Responses to Reviewer 1:

We would like to first emphasise that the explicit objective of this paper was to look for a practical methodology for soil hydraulic characterization based on an EMI sensor without the need to use parallel datasets to calibrate ECa data.

Coupled vs uncoupled approach:

Although in principle, we are perfectly aware of some of the points raised by Reviewer#1, we would like to give our reasons why we decided for using an uncoupled approach. In doing that, the response will unavoidably answer other important issues introduced by Reviewer#1, for example about the number of hydraulic parameters to be estimated by the inverse hydrological procedure.

Let's briefly introduce the main steps of the coupled and uncoupled approaches, by simultaneously highlighting their strengths and weaknesses. In order to remain close to the case examined in the paper, we will refer to the case of EMI apparent electrical conductivity readings, ECa_meas (the geophysical measurements) during a 1D vertical water infiltration experiment.

Coupled approach:

In the coupled approach, the hydrological model is the starting point of the procedure. Guess values of hydraulic parameters are initially fixed; thus, a hydrological simulation is carried out producing water content distributions along the soil profile, evolving over time. These water content distributions are converted to corresponding distributions of bulk electrical conductivity, σ_b, by using some empirical relationships. The σ_b distributions, in turn, are used as input in an EM forward model to produce estimations of apparent electrical conductivity, ECa_est. In the inversion, the objective function involves the residuals (ECa_meas - ECa_est). This objective function is eventually minimised by optimising the hydraulic parameters in the hydrological model.

The main strength of this approach relies on the fact that no EMI inversion is required. It is well known that the inversion of geophysical measurements is an ill-posed problem. Ill-posedness is generally treated by regularising the inverse solution. However, different regularisation schemes and parameters can have a significant impact on the results (e.g. Dragonetti et al., 2018; Zare et al., 2020); thus, inversion results of EMI data are always affected by uncertainties which can lead to artefacts, misinterpretations, and unphysical results (Camporese et al., 2015). These uncertainties can be minimised in case of prior information about the physical system under study. As discussed by Hinnell et al. (2010), the attractiveness of the coupled approach is that the hydrologic model may provide the physical context for a plausible interpretation of the geophysical measurements.

And yet, this strength is counterbalanced by a couple of weaknesses:

Firstly, at least for the EMI measurements, an instrumental shift in ECa readings can be frequently observed due to several well-known reasons, which is not the case to discuss here. The issue has also been raised by Reviewer#1, who correctly cited the work by von Hebel et al. (2014) where the authors used ECa values coming from the ERT measurements to remove the observed instrumental shift and correct the measured conductivity values by linear regression. The issue has been deeply discussed in the paper by Dragonetti et al. (2018). Firstly, this means that EMI-based readings do not immediately provide correct electrical conductivity distributions. Related to this and much more important for this discussion, if the shift in EMI readings was not removed, the coupled approach would necessarily lead to wrong and probably physically implausible, hydraulic parameters, as the ECa coming from the hydrological model would be forced to correspond to incorrect measured ECa distributions. Thus, the coupled approach always requires an independent dataset, obtained by different sensors (ERT, TDR, sampling) to remove the shift in the EMI-based ECa readings. This would contradict the spirit of our paper, which mainly aims at minimising the sensors and the data necessary for soil hydraulic characterization. Furthermore, the use of another methodology does not provide the true ECa data (See for example, the detailed answers below for the use of ERT), which further limits the application of coupled model. Another related problem lies in the empiricism involved in removing the shift, which means renouncing to understand its physical effects on the final water content and, from this, on the hydraulic property estimations. This will be explained better in the case of uncoupled approach);

Second, with the coupled approach, there is a problem related to the number of hydraulic parameters to be simultaneously optimised. In the ideal case of a single soil layer to be characterised (but quite unrealistic for a natural soil profile), the hydraulic parameters to be optimised are relatively limited (say at least θ_s, α, n and K_0, for the case of the unimodal van Genuchten-Mualem hydraulic properties, taking θ_r and tau fixed). If more than one layer has to be characterised, the coupled approach requires that all the parameters have to be simultaneously optimised. This is the only way to have the ECa imaging of the whole soil profile be compared to ECa readings in the objective function. In this case, the number of parameters increases significantly to a not-manageable number and may well produce problems of parameter correlation, uncertainty, and non-uniqueness of the solution. This is exactly the issue raised by the Reviewer#1 for our approach (later, we will explain how this problem may be minimised in the case of the uncoupled approach).

Uncoupled approach:

In the uncoupled approach, the geophysical model is the starting point of the procedure. As a result of geophysical inversion, the σ_b distributions are derived, which are then converted to as many distributions of water content. Let's call them "measured water contents", θmeas. These, in turn, are used as input in the hydrological model. Starting from initial guess values of the hydraulic parameters, the latter produces estimated water contents, θest. In the inversion, the objective function involves the residuals (θmeas - θest). This objective function is eventually minimised by optimising the hydraulic parameters in the hydrological model.

The main weakness of this approach corresponds to the strength of the coupled approach. The uncoupled approach requires geophysical inversion, involving all the problems discussed above about uncertainty coming from the problem's ill-posedness.

However, it should be noted that the methodology we propose in our paper does not require preliminary removal of the (unknown) shift in the EMI readings. Conversely, the shift effect is implicitly kept in the σ_b distributions, from this in the “measured” water content distributions and finally included in the hydrological inversion. This allowed us to see the effects of the EMI shift (as well as the technical limitations of the EMI sensor itself) in the water content estimations and from this in the hydraulic properties’ estimation. In the first case, by comparing the EMI-based water contents to the water contents coming from TDR, it was possible to see that the shift in the EMI readings produced parallel water content evolutions, thus meaning that the EMI shift is rather stable with water content change.

Related to this, in terms of hydraulic properties, the shift simply results in scaled saturated water content. Reviewer#1 considers this finding quite implausible. And yet, it may well be explained physically by just considering that the parallel behavior of the water contents over time, signifying similar water content changes over time. This is translated in similar hydraulic conductivities, which in the van Genuchten-Mualem model means similar α and n parameters, and thus water retention curves are simply scaled by the saturated water content ratio. All this (physical) behaviour would have remained completely hidden if the EMI shift had been removed.

The uncoupled approach may also allow for reducing the problems of parameter correlation and uniqueness, as it allows for sequential (from the upper to the lower horizon) parameter estimation. In the methodology proposed in the paper, the parameters were determined separately for each horizon of the profile. First, the parameters for the topsoil were estimated on the basis of the water contents “measured” in the first layer. Then these parameters were treated as known and those for the second layer were estimated in a similar way on the basis of the water contents and pressure heads in the same layer. According to Abbaspour et al. (1999) and Coppola et al. (2004), this approach makes parameter estimation of multi-layered profiles more feasible and accurate, however, this approach cannot be done within a coupled model, as already discussed above.

On an additional note, this research work is the first attempt to the best of our knowledge to explore the potential of the EMI method for the characterization of hydraulic and transport properties of the vadose zone in a very detailed and well-controlled experiment **(proof of concept)**. In this case study, parallel TDR and tensiometer measurements were also performed; our findings were compared in details to those obtained from these direct in-situ measurements.

Using ERT to calibrate ECa data:

We would like to point out some points about another major comment made by Reviewer #1 (Using ERT as a reference to calibrate ECa data prior to quantitative investigation). The authors have extensive experience with the ERT method and are aware of its pros and cons. Even though the ERT can be used to "evaluate" ECa data, calibration of ECa data using the ERT models has some limitations and does not necessarily provide corrected ECa data:

1- To obtain subsurface electrical conductivity distribution from ERT data, ERT data must be inverted. However, the inversion process is a highly nonlinear problem and the inverse solutions require regularisation procedures that impose additional constraints (e.g. smoothing). In the first general comment, Reviewer#1 correctly pointed out the same source of uncertainty. Other researchers that used the ERT method addressed this issue (e.g. Singha and Gorelick, 2005; Cassiani et al. 2012). The potential electrical static shift of apparent resistivity data (e.g. Meju, 2005) might need to be investigated in the case of ERT survey. We often use TDEM to correct the static shift of ERT data (e.g. Martínez-Moreno et al. 2017). These points obviously limit the use of ERT to calibrate other methods, especially in a "coupled" approach.

2- In monitoring experiments, such approaches are difficult to implement because the ECa ranges will change significantly during the experiments, and ERT measurements prior to the infiltration experiment is likely not sufficient. In other words, the calibration equation developed prior to the infiltration experiment cannot be clearly applied due to the lower values of ECa (and also smaller ranges of ECa changes) than later to be measured during the infiltration (see for example figure 8).

Finally, we believe that the motivation of our choice in applying an uncoupled inversion approach without calibration of EMI data should be provided and better justified in the revised version of the manuscript.

Sincerely,
Mohammad Farzamian on behalf of all authors

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