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GPR imaging of a sand dune aquifer: A case study in the niayes ecoregion of Tanma, Senegal

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ABSTRACT

Local agriculture in Senegal is dependent on truck farming, which is concentrated in the narrow interdunal zone of peat deposits, called "niayes". The viability of the niayes significantly depends on the sand dune aquifer, as a consequence of recent over-pumping. In the present paper, we discuss the ability of GPR to locate the water table, in a highly vegetated interdunal area which includes peat fields, as well as internal dips, which were shown to be complex. Three profiles determined in the interdunal zone have been associated with several boreholes. Analysis of the radargrams clearly shows that 1) the presence of dense vegetation is not a penalising factor; 2) phase inversion in the measured signal could be useful in distinguishing between the presence of a significant water contrast, and that of a strong stratigraphic reflector; 3) in sand dunes, the electromagnetic contrast resulting from a wetting front is likely to be of the same order as that of the water table. The outcome of this study may provide clues to the characterisation and management of water resources in niayes area.

1. Introduction

The viability of truck farms (or market gardening) situated in the Senegalese niayes depends on fresh water sand dune aquifers. The niayes (a name which originates from the vernacular for "palm tree") are groundwater-fed interdunal fens, often filled with peat at the bottom. Over-exploitation of these aquifers, which now suffer from salinisation and nitrate pollution problems (Sall & Vanclooster, 2009), together with a poor understanding of their spatial distribution, are the main issues preventing optimal water resource management. It is therefore crucial for farmers to be able to locate the water table, especially in the interdunes where most wells are located.

Ground Penetrating Radar (GPR) investigations have been undertaken world-wide, in an effort to reveal the internal structure of sand dunes, as well as water tables. (Bristow et al., 1996, 2000; Doolittle et al., 2006; Harari, 1996; Livingstone et al., 2007; Van Overmeeren, 1998). There is a good abundance of recent literature dealing with the theory of GPR and with sedimentary applications, and the publications of Annan(2005), Bristow and Jol(2003), Daniels(2004), Neal(2004) are particularly relevant. Most of these surveys have been performed in desert-like areas where there is negligible vegetation. In the Senegalese niayes, however, the very dense vegetation (gallery forest) located in the interdune zone limits accessibility, and is also found to be a potential source of numerous diffraction effects, from trees and roots. In addition, correct interpretation of the water table depth could suffer from uncertainties caused by the wetting front, or, although less likely, by internal bedding structures (i.e. preferential flow path) (Bristow et al., 2000).

Our objective in the present case study was to image the water table, despite the aforementioned severe vegetation problems. Our site is located close to the Tanma lake, which is currently completely drained. Very dense vegetation on the dune zone bordering the drained lake clearly indicates the proximity of the water table, which is only a few meters-deep. We discuss three profiles which were acquired with 100 MHz and 50 MHz antennas, using a PE100 PulseEkko GPR (Sensor and Software). Discrete traces were recorded at small step intervals of 25 cm (100 MHz) and 50 cm (50 MHz), in order 1) to achieve full-resolution imaging (Dogan et al., 2011; Grasmueck et al., 2005), and 2) because it was impossible to tow the antenna continuously through the vegetation, without interruption. The selected bandwidths allowed signal returns to be recorded from the top 15 m of soil. We also drilled five boreholes along the transects, in order to detect the shallow water-table and check our profile interpretations.

Since the profiles were acquired along a steep dip, the dips and curvatures of the reflectors associated with the water table and the stratigraphy required correction by means of topographic migration. This major processing step was carried out using Reflexw-Win

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software (Sandmeier, 2004). The radargram analysis provided not only a high resolution description of the internal structure of the interdunal zone, but also a means to distinguish between a significant water contrast, and a strong stratigraphic reflector, at all occurrences of a marked phase inversion.

2. Area description

The niayes ecoregion is located along the Senegalese north coast, between the cities of Dakar and Saint-Louis. We surveyed along the western border of the Tanma Lake, located at the approximate geographical coordinates of: 17.089°W and 14.931°N (Fig. 1). The landscape consists of three geomorphological units (Fig. 1): 1) active and semi-fixed sand dunes north of the study area; 2) the Tanma Lake depression towards the south; and 3) a narrow dune zone on which a gallery forest has developed (with relic species from the Guinean and Sudanese regions). The third unit separates the other two. Unit 1 is consists mainly of quartz sand, which is quite homogeneous, with no calcareous content, and has a characteristic size close to 250 μm and a porosity close to 33%. Unit 3 is basically identical to unit 1, but is also covered by near-surface, thin, sparse layers of organic matter. Unit 2 is a peaty soil made up from organic matter, small quantities of clay, and a low sand fraction.

The dune side geomorphology is characterised by steep slopes (locally surface topography gradient ~50%) on which the agricultural activities consist exclusively of wine palm and fruit trees. At the interdune location, a thin, shallow, fresh water perched aquifer is located above the saline water. Twenty years ago, the contact between fresh and salt water was located at a depth of almost 10 m, (Lézine & Chateauneuf, 1991). Presently, the interface between fresh and salt water, as well as the freshwater thickness, are not accurately defined. The reader can refer to a raw description relating to the hydrogeological context of Tanma lake in Fall(1986) and Raynal (1963a).

As the strip of dense vegetation is a few tens of meters wide (Fig. 2), and makes surveying and drilling difficult, only three straight profiles, corresponding to the red segments shown in Fig. 1, and five associated boreholes, were investigated.

3. GPR survey and processing

The profiles A, B and C, are 150, 80 and 90 m-long, respectively (Fig. 1). These profiles cut across the first and third geomorphological units described above, and were oriented in a direction that was imposed by the high vegetation density in the dune zone. The basic processing techniques for all radargrams included the use of a highpass filter (dewow), and a spatial moving average over three traces in order to smooth the images.

We corrected for horizon dip in the distance vs. echotime recording, through the use of a topographic migration process. Standard migration includes static elevation corrections, followed by conventional migration algorithms, usually based on 2DKirchhoff migration. However, this usually leads to poor depth reflector positioning whenever there is a significant surface topography gradient (>10%). (Berkhout, 1984) and (Schneider, 1978) are excellent references for the mathematical treatment of the Kirchhoff method, whereas its application is clearly described by Yilmaz (1987), pp 269. Such time-to-depth migration would have required mapping of the 2D velocity distribution, which in our case could not be extracted from hyperbolae adaptation (because too few of these were visible in the radargrams), or the use of continuous, time-

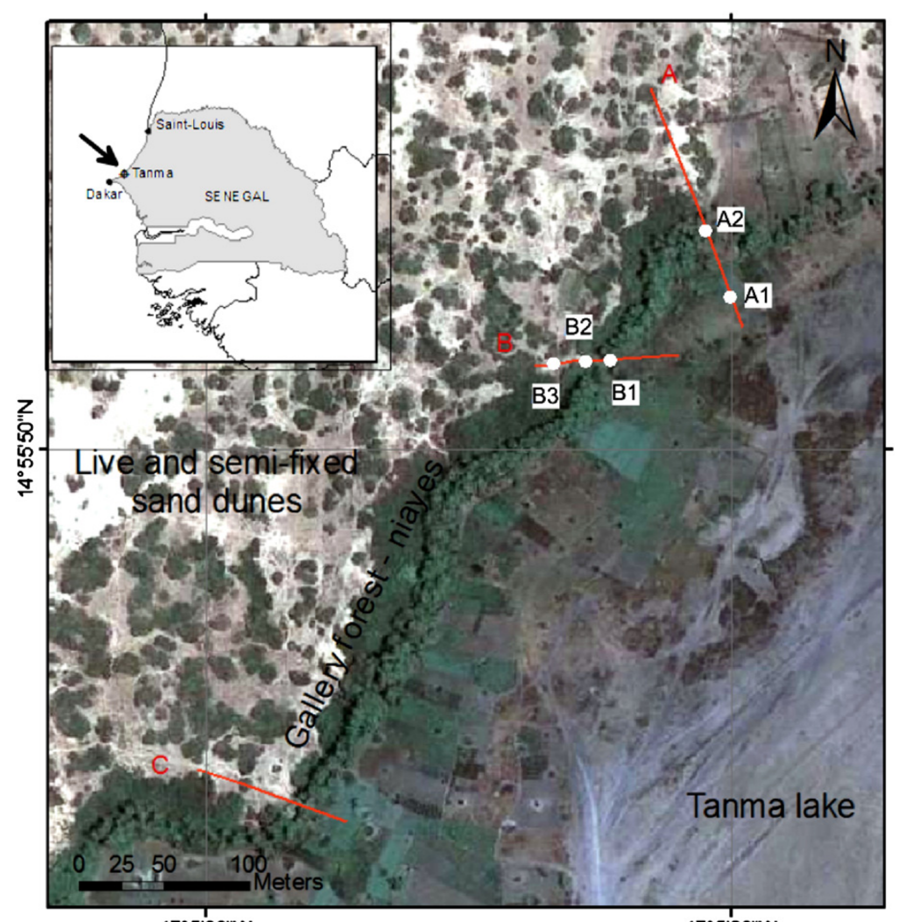

Fig. 1. Aerial photograph of the studied area (Google Earth images, Tanma lake). Location of the GPR profiles (labelled A to C, in red) and the boreholes(labelled A1 to B3, in white).

Fig. 2. Photograph of the lateral dune vegetation (foreground) and truck farm exploitation (background).

consuming Common-Mid-Point (CMP) measurements. Consequently, as described by Lehmann & Green(2000), we used a topographic migration process associated with a constant velocity. Topographic migration is desirable when (1) the surface gradients exceed 10%; but requires (2) a velocity accuracy better than 20%; and (3) antenna coordinates known to an accuracy of better than 10% of the dominant wavelength. In the case of the present study, (1) and (3) are certainly verified. To verify item (2), we performed a single velocity analysis from a CMP (acquired in profile B at a distance of 75 m, Fig. 3). The CMP analysis procedure is a classical velocity stack for a range of velocities. When traces are stacked at the correct velocity (i.e. along the theoretical hyperbolae path), they constructively add together and produce strong amplitudes. In the present case, the amplitude peaks correspond to a velocity range of (Fall, 1986; Grasmueck et al., 2005; Harari, 1996; Lehmann & Green, 2000; Lézine & Chateauneuf, 1991; Livingstone et al., 2007) cm/ns, which indicates that the theoretically required accuracy is nearly respected. The migration was performed with Reflexw-Win software (Sandmeier, 2004), using a constant mean velocity of 13 cm/ns. Finally, we applied AGC (Automatic Gain Control) to enhance the amplitudes of the internal features associated with the main reflectors, in particular that of the potential water-table.

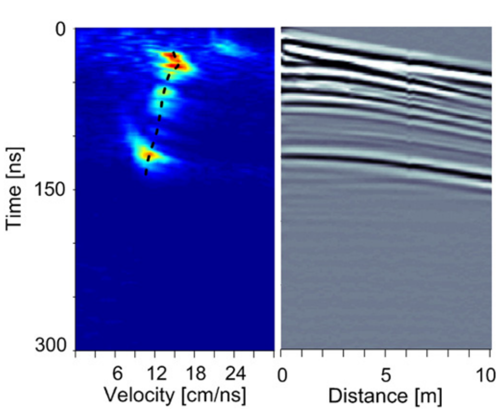

Fig. 3. CMP velocity analysis performed on profile B at 75 m. The shallow velocities vary between 11 cm/ns and 16 cm/ns. The mean velocity used for topographic migration is 13 cm/ns.

4. Results and discussion

Fig. 4 shows the migrated radargrams obtained at 50 MHz, for all profiles starting from Tanma lake and reaching the sand dune aquifer. In all profiles, a zone of high attenuation from 0 to 30 m corresponds to the accumulation of peaty and lacustrine deposits. In these zones the GPR signal vanishes completely, as shown in the B profile and the insets, in all full time range A profiles. The presumed water-table produced the major horizon, verified to be the water table at 60 m, 40 m and 30 m on profiles A, B and C, respectively. Below the

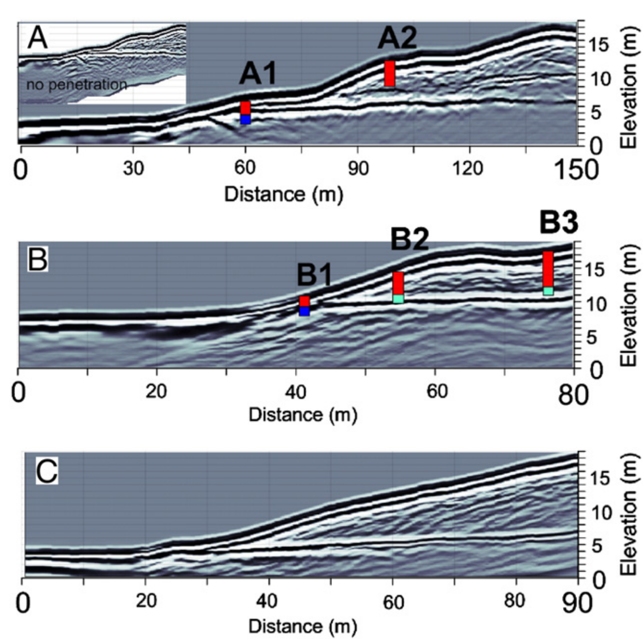

Fig. 4. Topographically migrated radargrams ($v = 13$ cm/ns) at 50 MHz, with superimposed log interpretation (dry sand in red, saturated sand in blue, wetting front in cyan). The inset shows the non-penetration area in radargrams A, with a full time window.

water table, the attenuation is more likely to be due to an increase in electrical conductivity, as well as to the strong contrast impedance associated with this interface. In theory (i.e. without dispersion and with a good signal-noise ratio), considering a 50 MHz-centered frequency and a step size of 50 cm (less than a quarter wavelength), the vertical "full"-resolution is ~1 m (λ/4 using a velocity of 13 cm/ns). This is still too coarse to allow any internal stratigraphic features to be accurately described, except for profile A.

Fig. 5 shows the corresponding radargrams measured at a 100 MHz, which improve the vertical resolution and the image of the internal structure of each sand dune. The 100 MHz radargrams reveal internal reflectors, which probably result from the lamination process occurring during the structural evolution of the dunes. Abrupt and contrasting differences in density and moisture content produce high amplitude reflections. In the nearby profiles A and B, not only is the water table clearly distinguishable, but also the geometry and structure of slip faces or bedding planes within the dune, as well as possible criss-cross layers, are visible. In profile C, a series of inclined reflections dip from right to left, like the foreslope, contrasting with the former profiles A and B, and suggesting that the dense vegetation prevents erosion. Clearly, a greater number of profiles, associated with several orientations measured at each location, would have been of considerable help invalidating this interpretation.

We drilled five boreholes along the profiles A and B (see locations and characteristics in Fig. 1 and Table 1. The maximum depth reached using a hand auger in desert sand hardly exceeds 6 m. The water-table in profile A was found at 3.3 m in borehole A1, and at a depth of *1 m* in profile B at borehole B1. In all other boreholes the water-table was not observed, but more likely wetting fronts, corresponding to strong variations in the moisture content, were found at depths of 5.5 m at borehole B3, and 4.5 m at borehole B2. The vertical resolution at 100 MHz is approximately 50 cm, as a result of the assumed mean velocity of 13 cm/ns; therefore, the proximity (less than a few decimeters) of the migrated subhorizontal reflectors in profiles A and B, to the water-table depth observed at the border of the sand dunes (boreholes A1 and B1), indicates that the horizon inherent to saturated sand could be readily followed. Despite the uncertainties resulting from the approximate constant velocity assumption, the water-table dips gently towards the dune's free surface (<6%), as a result of a continuous flow inducing a hydraulic gradient. In the present case, by considering the permeability of the sand dunes to be equal to $2e^{-4}cm/s$ (Ameta & Wayal, 2008), the slope analysis of profile C leads to an estimation of the permanent water flow rate, using Darcy's law, equal to $1.2e^{-7}m^3m^{-2}/s$.

Table 1
Characteristics of the five boreholes drilled along the GPR profiles A and B.

GPR profile	Borehole label	Depth (m)	Distance (m)
A	A1	4.2 Water table at 3.3 m	60
A	A2	4.0 No moisture variation	100
B	B1	2.5 Water table at 1 m	42
B	B2	5.5 Wetting front at 4.5 m	54
B	B3	6.5 Wetting front at 5.5 m	72

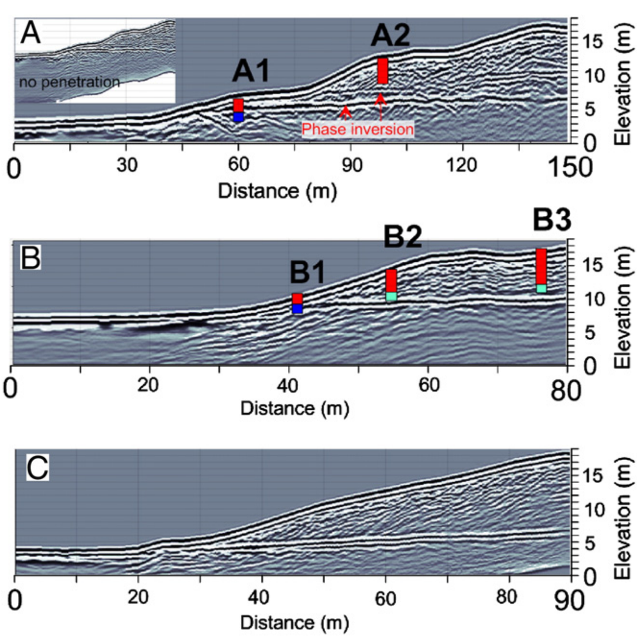

Fig. 5. Topographically migrated radargrams ($v = 13$ cm/ns) at 100 MHz, with superimposed log interpretation (dry sand in red, saturated sand in blue, wetting front in cyan). The inset shows the non-penetration zone as well as chaotic reflections due to the presence of very dense vegetation in radargrams A, with a full time window.

An interesting issue is that of the differences in depth between the upper water table position in the semi-fixed dune, and that of the peatland plain. Previous studies (Raynal, 1963b) indicate that the water table descends across the vegetation-covered side of the dune, towards the peatland, until the fresh and salt waters come into contact at the surface of Tanma lake. As no spring has been identified, the water table continuity associated with the steep slope of the dune could hardly be explained by classical surface tension behaviour due to pressure gradients. For this reason, the more likely explanation is that of a local perched aquifer, induced by the presence of a near-surface horizon in the peatland, which is less permeable than that of the sand dune.

Our interpretation of the main structural events, based on the radargrams, is shown in Fig. 6. The dominant interfaces are defined by dips in the range [30%−40%] towards the east and the southeast. In profile A, a marked stratigraphic change is more likely at a distance of 100 m, where two intermediate reflectors are visible (Fig. 6), and indicated by underlining with a red dashed line. This could possibly be found to be a single reflector only, if the continuity were extrapolated. A phase inversion of the wavelet associated with a sign inversion of the reflection coefficient (black-white-black horizon bounding, instead of white-black-white) is observed, and corresponds to a dielectric permittivity contrast, which is reversed when compared to the water table interface. This is the case, for example, when a reflection occurs from a less permeable and dryer material, characterised by a lower permittivity medium, situated below a wetter material. In general, such an observation is associated with a compaction, followed by an erosion process, which would suggest that the current dune has grown over an older, eroded fixed dune. Another physical explanation could be the presence of a thin, compact, dry horizon, which generates similar phase inversions; in such a case, this could provide evidence of crust mineralisation, possibly induced by oscillations in the groundwater level. However, additional GPR surveys in other directions, as well as deeper well-logs, are needed to validate any of the aforementioned geomorphological hypotheses.

The main uncertainty concerning the water-table depth is that associated with our velocity estimation, which we chose to be constant in the topographic migration process. We can only assume that the main reflectors, represented by the blue line in Fig. 6, correspond to the free surface of the water-table, because boreholes B3 and B2 do not reach the saturated zone, but only the wetting front. In addition, the AGC gain forced the continuity of this horizon. Nevertheless, the transition zone accuracy should not exceed a few decimeters because of the unconsolidated nature of sand, and its significant permeability.

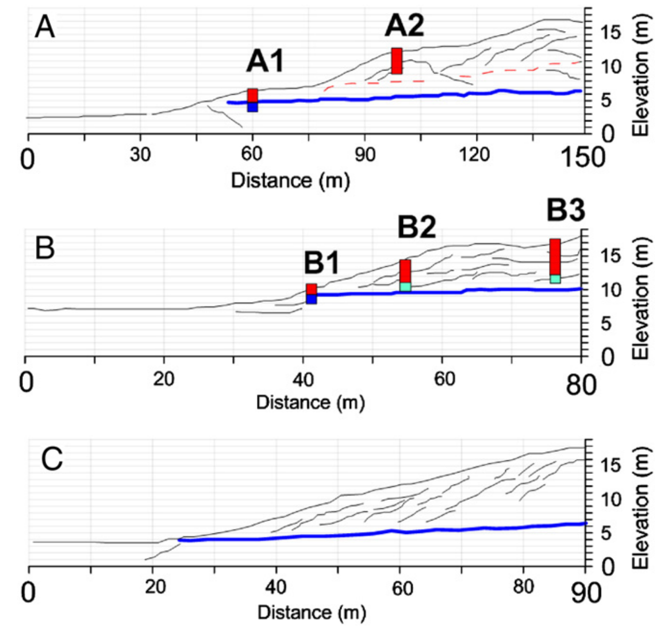

Fig. 6. Interpretation of the main internal features from all migrated profiles, together with a superimposed log interpretation (dry sand in red, saturated sand in blue, wetting front in cyan). In profile A, the red dashed line represents likely an older location of the current dune.

5. Conclusions

GPR imaging carried out in the Senegalese niayes ecoregion suggests that we have succeeded in locating the wetting front and the water-table, beneath a sand dune, and in imaging the internal structure of the sand dune. Nevertheless, the boreholes suggest that observed changes in soil moisture correspond only to a wetting front, because in most cases the water-table could not be reached. Improvements in sand dune drilling techniques are needed to achieve an accurate calibration. Considering the quality of the currently obtained discrete CMP, continuous CMP acquisition would provide more accurate 2D-mapping of the velocity distribution, which could significantly enhance the reliability of a 2D time-depth migration process.

In addition to the water table localisation, soil water content (SWC) mapping using GPR is of great interest for agronomists and farmers, for applications such as vegetation growth and for the management of efficient irrigation practices (Doolittle et al., 2010; Wijewardana and Galagedara, 2010). Usually, soil characterisation using GPR is performed in temperate areas, where agriculture is extensive, and is not commonly applied in arid areas. In the niayes, where intensive agriculture is carried out, similar studies could be proposed and should be perfectly suited to GPR SWC mapping, in addition to the fact that they provide high resolution imaging of subsurface horizons.

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