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Coupling geophysical measurements and hydrological modeling for the determination of longitudinal dispersivity.

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***Abstract* - The knowledge of the longitudinal dispersivity parameter is necessary to simulate solute transport in porous media. The direct measurement of this parameter is expensive and time consuming. Indirect methods based on the inverse modelling procedure provide an easier and reliable alternative, if measurements of solute concentration and soil water content are available.**

In this study, Hydrus 1D model was coupled with apparent electrical conductivity measured by means of the simple and rapid electromagnetic induction (EMI) technique in order to determine the longitudinal dispersion parameter in a sandy soil.

By means of forward Hydrus 1D simulations the temporal distribution of soil water content in 1 m depth soil profile was obtained. The soil water content and the inverted soil electrical conductivity were implemented in the Rhoades linear equation in order to determine the distribution of the soil solution electrical conductivity. Thereby, the longitudinal distribution parameter was finally determined by carrying out Hydrus 1D inversions.

The estimated dispersion parameter was 10.23 cm. The proposed procedure allows to obtain reasonable values of longitudinal dispersion with a good degree of approximation.

Keywords—Longitudinal dispersivity, Electromagnetic Induction, Hydrus 1D, Salinization, Soil water content, Electrical conductivity.

I. INTRODUCTION

Salinization is one of the main causes of soil degradation that limits agricultural productivity and can ultimately cause desertification and land abandonment [1].

In irrigated production systems, salinization risk depends on natural factors, such as soil type and local climate, but also on the quality of irrigation water and on irrigation and fertilization management practices. Therefore, adequate studies of solute transport play a key role in developing strategies that can contrast this phenomenon. These kinds of studies are particularly complex due to space and time variability of solute transport caused by chemical, biological and physical factors.

Traditional methods to determine soil salinity include direct field analyses and/or laboratory analyses of soil samples, which are costly in terms of time, money and work. These methodologies, based on local sampling, hardly provide information about the field soil conditions and soil properties, especially at the large scale and in case of heterogeneous materials.

On the other hand, at larger scales, geophysical methods provide enormous advantages respect to the traditional direct methods because they allow exhaustive and non-invasive analyses, cover large areas in less time and require little work efforts in the field [2]. Among geophysical methods, Electromagnetic Induction (EMI) has been widely used in agricultural applications because it allows accurate measurements in the root zone and the equipment is easy to set up, use and carry in the field [3]. EMI sensors provide measurements of the qualitative depth-weighted apparent electrical conductivity, σ_a [4]. In order to obtain the values of soil bulk electrical conductivity, σ_b in soil profiles, the σ_a measured by EMI sensors can be inverted by using the cumulative response [5] or the full solution of the Maxwell equation [6].

If on one hand EMI allows accurate measurements, on the other hand, to predict the salinization risk and fulfil soil management strategies, it is required to implement water flow and solute transport models of the root zone [7].

Hydrus-1D is a useful model to simulate the water flow and the solute transport in a variable saturated porous medium [8].

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The advection–dispersion equation (ADE) is applied for prediction of solute transport, both non-reactive and reactive (e.g. agrochemicals, salts), thus including – among many others – non-linear adsorption and decay equations:

$$\frac{\partial \theta C}{\partial t} + \rho_b \frac{\partial Q}{\partial t} = \frac{\partial q C}{\partial z} + \frac{\left(\partial \theta D \frac{\partial C}{\partial z}\right)}{\partial z} \qquad (1)$$

The hydrodynamic dispersion coefficient is a key parameter [9] related to the molecular diffusion constant of the substance in bulk water, D_0, and the pore water velocity, $v = q/\theta$, as:

$$D = \lambda v + \eta(\theta) D_0 \qquad (2)$$

where λ is the dispersivity and η a tortuosity coefficient. However, the contribution of diffusion to the hydrodynamic dispersion *D* is often very small. Accordingly, λ can simply derived from the ratio *D*/*v*.

λ depends on the scale of measurement and the distribution and interconnection of the pores [10], [11]. The λ value can be determined in the laboratory or in the field by using, in both cases, a tracer on soil columns. Concerning solute transport models, inverse optimization techniques are increasingly used to estimate the solute transport parameters [12]. These techniques allow to minimize the differences between the observed and the expected values.

The main objective of this study is to couple EMI measurements and Hydrus1D model in order to determine the longitudinal dispersion parameter of the investigated soil.

II. MATERIALS AND METHODS

The study was conducted in an experimental field of a commercial farm located in "Acerra" municipality, in southern Italy (Figure 1). The soil type was a *Mollic Vitric Andosol* [13] with a sandy loam texture and high chemical and physical fertility [14]. In the 18 x 68 m plot, the maize crop (*Zea mais*) was sown on April 16th and harvested on August 2nd 2018. The distance between two adjacent plant rows was 75 cm, whereas the distance between consecutive plants on the same row was 18 cm. The irrigation was managed by a drip irrigation system having drippers each 10 cm along the line. The flow rate was 1.5 l h^{-1}. Calcium Chloride, $CaCl_2$, was added to the irrigation water in order to obtain an electrical conductivity of 8 dS m^{-1}. EMI surveys were carried out during the period from 24th July to 02nd August using the CMD MiniExplorer (GF Instruments, s.r.o., Brno, Czech Republic) sensor to measure σ_a. A transect of 17 m was selected in the middle of experimental plot and the first measurements was performed in the last irrigation day (24th July) with site spacing of 1m. Measurements were performed twice per day for the first three days and once per day for the last five days.

To invert σ_a data and in order to obtain σ_b distribution, we used TerraEM. The 1D laterally constrained method [15] has been modified in this software to invert σ_a data, where each 1D conductivity model, obtained beneath each measurement site, is constrained by its neighbors. The earth model used in the forward model consists of a mesh of a number of blocks distributed according to the locations of the measurement sites and coil spacing. The full solution of the Maxwell equations is used in this software allowing the use of the algorithm in regions characterized by high-conductivity contrast. The damping factor in this program is a Lagrange multiplier and is used to control the balance between data fit and the smoothness difference of the model from the a priori model.

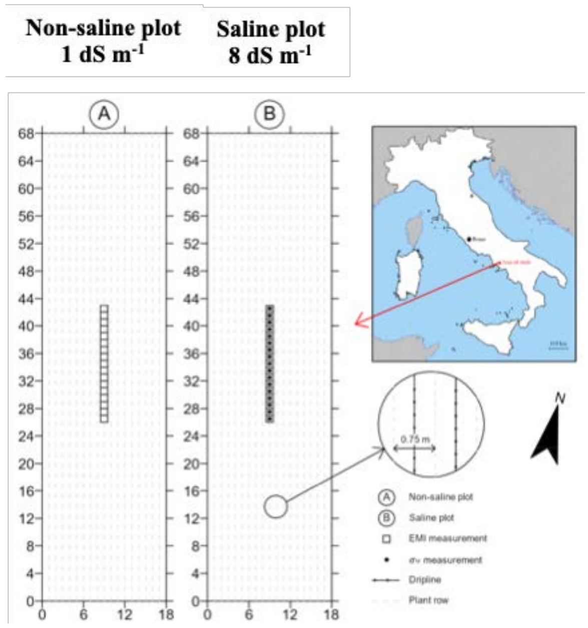

Fig. 1. Experimental field.

During the growing season, the volumetric soil water content *θ* and σ_b were also monitored by means of the TDR technique. In particular, a pair of 20 cm long three-wire TDR probes were installed at the depths of 15, 30, 45 and 55 cm along the soil profile. TDR measurements were performed by the Tektronix 1502C cable tester (Tektronix Inc., Baverton, OR, USA), and the acquired waveforms were analysed by using the WinTDR software [16].

On the last day of the experiment (2nd August), after the EMI measurements and the harvest, a trench was dug along the transect. In the trench at every meter of distance and at four depths (15, 50, 75 and 90 cm), TDR *θ* and σ_b measurements were performed (68 points in total).

The determination of the λ was carried out by implementing the procedure reported in Figure 2.

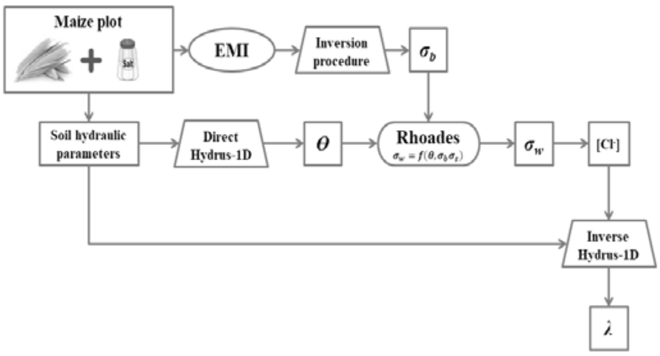

Fig. 2. Flowchart of the proposed procedure.

Specifically, the λ parameter was calculated for a 100 cm soil profile, by assuming a soil profile homogeneity. Such assumption was corroborated by independent measurements of soil homogeneity. Specifically, an exploratory EMI survey showed in both configurations (i.e. vertical and horizontal) a low range of variation, namely between 13 and 21 mS m^{-1}).

Moreover, the measured soil water retention and hydraulic conductivity curves along the profile show a relative homogeneity till the depth of 100 cm, as reported in the Table 1 of Bonfante et al. [14].

At the beginning of the implemented procedure, a Hydrus-1D forward simulation was performed in order to obtain the temporal dynamics of θ along a 1 m depth soil profile. The simulation domain has been divided into 100 nodes and the boundary conditions were set as atmospheric on the surface and free drainage in the bottom boundary. The simulation considered a period of 214 days from 1st January to 2nd August. The partition of the potential evapotranspiration in transpiration and potential evaporation was carried out following the Ritchie approach [17]. The main crop and soil parameters used in the simulation are shown in table 1. More specifically, hydraulic properties were determined in laboratory on undisturbed soil samples collected from each soil horizon. Soil samples were saturated from the bottom and the saturated hydraulic conductivity was measured by means of a variable head permeameter. After sealing the bottom surface to set a zero-flux boundary condition, measurements were taken during drying. At appropriate pre-set time intervals, the weight of the whole sample and the pressure head at three different depths were determined by means of tensiometers. An iterative procedure was applied for estimating the water retention curve from these measurements. The instantaneous profile method was used to determine the unsaturated hydraulic conductivity. Moreover, some points at a lower water content of the dry branch of the water retention curve were determined by a dew-point system (WP4 dew-point potentiometer, Decagon Devices Inc.). Details of the tests and overall calculation procedures have been described by Basile et al. [18].

TABLE I. MAIN CROP AND PARAMETERS OF SOIL HYDRAULIC PROPERTIES APPLYING MUALEM-VAN GENUCHTEN EQUATION [19]

Maximum root depth [cm]	51
Saturated soil water content [cm^3 cm^{-3}]	0.30
Residual water content [cm^3 cm^{-3}]	0.01
α parameter of van Genuchten equation [-]	0.006
n parameter of van Genuchten equation [-]	1.17
Saturated soil hydraulic conductivity [cm day^{-1}]	350

Then, the θ values resulting from Hydrus 1D forward simulations and the σ_b values obtained from EMI inversion were used in the Rhoades linear model [20] to determine the electrical conductivity of the soil solution, σ_w linearly related to the chloride concentration [Cl^-]:

$$\sigma_b = \theta T \sigma_w + \sigma_s \tag{3}$$

in which T is the transmission coefficient known as *tortuosity* which considers the tortuous nature of the current line and any decrease in the mobility of the solid-liquid and liquid-gas interfaces, while σ_s represents the electrical conductivity of the solid phase of the soil that is associated with the exchangeable ions in the solid-liquid interface. The tortuosity depends linearly with θ and takes the following form: $T = a\,\theta + b$, where a and b are constants parameters calibrated in laboratory for each type of soil.

Finally, by means of Hydrus 1D inversions, it was possible to obtain the λ parameter for the entire soil profile.

III. RESULTS

Time-lapse EMI measurements provided unique pictures of the redistribution of salt and water and insights into the infiltration process occurring within the soil.

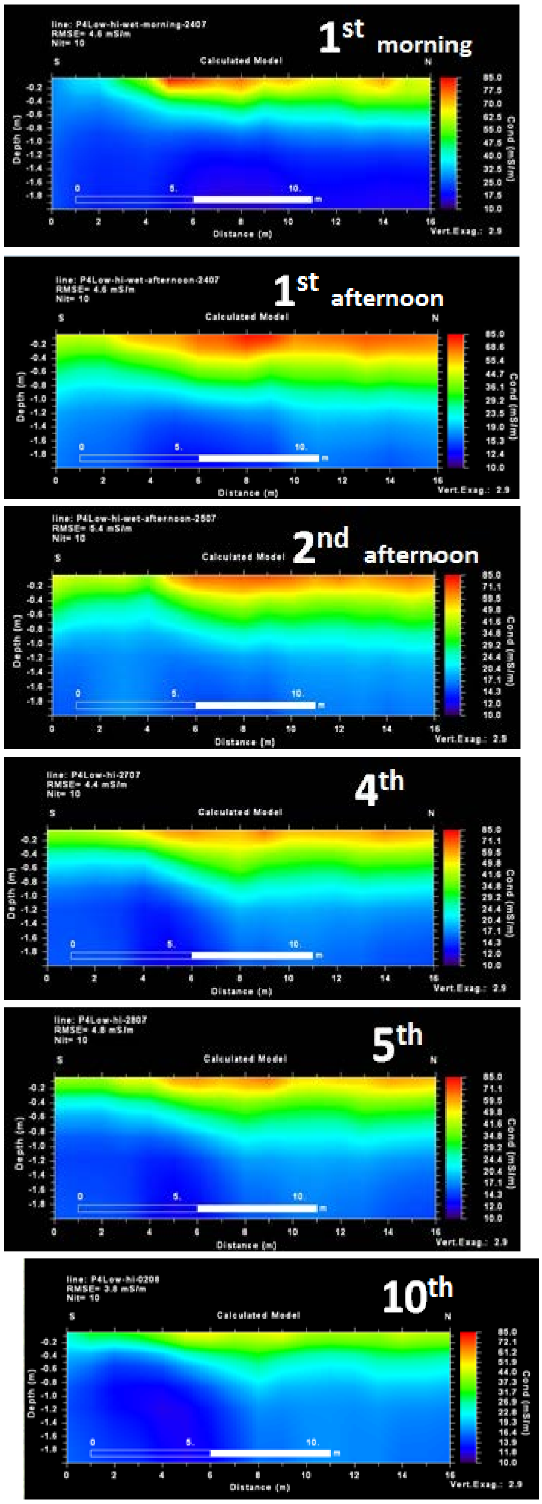

Fig. 3. Maps of σ_b during time laps experiment.

Figure 3 shows the variation of σ_b in space and time during the EMI measurement period which reflect the dynamic of soil and water changes after the last irrigation. From the time-lapse images, it is very evident that the σ_b values decreases after the 1st day, over time. Such dynamics provide information about the evolution of the wetting front in the soil profile, i.e. a deepening in the 1st day and then a clear regression. In addition, σ_b values sharply decreased from the near-surface to depth, suggesting that water and salt are accumulated in the shallowest soil horizons. The observed lateral variability is due to a non-uniform water distribution of the irrigation system (the pressure was systematically higher upstream than downstream). The statistical parameters resulting from the comparison between the values of θ calculated by Hydrus 1D and those measured in the field from TDR are reported in table II.

TABLE II. STATISTICAL PARAMETER OF SOIL WATER CONTENT

Depth	N	RMSE	Bias
[cm]	[-]	[cm^3 cm^{-3}]	[cm^3 cm^{-3}]
10	15	0.04	-0.01
30	16	0.01	0.00
45	16	0.02	0.02
55	14	0.01	0.01
All	61	0.02	0.00

The error expressed in terms of RMSE shows a reduction from the surface layers towards the deeper ones. Weak estimation in surface layers may be due to a negative effect on EMI measurements due to both surface irregularity and the possible influence of the rooting system.

Considering the entire profile, the average error expressed in terms of RMSE is 0.02 cm^3 cm^{-3}, whereas the bias is zero. This result demonstrates how the Hydrus-1D model has been correctly calibrated and therefore the dynamics of the estimated θ can be considered accurate.

The dispersion coefficient was determined by fitting the estimated and measured chloride concentration values. In our case, the longitudinal dispersion estimated by Hydrus 1D inversion was 10.23 cm. This value is representative of the field scale dispersion because the EMI measurements consider an entire volume of soil. The result agrees with dispersive values that were obtained at the field scale from other authors [11]. Moreover, it is not very far from the value of λ found in a sandy loam soil in New Zealand of 7.5 cm [21]. It is likely that the higher dispersive value of our soil is due to a higher variety of pore size distribution [11].

This result demonstrates that coupling the geophysical measurements with the hydrological modeling it is possible to obtain good estimation of the space-time variability of the soil bulk electrical conductivity, allowing among others the estimation of the solute dispersivity.

IV. CONCLUSION

In this work we developed a procedure aimed at estimating the soil longitudinal dispersion. Such a procedure combines EMI measurements and hydrological model. This procedure should be further tested on other soil types. In such a way, applicative issues at field scale on solute transport and salinization risk will be effective.

REFERENCES

[1] M. Farzamian et al., "Mapping soil salinity using electromagnetic conductivity imaging—A comparison of regional and location-specific calibrations," *L. Degrad. Dev.*, p. ldr.3317, May 2019.

[2] G. E. Moore, D. M. Burdick, C. R. Peter, and D. R. Keirstead, "Mapping soil pore water salinity of tidal marsh habitats using electromagnetic induction in great bay estuary, USA," *Wetlands*, vol. 31, no. 2, pp. 309–318, 2011.

[3] J. Robinet et al., "Spatial variability of soil water content and soil electrical conductivity across scales derived from Electromagnetic Induction and Time Domain Reflectometry," *Geoderma*, vol. 314, no. June, pp. 160–174, 2018.

[4] G. Dragonetti et al., "Calibrating electromagnetic induction conductivities with time-domain reflectometry measurements," Hydrol. *Earth Syst. Sci.*, vol. 22, no. 2, pp. 1509–1523, 2018.

[5] J.D. McNeill, "Electromagnetic terrain conductivity measurement at low induction numbers." *Geonics Limited, Technical Note TN-6*, 1980.

[6] A.A. Kaufman and G.V. Keller, "Frequency and transient soundings." *Methods in Geochem. and Geophys*. 16. Elsevier, New York, 1983.

[7] M. C. Gonçalves, J. S. Šimůnek, T. B. Ramos, J. C. Martins, M. J. Neves, and F. P. Pires, "Multicomponent solute transport in soil lysimeters irrigated with waters of different quality," *Water Resour. Res.*, vol. 42, pp. 1–17, 2006.

[8] J. Šimůnek, M. Šejna, H. Saito, M. Sakai, and M. T. van Genuchten, *The HYDRUS-1D Software Package for Simulating theOne-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media*, no. June. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 2013.

[9] B. H. Schmid and M. Asce, "Can Longitudinal Solute Transport Parameters Be Transferred to Different Flow Rates?" *J. Hydrol. Eng.*, vol. Vol. 13, I, no. June, pp. 505–509, 2008.

[10] P. Chakraborty and B. S. Das, "Measurement and Modeling of Longitudinal Dispersivity in Undisturbed Saturated Soil: An Experimental Approach,"*Soil Sci. Soc. Am. J.*, vol. 82, no. 5, p. 1117, 2018.

[11] D. E. Radcliffe and J. Simunek, *Soil Physics with HYDRUS*. Boca Raton: CRC Press, 2010.

[12] J. Šimůnek, D. Jacques, J. W. Hopmans, M. Inoue, M. Flury, and M. T. van Genuchten, "Solute Transport During Variably Saturated Flow — Inverse Methods," in *Method of Soil Analysis: Part 1. Physical Method*, 3rd ed., J. H. Dane and C. G. Topp, Eds. Madison, Wisc,: SSSA, 2002, pp. 1435–1449.

[13] IUSS Working Group WRB, *World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps Update 2015*. Rome: Food and Agriculture Organization of the United Nations, 2015.

[14] A. Bonfante et al., "LCIS DSS — An irrigation supporting system for water use efficiency improvement in precision agriculture: A maize case study," *Agric. Syst.*, vol. 176, no. January, p. 102646, 2019.

[15] F. A. Monteiro Santos, "1-D laterally constrained inversion of EM34 profiling data," *J. Appl. Geophys.*, vol. 56, no. 2, pp. 123–134, Jun. 2004.

[16] J.T. Ritchie, "Model for predicting evaporation from a row crop with incomplete cover," *Water Resources Research*, vol. 8, p. 1204–1213, 1972.

[17] D. Or, S. B. Jones, J. R. VanShaar, S. Humphries, and L. Koberstein, *WinTDR soil analysis software. Version 6.1*. Utah: Soil Physics @ Utah State University AND Envorimental Physics @ UConn, 2004.

[18] A. Basile, G. Buttafuoco, G. Mele, and A. Tedeschi, "Complementary techniques to assess physical properties of a fine soil irrigated with saline water," *Environ. Earth Sci*., vol. 66, p. 1797-1807, 2012.

[19] M.T. Van Genuchten, "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," *Soil Sci. Soc. Am. J*., vol. 44, p. 892–898, 1980.

[20] J. D. Rhoades, P. A. C. Raats, and R. J. Prather, “Effects of Liquid-phase Electrical Conductivity, Water Content, and Surface Conductivity on Bulk Soil Electrical Conductivity,” *Soil Sci. Soc. Am. J*., vol. 40, no. 5, p. 651, 1976.

[20] I. Vogeler, S. Green, A. Nadler, and C. Duwig, “Measuring transient solute transport through the vadoze zone using time domain reflectometry,” *Aust. J. Soil Res*., vol. 39, 2001.