

Research Article

Assessing soil attributes in puddled no-tilled vs. tilled fields amid an irrigation cycle using electrical resistivity

Gamal S. M. Swileam¹, Reda R. Shahin^{1*}, Noha H. Abdelkader¹, Khalid S. A. Essa²

¹Soil and Water Department, Faculty of Agriculture, Cairo University, Egypt

²Department of Geophysics, Faculty of Science, Cairo University, Egypt

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*Corresponding author: Reda R. Shahin, E-mail: dredashahin@agr.cu.edu.eg

Abstract

The objective of this study was to determine the effectiveness of electrical resistivity (ER) for monitoring soil management systems – conventional tillage (CT) and puddled no-till (PNT) throughout an irrigation cycle in a field located in El-Fayoum, Egypt. We selected a pair of adjacent fields, one dominated by CT and another with PNT. The two fields were basin irrigated and measurements of soil moisture (% SM), salinity (EC, dS m^{-1}), bulk density (BD, g cm^{-3}), and ER were taken at 3, 15, and 30 days post-irrigation. Conventional tillage (CT) enabled salt to be redistributed within the soil profile, decreasing surface salt content that originated from soil disturbance. In contrast, PNT experienced its soil surface salinity level increase rapidly as salts were trapped in the compacted topsoil. By day 30, salinity in the PNT plot was 3.0-5.6 dS m^{-1} higher than in the CT plot, demonstrating a limitation of PNT related to excessive salt accumulation, especially under arid conditions. While the CT plot had lower BD initially and became more compacted over time, compaction increased in the PNT treatment throughout the study mostly due to its high compaction level resulting from puddling. Application of 2D Apparent Electrical Resistivity Tomography (AERT) and 1D layered resistivity models (LERM) to ER measurements revealed significant ER pattern differences between the two systems. Puddled no-till (PNT), especially in the topsoil, showed lower ER rates due to the pronounced high moisture and salinity. Conventional tillage (CT) demonstrated greater ER variation, which improved with the migration of water. The statistical analysis validated the strong positive correlation of higher moisture, salinity, and BD with lower ER values. Overall, this study showed that ER methodology could be effective in assessing soil behavior under various tillage systems quickly and non-destructively.

Keywords: Electrical resistivity tomography, Conventionally tilled (CT), Puddled no-tilled (PNT), Soil moisture, Soil salinity, Bulk density

Introduction

Egypt stands out as one of Africa's leading rice producers, where the cultivated area reached about 630,000 hectares of rice (*Oryza sativa* L.), yielding roughly 4 million tons annually (IPAD-FAS, 2024). Growing rice in Egypt relies on an inherited soil preparation method known as "puddling," which remains the standard practice in most rice fields across the country and which (i.e. puddling) involves leveling the soil under very wet conditions using mechanical tools to break up soil aggregates and create a soft, muddy layer (Zhang *et al.*, 2016; Fang *et al.*, 2019; Malo, 2021 & Samejima *et al.*, 2022). This process, while it is intended to benefit rice cultivation and retain water by reducing losses through percolation and making it easier to transplant rice seedlings, it can also contribute to soil degradation over time.

Several studies have highlighted the downsides of traditional paddy field management; for example, Mohanty *et al.* (2004) and Romadhon *et al.* (2023) observed that such practices can induce different forms of soil degradation, including the development of hardpan layers underneath the soft topsoil (Kalita *et al.*, 2020) that can reduce root penetration and water flow. Further, several researchers such as Bajpai and Tripathi (2000), Sharma *et al.* (2005), El-Henawy (2013) and Dewanti and Mandang (2022) observed that puddling increased the bulk density of the soil and caused compaction in topsoil, especially in the heavy textured, relatively compared to light textured soils (Kukul

& Aggarwal, 2003; Behera *et al.*, 2009). Priyadharshini *et al.* (2024) concluded that the puddling process breaks up soil aggregates thus increasing the number of micropores at the expense of macropores. Puddling can also reduce the soil hydraulic conductivity, and the particle density can increase from 1.44 Mg/m^3 to approximately 1.51 Mg/m^3 within 30 days.

Muhandiram *et al.* (2020) performed an extensive review of 264 studies conducted around the world and observed that the mean aggregate diameter (MAD), water-stable aggregates, and water holding capacity (WHC) were significantly higher under no-till (NT) systems under high soil compaction conditions. Recently, Thiengo *et al.* (2024) observed that compacted no-tilled soils were significantly denser by 9.5% than conventional-tilled (CT) soils and associated with significant reductions in total porosity (8.3%), macroporosity (22.2%), and aeration porosity (16.7%). Research by De Vita *et al.* (2007), Fernández-Ugalde *et al.* (2009), Ferreras *et al.* (2000) and Lenssen *et al.* (2007) had demonstrated that NT systems typically have higher water retention than CT systems, which contributes to greater water storage and reduced evaporation. Alam *et al.* (2024) and Thiengo *et al.* (2024) reported that NT aids in preserving soil structure, thus enhancing both water infiltration and retention, with particular focus on the topsoil, which is critical in dry and semi-arid areas where water scarcity prevails and each drop of water must be judiciously utilized for agricultural production.

On the other hand, according to López-Fando and Pardo (2009), if CT is continued over time, it might result in drier soils, primarily due to its contribution to enhanced evaporation and decreased the total soil moisture. Sometimes, however, CT technology can break up compacted layers and increase the rate of drainage, which helps to prevent waterlogging and promote root growth. Conventional Tillage (CT) is even worse in terms of soil salinity. The salinity in CT is influenced by the exposure of the salt to the surface through the disruption of the natural soil structure and subsequently inducing the drying of the soil, has in the long term caused the salt concentration to increase in the top layers through capillary rise and evaporation, thereby enhancing the salinization (Gholami *et al.*, 2014). In contrast, several reports have demonstrated that no-till (NT) increases salinity amelioration in soil. Aziz *et al.* (2013) and Abou Hussien *et al.* (2022) indicated that NT managed fields frequently have lower salinity than CT managed ones, which can be an advantage in keeping the soil in good condition and increasing crop productivity. However, NT systems can sometimes cause salts to build up near the surface, especially in dry regions, because less water moves downward to leach salts away. Still, the extra water held in NT soils can also help dilute salt concentrations and make it easier for plants to take up water. As Cordero-Vázquez *et al.* (2023) pointed out, there's an inverse relationship between soil moisture and salinity; as the soil dries out, salinity tends to increase, mainly because evaporation leaves salts behind.

Soil electrical resistivity (ER) is a non-destructive and fast tool that can uncover the characteristics of the underground soil layers through differences in moisture (Brillante *et al.*, 2015), salinity (Werban *et al.*, 2009), packing system (García-Tomillo *et al.*, 2017), mineralogical composition (Azmi *et al.*, 2021), and even organic matter content (Jia *et al.*, 2021). A growing interest among researchers over the past decade has shown that various tillage methods of conventional tillage (CT) and no-till (NT) can change their ER characteristics, which may help us understand the actual changes that are taking place in soils under different tillage practices.

Many researchers (Aditama *et al.*, 2017; Akhtar, 2021) used ER as a useful tool for soil mapping to distinguish variations in soil properties that are induced by different tillage practices, as they found that no-till (NT) managed soils often show higher ER values, which could be linked to higher compaction. They added that higher ER in NT soils might indicate less aeration, but it also points to greater soil stability against the risk of soil erosion. Furthermore, Jakalia *et al.* (2015) suggested that NT systems may encourage the soil to retain moisture and enhance the building up of soil organic carbon, which both can influence ER images. However, the long-term no-till practices (NT) could improve soil health attributes and stabilize ER values over time as suggested by Zhang *et al.* (2022). Soils that are conventionally tilled (CT) recorded lower ER readings, due to the increase in the aeration pores which help water to move easily through the soil, as confirmed by the findings of

Brillante *et al.* (2015). They added that repeated and heavy tillage over time may cause soil erosion, organic matter depletion, and emerging symptoms of soil degradation.

Soil electrical resistivity (ER) is also very sensitive to changes in soil structure, suggesting it is a valuable tool for detecting both natural and management-induced compaction (Tabbagh *et al.*, 2000; Besson *et al.*, 2004) and can be used to non-destructively distinguish between ploughed and unploughed layers (Séger *et al.*, 2009). Freshly tilled soils showed higher electrical resistivity (ER) when compared to the older tilled fields where the disturbance had settled, particles became more contacted facilitating electrical conduction (Basso *et al.*, 2010) and increasing its ability to retain moisture (Müller *et al.*, 2009). The impact of tillage on electrical resistivity (ER) is prevalent as some studies claim resistivity increases by one to two orders of magnitude from 10-100 Ωm (Müller *et al.*, 2009; Basso *et al.*, 2010). Aditama *et al.* (2017) and Cordero Vázquez *et al.* (2021) support that applications of electrical resistivity tomography (ERT), with the aid of soil moisture and salinity measurements, yield the best observations of soil properties and heterogeneity in situ. In contrast, Rossi *et al.* (2013) found that tilled areas exhibited a higher average ER under specific conditions over time with a maximum ER of 1700 Ωm . However, sometimes using a mixed effects model to control for anticipated and spatiotemporal trends, no difference in statistical significance was found between tilled and non-tilled areas (Cordero Vázquez *et al.* 2021). They also suggested that tilled areas were associated with less spatial autocorrelation and more heterogeneity in the readings. Most recently, Moreira da Silva *et al.* (2023) found that a 2-D ERT could relate moisture changes and porosity to different crop input regimes for a better understanding of the soil-plant interface.

It is worthy to notice in the ongoing research that there is still a gap within the literature regarding the electrical resistivity properties of puddled soils. Thus, this gap poses an opportunity for being investigated and may add to the body of knowledge about how puddled soils behave in terms of electrical resistivity.

In the present study, we considered post-rice puddled soil as a puddled no-tilled (PNT) plot. The objective of the present study is to test whether the electrical resistivity technique is capable of discerning the variability caused by tillage systems (i.e. conventional tillage (CT)/Puddled no-tilled (PNT)) from management-induced changes in soil structure and other properties even throughout an irrigation cycle.

Material and Methods

Site description

The present work was conducted in El Fayoum which is a typical closed depression naturally excavated in the Eocene limestone plateau with no external drainage (Hammad *et al.*, 1983). It is located approximately 90 Km southwest of Cairo, between latitude 29° 02' N and 29°

35° N and longitude 30° 23' E and 31° 5' E, and irrigated from the Nile River through the Bahr Yousef canal (Ali & Abdel Kawy, 2013). Three main physiographic landscape plains characterize El-Fayoum depression (i.e. alluvial; fluvio-lacustrine and lacustrine). Recent and old lake terraces, depressions, plains and basins characterize the different landforms (Abo-El-Ennan, 1985; Shendi, 1990). Two neighboring fields were selected in El Fayoum to meet the expected objectives of the study and were selected to represent conventional tilled (CT) and puddled no-tilled (PNT) management. Table 1 shows the location, crop, and soil management history of fields under investigation.

Soil specimens were sampled at four depths (0-15, 15-30, 30-45 and 45-60 cm) from two profiles which were dug in the studied two farms. The air dried samples were ground softly with the help of a pestle and passed through a 2.0 mm sieve and subjected to determinations of: particle size distribution (Piper, 1950), total CaCO₃ (Nelson, 1982), Organic matter (Page, 1982; Nelson & Sommers, 1996), electrical conductivity (EC) in 1:2.5 soil: water extract (Rhoades, 1996). The EC (e.g., ECe or ECw) determined at room temperature (t) (°C), ECt (dS m⁻¹) was then converted to a reference EC value at 25 °C, using the following equation as suggested by Sheets and Hendrickx (1995).

$$EC_{25} = f_i \cdot EC_t \quad (1)$$

$$f_i = 0.4470 + 1.4034 \exp(-t/26.815)$$

Bulk density was determined in undisturbed soil samples (Blake & Hartge 1986). The obtained characterization of the investigated two farms is presented in Table 2.

Table 1: Location GPS, crop and soil management history of the investigated fields

Management type	Conventional tilled (CT)	Puddled no-tilled (PNT)
Location (GPS)	N=29° 21' 32.2" E=30° 48' 48.5"	N=29° 28' 8.1" E=30° 46' 44.9"
Elevation	32 masl	22 masl
Field area (acres)	1.3	0.3
Previous crop	Eggplant	Rice
Previous soil management	Conventional	Puddled
Post crop	Lettuce	Clover (Barseem)
Present soil management	Conventional	Puddled no- tilled (PNT)
Irrigation Type	Basin	Basin
Irrigation date	26/11/2024	4/11/2024

Table 2: Soil characterization of the investigated farms

Farm treatment	Depth cm.	Mechanical fractions				Texture class	O.M %	CaCO ₃ %	*EC dS/m 25°C	Bulk density g/cm ³
		Coarse S.	Fine S.	Silt	Clay					
Puddled no-tilled (PNT)	0-15	3.16	16.54	51.51	28.79	Silty Clay Loam	1.53	2.62	1.65	1.62
	15-30	3.55	20.43	40.67	35.35	Clay Loam	1.84	2.41	1.93	1.53
	30-45	3.48	17.56	41.46	37.50	Clay Loam	1.42	2.12	1.70	1.31
	45-60	2.54	16.70	40.46	40.30	Silty Clay Loam	1.12	2.03	1.57	1.32
Conventional tilled (CT)	0-15	2.90	30.35	43.28	23.47	Loam	2.77	2.54	1.66	1.44
	15-30	3.40	19.21	46.83	30.56	Clay Loam	2.24	2.11	1.71	1.33
	30-45	5.78	36.86	38.43	18.93	Loam	1.91	1.85	1.74	1.21
	45-60	2.61	25.92	34.08	37.39	Clay Loam	1.88	1.92	1.84	1.22

*EC (1:2.5 soil: water)

Soil management and irrigation cycle

The first farm which was previously puddled and cropped by rice followed by clover was kept as puddled no- tilled (PNT), while the second one which was previously cropped by eggplant followed by lettuce had continuous conventional tillage (CT). The two farms were basin irrigated at the same time with the recommended amounts of water in September 2024. An irrigation cycle was investigated at 3, 15 and 30 days in both PNT and CT farms. At each period, depthwise soil samples were collected at the same time as measuring electrical resistivity. Disturbed samples were collected with a soil auger (10 cm depth until the water table level). Undisturbed samples were obtained with a locally made stainless steel auger tube sampler, internally containing replaceable stainless small tube (50 h × 50 mm external diameter) with a removable sharpened edge stopper to facilitate its insertion into soil layers. Soil augering was targeted every 10 centimeter depth and tightly packed for the instant soil moisture determination while soil cores were taken from the 5 cm depth following every 10 cm auger sample. After soil sampling, the augerhole was left to stand for 2 hours and the depth of the water table was measured, sampled and stored separately for measuring its EC. Soil moisture, EC (1:2.5 soil: water) and bulk density in the collected samples were determined as mentioned above.

Electrical resistivity measurement

Theoretical background

The electrical resistivity (ER) measurement is carried out through the injection of an electrical current in the subsoil by applying a voltage difference to the outer two electrodes (current (AB) electrodes, I) and then measuring the induced subsoil voltage at the inner MN pair of electrodes (potential electrodes, V). The four electrodes are usually placed on the surface in equal distance (a) according to Wenner's array (Dahlin, 2000; Zhou & Dahlin, 2003). Current (I) and voltage (V) data are collected from the four electrodes as shown in Figure 1.

The resistivity meter (KYORITSU-KEW-4106) was used in the present study. KYORITSU-KEW-4106 is a 4-Wire digital earth resistivity meter (Figure 2) equipped with a microcomputer and can acquire current and voltage

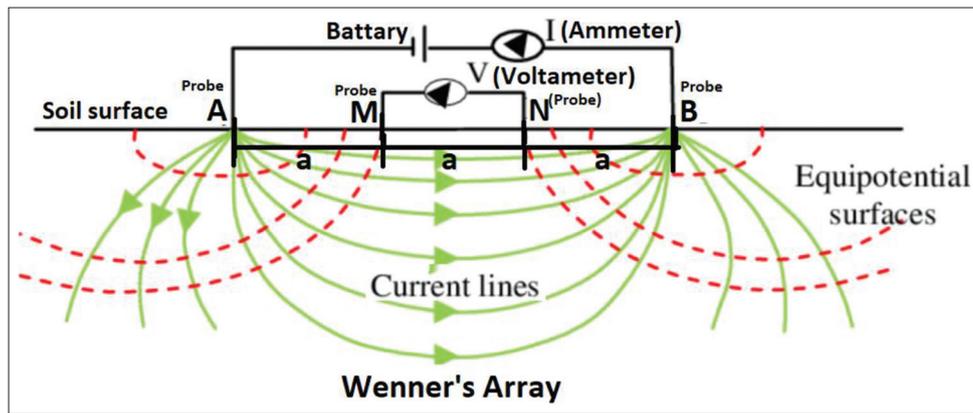


Figure 1: The Wenner array four probe configuration (AMNB) and distribution of electric field underneath in measuring soil electrical resistivity (modified from Zhou & Dahlin, 2003)

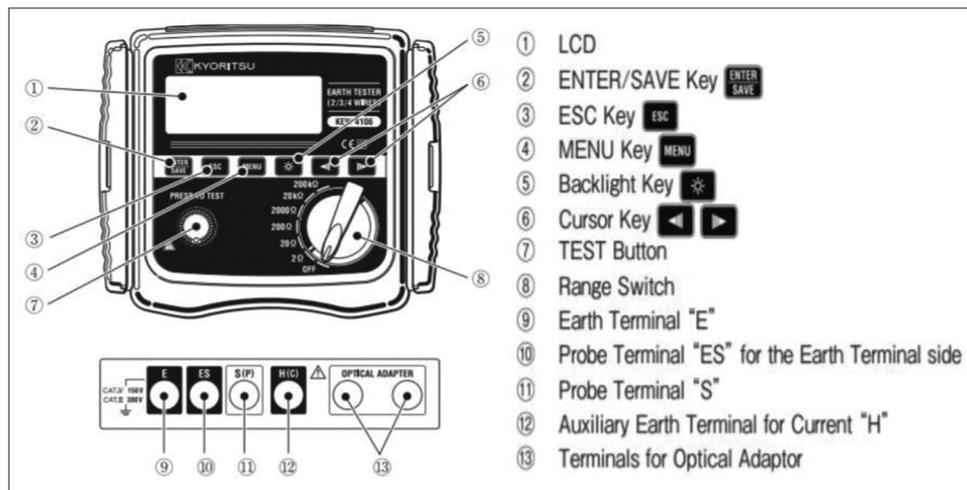


Figure 2: Layout of the electrical resistivity apparatus (KYORITSU-KEW-4106)

values giving resistance reading (R). The operating uncertainty (B) of this apparatus is an error obtained within the rated operating condition, and is calculated with the intrinsic error (A) and error E_n due to soil variations as follows:

$$B = \pm(|A| + 1.15\sqrt{E_2^2 + E_3^2 + E_4^2 + E_5^2})$$

where A = intrinsic error, E_2 = variation due to changing supply voltage, E_3 = variation due to changing temperature, E_4 = variation due to interference voltage, E_5 = variation due to changing probes resistance.

The obtained resistance readings ($R = \Delta V / I$) were transformed into apparent resistivity values (ρ_a) using the following equation:

$$\rho_a = (2\pi a)R$$

Where ρ_a = apparent resistivity (i.e measured resistivity), a = electrode spacing, R = the resistance measured by the apparatus.

The apparent resistivity data (ρ_a) obtained from the field measurements were processed using EarthImager 1D software

(AGI, 2007) to obtain one-dimensional (1D) or Res2DInv software to obtain two-dimensional (2D) models for resistivity of the soil subsurface according to Wenner's array (Loke, 1996-2001, 2001; Loke & Barker, 1996; Loke *et al.*, 2003), which must be converted into true resistivity by solving the inverse modeling problem (Patrizi *et al.*, 2022; Vanella *et al.*, 2022).

Sounding data acquisition of soil resistivity in an irrigation cycle

The four electrode Wenner vertical electrical sounding (VES) array was applied to monitor an irrigation cycle in the present study. Two sounding methods of data acquisition were applied along two lines on both farms in order to monitor the changes of soil electrical resistivity throughout an irrigation cycle:

- a- One dimensional (1D)-Symmetric Wenner Array (1D-VES) and
- b- Two dimensional (2D)-Symmetric Wenner Array (2D-VES)

Sounding 1D-VES array: consists of a series of the electrode combinations AMNB with gradually increasing central distances (Figure 3). In the studied farms the distances between probes were 0.5, 1.0, 2.0**, **3.0, 4.0, 5.0, and 6.0 m, so the total transect length was 18 meters.

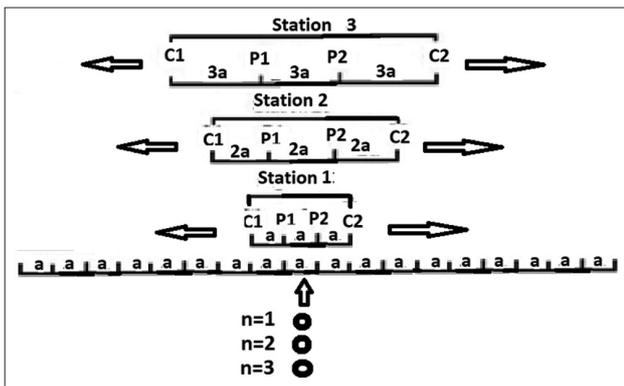


Figure 3: Distribution of apparent electrical resistivity data points for 1D electrical sounding with a Wenner's array

It is well known that the depth of sounding increases with increasing the distance between A and B electrodes. The result of 1D-VES measurements with central-symmetric arrays is apparent electrical resistivity (ρ_a) as a function of half of the distance between the current electrodes, i.e. $ER = f(AB/2)$ (Beck, 1981). The relationship between ρ_a and $AB/2$ can be converted into a relationship between electrical resistivity and actual soil depth through computer interpretation. The obtained apparent resistivity data were inverted to true resistivity values (ρ_t) and soil layer sections were generated by EarthImager 1D software (AGI, 2007; Shevnin & Modin, 2003).

Sounding 2D-VES array: Soil apparent electrical resistivity was measured at increasing distances between probes (0.5, 1.0, 2.0 and 3.0, 4.0, 5.0, and 6.0 m) from a starting point along a 18 m transect (Figure 4). The apparent resistivity (ρ_a) was calculated from the measured field data and referenced to the electrode position using RES2DInv software to obtain a plot of true resistivity (ρ_t) variation with depth at each point (Shevnin & Modin, 2003; Loke, 2011). The interpreted and calculated apparent resistivity pseudosections and the true resistivity model are derived by inversion using RES2DInv software and were calibrated according to the least root-mean-square (RMS) principle. The end product is presented as a color image, in which several colors correspond to various subsurface electrical resistivity values (Li *et al.*, 2021).

Statistical analysis

Simple and multiple linear regression analysis were carried out using SPSS software (IBM, 2012). The relative contribution of each predictor (M, EC, BD) to variance in ER was calculated using multiple linear regression according to Tonidandel and LeBreton (2011) and Zhang and Wang (2017).

Results

Monitoring of soil properties under an irrigation cycle in conventional tilled (CT) and puddled no-tilled (PNT) plots

The changes of the three main soil properties (i.e. Soil moisture, EC and BD) with depth at different periods after

irrigation for the conventional tilled (CT) and puddled no-tilled (PNT) plot were investigated. The monitoring of each soil property throughout the applied irrigation cycle is presented in the following:

Soil moisture profiles of the conventionally tilled (CT) and puddled no-tilled (PNT) plots during an irrigation cycle

As shown in Figure 5, at the start of the irrigation cycle (after 3 days), the highest soil moisture was found in the top layer (0-10 cm), with values of 43.8% for the conventionally tilled (CT) plot and 51.97% for the puddled no-tilled (PNT) plot. The greater moisture retention in the PNT topsoil is likely due to the abundance of micropores created by the puddling process. The data of the deeper soil layers indicated that the moisture profile steadily decreased in both CT and PNT plots until reaching the water table, at about 100 cm for CT and 80 cm for PNT, where moisture levels rose again starting from the vadose zone reaching around 50% beyond those depths. Over time, moisture content dropped in both treatments, but the rate of decline is different. After 30 days, the CT plot showed a much sharper decrease in surface moisture, while the PNT plot retained moisture more effectively, especially in the middle soil layers (20-60 cm). In this zone, CT lost moisture more quickly than PNT. Additionally, the water table in the PNT plot was found at a shallower depth (80-90 cm) compared to the CT plot (100-120 cm), suggesting that the PNT plot has poorer drainage, likely as a result of the puddling process.

Soil salinity profiles of the conventionally tilled (CT) and puddled no-tilled (PNT) soils during an irrigation cycle

The obtained data in Figure 6 illustrate how salinity (measured as electrical conductivity, EC, in dS/m) changes with soil depth for both conventional tillage (CT) and puddled no-till (PNT) treatments over 3, 15, and 30 days. In the CT plots, salinity started off low at the surface (1.71 dS/m at 10 cm after 3 days) and gradually decreased with depth. Over time, especially after 15 and 30 days, there's a noticeable increase in salinity in the upper 40-50 cm, reaching up to 2.51 dS/m, but overall, the rise is moderate both with depth and over time. The story is different for the puddled no-till (PNT) plots, where salinity levels are generally higher than in the CT plots at almost every depth and at every time point. There's a sharp jump in EC from the surface down to about 40-50 cm, especially after 30 days, where values climb above 3 dS/m. Even at deeper layers (80 cm and below), salinity remains higher in the PNT plots, peaking around 2.5 dS/m. By the end of the 30-day period, the PNT soil profile became more uniformly saline, while the CT profile still showed a gentler change with depth.

Looking at the relationship between soil moisture and salinity (Table 3), there are clear differences between the two tillage systems and how they change over time. In the PNT system, there's a strong negative correlation between moisture and salinity at both 3 days ($r = -0.67$, $p < 0.01$) and the significance became very strong at 30 days ($r = -0.90$, $p < 0.001$) after irrigation. This may indicate that as the soil dries out with time, salinity increases, likely because

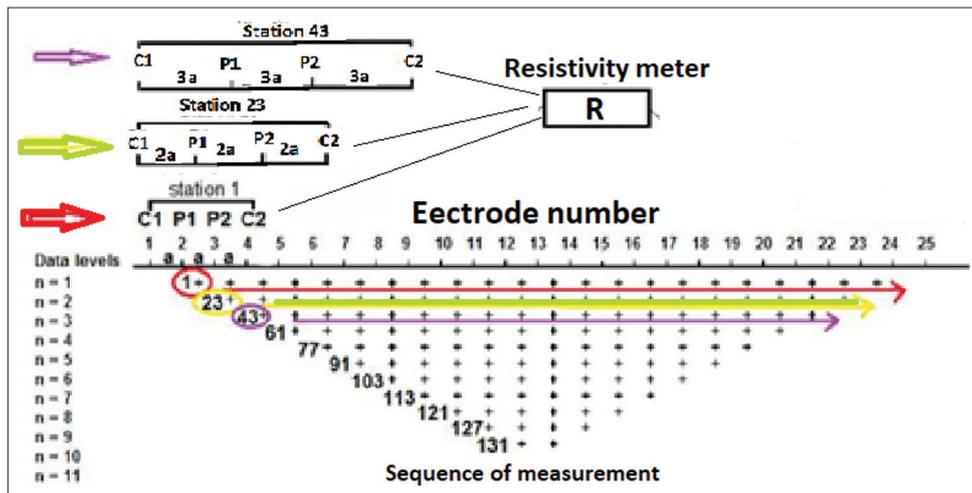


Figure 4: Typical 2D-resistivity data measurement sequence in Wenner array

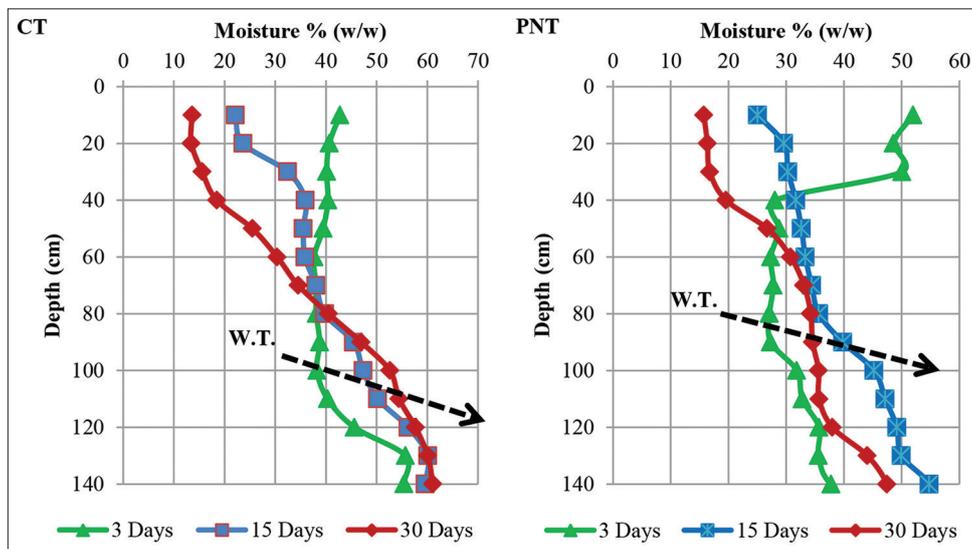


Figure 5: Depthwise moisture content in conventionally tilled (CT) and puddled no- tilled (PNT) plots at different periods after irrigation

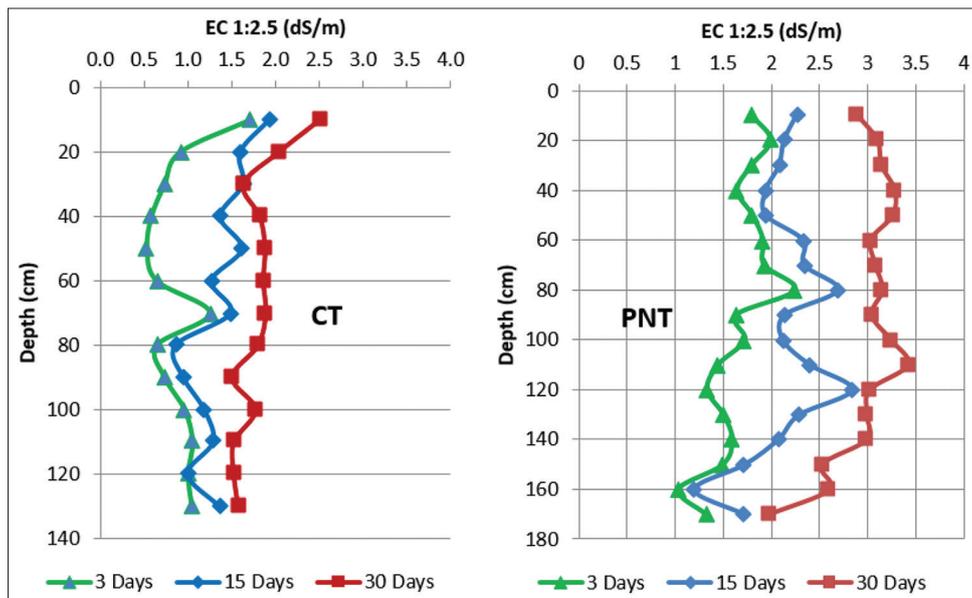


Figure 6: Depthwise salinity distribution in conventionally tilled (CT) and puddled no-tilled (PNT) plots at different periods after irrigation

evaporation pulls water out and leaves salts behind, with limited leaching taking place at the surface. On the other hand, the CT plots don't show a significant link between moisture and salinity at 3 days. Therefore, these results suggest that conventional tillage (CT) encourages more active water movement through the soil, which helps prevent salt from building up, whereas puddled no-till (PNT) systems, while good at holding onto moisture at first, may end up accumulating salts near the surface over time.

Soil bulk density profiles of the conventionally tilled (CT) and puddled no-tilled (PNT) soils during an irrigation cycle

Regarding Figure 7, some interesting trends were noticed in bulk density after irrigation; for instance, in the conventionally tilled (CT) plots, the soil was noticeably looser just three days after irrigation, especially in the top 15 centimeters, where the bulk density recorded the lowest value (1.04 g/cm³). As time passed, at both 15 and 30 days, the loose soil started to settle, with rising bulk density and an obvious increase in the upper layers (from the surface down to 45 cm), while deeper layers showed fewer changes. This trend was somewhat different for the puddled no-till (PNT) plots, where the soil started out much denser right from the beginning, especially in the top 15 cm, as shown by the measured bulk density of 1.37 g/cm³, which is quite a bit higher than in the CT plots. Over time, the bulk density in the PNT plots slightly increased, but overall, it stayed consistently higher than in the CT plots at every tested depth. Interestingly, the change in bulk density from day 3 to day 30 in the PNT plots wasn't as dramatic as that noticed in the CT plots. After a month, the CT soils were still just a bit less compact than the PNT soils at the same depths, which held onto their higher bulk density across the whole profile, staying in the range of about 1.39 to 1.46 g/cm³ and not fluctuating much with depth.

1D electrical resistivity of the conventionally tilled (CT) and puddled no-tilled (PNT) soils during an irrigation cycle

There are some notable patterns worth showing from Figure 8, which presents the layered resistivity models (LRM) generated by Earthimager software. For example, the electrical resistivity (ER) values at all depths are higher in the 30-day profile compared to the 3-day profile in the puddled no-tilled (PNT) treatment. This difference is especially striking at the surface layer (0-26 cm), where ER jumps from 2.78 Ωm at 3 days to 6.73 Ωm at 30 days, which could be attributed possibly to drying or increased compaction. Both profiles show a general trend where resistivity decreases with depth, but the 30-day profile seems to drop off more quickly in the upper layers, while the 3-day profile is more uniform overall.

Turning to the conventionally tilled (CT) plots, the trend is somewhat different; as Figure 8 shows, in the upper layers (20 to 50 cm), resistivity values are much higher in the 30-day profile than in the 3-day profile. Unlike the PNT profiles, the CT profiles don't show a simple, steady decrease in electrical resistivity (ER) with depth, as resistivity actually increases from 20 cm down to 94 cm before dropping off. It's also worth noting that the CT 30-day profile covers a wider range of resistivity values (from 2.60 to 11.64 Ωm) than the CT 3-day profile (from 3.89 to 7.22 Ωm). These changes are more evident over extended periods of time (3 to 30 days), which likely capture the persistent effects of tillage on soil structure and degradation.

In order to perform Pearson's correlation coefficients, moisture %, EC, and bulk density data were recalculated as weighted values at depths relevant to those of their electrical resistivity (ER) values; regression analyses were performed and are presented in Table 3. Several important relationships were developed; the most consistent and

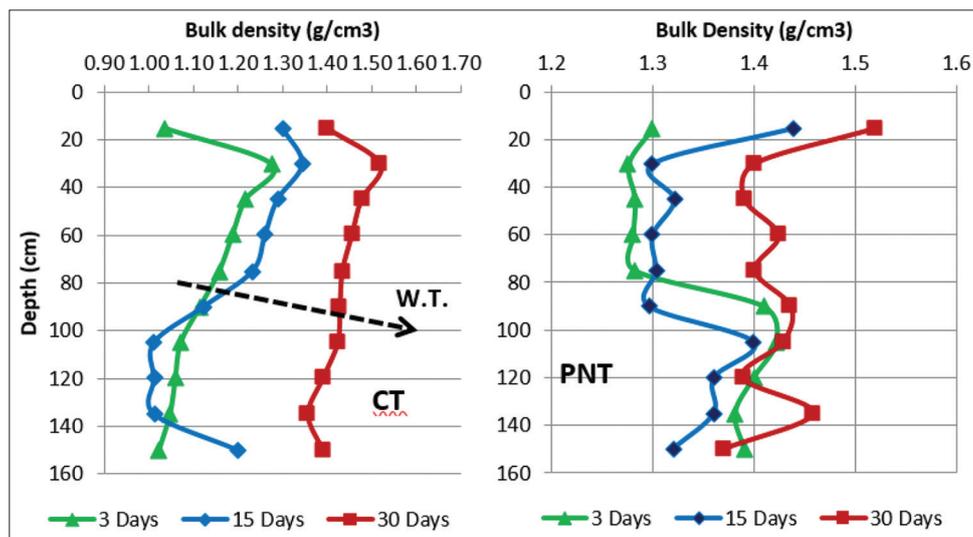


Figure 7: Depthwise bulk density values in conventionally tilled (CT) and puddled no-tilled (PNT) plots at different periods after irrigation

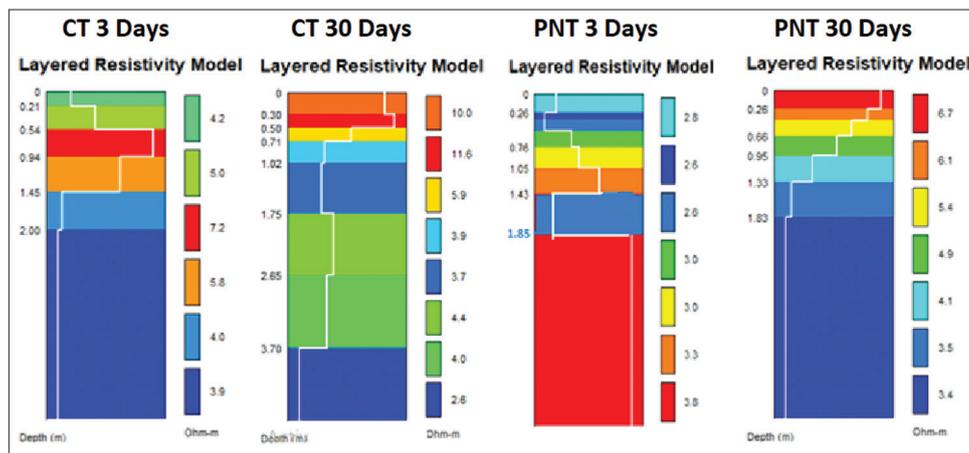


Figure 8: Layered resistivity models (LRM) of conventionally tilled (CT) and puddled no-tilled (PNT) treatments after 3 and 30 days of irrigation as processed by Earthimager software (AGI, 2007)

theoretically expected finding was a negative correlation between moisture content and ER, as when the soil holds more water, its resistance to electrical current drops. The obtained correlation coefficients ranged from -0.10 to -0.88, with the strongest negative correlation in the PNT treatment at 30 days ($r = -0.88$) and the CT treatment at 3 days ($r = -0.83$). It seems that moisture has a particularly strong influence on resistivity, especially as the soil settles after irrigation.

Another key result was the negative correlation between EC and ER, which fits with the idea that higher salt concentrations (higher EC) boost ionic conductivity and lower resistivity. The most pronounced effect was seen in the PNT treatment at 30 days ($r = -0.95$), suggesting that salts play a major role in shaping resistivity in undisturbed soils over time. The CT treatment at 30 days also showed a strong negative correlation ($r = -0.82$). There was one exception: the CT treatment at 3 days showed a weak positive correlation ($r = 0.43$), but this is likely due to the small sample size and may not be meaningful.

Concerning the relationship between bulk density and ER, we found a consistent negative correlation, which suggests that as the soil becomes more compact (higher bulk density), resistivity tends to drop. The likely reason is that compaction reduces pore space and increases contact between soil particles, making it easier for electricity to flow. The strongest negative correlations were found in both the CT ($r = -0.88$) and PNT treatments at 30 days ($r = -0.76$), which might indicate that tillage practices enhance the link between bulk density and ER as the soil settles and changes over time.

In addition, multiple regression models were obtained for each treatment and time point and are presented in Table 4, which shows that the interactive and combined effects of moisture (M), salinity (EC), and bulk density (BD) significantly strengthen the effect on electrical resistivity (ER).

In a further statistical investigation, the relative contribution of each predictor (M, EC, BD) to variance

Table 3: Pearson’s correlation coefficients for each treatment and time point between resistivity values (ER) extracted from the layer resistivity model (LRM) and soil moisture (M), EC, and bulk density (BD)

Treatment	Time (Days)	M vs. EC	M vs. ER	EC vs. ER	BD vs. ER
PNT	3	-0.65	-0.10	-0.61	-0.16
PNT	30	-0.86	-0.88	-0.95	-0.72
CT	3	-0.37	-0.83	0.43	-0.65
CT	30	-0.62	-0.71	-0.82	-0.88

Table 4: Multiple regression models for each treatment and time point relating electrical resistivity values (ER) extracted from the layer resistivity model (LRM) and soil moisture (M), EC, and bulk density (BD)

Treatment	Multiple Regression Equation	R
No-Till 3 Days	$ER = 3.726 - 0.0219 \cdot M + 0.452 \cdot EC - 0.8885 \cdot BD$	0.872
No-Till 30 Days	$ER = 13.08 - 0.161 \cdot M + 0.476 \cdot EC - 1.94 \cdot BD$	0.997
Till 3 Days	$ER = 16.46 - 0.114 \cdot M - 1.09 \cdot EC - 3.63 \cdot BD$	0.983
Till 30 Days	$ER = 27.88 - 0.398 \cdot M + 3.29 \cdot EC - 8.86 \cdot BD$	0.993

in ER was calculated using multiple linear regression, following up significant beta values with squared beta values as a proportion of the total R^2 according to Tonidandel and LeBreton (2011) and Zhang and Wang (2017), as presented in Table 5. The main conclusion that can be drawn from this table is that the most effective factor responding to ER was moisture (%M) content (33.6 to 53.6%), followed by bulk density (BD), as its relative contribution ranges between 35.4 and 42.2%, whereas salinity had the least effect (3.8 to 15.9%). An exception was recorded in the PNT 3 Days treatment, where ER responded more to EC (38.10%) than BD (8.3%).

2D Apparent electrical resistivity tomography (AERT) of the conventionally tilled (CT) and puddled no-tilled (PNT) fields during an irrigation cycle

From Figure 9, the 2D AERT profile for the conventionally tilled (CT) field just three days after irrigation (CT 3 days) provides a unique picture of the electrical resistivity profile characteristics. The surface

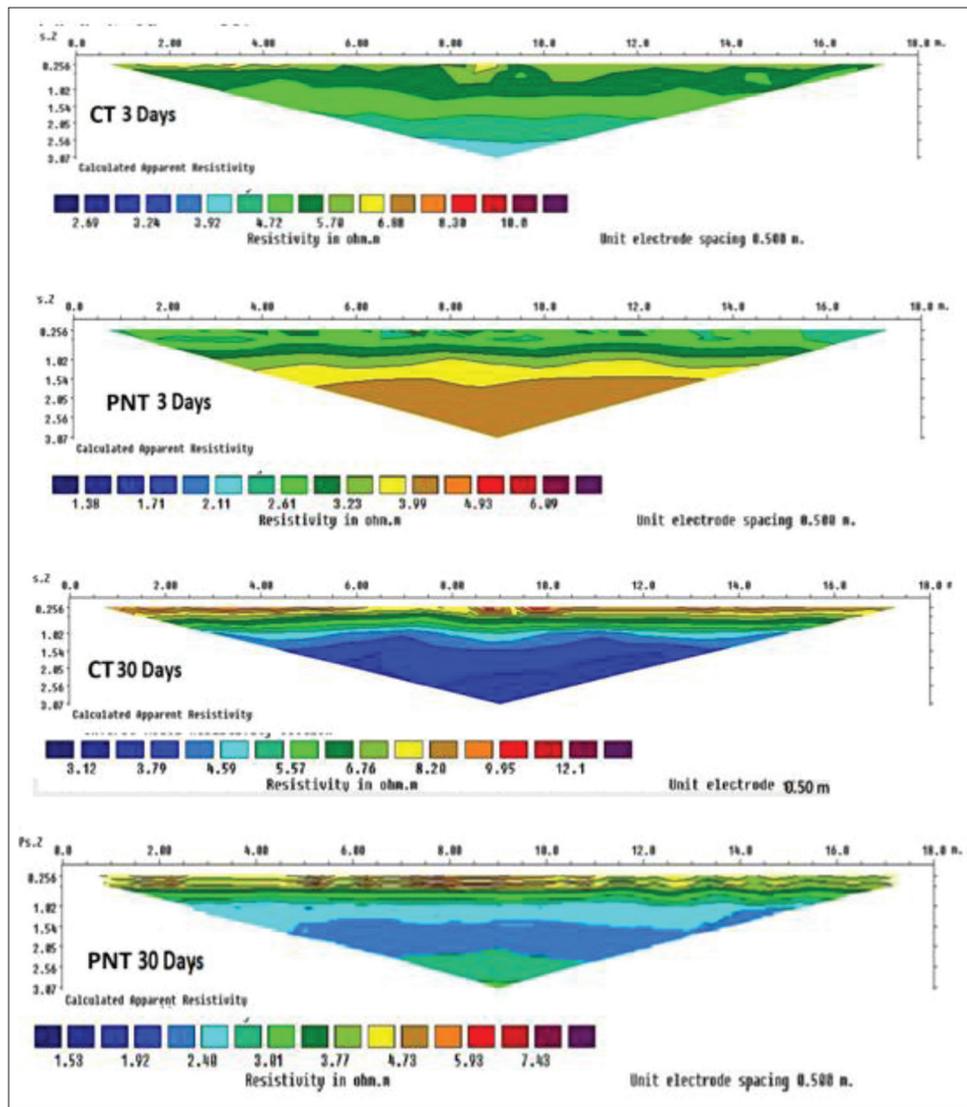


Figure 9: Apparent electrical resistivity tomography (AERT) of the conventionally tilled (CT) and puddled no-tilled (PNT) soils for 3 and 30 days after irrigation

Table 5: Relative contribution of each predictor (M, EC, BD) to variance in ER using multiple linear regression for each treatment and time point

Treatment	M (%)	EC (%)	BD (%)
PNT 3 Days	53.60	38.10	8.30
PNT 30 Days	42.70	8.00	42.20
CT 3 Days	33.60	3.80	43.90
CT 30 Days	45.10	15.90	35.40

layers are a patchwork of blue, green, and yellow colors that point to a wide range of apparent resistivity values, roughly ranging from 2.49 to 6.08 Ωm . This colorful mix likely reflects the disturbed, wet topsoil right after irrigation. Going deeper, spots of orange and red patches are noticed, where resistivity jumps above 8.08 Ωm , which might represent denser and/or drier pockets in the soil. After 30 days, the CT profile looks much more uniform, and the lower part of the profile is mostly blue, with resistivity values dropping to between 3.12 and 4.59 Ωm ; this could be a sign of downward movement of excess water to the water table, leaving the upper layers drier and more settled. Regarding the puddled no-till (PNT) field at 3 days, the trend changes as the AERT profile shows a more layered

structure; the surface is dominated by blue and green, with low resistivity values ranging from 1.38 to 3.23 Ωm . When going deeper, resistivity starts to climb, with some yellow and orange areas reaching up to 5.95 Ωm , which might suggest that moisture drops off with depth, or maybe there’s a higher concentration of salts in those deeper layers. At 30 days after irrigation, the trend has shifted again, as the PNT profile shows a noticeable increase in resistivity at the surface compared to day 3, probably due to drying and compaction over time. Meanwhile, the lower depths are mostly blue, with relatively low resistivity values (1.53 to 3.01 Ωm), which could mean there’s more moisture near the water table.

It is interesting to notice that the CT treatment generally shows higher resistivity values than the PNT treatment, which could reflect that water moves and spreads differently in tilled versus undisturbed soils. After 30 days, both CT and PNT fields show lower resistivity values than they did at 3 days, but the drop is much more dramatic in the PNT plot—especially in the topsoil, where resistivity is significantly lower than in the CT plot.

Discussion

The results of the present study provide insights into the patterns of soil moisture, salinity, and bulk density in relation to electrical resistivity changes throughout an irrigation cycle. Three days after irrigation, the top 0-10 cm layer held the maximum soil moisture, which is logical regarding surface irrigation where water starts to flow from above; this is a classic principle of soil physics (Hillel, 1998). Over time, by day 30, the surface layer dries out while deeper layers become wetter; this redistribution of water, driven by gravity and capillary action, means that moisture moves downward, leaving the surface drier and the subsoil more hydrated—a process well-documented by Ali Ibrahim *et al.* (2025). By comparing conventional tillage (CT) and puddled no-till (PNT) systems, the PNT fields consistently retained more moisture at all depths, especially in the mid-soil layers (30-90 cm). This isn't surprising, as puddling breaks up soil aggregates, increases micropores, slows evaporation, and generally helps the soil hold more water (Lal, 2004; Behera *et al.*, 2009). The presence of a water table at 90-120 cm, which leads to high moisture at that depth, is also a common feature in these soils (Fetter, 2001). Notably, the water table in PNT plots was shallower (80-90 cm) than in CT plots (100-120 cm), suggesting poorer drainage in the puddled fields, a likely consequence of the puddling process itself. This observation aligns with Bajpai and Tripathi (2000) and Priyadharshini *et al.* (2024), who found that puddling reduces macropores and increases micropores, ultimately lowering hydraulic conductivity.

Salinity dynamics tell another part of the story; in CT plots, salinity started low at the surface but increased over time, especially in the top 40–50 cm. This is probably due to the evaporation process; as water leaves the soil, salts are left behind, concentrating near the surface (Rengasamy, 2006). In contrast, PNT plots showed higher salinity overall, particularly after 30 days, as reduced tillage seems to limit salt leaching, causing salts to accumulate in the topsoil (Govaerts *et al.*, 2009; Haruna & Anderson, 2020). The strong negative correlation between soil moisture and salinity in the PNT system, meaning that as the soil dries, salinity rises, is a well-known phenomenon in arid and semi-arid regions (Wong *et al.*, 2010; Elsoury *et al.*, 2015). Moisture and salinity are directly related to soil electrical resistivity when the soil is saturated and changes are caused by evaporation (Cordero-Vázquez *et al.*, 2023); thus, it was logical to analyze the two in order to better interpret the resistivity differences under both PNT and CT systems during the irrigation cycle. A recent study by Innocenti *et al.* (2024) showed that time-lapse electrical resistivity tomography (ERT) could be a non-destructive measure of these changes and a tool to estimate irrigation efficacy. Bulk density dynamics were also notable, since immediately after tillage, the 15 cm topsoil was looser in the CT treatment, reaching its lowest value due to plowing and the immediate disturbance effect. However, bulk density rose as the soil settled and the pores collapsed over time.

In contrast, PNT soils began and remained denser, a common feature of puddled rice fields where tillage is

absent to create pore space. This is in agreement with the results also reported by Blanco-Canqui and Ruis (2018) in a meta-analysis stressing that no-tillage management affects soil porosity distribution by increasing micropores at the expense of macropores. Bekele (2020) concluded that CT soils can store more water in the short-term compared to reduced-till or no-till soils, but other studies (Gozubuyuk *et al.*, 2015) find that water-holding capacity may be enhanced with no-till practices over time. This indicates that CT systems may contribute to a short-term increase in moisture, but PNT systems might be better at retaining water in the long term (Kukul & Sidhu, 2004).

Layered electrical resistivity models (LRM) exhibited a significant increase in surface resistivity between 3 and 30 days at the 26 cm depth for the PNT treatment, which is probably due to drying at the surface as time passes (Dahlin *et al.*, 2014). Higher ER values (13.0 Ωcm) at 30 days suggest the possibility of wetter conditions drying out more in the soil, which is consistent with the observation that puddled no-till systems can show both compaction and moisture features (Alam *et al.*, 2024). The obtained results demonstrate that ER in CT profiles was significantly greater at 30 days than at 3 days in the upper layer (20-50 cm). A spike in ER from 20 to 94 cm depth in the 3 day profile may signify subsurface compaction or differential moisture retention due to continuous tillage at the same depth. The temporal variation in LRM profiles indicates that tillage may, in fact, cumulatively influence degradation and moisture migration in soil (Acosta *et al.*, 2022).

Considering the depth-dependence, both the CT and PNT treatments tended to show a decline in ER with depth, similar to the pattern found at 30 days, but with sharper declines in the upper layers. This indicates a higher variation in soil characteristics, most probably because of the compacted topsoil found in the PNT plots, compared with the control plots, which also increases water retention due to reduced infiltration (Alam *et al.*, 2024). The negative relationship between moisture and LRM values suggests that moist soils are better electrical conductors (Samouëlian *et al.*, 2005 and Brillante *et al.*, 2015). The strong negative correlation between EC and LRM values also indicates the trend that a higher concentration of salts leads to lower resistivity, especially in undisturbed soil conditions (Werban *et al.*, 2009). The correlation between bulk density and LRM values also indicates that compacted soils have lower resistivity (due to reduced pore spaces) along the same lines (García-Tomillo *et al.*, 2017). Swileam *et al.* (2019) stated that highly significant negative correlations were recorded in the topsoil between apparent or true resistivity and soil moisture, EC, or bulk density. The best-fitting relationship models ranged between linear, power, logarithmic, and exponential models. In the present work, the obtained multiple regression models for each treatment and time point relating electrical resistivity values (ER)—extracted from the layer resistivity model (LRM)—and soil moisture (M), EC, and bulk density (BD) were used to calculate the relative contribution of each predictor (M, EC, BD) to variance. The results indicated that the most effective

factor responding to ER was moisture (%M) content, followed by bulk density (BD), whereas salinity had the least effect; this is in agreement to a large extent with the findings of Abidin *et al.* (2013) and Nguyen *et al.* (2023). In some cases, large voids and cracks—observed visually upon drying—in combination with the small water content variations of the first few centimeters of soil could limit the correlation between soil water content and electrical resistivity, as reported by Besson *et al.* (2010).

The 2D apparent electrical resistivity tomography (AERT) response for CT 3 days after irrigation showed a patchy distribution of resistivity values (2.49 to 6.08 Ωm) in the surface layers, which could indicate that moisture is different in the two treatments, just as we had proposed for freshly tilled soil (Innocenti *et al.*, 2024). At 30 days, the CT profile tended toward uniformity, which might be related to the water going down and to better drainage as reported by Wu *et al.* (2023). In the PNT graphs, the (ER) at the surface was low at 3 days (1.38 to 3.23 Ωm), indicating higher moisture or salt content and compaction. The occurrence of ER at 30 days with a higher magnitude indicates drying, whereas the continuously lower ER at depth indicates moisture preservation in the subsoil, which could be in agreement with Innocenti *et al.* (2024). Rossi *et al.* (2013) employed 2D ERT to compare CT and NT systems and reported that considerable variations in resistivity patterns existed, highlighting the spatial correlation that is essential in interpreting these data. Resistivity values (ER) drawn from 2D apparent electrical resistivity tomography (AERT) were greater in the CT treatment than in the PNT treatment overall, possibly resulting from differences in water infiltration and retention. There is a sharp decrease in ER in the PNT plots after 30 days, which indicates that puddled no-till practices can improve the storage of water in the shallower layers (Cavalari *et al.*, 2023).

This study contributes to partially filling a knowledge gap in the understanding of the behavior of the electrical resistivity of no-till puddled soils during an irrigation cycle. Naturally, there is always some uncertainty in unpacking these complex relationships, but the patterns are clear: both tillage and puddling leave a unique signature on soil electrical resistivity through time.

Conclusion

In conclusion, the electrical resistivity method can be used to ascertain and forecast the differences introduced by different tillage systems. The results showed that electrical resistivity decreases with increases in moisture, salinity, and the soil compaction of the PNT system. Results of both 1D and 2D electrical resistivity analyses clearly show the effect of tillage on soil moisture dynamics and resistivity properties. The relationships between electrical resistivity and soil moisture, EC, and bulk density provide insight into the complex interdependencies of soil responses under different management regimes. The temporal changes in AERT profiles are indicative of the interactions among moisture, salinity, and soil structure in the CT and PNT

agricultural systems. The rise in electrical resistivity values from day 3 to day 30 indicates a loss in soil moisture or salt redistribution throughout the soil profile. Differences between the CT and PNT treatments emphasize the effect of different soil management practices on water infiltration, storage, and salt distribution. Soil modified structurally by CT may have more uniform water movement and distribution. However, this can also raise the evaporation rate, and thus lower the total moisture content as time goes on. Puddled no-till (PNT) systems destroy topsoil structure, which has a negative effect on water infiltration and retention in the soil. This could explain the bigger drop in electrical resistivity values in PNT, indicating higher moisture content. These interpretations are inferred visually from the AERT profiles along with their digital data, and can possibly be verified by the soil moisture, EC, and/or bulk density data. The paper reveals some of the behaviors of puddled no-tilled soil in terms of electrical resistivity, which in turn indicates sustainable management possibilities.

Future Research Outlook

The present work paves the way for several directions that need further exploration in order to improve the applicability of electrical resistivity for puddled soil evaluation, which could be summarized as follows: Unpacking ER differences will require multiple seasons of long-term monitoring to isolate moisture and salinity influences. The combined application of ER information and physio-hydrological models may be promising for a more predictive understanding of water and salt-transport processes, in particular within puddled soils. Future research should also take into account the effect of soil texture, mineralogy, and organic matter on ER values to further enhance interpretation for different agro-ecological areas. This would enable field practitioners to convert geophysical data into soil management decisions, autonomously identifying threshold ER levels that relate directly to critical compaction levels, salinity, and water stress. Additionally, the coupling of field ER data with remote sensing sensors, as well as machine learning techniques, might offer ways to deliver solutions for regional soil monitoring at scale.

Authors' contribution

Gamal S. M. Swileam - Conceptualization, methodology, field investigation and data collection, Reda R. Shahin - Supervision, conceptualization of the research framework data acquisition, and Writing original draft – review & editing, Noha H. Abdelkader - Soil laboratory analysis, Validation, and Formal analysis, Khalid S. A. Essa - Data curation, geophysical instrumentation (Electrical Resistivity setup), and Software/Visualization. All authors approved the final manuscript.

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