GPR for large-scale estimation of groundwater recharge distribution

Investigation of the shallow hydrogeology at the central Gnangara Mound, Perth

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***Abstract*— The Gnangara Mound, north of Perth, Western Australia, has been investigated using Ground-Penetrating Radar (GPR). Several hundred line-kilometers of GPR of common offset data have been acquired over an area of approximately 800 km^2. The acquisition of these datatsets was performed at two different center frequencies (50 and 250 MHz) in order to better resolve the complexity of the hydrogeological targets of interest which are water retentive layers found above the water table. These layers impede the recharge of the surficial aquifer and may have important impact on local ecosystems but also on the management of the ground water resource. The data presented here-in demonstrate the successful imaging of the regional water table and of these water retentive layers. For the first time, these data provide insight into the spatial distribution and the continuity of these water retentive layers and provide important information to be included in the flow modeling of the ground water in this region of the world.**

Keywords-large-scale GPR; water-retention; groundwater-recharge

I. Introduction

Understanding the near-surface geology particular of the vadose zone is of great importance for sustainable water management. This information is required to develop accurate hydrogeological recharge models on which water usage and allocation decision are based. Water-retentive layers above the water table can impede the vertical migration of water to the aquifer. Those impermeable layers close to the surface can create swamps and lakes and make water available for local ecosystems leading to high evapotranspiration rates. A large portion of precipitation to these areas does not contribute significantly to the recharge of the aquifers and thus is not available for human use. GPR has the ability to detect these layers and the potential to quantify their water content [1].

A. Hydrogeology of the surficial aquifers

The Gnangara Mound is located north of Perth and spans an area of more than 2000 km^2 (Figure 1). Different aquifers within the mound are Perth's most important groundwater source. The growing demand from an increasing population and smaller precipitation makes its management increasingly challenging. In order to manage this resource sustainably, the Department of Water of Western Australia and the Water

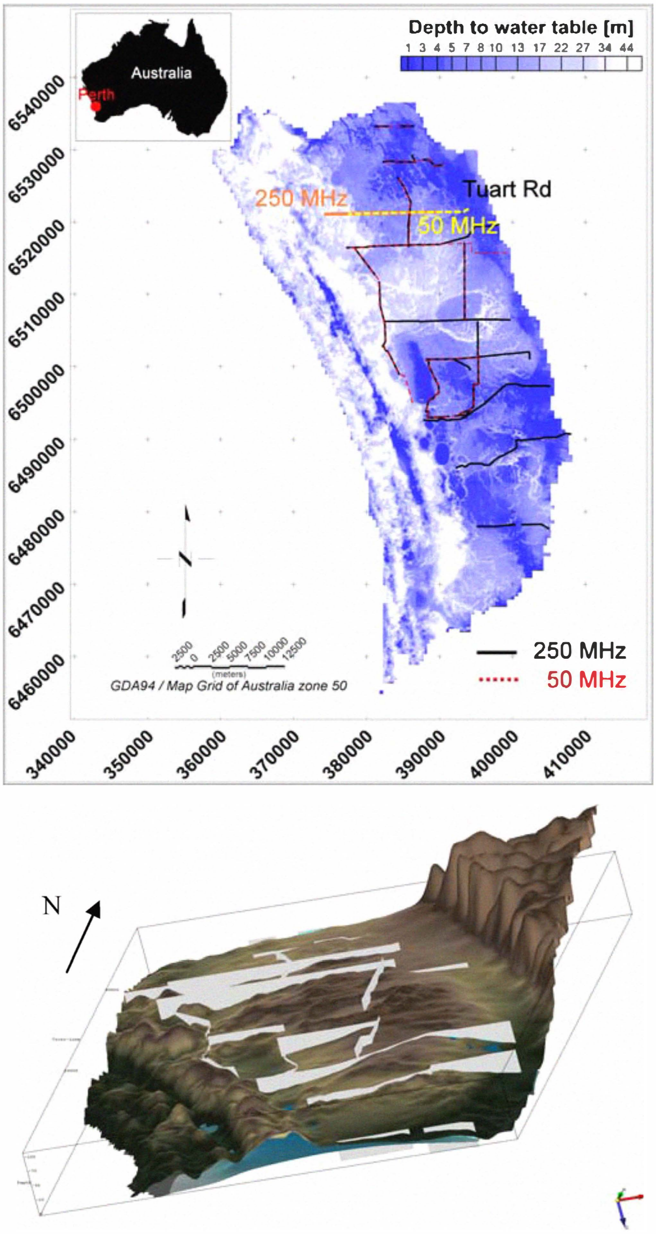

Figure 1. Depth to water table map (upper) and OpendTect image (lower) with imported GPR-sections, DEM and water table from the Gnangara Mound, the size of the OpendTect cube is 35 x 56 km and is displayed with vertical exaggeration (~100x)

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Corporation developed a groundwater model called Perth Regional Aquifer Modelling System (PRAMS) [2]. The vertical flux model is at the core of PRAMS [3] and estimates the aquifer recharge for a range of land and climate variables. The climate of south-western Australia is Mediterranean with long very dry and warm summers and short mild winters. Average annual rainfall has decline from ca. 850 mm/ to less than 750 mm/a in the last decade.

The regional superficial water table mounds in the center of the Gnangara Mound and discharges in the east and south to the swan river system, to the Gingin Brook and Moore River in the north and to the Indian Ocean in the west. The Gnangara Mound is composed of three main aquifers; (1) the Superficial the (2) Leederville and the (3) Yaragadee [4]. The top-soils and formations of the superficial aquifer consist of concretionary and loose eolian calcareous sand in the west (Tamala Limestone forming Spearwood and Quindalup dunes), leached quartz sand in the center (Bassendean Sand and dune system) and silty clay and sand deposits in the east (Guildford Clay) [5]. The Guildford Clay interfingers westwards with the Bassendean Sands as silty, sandy clays or loam. These formations were deposited while sea-level changes lead to depositional environments of shallow marine, estuarine and river and lake sedimentation and successive dune development. Layers of fine materials will therefore be interbedded with sands and form an inhomogeneous formation. Main lakes and wetlands can be found along the boundary between Bassendean and Spearwood dunes in the west, and in the east associated with Guildford Clay.

Concretionary layers of limonite-cemented sand called "coffee rock" developed at the water-air interface throughout the central area of the mound within the Bassendean sands. These layers vary in thickness and degree of cementation. Also several levels of "coffee rock" have been reported [6]. Water content measurements and Neutron-logs indicate that these layers contain elevated water contents and could therefore be water-retentive or form perching layers following heavy rain.

II. METHODS

A. Data acquisition

Preliminary tests to determine the effectiveness of GPR in order to image hydrogeological targets in this environment revealed that the best results could be obtained by using two different frequencies, namely 50 and 250 MHz. A local contractor performed measurements using a monostatic system (MALA ProEx system) to which a 50 MHz unshielded antenna and a 250 MHz shielded antenna were coupled in turns. The antenna was dragged behind a Quad-bike at approximately 5 km/h and at common offset distances of 0.3 m for the 250 MHz antenna and 4.5 m for the 50 MHz antenna. A comparison between manually pulled and vehicle aided measurements gave, that most features were captured with the faster measurements at similar spatial trace increments (1 – 10 cm). As one may expect, the data quality varied according to surface conditions encountered along the surveyed lines. The GPR surveys were acquired along existing tracks which were either paved with a consolidated clayey matrix and limestone fragments or unpaved on natural sand. While the latter showed strong and clear GPR signals from deeper reflectors, the paved surface attenuated and disturbed the electromagnetic waves, probably due to significant clay content and associated high conductivity and scattering effects from the limestone cobbles. The data collected with the unshielded antenna were severly affected in regions where important diffractors, such as large pine trees and electrical distribution lines were encountered.

In order to map the regional water table accurately it is critical to integrate accurate spatial information with the data collected. Generally, global positioning systems (GPS) provide sufficient accuracy in the horizontal plane but often lack in vertical accuracy. The observed deterioration of positional data in the vertical plane can cause mis-ties between horizons and may impart topography to reflectors which is the result of improper topography corrections. A real-time kinematic GPS system (Thales ZMAX) was used to acquire topographical information accurate to better than 10 cm. While RTK systems provide greater accuracy, it comes at a cost of increased complexity. The contractors who collected the GPS data along with the GPR encountered problems which rendered the data positional information, especially in the vertical plane, of little use. In order to obtain the topographical information, we had to extract the elevation data from a digital surface model DSM obtained from an airborne Light Detection And Ranging LIDAR survey which meanwhile became available and greatly improved the topographic correction.

B. Data processing

The data were processed using ReflexW and Promax. The processing flows used are summarized in Figure 2. The large volume of data (up to 2 Gb per profile), requires a structured methodological approach. In order to make it possible to handle these datasets using current computing resources, spatial averaging and down sampling was required. From the previous 10 cm (30 cm) trace distance, 1 m of traces was summarized in one trace. While the down sampled sections inherently contain less information, they retained sufficient information for us to achieve our objectives which were to map the regional water table and the water retentive layers found amongst the vadose zone. In addition to making the datasets more manageable, the spatial averaging reduced the amount of diffractions observed on the original data which often obscured the reflections of interest. An energy decay gain function was used to enhance weak reflections from deeper reflectors. It was also expected to correct for geometrical spreading and conductive losses while preserving relative amplitudes. The topography of the sand-dunes over which the data were acquired was corrected by using a common topographic correction including a zero-offset correction from first-arrival picks of airwave that is critical for the 50 MHz data measured at 4.5 m offset. For the topographic correction, time $t_{tc,\,i}$ was added at the beginning of the trace i according to the equation $t_{tc,\,i} = (h_{max}-h_i)/v_1$, where h_{max} and h_i are the elevation of the highest point and at trace i, respectively, and v_1 the propagation velocity of the first layer for the unsaturated zone. We chose v_1 as 0.13 m/ns which represents a mean value obtained from walk-away CMP experiments, vertical radar profiling and diffraction hyperbolas. The topographic corrections done using this velocity estimate for the vadose zone flattened the horizon which was picked at the water table along the central part of the profile. This is an indication that our velocity estimate is

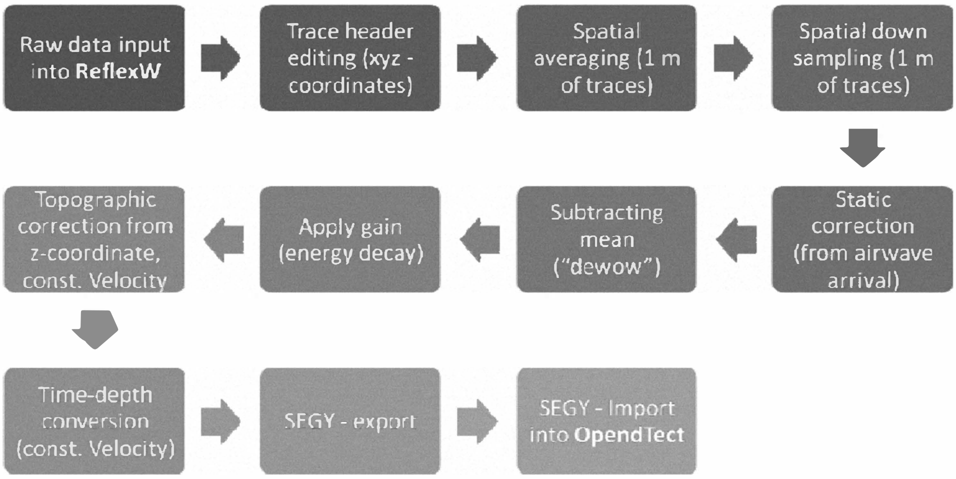

Figure 2. General processing flow for the large-scale GPR dataset

appropriate for this area as this reflector should not exhibit major topographic changes. This velocity estimate for the vadose zone was used to perform time to depth conversions along all profiles in order to import the multiple datasets into a seismic 3D-visualization and interpretation package called OpendTect[1] (Figure 1, lower). The spatial information and model for the regional water table surface were also loaded into this 3D-visualization package together with geospatial information such as the DEM and regional water table surfaces.

III. Results

Figure 3 shows the GPR sections acquired along 'Tuart Rd' at 250 and 50 MHz. Both sections, approximately 16 km in length, span the calcareous Spearwood dunes and Tamala limestone formation in the west, and the Bassendean Sand and dunes in the central part of the Gnangara mound. The most eastern part of the 50 MHz profile reaches the Guildford clay formation. Note that the 250 MHz section starts and ends further to the west.

The western part of the profiles (0 to 6 km) shows very weak GPR responses from depth. The water table is dipping westwards but is not detected in the GPR data beneath the Spearwood sand dunes. The radar response from these dunes is very weak in the 50 MHz data and does not show any structure from main reflectors in the 250 MHz, where diffraction hyperbolae occur sporadically at the near surface. The 50 MHz section is strongly influenced by diffractions from pine trees at the surface as well as power line reflections. However, there is some structure noticeable. The absence or weakness of reflections from depth could coincide with an abnormal EM-wave attenuation. Possible loss mechanisms could be due to mineral coating around the less leached sand grains ([4], [7]), or near-surface effects in combination with much smaller impedance contrasts. Further investigation has to be undertaken in order to explain the lack of response in this section of the profile. Conclusions regarding water-retentive properties from reflective layers in this area are not possible at this stage.

Progressing east towards the boundary of the Spearwood dunes and the Bassendean Sand and dune system in the west at kilometer six in Figure 3, we observe the water table gradually moving towards surface. This is in good agreement with borehole information and modeling results from PRAMS. The position of the water table reflection was generally within 1 - 2 m of the expected location from the minimum regional water table surface from 2005 (see Figure 4). The reflected energy from the water table varies in amplitude between absent and quite strong. Reflections from layers found above the water table, which are of interest in these surveys, appear, at this scale, as patchy and inhomogeneous reflectors but retain some internal structure (see Figure 4). The sparse lithological information from the available boreholes in this area suggest that these reflections reveal a material change from fine to medium grained sand, to silty, sandy clay or clayey sands or loam. The composition and the relative high reflectivity suggest higher water contents associated with these layers. The topography of these sediments is irregular. We can observe that some of these reflectors dip underneath the water table or conversely come very close to the surface. The spatial characteristics of these layers have important implications for groundwater migration through the soil and its availability for plant consumption. Profiles perpendicular to 'Tuart Rd' suggest that the GPR fingerprint of this formation is similar throughout this area. Lithological borehole logs also describe "coffee rock" beside the clayey sections within the unsaturated zone in this part of the profile. The clayey sediments of the Guildford formation interfinger with the Bassendean formation according to Davidson [4]. The clayey parts could resemble his description, although it is unclear if reflections observed belong to the loams of the Guildford formation or the "coffee rock" within the Bassendean sands. Some characteristics of the observed reflectors lead to the conclusion that they may not originate from clays or loams because of their low loss characteristics evident from the response of the water table underneath. It is however possible to observe distinct variations in the strength of the water table reflection (i.e. Figure 4, 9020 m – 9050 m and 9220 m – 9280 m versus 8900 m – 9000 m). In Figure 4 we can observe distinct reflections from at least three material transitions above the water table. Note that this section has not been spatially averaged and a Kirchhoff

[1] www.opendtect.org

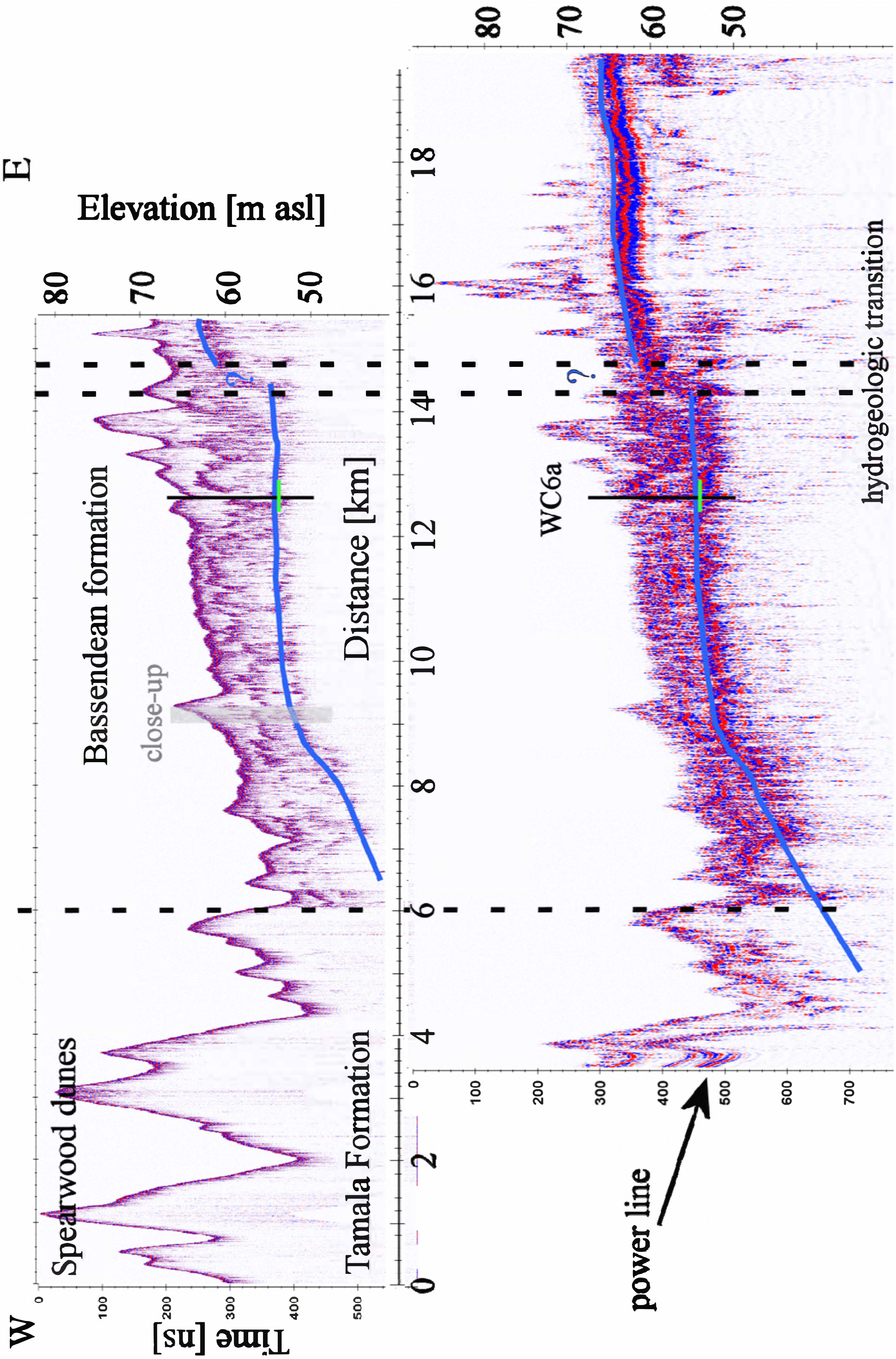

Figure 3. 250 MHz (upper) and 50 MHz (lower) GPR sections from 'Tuart Rd', the elevation axis was calculated from two-way traveltime with a constant velocity of 0.13 m/ns (vadose zone), the borehole 'WC6a' puts the water table (green mark) from January 2008 at the expected position, GPR measurements were performed in November at a water table high, the annual water table variations follow a sinusoidal course with a magnitude of up to 1 m with maxima and minima in November and April, respectively

migration with a constant velocity of 0.13 m/ns over a summation window of 80 traces has been performed which collapsed most diffractions. At this stage it is not clear if the two parallel reflections belong to 2 separate layers, or one thick one with impedance contrasts at its top and bottom.

The eastern part of 'Tuart Rd' exhibits a different GPR response. At kilometer twelve along the profile, the signal strength improves markedly. This improvement is due to a transition from a limestone-clay pavement to loose sand. The general picture with reflectors above the water-table reflection does not change yet. The GPR response changes between kilometer 14 and 14.5 notedly. The reflection that is believed to originate from the water table becomes the first reflector and has a continuous and much stronger appearance. The strength of this reflector is emphasized by the generation of a multiple reflection seen in the 50 MHz data. The depth of the reflection attributed to the water table changes abruptly from 55 m above sea level (asl) to 65 m asl within an interval that spans approximately 500 m. While some of this abrupt change may be attributed to the crudeness of our elevation information in this area and the chosen constant velocity model of the vadose zone (0.13 m/ns vs 0.15 m/ns in dry sand → 1.5 m offset for reflection event at 150 ns) we propose that there exists a transition in lithology and thus in hydrogeological properties. The implications of this abrupt transition in local water table depth, even qualified by velocity variations, suggest a larger hydraulic gradient in this area. Another explanation for this observation is a perched water table formed above the underlying Guildford Clay. Wetlands and multilevel boreholes at the east end of the displayed profile in Figure 3 support this theory.

The profiles in Figure 3 provide an example of the additional resolution that can be obtained by using higher frequencies (250 MHz versus 50 MHz). Features which are large in terms of wavelengths, such as the water table, are easy to identify at lower frequencies. There is also a reduction in the potential for near surface clutter generated by small diffractors and the depth of penetration is improved due to comparatively low losses. In order to characterize layers that are smaller, in terms of wavelength, the improved resolution afforded by the 250 MHz above the water table is significant. In dry and sandy environments such as the site in this study, the choice of higher frequencies is warranted if the targeted structures are found above the water table where the sediments exhibit high resistivities and low water saturations leading to low loss properties and high propagation velocities. Here, the resolution is more critical due to the comparable long wavelength even at higher frequencies due to low permittivity. The wavelength for electromagnetic wave frequencies of 50, 250 and 500 MHz in this study are approx. 2.6 m, 0.52 m and 0.26 m respectively, for a propagation velocity of 0.13 m/ns (the consequential approximate relative permittivity of 5.33 is consistent with published values for unsaturated sand, e.g. [1] and references therein).

While the higher frequency of 250 MHz enhances the vertical resolution, it lacks in depth of penetration. Structures underneath the water-table are hardly imaged, whereas they appear as clear reflection from the measurements with the lower frequency. Also the reflection originating at the water table is continuous and stronger in the 50 MHz data. Furthermore, in the Spearwood dunes (west of the dashed line in Figure 3) the 50 MHz shows some weak reflections at shallow depth which are completely absent in the 250 MHz profile. This is an indication for frequency dependent attenuation that could be caused by iron oxide coating of the less leached sands found at the Spearwood dune sands and associated elevated water content ([7] and references therein).

IV. CONCLUSIONS

The large scale GPR study presented in this work has shown that GPR is well suited for the investigation of hydrogeologic relevant near surface characteristics over large areas. It is possible to examine soil heterogeneity and water table variations in dry and sandy environments and help develop a better understanding of how hydrogeological features may affect the recharge of aquifers. Difficulties encountered in this study have included dead zones where there is a very weak or even a lack of response from the subsurface (e.g. within the Spearwood dunes). It is expected that these can be attributed in part to near-surface conditions

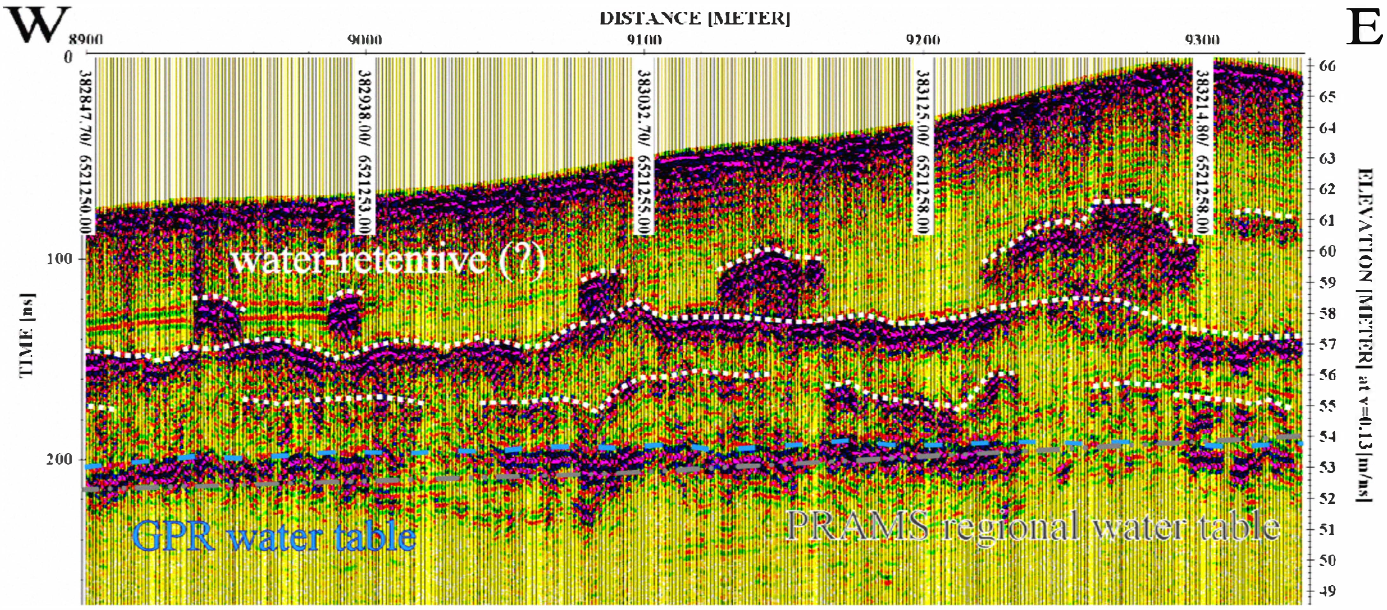

Figure 4. Close-up of 250 MHz section along Tuart Rd within the Bassendean Sands (see gray shaded area in Figure 3) showing the variation of water-retentive layers above the regional water-table, note the varying strength of signal response from the water table, the gray dash-dotted line represents the 2005 minimum regional water table modeled within PRAMS, for a higher resolution this image has not been downsampled and a Kirchhoff migration was performed, a trace at every ~1 m is displayed as colored wiggle

(scattering, conductive losses) along clayey limestone tracks in pine tree plantations and iron oxide coating around sand grains and associated higher water content leading to frequency dependent dielectric losses. Additional difficulties arose because of the sparcity of reliable topographical information whilst the data was originally acquired. Despite these challenges, we have demonstrated the successeful detection of strong reflectors above the regional water-table which are attributed to water retentive layers found amongst the sediments of a superficial aquifer over portions of our transects. The composition of the layers found above the water table are interpreted to be precipitation horizons, "coffee rock" and/or clayey deposits. These layers are expected to be water-retentive based on neutron-neutron logs and soil moisture measurements. The 50 MHz data demonstrated to be well suited to detect the water table and structures underneath, while the 250 MHz offered higher resolution of the target layers above. Hence, this study can lead to important insights into the water-recharge mechanisms and the spatial distribution of water retentive layers at a regional scale.

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