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GEOPHYSICAL CHARACTERISATION OF MEDITERRANEAN SOILS IN A TUNISIAN HILL RESERVOIR SYSTEM

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Introduction

Water scarcity, mainly because of low and erratic rainfall, always posed a recurrent problem for farmers and herders in the semiarid areas. In the last century, the growth of the global population has tremendously increased the pressure on water resources. To secure water supply and intensify agricultural production, water harvesting is traditionally used to solve the problems of varying rainfall rates and population densities.

Since the early 1990's, the Tunisian Government has undertaken the implementation of the "National Strategy of Surface Runoff Mobilisation" which aims at building numerous large dams, small earth dams and other works for irrigation and water table recharge (Albergel and Rejeb, 1997). More than 500 small earth-worked reservoirs, in North Africa called *hill reservoirs*, have already been constructed and the construction is still in progress.

They are mainly localised in the central part of the country, along the Atlas mountain range within the semiarid zone that receives from 250 to 500 mm of rainfall annually. Hill reservoirs show a high diversity in capacity, ranging from a few ten thousand cubic meters to several hundred thousand cubic meters, and watershed areas vary from a few hectares to several dozen square kilometres. Land use in the watershed consists of a varied proportion of forestry and agriculture (Albergel *et al.,* 1999). According to the Food and Agriculture Organisation (FAO, 1997), the area of irrigated land under water harvesting (FWH) in Tunisia amounts to 30,000 hectares. About 20 Million m^3 of water are annually harvested covering 4,250 ha (Prinz, 1999).

The functions assigned to these reservoirs are: to decrease soil loss caused by runoff, to reduce reservoir sedimentation and to replenish the groundwater tables (Talineau *et al.,* 1994; Selmi, 1996; Albergel and Rejeb, 1997). At present, thirty reservoirs are monitored using a hydrological network within one catchment allowing the calculation of water budgets and modelling of catchment water flows. For some reservoirs, the water balance is highly negative and suggests a water loss by infiltration leading to a reservoir leakage and an alluvial aquifer recharge. Based on a geochemical approach, a recent study permits the determination of the groundwater inflow and outflow rates (Montoroi *et al.,* 1999, 2000) and a modelling was performed for this (Nasri, 1999). However, for modelling the groundwater pathways, there is a lack of knowledge in the structural pattern of the weathering formations.

The goal of our study consists in using the geophysical approach to characterise the soil and subsoil structures in the vicinity of an infiltrated reservoir. We, therefore, propose to perform the vertical electrical sounding (VES) and the electromagnetic induction (EMI) methods, which can provide means for acquiring spatialised soil information at the field scale.

Study site

The study site is described in detail by Montoroi *et al.,* (2002). The main characteristics are summarised as follows. The El Gouazine watershed (35°55'N - 9°45'E) is about 50 km northwest of the city of Kairouan. Steppe vegetation and rainfed cereals cover the 18.1 km^2 watershed area. The mean annual rainfall in the watershed is 339 mm (estimated from 1994 to 1998, Montoroi *et al.,* 2000) and class-A pan evaporation was on the order of 1,775 mm yr^{-1} during the 1996-1998 period.

The El Gouazine watershed resides at the east boundary of the SW-NE orientated Ousseltia syncline. Pedological formations have developed on Tertiary sedimentary parent materials (marly calcareous and gritty deposits), which were highly raised and folded by Atlasian tectonic movements resulting in rock layers dipping steeply southeast to nearly vertical in the eastern part of the watershed (Castany, 1951; Jauzein, 1967, Fournet, 1969).

Most soils are highly calcareous and clayey and locally calcreted. Colluvium mixed with high stone content occurs on the hillslope. According to the World Reference Base for Soil Resources (ISSS Working group WRB, 1998), the main soils in the catchment include Calcisols and Calcaric Cambisols. Cambisols are mainly formed from marl deposits and locally from limey sandstone deposits.

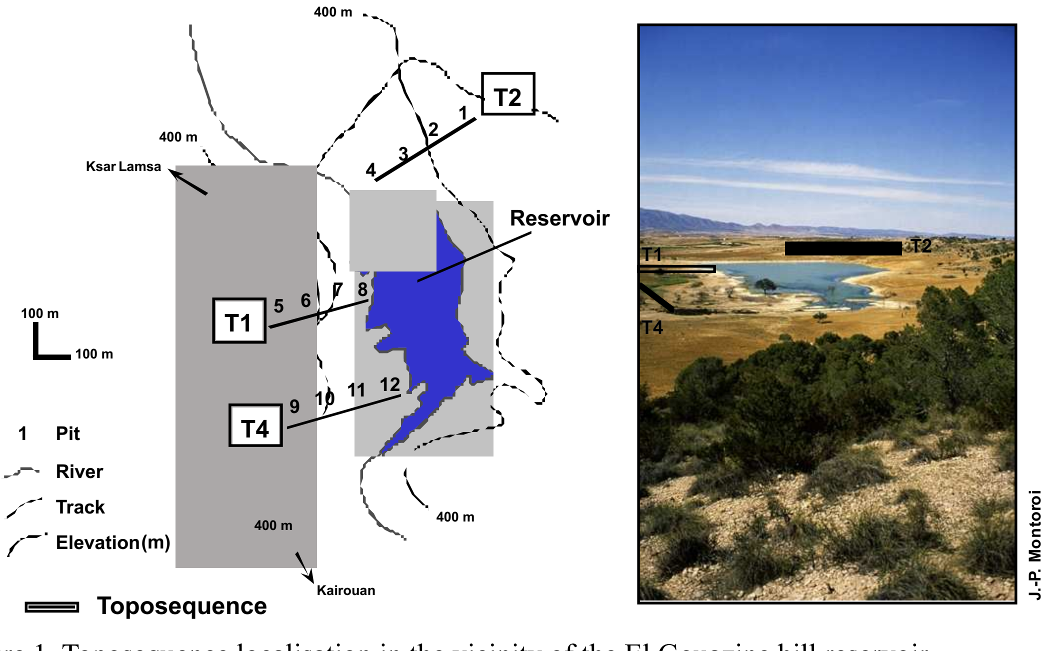

Figure 1. Toposequence localisation in the vicinity of the El Gouazine hill reservoir

Materials and Methods

In VES method, the goal is to observe the variation of electrical resistivity with depth. The technique is best adapted to determining depth and resistivity for flat-lying layered rock structures, such as sedimentary beds, or the depth to the water table. The principle is detailed by Lowrie, 1997. For a particular four-electrode array, two electrodes are used to supply a controlled electrical current to the ground. The VES method measures apparent bulk electrical resistivity (ρ_a) expressed in Ohm meter (Ω m). The Wenner configuration includes a common mid-point for the current and potential electrode pairs. At a given location, the size of an array is increased leading to a deeper investigated volume and providing qualitative information about resistivity lateral variations in the range of the investigation depth (Roy and Apparao, 1971).

For T2 and T4 toposequences, a total of 11 electrical soundings were performed using a Wenner array. On each site, 14 apparent resistivity measurements (ρ_a, in Ω m) were recorded from the subsurface to the nearly 7.5 m depth using an electrode spacing ranging from 0.2 m to 10 m. An inversion model transformed the ρ_a values in terms of layer thickness and layer resistivity. The 1-D VES method was constrained by field observations (pits, groundwater levels) and soil analysis.

The EMI used in this study were the two Geonics EM31 and EM38 meters (Geonics Ltd. Mississauga, Ontario, Canada). The theoretical basis for EMI measurements is described by McNeill (1992). The EMI instruments measure apparent bulk electrical conductivity (EC_a) from above the soil surface. Reported in milliSiemens per meter (mS m^{-1}), EC_a is the weighted average of electrical conductivity within a volume of soil. The effective depth of measurement is dependant upon the intercoil spacing of the instrument, transmission frequency, and dipole orientation (Scanlon *et al.,* 1997).

A profiling survey of EC_a was undertaken at 10 m increments along three soil toposequences located in the vicinity of the El Gouazine reservoir (Figure 1), upstream at the left embankment (T1 and T4) and downstream at the right embankment (T2). Both EMI instruments were held at soil surface and data were collected in both the horizontal dipole and vertical dipole orientations.

In addition, the EM31 device was held at waist height (1m), data being recorded only in the vertical dipole orientation. Effective measurement depth are noted in Table 1 for each device and dipole mode. As each soil depth layer within the investigated volume has a weighted contribution to the EC_a measurement, we considered a "mean" measurement depth corresponding to a major signal source. Data from the EMI were merged into a file format compatible with Surfer™ 7.0 software to produce electrical conductivity images of the soil section. Using these maps of EC_a, areas of high or low conductivity were identified.

Table 1 EMI characteristic and measurement configuration (after McNeill, 1992)

Device Coil spacing	**Frequency (m)**	**Dp (KHz)**	**Dm (m)**	**Emd**	**Mmd (m)**	**(m)**
EM31	3.66	9.81	0	V	6	3
			≈1	V	4	2
			0	H	3	1.5
EM38	1	14.6	0	V	1.5	0.8
			0	H	0.8	0.4

Dp device position (0 m for ground level, 1 for waist level), Dm dipole mode (V vertical, H horizontal), Emd effective measurement depth, Mmd half measurement depth.

Although the VES and EMI methods do not measure the same parameters, a relationship allows to transform ρ_a (Ω m) value in EC_a (mS m^{-1}) value and vice versa, buy using the following formulae:

$$\rho_a = 10^3 / CE_a$$

Results and Discussions

VES method

The soundings present different patterns according to the encountered deposits. The highest electrical resistivity values are attributed either to calcareous colluviums for the T2 toposequence, partly or totally encrusted (Figure 2), or to a sandy layer for the T4 toposequence (Figure 3). In turn, the lowest values correspond to the marly deposits.

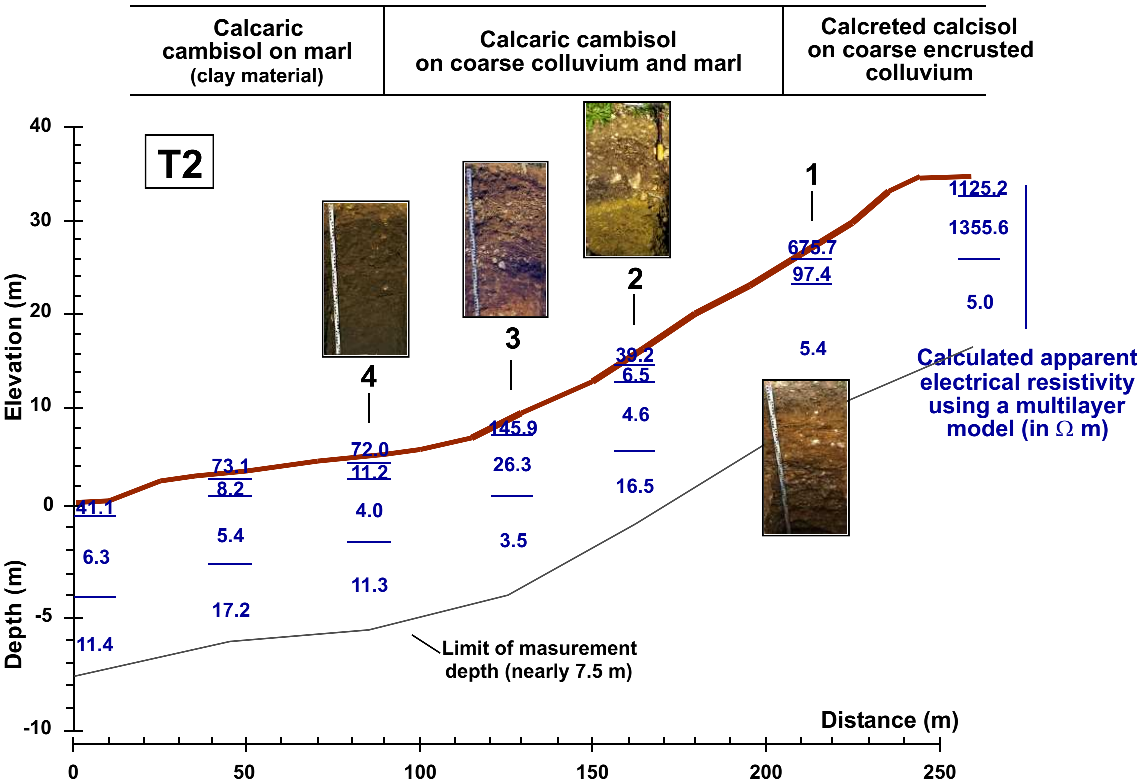

Figure 2. Soil apparent electrical resistivity along the T2 El Gouazine toposequence

For the T4 toposequence, the lowest ρ_a values in depth are attributed to the effective presence of groundwater flowing throughout the sandy soil containing over 70 g $100g^{-1}$ of sand and forming an temporary aquifer. The formation of the aquifer may result from weathering and erosion of the sandstone host rock that is connected with the downstream alluvial aquifer.

As the reservoir was empty in 1998, a sandy layer was observed on the western embankment and in the sediment of the reservoir confirming the extension area of the aquifer. The high permeability of the sandy layer, being at a 5 m elevation above the reservoir bottom, partly explains the high water loss from the reservoir, especially when the reservoir water level exceeds 4.5 m, which also corresponds to a great change in daily groundwater balance (Montoroi *et al.,* 1999).

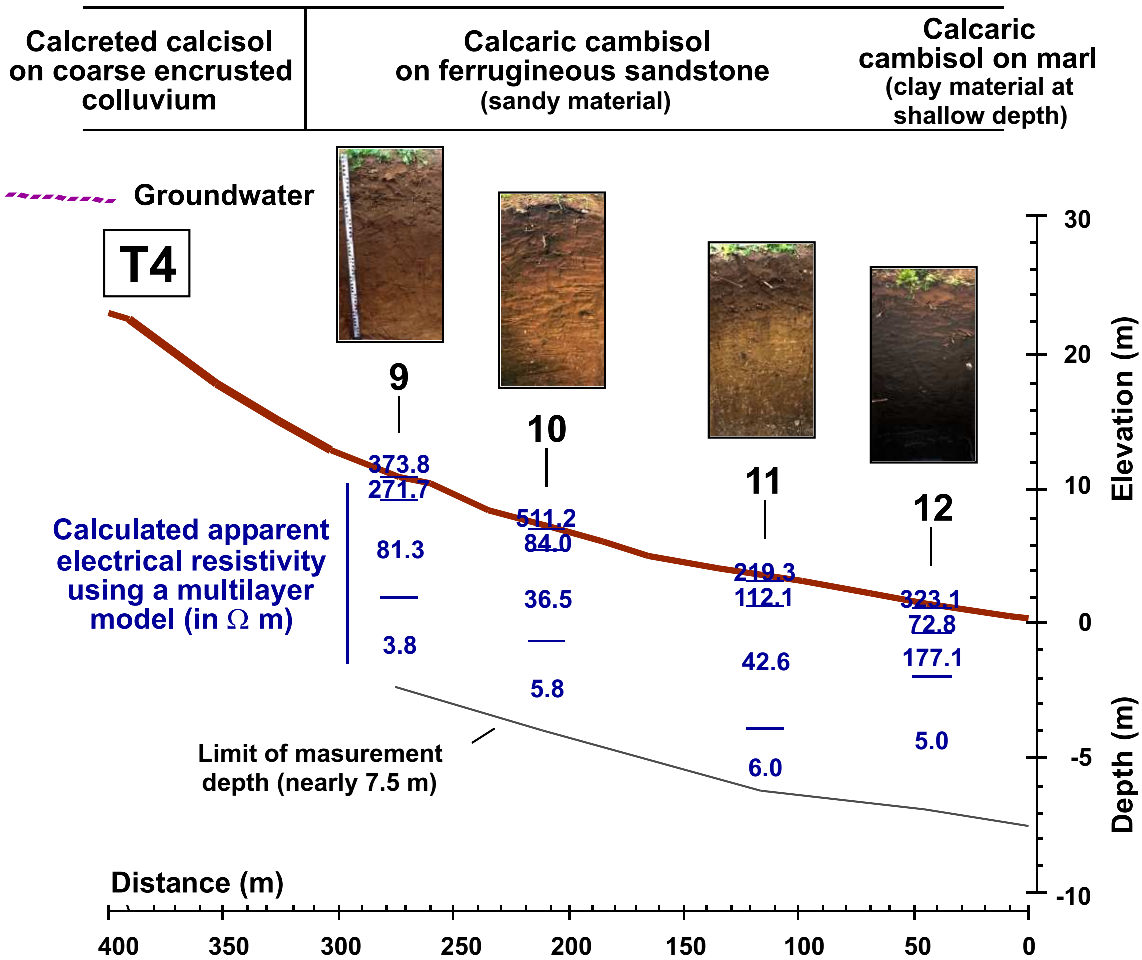

Figure 3. Soil apparent electrical resistivity along the T4 El Gouazine toposequence

EMI method

Profiling

Figure 4 presents of the lateral variations of the electrical conductivity along the T4 toposequence. The EMI values, measured by the two devices using in different positions, show a quite similar variation along the toposequence. For each EMI device, the data values provided by the different device positions are nearly similar. A device comparison shows that the measurement range is quite different because of the investigation of various soil volumes. These remarks are valid also for the others toposequences.

Imaging

Profiling is not suitable to visualise the vertical variations of the electrical conductivity. The combination of all the data collected for each toposequence allows generating more eloquent 2D-images.

All the toposequences include a more conductive layer in depth, which corresponds to the marly formations (Figure 5). The T2 toposequence shows a highly resistant area corresponding to a calcreted layer formed in the hilltop soils. Along the hillslope, the soil surface is more resistant than the deep layers due to colluvium formations as well as the less sloped T1 toposequence. The T4 toposequence image reveals a resistant body which is related to sandy soils formed by sandstone weathering, as previously described by Montoroi *et al.,* 2000).

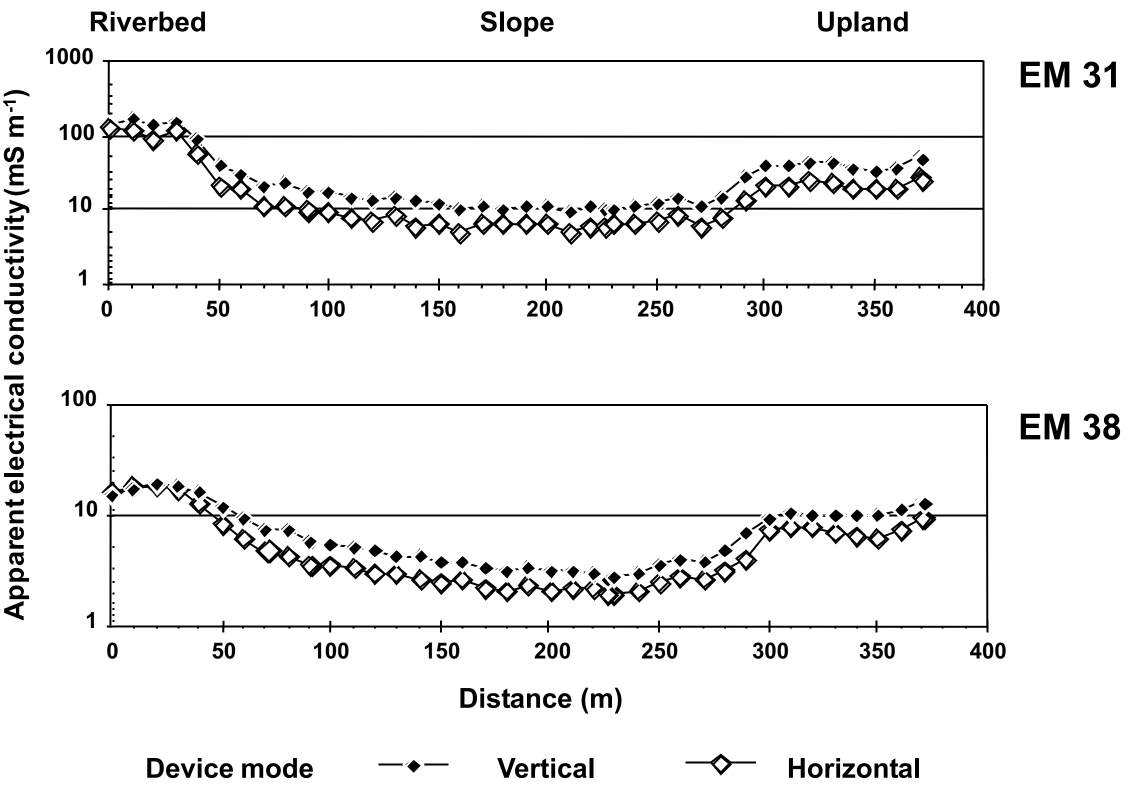

Figure 4. Soil apparent electrical conductivity along the T4 El Gouazine toposequence

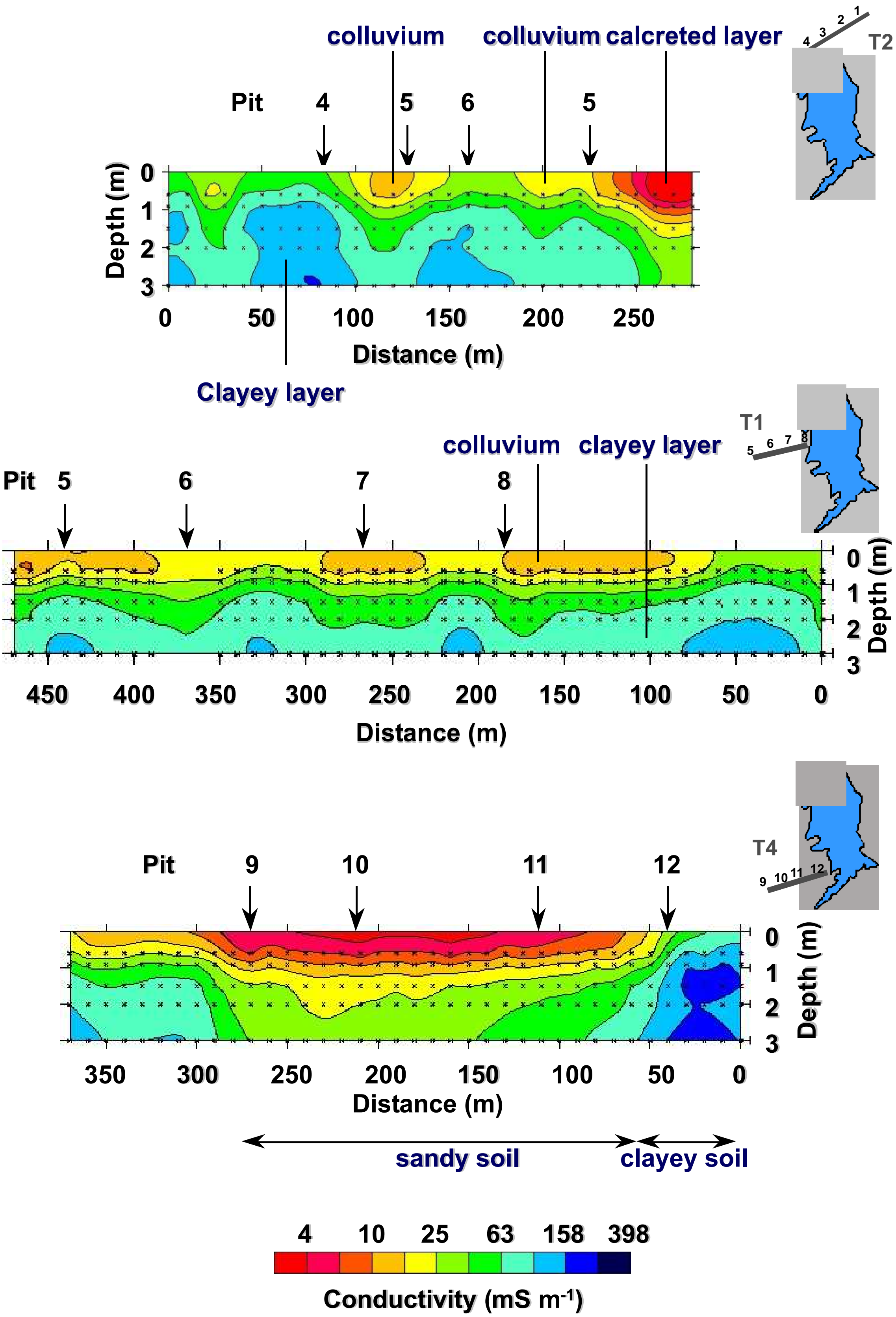

Figure 5. Images of soil apparent electrical conductivity along the T1, T2 and T4 El Gouazine toposequences

Conclusion

Applied geophysics are useful tools for preserving the structure and the functioning of soils, and providing a spatialised and well sampled information. Based on surface measurements using a current injection or an electromagnetic induction, the principle is to determine the physical properties of a soil volume, and the vertical and horizontal variations.

The 1-D geophysical method provides accurate structural data completing the hydrological and geochemical data sets and defining a more precise model of the reservoir functioning. However, the insufficient measurements along the toposequence do not allow a lateral interpolation. Recent geophysical methods, such as the 2-D imaging approach, could provide more spatialised information of the vertical formation structure. Applied geophysics could be extended to the other infiltrating hydrosystem encountered in the Tunisian water management projects.

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