

Technical note: Monitoring diel soil water variations below trees using high-resolution electrical resistivity tomography

Hoppenbrock et al.

Summary

This manuscript presents a highly interesting study using time-lapse electrical resistivity tomography (ERT) to monitor changes in soil water content caused by urban trees. The results show a clear diel signal in electrical conductivity due to root water uptake during the day and hydraulic redistribution during the night. The results are complemented by in situ soil moisture and sap flow measurements.

The manuscript starts with a well-written introduction that clearly establishes the state of the art in ERT monitoring, with a focus on soil–tree interactions. In the methods section, several methodological and theoretical aspects require significant improvement. These include restructuring the theory and methods section, correcting technical inaccuracies regarding Archie’s laws and conduction mechanisms, and refining the model-fitting procedure for soil moisture estimation. Furthermore, the results are well presented, but a clear distinction between the description of the results and their interpretation is needed.

Therefore, I recommend that the manuscript be considered for publication after major revisions.

General Comments

- **Structure and thematic overlap:** There is a noticeable thematic overlap and misplacement of content between sections 2 and 3 (Theory and Material and methods); some aspects discussed in section 2 actually belong in section 3, and vice versa. I strongly suggest merging sections 2 and 3 into a single section “Material and Methods”:

(2.1) Overview of the ERT method and conduction mechanisms:

- ERT method (lines 106–112)
- Conduction mechanisms (lines 86–105)

(2.2) Field data collection: Installation of the ERT profile, as well as soil moisture and sap flow sensors installation.

(2.3) Processing and inversion of the ERT data

- **Conduction mechanisms and Archie’s law:** Section 3 contains technically vague statements regarding conduction mechanisms, and the equation used to describe Archie’s law is incorrect. This part requires careful revision (see specific comments).
- **Mixing of results and interpretation:** Section 4 (Results) contains interpretive sentences. These statements should either be shifted to the discussion section, or the section should be renamed accordingly (e.g., Results and Interpretation).
- **Soil moisture estimation:** The fitting procedure of the “modified Archie relationship” presented in Figure 4 requires a critical revision, particularly regarding the equation used (see comment above) and the physical plausibility of the resulting estimated values.
- **Potential of induced polarization:** The capacitive properties of the subsurface, which can be measured simultaneously using the same instrumentation as electrical conductivity, were not recorded in this study. Incorporating induced polarization data into the analysis and soil water

estimation could have provided valuable constraints to help resolve the model-fit issues encountered here.

- **Terminology and Formatting:** Please ensure symbols are consistently used throughout the manuscript. For instance, three different symbols are used for electrical conductivity (σ_b , σ , EC). Furthermore, I recommend using either resistivity or conductivity throughout the text.

Specific comments and technical corrections

Line 13: For the phrase „While soil moisture sensors and soil sampling provide only point-scale information and are often invasive...” consider reordering to „While soil moisture sensors and soil sampling are often invasive and provide only point-scale information...” (though this is left to the authors)

Line 18: Remove “during these periods” as this is already clear from the previous sentence.

Line 19: “showed” → “show”

Line 28: “drought” → “droughts”

Line 31: Regarding “water movement”, please specify the source of the water.

Line 38: I suggest replacing “at a discrete location” with “over time” as this paragraph focuses primarily on the temporal aspect.

Line 47: Instead of “... geophysical methods usually capture a larger subsurface volume. Therefore, they are less affected by small-scale heterogeneities and help upscaling information obtained from direct measurements (Beff et al., 2013).”, I recommend replacing it with “... geophysical methods allow to delineate spatial and temporal changes of subsurface physical properties in a quasi-continuous way (Binley et al., 2015).”

Line 49: “determine” → “resolve”

Line 51: “monitoring can therefore be used to...” → “has therefore been demonstrated to reliably detect...”

Line 74: “measurements” → “data”

Line 86: “determining” → “resolving”

Lines 87–99: These lines require revision as they are currently too vague. For instance: “Electrical conduction takes place via the pore water (electrolytic conduction) and along grain–water interfaces. The former one is related to the porosity, saturation,... (Archie, 1942).” Then, you integrate the Archie equation ($\sigma_{el} = \dots$) before introducing surface conduction and the Waxman and Smits (1968) equation.

Equation 1: This equation is not the original formulation based on Archie’s two laws. It has been shown to be only valid if $a=1$, and its use is generally discouraged (see Revil, 2013; Glover, 2015; or the overview in Binley and Slater, 2020). Furthermore, please clarify why “ $m-n$ ” is used instead of “ m ” as the cementation exponent. Please update to the correct equation and revise lines 93–94 accordingly.

Line 92–93: Please clarify the meaning of the parameters n and m and explain why they are “often assumed to be approximately 2”.

Line 93: Why do you use “qualitative”? The equation provides a quantitative relationship, describing it as a “qualitative relationship” is inaccurate.

Line 94: Please reformulate the sentence “applicability of this relationship depends strongly on several assumptions”. The relationship itself is true but surface conduction (and matrix conduction in presence of metallic materials) is missing.

Line 95: “modified” → “an extension”

Equation 2: See my comment above about equation 1.

Lines 98–99: Please clearly distinguish between surface and matrix conductivity. I recommend addressing them separately.

Line 102: Generalize the temperature correction: change “can be corrected to a reference temperature of 25 °C using ...” to “can be corrected from a temperature T to a reference temperature T_{ref} using ...”. I suggest formulating the equation accordingly: $\sigma(T_{ref}) = \frac{\sigma_T}{1+\alpha(T-T_{ref})}$. Later, when the processing steps are described, you can state what reference temperature you have used. Additionally, please use an older, well-established reference for the temperature–conductivity relationship (and the empirical coefficient), such as Keller and Frischknecht (1966) or Revil et al. (1998).

Lines 107–108: There is an error in the following sentence: “From these quantities and the geometry of the electrode layout, the apparent resistivity of the subsurface can be calculated using Ohm’s law.” Apparent resistivity cannot be calculated directly from Ohm’s law, Ohm’s law gives the resistance. Apparent resistivity is calculated from the resistance using a geometric factor (assuming homogeneous conductivity distribution), which depends on the electrode layout and the topography. Please revise.

Lines 109–112: Please carefully reformulate these lines.

- (1) “using multiple electrodes and varying their position and spacing” does not directly image the subsurface, it yields a dataset that helps resolving spatial changes in electrical properties, but the data still need to be inverted to “image” the subsurface.
- (2) Avoid the term “measured resistivities” as you only measure potentials/voltages and currents.
- (3) “realistic representation” is vague, consider using “subsurface model” instead.

Line 116: What values did you use for the spatial and temporal smoothing parameters?

Line 119: “measurements” → “data”

Line 119: “consistency” → “temporal stability”

Lines 120–137: Since this paper applies a time-lapse approach successfully tested in your previous work, please describe the applied steps more actively (with a reference to your former paper) rather than repeating theoretical background.

Line 132: “modelled apparent resistivities” → “forward modelled data $f_i(m)$ ”

Equation 5: I recommend to add “(m)” in $f_i(m)$ to make clear that this is the result of the forward modeling.

Lines 139–158: Do you have any information about the uncertainty or standard deviation of the data provided by your sensors?

Line 161: “grassy” → “covered by grass”

Line 162: Is the description “sandy material” based on field observations during excavations or grain size analyses? Please clarify.

Line 163: How was the groundwater level measured?

Line 168: The phrase “For this purpose” reads awkwardly in relation to the spacing and temporal resolution mentioned previously. Please reformulate.

Line 170: Why is the profile 23.5 m long instead of 24.5 m (given that you used 50 electrodes and 0.5 m spacing)?

Lines 172–173: Rephrase for clarity: “using slightly different measurement configurations” What is the difference between the configurations and why did you change them? Please also explain briefly Wenner and Dipole-Dipole configuration and move them as follows: “were recorded using Wenner and Dipole-Dipole configurations with slightly different...”.

Lines 161–173: Please include details on the number of quadrupoles, measurement time per time step and pulse length / frequency used for current injection.

Figure 1a:

- Please add submap labels.
- For the Germany map, instead of “Esri, TomTom,...” I recommend using publicly available geodata borders, (e.g., Eurostat) Include a scale bar.
- Improve the Braunschweig map by adding grid coordinates, labels and potentially an orthophoto or digital elevation model to better display green space distribution.
- Subplot b indicates that the profile crosses a footpath. Is the footpath paved and if yes how did you install electrodes there?

Line 185–197: Please state how geometric factors were calculated.

Line 193–196: How did you define the thresholds?

Line 195: Avoid subjective terms like “very”.

Line 196: What is meant by “both datasets”?

Line 198: The sentence “The error model also plays a crucial role.” is incomplete—what is it crucial for?

Lines 198–205: Present the applied steps more actively rather than explaining theoretical aspects.

Line 200: “exchange” → “interchange”

Lines 199–200: Did you perform the normal–reciprocal analysis for Dipole–Dipole and Wenner?

Equation 6: Why not designate the “normal” resistance measurement explicitly (R_N)?

Line 206: You noted earlier that the apparent resistivities are your data used in the inversion but you estimate data errors for resistances. How did you apply the data error to the apparent resistivities?

Line 227: Regarding “following Hayley et al. (2010)”, please see my comment above.

Lines 231–237: Section 4.1 mixes results with interpretation (e.g., “most likely reflecting predominantly dry soil conditions”, “probably related to increased organic content”). Please either remove interpretive statements from this section or rename the section: “Results” → “Results and Interpretation”

Line 251: Avoid “significantly” unless a formal statistical test supports it.

Figure 2: Why are temperature and soil moisture content plotted as points while sap flow is a line? Are not all three parameters discrete data types?

Line 265: “ERT results at the corresponding sensor positions (red). The extracted ERT conductivities were calculated...” → “ERT images at the corresponding sensor positions (red), calculated...”

Line 281: Move sentences like “The positions of the soil moisture sensors are indicated by black dots.” Directly into the figure caption.

Line 283: The phrase “which are marked by black dots at the surface.” belongs to the figure caption and black dots have been already used for the sensor positions. I recommend using a different symbol for the sensors.

Lines 284–286: Reformulate: “Here, the opposite pattern to Fig. 3b is visible: the areas where resistivity decreased most strongly in Fig. 3b now show a strong increase. Overall, however, a general increase in resistivity can be observed.” → “Overall, a general increase in resistivity can be observed but the opposite pattern to Fig. 3b is visible: the areas where resistivity decreased most strongly in Fig. 3b now show a strong increase.”

Figure 3: Subplot a marks sunrise/sunset on top but symbols are missing for the first two days. Please add electrode positions in subplot b and c.

Line 296: Here, you refer to Archie’s second law: “Archie’s law” → “Archie’s second law”

Line 296–297: “can be used to relate EC to SWC” → “describes the relationship between EC and SWC”

Line 297–298: Please avoid “measured conductivities”, see my comment above.

Line 298: Did you use the conductivity of all time steps?

Line 299: Please avoid the term “modified Archie relationship”

Line 300: Regarding “fixing $a=1$ ” please see my comment above.

Line 300: Please clarify why a saturation exponent of 2 and a porosity of 30–50 percent were assumed.

Line 303–304: Why was the fit restricted only to the second period rather than evaluated separately for each period?

Figure 4:

- Ensure symbol consistency throughout the manuscript (e.g., σ_b , σ , EC).
- In subplots a and b, the changes in water content and electrical conductivity are small (2–3 percent) yet the axes use large ranges, masking the data fit quality. Given a 4 percent data error used in the inversion, are these small variations above the noise floor?
- There is a large, unrealistic contrast in the estimated values for σ_w (7.23 vs. 276.20 mS/m) over a distance of just 1 m (subplots a and b).
- Subplots c and d compare measured vs. estimated soil water content. but since the model was fit to this exact data, close correlation is expected and does not constitute independent "validation". As an alternative, you could consider splitting data into training and validation sets.

Line 339: “A higher clay content and/or an increased fluid EC may explain this change.” A more critical discussion is needed here, as such a drastic change in fluid conductivity over 1 m is not realistic.

Line 345–346: Be consistent in time formatting (choose either 6 am or 6 AM throughout).

Line 347: The time-lapse changes in EC are smaller than the error level you have used in the inversion. Please discuss this limitation critically.

Lines 353–354: The statement “geophysical methods can only help to make the water movement visible.” underestimates the quantitative potential of geophysical methods (especially when combined with induced polarization and/or seismics).

Line 375: Mention in Material and Methods that your soil moisture sensors were not calibrated. What is the expected error range without calibration? This may explain the large contrast in σ_w and σ_s between the two points under investigation.

Line 388: “measured conductivities” – see my comment above.

Figure 6: Please add subplot labels.

Line 446: “relative geoelectrical changes” → “conductivity changes”

Line 452: “disturbing” → “additional”

Line 452: “noise” → “errors”

Appendix B: Consider revising the title.

Figure B1: The label “second period” in the caption might not be clear for the reader.

Figure C1: 304–305 mention that Figure C1 shows changes in σ_w but they are not visualized here.

Lines 485–488: Were these EC values measured with an independent fluid conductivity meter, or extracted directly from the ERT inversion? Please clarify.

References

Binley, A., & Slater, L. (2020). Resistivity and Induced Polarization: Theory and Applications to the Near-Surface Earth. Cambridge: Cambridge University Press.

Glover, P. W. J. (2015). Geophysical properties of the near surface earth: Electrical properties. Treatise on Geophysics, 89, 89–137.

Keller, G. V., & Frischknecht, F. C. (1966): Electrical Methods in Geophysical Prospecting. Pergamon Press, Oxford, 517.

Revil, A., Cathles III, L. M., & Losh, S. (1998): Electrical conductivity in shaly sands with geophysical applications. Journal of Geophysical Research, 103(B10), 23925–23936.

Revil, A. (2013): On charge accumulation in heterogeneous porous rocks under the influence of an external electric field. Geophysics, 78(4), D271–D291.