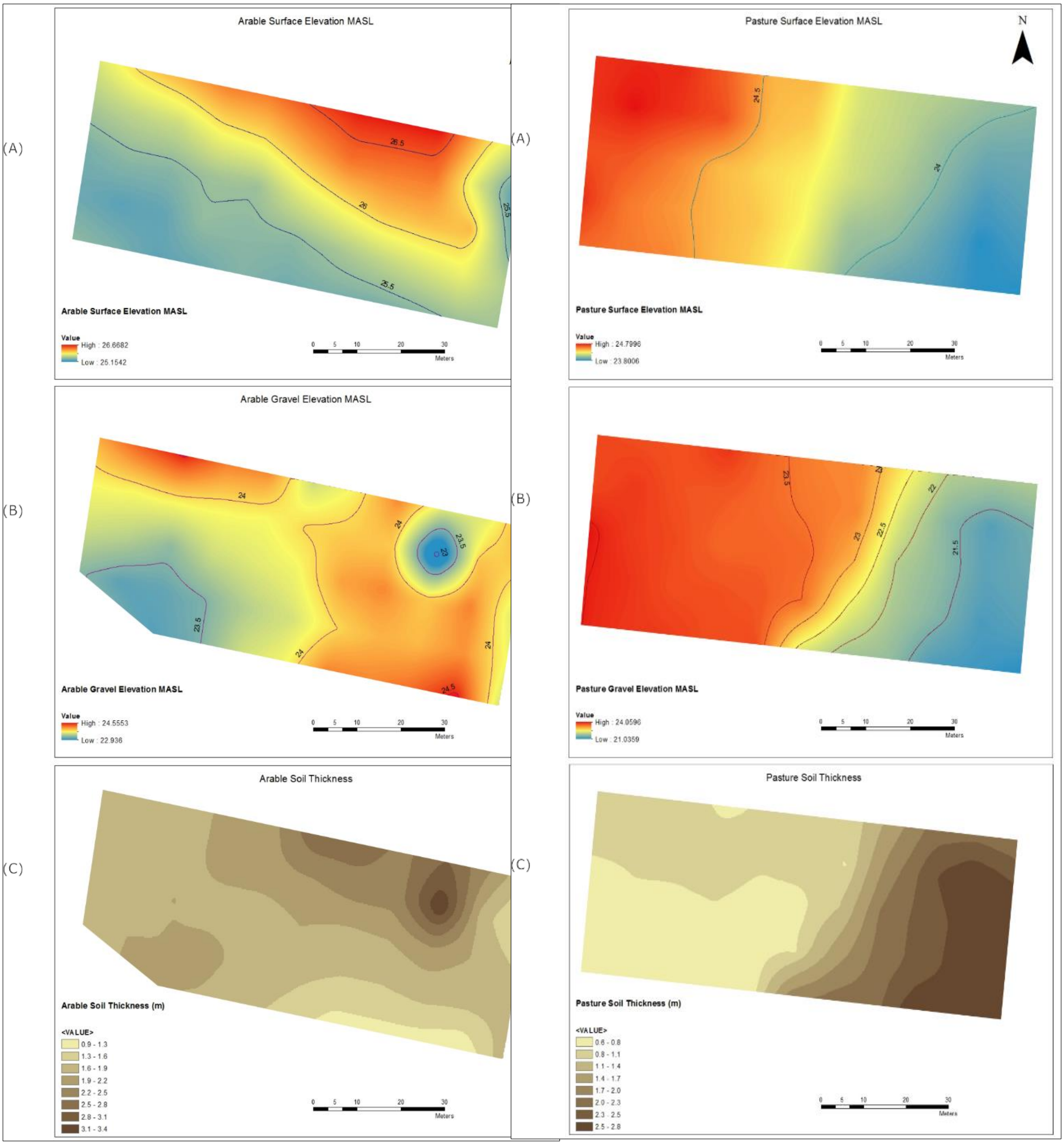

Figure 8: Interpretation of **(A) s**urface elevation, **(B)** gravel elevation and **(C)** soil thickness across the Arable and Pasture plots.

Discussion and Conclusion

The results from this research indicate that: i) textural and soil moisture changes within an alluvial soil profile can be detected when GPR surveying with 200 MHz unshielded antennas from ~0.5 m to ~3 m depth; ii) identifying features that control flow pathways (i.e. layering inclinations, depth to gravel and water table) can be identified using 100 MHz and 200 MHz antennas where groundwater depth is ~5 m.

Although the use of 200 MHz antennas proved useful in determining textural changes within the soil profile, and additionally highlighted layering stratigraphy of soils and depth to gravel, finer layering features (i.e. thin silt banding) have been concealed by the strong radar reflectors. The stronger signals identified on a radargram relate to features with a high electrical conductivity. These strong signals then conceal other finer features (Doolittle et al., 2006; Shih & Doolittle, 1984). Shifting to a higher frequency with a narrower bandwidth (e.g. >300MHz), waiting for drier soil conditions, or processing the signal through higher filtration settings in post processing could eliminate this noise (Doolittle et al., 2006; Shih & Doolittle, 1984).

The identification of gravel becomes more obvious in the drier season suggesting surveying in drier soil conditions can assist with identifying soil – gravel interfaces. This finding is in accord with Zhang et al. (2014) where identifying soil-bedrock interfaces and weathered-unweathered rock interfaces in shallow soils was more suited to drier soil conditions.

Surface and subsurface gravel contour and soil thickness maps from the arable and pasture plot gave a good visual representation of variation in ground surface and gravel topography, and the areas throughout both plots where soil thickness varied (Fig 8).

When using the 100 MHz antennas, the water table was represented by a clear three band feature that became distorted when soil type changed from the Manawatu fine sandy loam to the Rangitikei silt loam over sand (Fig 7). The finer layering features within the Rangitikei silt loam over sand prevented a clear representation of the water table. This observation is supported by Doolittle et al. (2006) who states that closely spaced horizons can cause difficulty in identifying water tables.

In summary, this research demonstrates the ability of GPR when using 100 MHz and 200 MHz antennas to acquire subsurface data for alluvial soils to depths >5 m. The use of GPR data coupled with minimal soil textural and piezometer data to identify soil stratigraphy and potential flow pathways has proved useful when assessing a large area. The use of GPR to identify flow pathways and water tables would provide valuable information to land users to identify potential flow pathways or zones where there is an increased risk of nutrients and pathogens that could enter groundwater via preferential flow. On the other hand, GPR could assist with identification of potential zones where denitrification occurs (reduced conditions). This could also assist with matching land use intensity to a vadose zones capacity to convert NO^{-}_{3} to dinitrogen (N_2) gas.

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