Improving the estimation of complete field soil water characteristic curves through field monitoring data

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Title: Improving the estimation of complete field Soil Water Characteristic Curves through field monitoring data

Article Type: Research paper

Keywords: Soil Water Characteristic Curves; hysteresis; laboratory; monitoring; soil water storage

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Order of Authors: Massimiliano Bordoni, Ph.D.; Marco Bittelli; Roberto Valentino; Silvia Chersich; Claudia Meisina

Abstract: In this work, Soil Water Characteristic Curves (SWCCs) were reconstructed through simultaneous field measurements of soil pore water pressure and water content. The objective was to evaluate whether field-based monitoring can allow for the improvement of the accuracy in SWCCs estimation with respect to the use of laboratory techniques. Moreover, field assessment of SWCCs allowed to: a) quantify the hydrological hysteresis affecting SWCCs through field data; b) analyze the effect of different temporal resolution of field measures; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed and measured trends of a component of the soil water balance. These aspects were fundamental for assessing the reliability of the field reconstructed SWCCs. Field data at two Italian test-sites were measured. These test-sites were used to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. Field measured or laboratory measured SWCCs data of 5 soil horizons (3 in a predominantly silty soil, 2 in a predominantly clayey one) were fitted by Van Genuchten model. Different field drying and wetting periods were identified, based on monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts, of different cycles. This method allowed for a correct discrimination of the main drying and the main wetting paths from field data related and for a more reliable quantification of soil hydrological properties with respect to laboratory methodologies. Particular patterns of changes in SWCCs forms along depth could be also identified. Field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days), as testified by similar values of Van Genuchten equation fitting parameters. Instead, hourly data may offer a clearer vision of the drying and wetting paths, due to the highest number of experimental data points. Moreover, in temperate climate situations as those of the test-sites, main drying curves and main wetting curves of a particular soil were substantially similar also for different hydrological cycles with peculiar meteorological conditions. SWCCs parameters were implemented in

a numerical code (HYDRUS-1D) to simulate soil water storage for different soil horizons. Field reconstructed SWCCs allowed for simulating with a higher precision these trends, confirming the reliability of the reconstructed field curves by a quantitative point of view. Moreover, best results were obtained considering hysteresis in the modeling.

Response to Reviewers: Response to Reviewers

We want to thank the Associate Editor and the Reviewer for the interest in our research and for your valuable comments and revisions. All their suggestions have been carefully considered and taken as a guide to modify and improve our paper.
Please, find below point-by-point replies to the comments. For the references present in the responses, we refer to the References section of the revised version of the paper.
We submit a revised version of the original paper, where the texts and the figures which have been modified or added respect to the original version are highlighted in yellow color. Moreover, we provide a clean version of the revised paper.

Associate Editor

Comment 1
AE comment: One of the reviewers suggested some minor revisions to the paper. If the Authors will address these, the paper will become worthy of publication.

Response to Comment 1
We thank the Associate Editor for the appreciation of the paper. As described in the following Responses to the Comments, we considered all the revisions suggested by the Reviewer. These guaranteed an improvement for the overall quality of the paper. Point-by-point replies to Reviewer's comments follow.

Reviewer 1

Comment 1
Reviewer #1: HYDRL24589R1: Estimation of complete field Soil Water Characteristic Curves through field monitoring data" by Dr. Massimiliano Bordoni for Journal of Hydrology - second review by Peter Frederiksen
Overall comments
* The manuscript has been significantly improved by omitting less relevant sections on climate that were unrelated to the purpose of the article.

Response to Comment 1
We thank the Reviewer for the appreciation of the improvements made through the first revision of the paper.

Comment 2
* The purpose, experimental design, methods and results are still not properly distinguished.

Response to Comment 2
We thank the Reviewer for this suggestion, which allowed to improve the comprehension of the paper. We clarified better the presentation of these aspects of the paper. Regarding this revision, we refer to responses to Comments 3, 4, 5, 6 and 7.

Comment 3
* Is the purpose to investigate whether field-based monitoring can improve results from laboratory investigations. This strongly suggested by the Abstract and Introduction, but appear implicitly and not explicitly stated.

Response to Comment 3
We made the purpose to investigate whether field-based monitoring can improve the assessment of SWCCs explicit. We stated this information at pag. 2 lines 3-5 of the Abstract section and pag. 9 lines 1-3 of the Introduction section of the revised version of the manuscript.

Comment 4
* The experimental design is not explicitly stated. If the purpose is the purpose the experimental design is the guiding principle. Why did the authors select the two test-sites? Substantial and comparable data were collected - supposedly for comparative purposes. Was a clayey and silty soil selected, because it was assumed that soil texture differences would lead to different SWCC? Please explain your decisions explicitly - why did you select two sites?

Response to Comment 4
Two different test-sites were considered to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. We clarified this aspect at pag. 2 lines 11-13 of the Abstract section and pag. 9 lines 15-18 of the Introduction section of the revised version of the manuscript.

Comment 5
* The "aim" seems to be a more detailed account of the experimental design. Why did you select to investigate the mentioned points? The aim is not the real purpose. The purpose controls the experimental design and methods applied, whereas the "aim" is closer to a table of contents for the discussion.

Response to Comment 5
As indicated at pag. 7 lines 21-24 and pag. 8 lines 1-23 of the revised version of the manuscript, literature review highlighted that some aspects need to be investigated more in detail for evaluating if field reconstructed SWCCs may or may not improve the reconstruction of reliable SWCCs of the real soil hydrological features. These aspects can be summarized in:

a) the possibility of measuring and quantifying hysteresis, that may affect soil water processes, through an identification of the events or periods of a hydrological year that are representative of soil drying or wetting conditions;

b) the effects of considering different resolution time of the field measurements (e.g hourly or daily measures) in the reconstruction of the

SWCCs. Cristiano et al. (2016) and Persson and Saifadeen (2016) reviewed main researches about the influence of temporal and spatial resolution of the measures of contaminant fluxes in soils, rainfall amount and superficial water fluxes in understanding the hydrological behaviors of a certain area. They concluded that time scaling techniques and time resolution of these measures can influence the complete comprehension of the hydrological response of a soil or of a catchment to particular meteorological conditions. Starting from this, it is important to investigate the effects of temporal resolution on field reconstructed SWCCs, which can be obtained from monitoring data measured at different scaling times;

c) the variation in SWCCs patterns according to different field meteorological conditions along a complete hydrological cycle (a cycle is defined as a drying period followed by a wetting one; Hopmans and Dane, 1986). During a two-year monitoring campaign in a hillslope of a tropical region in Hong Kong country, Leung and Ng (2013) observed a change in SWCC path and in the amount of hysteresis from one year to the other one. In particular, remarkable hysteretic behavior was measured for the year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity), while hysteresis was substantially negligible in a year with lower rain events. Starting from this, it is important to analyze more in detail the possible changes which can occur on field SWCCs paths along several years with peculiar meteorological conditions;

d) the goodness of the field reconstructed SWCCs, obtained by implementing their characteristic parameters in a hydrological model for the assessment of a variable of the water balance in soil.

Thus, in this paper, we aimed to: a) quantify the hydrological hysteresis affecting SWCCs by indentifying the drying and the wetting phases through an objective method which takes into account the main meteorological patterns along a hydrological year; b) analyze the effect of considering hourly or daily field measures of soil pore water pressure and water content in the reconstruction of SWCCs; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed (through the implementation of the field SWCCs parameters in a hydrological model) and measured soil water storages during a hydrological cycle. Thus, the comprehension of these aims were fundamental to fill the gaps in the evaluation of the reliability of a field-based estimation of SWCCs.

Comment 6

* The author's selection of methods is a logical consequence of the Abstract and Introduction, and are highly relevant, but omitted from an experimental design not yet present in the manuscript

Response to Comment 6

We clarified this aspect at pag. 9 lines 18-24 and pag. 10 lines 1-4 of the revised version of the manuscript.

Comment 7

* Conclusion: The presented arguments suggest that a clear distinction between purpose, experimental design, methods and results is required, but not found to be relevant by the authors.

Response to Comment 7

We re-arranged Conclusions section, in order to present in a clearer way purpose, experimental design, methods and results of the paper. In particular, this clarification was added at pag. 43 lines 7-15 of the revised version of the manuscript.

Comment 8
* not found t , at is relevant, and should The comments on the soil landscape and properties are still valid and are detailed below
Soil property and SWCC comments
* The geological, geomorphological and soil taxonomical information provide limited information on soil profile and horizon properties of relevance to SWCC. Please consider only to present information of importance to SWCC. Select hose of relevance only.

Response to Comment 8
We re-arranged sections 2.1.1 and 2.1.2, deleting the redundant sentences. Also the parts, which had not significant importance to SWCCs, were deleted.

Comment 9
* The authors indicate that soil matrix properties do not influence SWCC. Why is no information soil properties of individual horizons, vertical differences in soil properties and among profiles presented? At present, soil information is limited to clayey and silty, whereas extensive information is given on geology, geomorphology and taxonomy of limited importance to SWCC. How does the clay mineralogy, soil texture and structure, stone content, chalk and marl influence SWCC? Please provide relevant information given their influence on SWCC and given that the two soils differ or why their difference is irrelevant to SWCC?

Response to Comment 9
We improved the description of the two soil profiles, in order to clarify some features which can influences SWCCs.
As indicated at pag. 11 lines 6-24 and pag. 12 lines 1-18 of the revised version of the manuscript, all the soil layers of Montuè soil profile have a subangolar polihedral structure. Aggregation is weak till 0.2 m from ground, while it is compact in deepest levels. Soil horizons are mineral, with a basic pH (< 9) that is steady along depth. Moreover, they have organic carbon content lower than 5%, and are characterized by the presence of millimetric carbonate coatings, which determine a carbonate content higher than 10%, till 35.3% in G-M horizon. Evidences of marls levels is absent in the soil profile. Grain size distribution is uniform along depth in the soil. All the soil horizons have a clayey sandy silt texture, with high silt contents ranging from 51 to 66%, clay content between 21 and 29% and steady sand content between 7 and 13% (Tab. 1). Gravel content is low and keeps quite steady, in a range every lower than 15% (Tab. 1). Thus, the soil horizons have not gravelly features, according to United States Department of Agriculture (2014). Gravel class is constituted of pebbles made by fragments of bedrock materials and with diameters till few centimeters. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are prevalently non-plastic or slightly plastic (CL). The liquid limit (wL) ranges from 38 to 42%, while the plasticity index (PI) ranges from 14 to 17% (Tab. 1). Unit weight (γ) ranges between 16.7 and 18.6 kN/m3 (Tab. 1). Also all these features keep substantially uniform along the depth in the soil profile. It is worth noting that all the soil horizons have

similar mineralogical features, with a substantially similar amount in carbonates and clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is characterized by the presence of smectite and chlorite. In particular, smectite represents about the 50%, thus about 8-10% of the solid particles in the studied soils. These percentages keep steady along depth in the different layers. The amount in this swelling clay mineral is approximately lower than the minimum one (12-15%; Dexter, 1988) responsible to the creation of pedological processes which can provoke turbation on the soil profile. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling soils in the studied materials, such as slickensides, wedge-shaped aggregate units, cyclic sub-surface horizons, gilgai microtopography (Blokhuis et al., 1990). There are only superficial cracks that form in dry summer months and extend few centimeters in depth. It is also important to note that natural revegetation of this slope have started since 2000. In fact, the slope had been cultivated with vineyards for at least 50 years before.

As indicated at pag. 13 lines 13-24 and pag. 14 lines 1-22 of the revised version of the manuscript, as in Montuè test-site, all the soil layers of Centonara slope have a subangolar polihedral structure and the soil aggregation change from weak to low strong aggregation below 0.2 m from ground. The soil horizons are mineral (organic carbon content lower than 5%), calcareous (testified by the presence of millimetric carbonate coatings) and with a basic pH (< 9) (Bittelli et al., 2012) as Montuè test-site. All these features keep steady along depth in this soil profile. As in Montuè soil profile, evidences of marls levels is absent in the soil profile. Within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, there is a layer of compacted material, with strong gleying, revealing stagnant saturated and reducing conditions along most wet periods of the year. All the soil horizons have a silty clay texture, with steady grain size distribution along depth. Clay content is high, ranging between 46 and 60% (Tab. 2). Silt and sand amounts are similar in all the horizons (23-38% for silt amount, 15-17% for sand amount). Stones and gravels are absent in all the soil levels. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are inorganic clay with high plasticity (HL). wL and PI are the same along the soil profile, with values of 76 and 46% respectively (Tab. 2). Also the unit weight of the soil (γ) is similar in all the soil profiles (18.0 kN/m3; Tab. 2). Also all these features keep substantially uniform along the depth in the soil profile. It is worth noting that all the soil horizons have similar mineralogical features, with a predominance in clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is mainly composed by smectite and vermiculite and it keeps steady along depth. The amount in these swelling clays is higher than in Montuè test-site (more than 15%). Thus, swelling-shrinking is more pronounced, even if the soil profile is not significantly disturbed. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling materials, as already observed in Montuè test-site. Shrinking cracks form in dry summer months, extending more in depth than in Montuè soil profile, till around the first 0.4 m along the profile. Moreover, anthropogenic disturbance is absent because the site is on a naturally-vegetated slope.

According to the features of Montuè and Centonara soils, main relevant differences between the soil profiles are related to: i) the soil texture, because Montuè horizons have clayey sandy silt texture, while Centonara layers have silty clay texture; ii) the soil mineralogy, because Montuè soils are characterized by a similar percentage in carbonates and clay minerals, while clays are significantly predominant in Centonara layers; iii) the soil plasticity, which is a direct consequence of difference in soil texture and mineralogy, because Montuè soils and Centonara soils are low plastic and high plastic soils, respectively; iv) the aggregation features in the deep soil layers, because Montuè horizons under 0.2 m from ground have a compact structure, while all the horizons in Centonara profile have a weak aggregation. Considering the same soil profile, the most significant difference in the horizons along depth is linked to the soil aggregation at both test-sites. Below 0.2 m from ground level, both studied soils change their aggregation, passing from a weak to low strong aggregation. This was added at pag. 35 lines 11-20 of the revised version of the manuscript. SWCCs of the two tested profiles present differences, according to the differences in terms of texture, that also reflect their difference in plasticity degree and mineralogy. θs and θr are averagely higher in Centonara silty clay soils, because soils with a predominant clay texture and mineralogy have a higher porosity and a higher amount of residual water than predominant silty soils such as Montuè ones (Terzaghi et al., 1996). According to soil texture, α parameter of predominantly silty Montuè soils and of silty clay Centonara soils are in the typical ranges of these textural class, respectively (0.019±0.015 kPa-1 and 0.005±0.005 kPa-1 for predominant silty and silty clay soils, resepctively; Carsel and Parrish, 1988). Instead, n parameter of predominantly silty Montuè soils is near to the typical range of this type of soil (1.31±0.09; Carsel and Parrish, 1988), while this parameter is significantly higher in Centonara soils than its typical range in clay soils (1.09±0.06; Carsel and Parrish, 1988), probably for the intrinsic physical/geotechnical features of the soil profile. This clarification was added at pag. 36 lines 11-22 of the revised version of the manuscript.

Taking into account the variations on SWCCs curves in different depths of the same soil profile, it is important to note that only θs parameter varied in the studied layers at Montuè test-site. In fact, θs values of MDCs and MWCs of the C-M horizon were lower of 0.08-0.11 m3/m3 (Tab. 7) than the values of the paths for the other studied levels (E-M and G-M horizon). C-M horizon is the most superficial studied level at Montuè test-site (0.2 m from ground level) and has a weak aggregated structure. Its θs may be affected by the past tillage operations related to grapevines cultivations, which occurred in Montuè test site before 2000s. In fact, tillage operations generally reduce soil θs respect to uncultivated fields. Azooz et al. (1996) found a maximum reduction in soil water content close to saturation of 0.12 m3/m3 in the first 0.3 m from the ground level of soils with tillage. This range is consistent with the data measured at Montuè site. Increase in θs parameter registered in G-M horizon respect to E-M level is less significant and is of only 6%. This could be linked only to a slight natural heterogeneity of physical features along depth. Instead, considering an uncultivated slope, as Centonara test-site, where soil physical and mineralogical features are substantially similar in the different layers (Tab. 2), it is important to note that several fitting parameters of SWCCs changed along depth (Tab. 8). In particular, n parameter values decreased in the order of 0.35-0.90 both for MDC and MWC curves, while, only for MWCs, θs and α increased from 0.41 to 0.49 m3/m3 and from 0.003 to 0.017 kPa-1, respectively. Lohse and Dietrich (2005) found similar results in the first 0.5 m of silty clayey soil, stating in particular that θs and α increased along depth in a statistically significant way. It could be hypothesized that, in correspondence of uncultivated sites, SWCCs may change along depth in the soil profile, as a consequence of changes in horizons structure caused by a decrease in soil weathering which may influence hydrological features (Lohse and Dietrich, 2005). These explanations were described at pag. 36 lines 23-24 and pag. 37 lines 1-20 of the revised version of the manuscript.

Comment 10
* The authors indicate that soil water properties do not influence SWCC. The profile description of the Montué soil suggests that gley is present seen in the Aquic designation. Which is the importance of the groundwater table and clay content for gley and/or pseududogley specific to individual horizons, pore saturations, hydraulic conductivity/resistance and SWCC? Given that gley or pseudogley is present, does the soil profile receive upslope groundwater?

Response to Comment 10
We clarified the role of soil water properties on SWCCs features.
At Montuè site, soil texture and clay content are similar all along the soil profile. Reddish cutans, related to gleying features, are present in all the horizons of the soil profile, revealing a possible water table uprise. According to the monitored data collected in this site, a perched water table forms in the G-M horizon during most wet seasons (winter and spring) and can uprise in soil profile during most intense rainfalls of wet season. This condition keeps for the most wet period of the year (Bordoni et al., 2015a). Analyzed data also suggest a predominant recharge for vertical rainfall infiltration along the year, from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bordoni et al., 2015). These clarifications were added at pag. 11 lines 10-12 and pag. 26 lines 14-18 of the revised version of the manuscript. According to this, SWCCs of the three analyzed horizons at Montuè site (C-M at 0.2 m from ground, E-M at 0.6 m from ground and G-M at 1.2 m from ground) are not influenced by lateral fluxes in soils, while gleying conditions are present in all the tested layers. Furthermore, it is worth noting that the perched water table present in G-M horizon during most wet seasons (winter and spring) does not influence significantly SWCC. This water table is not present for an entire year, thus this layer can experience a wide range of water content and pore water pressure allowing to reconstruct well a complete SWCC. This explanation was added at pag. 35 lines 21-24 and pag. 36 lines 1-2 of the revised version of the manuscript.
At Centonara site, clay content and soil texture are similar all along the soil profile. Gleying evidences (reddish cutans) are present only within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, revealing stagnant saturated and reducing conditions along most wet periods of the year. Gleying features are absent in the other soil layers, testifying the uprise of the ground water table only till 1.45 m from ground level. Monitoring data collected at this test-site also suggest a predominant recharge in the soil for vertical rainfall infiltration from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bittelli et al., 2012). These clarifications were added at pag. 13 lines 19-22 and pag. 28 lines 2-4 of the revised version of the manuscript. According to this, it is worth noting that SWCCs of the two analyzed horizons (A-C at 0.2 m from ground and B-C at 0.4 m from ground) are not influenced by particular soil hydrological features, as ground water tables, gleying condtions, lateral fluxes. In fact, pedological features and monitoring data of these levels do not present particular signs of those hydrological conditions. Even if monitored data were not acquired and,

thus, SWCCs were not reconstructed, only D-C layer may be influenced by these properties, because it presents gleying evidences which testify the presence of stagnant reducing conditions typical of the persistence of a water table. This explanation was added at pag. 36 lines 3-10 of the revised version of the manuscript.

Highlights

- Soil Water Characteristic Curves (SWCCs) were obtained from field monitored data at two Italian test-sites.
- An effective estimation of drying and wetting paths based on meteorological data was proposed.
- Hydrological parameters and hysteresis was quantified in a more reliable way than laboratory methodologies.
- Field SWCCs estimation is not affected by the temporal resolution of the acquisition or using data of different hydrological years.
- Field SWCCs allowed for simulating better observed trends of soil water storages.

UNIVERSITÀ DEGLI STUDI DI PAVIA
DIPARTIMENTO DI SCIENZE DELLA TERRA E DELL'AMBIENTE

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Pavia, 28 March 2017

Object: submission of the paper Bordoni M., Bittelli M., Valentino R., Chersich S., Meisina C. "Estimation of complete field Soil Water Characteristic Curves through field monitoring data"

Dear editor,

We wish to submit an original research article entitled "*Estimation of complete field Soil Water Characteristic Curves through field monitoring data*" by Bordoni M., Bittelli M., Valentino R., Chersich S. and Meisina C. for consideration for publication in *Journal of Hydrology* journal.

A research has been carried out by University of Pavia, in collaboration with University of Bologna and University of Parma, to fill the gaps in the methodology of assessment of Soil Water Characteristic Curves (SWCCs) by means of data collected through field monitoring. SWCC is a fundamental hydrological property of the soil and its correct reconstruction, comprising Main Drying Curve (MDC) and Main Wetting Curve (MWC) paths, is required for a reliable soil water balance estimation and for other agronomical/geological/engineering problems.

For improving the reliability in the analysis and the interpretation of field data in reconstructing SWCCs, several aspects needed to be clarified:

a) the possibility of measuring and quantifying hysteresis, that may affect soil water processes, through an identification of the events or periods of a hydrological year that are representative of soil drying or wetting conditions;
b) the effects of considering different resolution time of the field measurements (e.g hourly or daily measures) in the reconstruction of the SWCCs and in the assessment of their properties;

c) the variation in SWCCs patterns according to different field meteorological conditions along a complete hydrological cycle (e.g. hydrological years characterized by significantly different rainfall amounts and/or by different average temperatures);
d) the goodness of the field reconstructed SWCCs, assessed implementing their characteristic parameters in a hydrological model for the assessment of a variable of the water balance in soil.

For these reasons, this paper aimed to reconstruct SWCCs through simultaneous field measurements of soil pore water pressure and water content, in order to: a) quantify the hydrological hysteresis affecting SWCCs, indentifying the drying and the wetting phases by an objective method which takes into account the main meteorological patterns along a hydrological year; b) analyze the effect of considering hourly or daily field measures of soil pore water pressure and water content in the reconstruction of SWCCs; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed, through the implementation of the field SWCCs parameters in a hydrological model, and measured soil water storages during a hydrological cycle.

An effective method for assessing different hydrological cycles of each site was implemented on the basis of monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts. This approach guarantees the distinction of drying and wetting periods, allowing to discriminate correctly field data related to MDC or to MWC paths of a soil. Field reconstructed SWCCs are then assessed in both their components, quantifying hydrological parameters and hysteresis in a more reliable way than laboratory methodologies. Field methods allow to measure a bigger amount of data than the few tens of laboratory experimental points. This permits to identify better the soil hydrological behaviors and to obtain more robust fitted curves.
Besides the limited number of tested soils (5), it is important to note that field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days). Moreover, MDCs and MWCs of a particular soil are substantially similar for different hydrological cycles with peculiar meteorological conditions, confirming how a soil follows the same SWCC paths along different years. According to this behavior, reliable field SWCCs can be reconstructed after only one complete hydrological cycle (a drying phase followed by a wetting one), even if collection of experimental data from more cycles may guarantee a better comprehension of MDC and MWC paths, thanks to the higher number of influencing meteorological events.
The effectiveness of the field reconstructed SWCCs are demonstrated also by the implementation of their parameters for modeling a component of the soil water balance as the soil water storage. Considering field SWCCs allows to simulate the observed trends of soil water storages for different soil horizons with a higher reliability than using laboratory reconstructed SWCCs. This means that field experimental SWCCs allow to represent better the environmental soil hydrological behaviors and the variability of soil response to different meteorological and climatic conditions.
It is also important to highlight that neglecting hysteretic effects on modeling soil water balance can induce significant errors in the results of the modeling. Thus, a complete (MDC+MWC) SWCC is required for a better simulation of the observed trends of the components in the soil water balance.

As a general conclusion, experimental data of field hydrological monitoring devices can be useful tools for assessing SWCCs, allowing in particular to quantify better the real hysteretic features of a soil and to obtain more accurately the hydrological parameters representative of the real soil behaviors. Instead, it is fundamental an accurate distinction between drying and wetting periods that characterize a field site, in order to discriminate MDC and MWC of a soil.

We believe that this manuscript is appropriate for publication by Journal of Hydrology because it analyzes and discusses several aspects which could allow to improve the effectiveness of SWCC using field monitoring data. In fact, important results were reached, allowing to clarify different gaps on field SWCC estimation. Moreover, the results of this paper contribute at: 1) demonstrating the possibility on reconstructing complete SWCCs, quantifying, in particular, hydrological hysteresis during the entire hydrological path of a soil; 2) furnishing a reliable method to distinguish drying and wetting periods of a site, according to easily measured meteorological data; 3) obtaining a better assessment of the main components of soil water balance (such as soil water storage) than using only laboratory determined SWCCs.

We confirm that this manuscript has not been published elsewhere and it is not under consideration by another journal.

All authors have approved the manuscript and agree with its submission to Journal of Hydrology.

Please address all correspondence concerning this manuscript to me at massimiliano.bordoni01@universitadipavia.it.

Thank you for your consideration of this manuscript.

Sincerely

Massimiliano Bordoni

Response to Reviewers

We want to thank the Associate Editor and the Reviewer for the interest in our research and for your valuable comments and revisions. All their suggestions have been carefully considered and taken as a guide to modify and improve our paper.
Please, find below point-by-point replies to the comments. For the references present in the responses, we refer to the References section of the revised version of the paper.
We submit a revised version of the original paper, where the texts and the figures which have been modified or added respect to the original version are highlighted in yellow color. Moreover, we provide a clean version of the revised paper.

Associate Editor

Comment 1

AE comment: One of the reviewers suggested some minor revisions to the paper. If the Authors will address these, the paper will become worthy of publication.

Response to Comment 1

We thank the Associate Editor for the appreciation of the paper. As described in the following Responses to the Comments, we considered all the revisions suggested by the Reviewer. These guaranteed an improvement for the overall quality of the paper. Point-by-point replies to Reviewer's comments follow.

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Overall comments

** The manuscript has been significantly improved by omitting less relevant sections on climate that were unrelated to the purpose of the article.*

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We thank the Reviewer for the appreciation of the improvements made through the first revision of the paper.

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** The purpose, experimental design, methods and results are still not properly distinguished.*

Response to Comment 2

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Comment 4

** The experimental design is not explicitly stated. If the purpose is the purpose the experimental design is the guiding principle. Why did the authors select the two test-sites? Substantial and comparable data were collected - supposedly for comparative purposes. Was a clayey and silty soil selected, because it was assumed that soil texture differences would lead to different SWCC? Please explain your decisions explicitly - why did you select two sites?*

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We clarified this aspect at pag. 2 lines 11-13 of the Abstract section and pag. 9 lines 15-18 of the Introduction section of the revised version of the manuscript.

Comment 5

** The "aim" seems to be a more detailed account of the experimental design. Why did you select to investigate the mentioned points? The aim is not the real purpose. The purpose controls the experimental design and methods applied, whereas the "aim" is closer to a table of contents for the discussion.*

Response to Comment 5

As indicated at pag. 7 lines 21-24 and pag. 8 lines 1-23 of the revised version of the manuscript, literature review highlighted that some aspects need to be investigated more in detail for evaluating if field reconstructed SWCCs may or may not improve the reconstruction of reliable SWCCs of the real soil hydrological features. These aspects can be summarized in:

a) the possibility of measuring and quantifying hysteresis, that may affect soil water processes, through an identification of the events or periods of a hydrological year that are representative of soil drying or wetting conditions;
b) the effects of considering different resolution time of the field measurements (e.g hourly or daily measures) in the reconstruction of the SWCCs. Cristiano et al. (2016) and Persson and Saifadeen (2016) reviewed main researches about the influence of temporal and spatial resolution of the measures of contaminant fluxes in soils, rainfall amount and superficial water fluxes in understanding the hydrological behaviors of a certain area. They concluded that time scaling techniques and time resolution of these measures can influence the complete comprehension of the hydrological response of a soil or of a catchment to particular meteorological conditions. Starting from this, it is important to investigate the effects of temporal resolution on field reconstructed SWCCs, which can be obtained from monitoring data measured at different scaling times;
c) the variation in SWCCs patterns according to different field meteorological conditions along a complete hydrological cycle (a cycle is defined as a drying period followed by a wetting one; Hopmans and Dane, 1986). During a two-year monitoring campaign in a hillslope of a tropical region in Hong Kong country, Leung and Ng (2013) observed a change in SWCC path and in the amount of hysteresis from one year to the other one. In particular, remarkable hysteretic behavior was measured for the year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity), while hysteresis was substantially negligible in a year with lower rain events. Starting from this, it is important to analyze more in detail the possible changes which can occur on field SWCCs paths along several years with peculiar meteorological conditions;
d) the goodness of the field reconstructed SWCCs, obtained by implementing their characteristic parameters in a hydrological model for the assessment of a variable of the water balance in soil.

Thus, in this paper, we aimed to: a) quantify the hydrological hysteresis affecting SWCCs by indentifying the drying and the wetting phases through an objective method which takes into account the main meteorological patterns along a hydrological year; b) analyze the effect of considering hourly or daily field measures of soil pore water pressure and water content in the reconstruction of SWCCs; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed (through the implementation of the field SWCCs parameters in a hydrological model) and measured soil water storages during a hydrological cycle. Thus, the comprehension of these aims were fundamental to fill the gaps in the evaluation of the reliability of a field-based estimation of SWCCs.

Comment 6

** The author's selection of methods is a logical consequence of the Abstract and Introduction, and are highly relevant, but omitted from an experimental design not yet present in the manuscript*

Response to Comment 6

We clarified this aspect at pag. 9 lines 18-24 and pag. 10 lines 1-4 of the revised version of the manuscript.

Comment 7

** Conclusion: The presented arguments suggest that a clear distinction between purpose, experimental design, methods and results is required, but not found to be relevant by the authors.*

Response to Comment 7

We re-arranged Conclusions section, in order to present in a clearer way purpose, experimental design, methods and results of the paper. In particular, this clarification was added at pag. 43 lines 7-15 of the revised version of the manuscript.

Comment 8

** not found t , at is relevant, and should The comments on the soil landscape and properties are still valid and are detailed below*

Soil property and SWCC comments

** The geological, geomorphological and soil taxonomical information provide limited information on soil profile and horizon properties of relevance to SWCC. Please consider only to present information of importance to SWCC. Select hose of relevance only.*

Response to Comment 8

We re-arranged sections 2.1.1 and 2.1.2, deleting the redundant sentences. Also the parts, which had not significant importance to SWCCs, were deleted.

Comment 9

** The authors indicate that soil matrix properties do not influence SWCC. Why is no information soil properties of individual horizons, vertical differences in soil properties and among profiles presented? At present, soil information is limited to clayey and silty, whereas extensive information is given on geology, geomorphology and taxonomy of limited importance to SWCC. How does the* *clay mineralogy, soil texture and structure, stone content, chalk and marl influence SWCC? Please provide relevant information given their influence on SWCC and given that the two soils differ or why their difference is irrelevant to SWCC?*

Response to Comment 9

We improved the description of the two soil profiles, in order to clarify some features which can influences SWCCs.

As indicated at pag. 11 lines 6-24 and pag. 12 lines 1-18 of the revised version of the manuscript, all the soil layers of Montuè soil profile have a subangolar polihedral structure. Aggregation is weak till 0.2 m from ground, while it is compact in deepest levels. Soil horizons are mineral, with a basic pH (< 9) that is steady along depth. Moreover, they have organic carbon content lower than 5%, and are characterized by the presence of millimetric carbonate coatings, which determine a carbonate content higher than 10%, till 35.3% in G-M horizon. Evidences of marls levels is absent in the soil profile. Grain size distribution is uniform along depth in the soil. All the soil horizons have a clayey sandy silt texture, with high silt contents ranging from 51 to 66%, clay content between 21 and 29% and steady sand content between 7 and 13% (Tab. 1). Gravel content is low and keeps quite steady, in a range every lower than 15% (Tab. 1). Thus, the soil horizons have not gravelly features, according to United States Department of Agriculture (2014). Gravel class is constituted of pebbles made by fragments of bedrock materials and with diameters till few centimeters. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are prevalently non-plastic or slightly plastic (CL). The liquid limit (w_L) ranges from 38 to 42%, while the plasticity index (P_I) ranges from 14 to 17% (Tab. 1). Unit weight (γ) ranges between 16.7 and 18.6 kN/m^3 (Tab. 1). Also all these features keep substantially uniform along the depth in the soil profile. It is worth noting that all the soil horizons have similar mineralogical features, with a substantially similar amount in carbonates and clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is characterized by the presence of smectite and chlorite. In particular, smectite represents about the 50%, thus about 8-10% of the solid particles in the studied soils. These percentages keep steady along depth in the different layers. The amount in this swelling clay mineral is approximately lower than the minimum one (12-15%; Dexter, 1988) responsible to the creation of pedological processes which can provoke turbation on the soil profile. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling soils in the studied materials, such as slickensides, wedge-shaped aggregate units, cyclic sub-surface horizons, gilgai microtopography (Blokhuis et al., 1990). There are only superficial cracks that form in dry summer months and extend few centimeters in depth. It is also important to note that natural revegetation of this slope have started since 2000. In fact, the slope had been cultivated with vineyards for at least 50 years before.

As indicated at pag. 13 lines 13-24 and pag. 14 lines 1-22 of the revised version of the manuscript, as in Montuè test-site, all the soil layers of Centonara slope have a subangolar polihedral structure and the soil aggregation change from weak to low strong aggregation below 0.2 m from ground. The soil horizons are mineral (organic carbon content lower than 5%), calcareous (testified by the presence of millimetric carbonate coatings) and with a basic pH (< 9) (Bittelli et al., 2012) as Montuè test-site. All these features keep steady along depth in this soil profile. As in Montuè soil profile, evidences of marls levels is absent in the soil profile. Within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, there is a layer of compacted material, with strong gleying, revealing stagnant saturated and reducing conditions along most wet periods of the year.

All the soil horizons have a silty clay texture, with steady grain size distribution along depth. Clay content is high, ranging between 46 and 60% (Tab. 2). Silt and sand amounts are similar in all the horizons (23-38% for silt amount, 15-17% for sand amount). Stones and gravels are absent in all the soil levels. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are inorganic clay with high plasticity (HL). w_L and P_I are the same along the soil profile, with values of 76 and 46% respectively (Tab. 2). Also the unit weight of the soil (γ) is similar in all the soil profiles (18.0 kN/m^3; Tab. 2). Also all these features keep substantially uniform along the depth in the soil profile. It is worth noting that all the soil horizons have similar mineralogical features, with a predominance in clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is mainly composed by smectite and vermiculite and it keeps steady along depth. The amount in these swelling clays is higher than in Montuè test-site (more than 15%). Thus, swelling-shrinking is more pronounced, even if the soil profile is not significantly disturbed. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling materials, as already observed in Montuè test-site. Shrinking cracks form in dry summer months, extending more in depth than in Montuè soil profile, till around the first 0.4 m along the profile. Moreover, anthropogenic disturbance is absent because the site is on a naturally-vegetated slope.
According to the features of Montuè and Centonara soils, main relevant differences between the soil profiles are related to: i) the soil texture, because Montuè horizons have clayey sandy silt texture, while Centonara layers have silty clay texture; ii) the soil mineralogy, because Montuè soils are characterized by a similar percentage in carbonates and clay minerals, while clays are significantly predominant in Centonara layers; iii) the soil plasticity, which is a direct consequence of difference in soil texture and mineralogy, because Montuè soils and Centonara soils are low plastic and high plastic soils, respectively; iv) the aggregation features in the deep soil layers, because Montuè horizons under 0.2 m from ground have a compact structure, while all the horizons in Centonara profile have a weak aggregation. Considering the same soil profile, the most significant difference in the horizons along depth is linked to the soil aggregation at both test-sites. Below 0.2 m from ground level, both studied soils change their aggregation, passing from a weak to low strong aggregation. This was added at pag. 35 lines 11-20 of the revised version of the manuscript.
SWCCs of the two tested profiles present differences, according to the differences in terms of texture, that also reflect their difference in plasticity degree and mineralogy. θ_s and θ_r are averagely higher in Centonara silty clay soils, because soils with a predominant clay texture and mineralogy have a higher porosity and a higher amount of residual water than predominant silty soils such as Montuè ones (Terzaghi et al., 1996). According to soil texture, α parameter of predominantly silty Montuè soils and of silty clay Centonara soils are in the typical ranges of these textural class, respectively (0.019±0.015 kPa^{-1} and 0.005±0.005 kPa^{-1} for predominant silty and silty clay soils, resepctively; Carsel and Parrish, 1988). Instead, n parameter of predominantly silty Montuè soils is near to the typical range of this type of soil (1.31±0.09; Carsel and Parrish, 1988), while this parameter is significantly higher in Centonara soils than its typical range in clay soils (1.09±0.06; Carsel and Parrish, 1988), probably for the intrinsic physical/geotechnical features of the soil profile. This clarification was added at pag. 36 lines 11-22 of the revised version of the manuscript.
Taking into account the variations on SWCCs curves in different depths of the same soil profile, it is important to note that only θ_s parameter varied in the studied layers at Montuè test-site. In fact, θ_s values of MDCs and MWCs of the C-M horizon were lower of 0.08-0.11 m^3/m^3 (Tab. 7) than the values of the paths for the other studied levels (E-M and G-M horizon). C-M horizon is the most

superficial studied level at Montuè test-site (0.2 m from ground level) and has a weak aggregated structure. Its θ_s may be affected by the past tillage operations related to grapevines cultivations, which occurred in Montuè test site before 2000s. In fact, tillage operations generally reduce soil θ_s respect to uncultivated fields. Azooz et al. (1996) found a maximum reduction in soil water content close to saturation of 0.12 m^3/m^3 in the first 0.3 m from the ground level of soils with tillage. This range is consistent with the data measured at Montuè site. Increase in θ_s parameter registered in G-M horizon respect to E-M level is less significant and is of only 6%. This could be linked only to a slight natural heterogeneity of physical features along depth. Instead, considering an uncultivated slope, as Centonara test-site, where soil physical and mineralogical features are substantially similar in the different layers (Tab. 2), it is important to note that several fitting parameters of SWCCs changed along depth (Tab. 8). In particular, n parameter values decreased in the order of 0.35-0.90 both for MDC and MWC curves, while, only for MWCs, θ_s and α increased from 0.41 to 0.49 m^3/m^3 and from 0.003 to 0.017 kPa^{-1}, respectively. Lohse and Dietrich (2005) found similar results in the first 0.5 m of silty clayey soil, stating in particular that θ_s and α increased along depth in a statistically significant way. It could be hypothesized that, in correspondence of uncultivated sites, SWCCs may change along depth in the soil profile, as a consequence of changes in horizons structure caused by a decrease in soil weathering which may influence hydrological features (Lohse and Dietrich, 2005). These explanations were described at pag. 36 lines 23-24 and pag. 37 lines 1-20 of the revised version of the manuscript.

Comment 10

** The authors indicate that soil water properties do not influence SWCC. The profile description of the Montué soil suggests that gley is present seen in the Aquic designation. Which is the importance of the groundwater table and clay content for gley and/or pseududogley specific to individual horizons, pore saturations, hydraulic conductivity/resistance and SWCC? Given that gley or pseudogley is present, does the soil profile receive upslope groundwater?*

Response to Comment 10

We clarified the role of soil water properties on SWCCs features.

At Montuè site, soil texture and clay content are similar all along the soil profile. Reddish cutans, related to gleying features, are present in all the horizons of the soil profile, revealing a possible water table uprise. According to the monitored data collected in this site, a perched water table forms in the G-M horizon during most wet seasons (winter and spring) and can uprise in soil profile during most intense rainfalls of wet season. This condition keeps for the most wet period of the year (Bordoni et al., 2015a). Analyzed data also suggest a predominant recharge for vertical rainfall infiltration along the year, from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bordoni et al., 2015). These clarifications were added at pag. 11 lines 10-12 and pag. 26 lines 14-18 of the revised version of the manuscript. According to this, SWCCs of the three analyzed horizons at Montuè site (C-M at 0.2 m from ground, E-M at 0.6 m from ground and G-M at 1.2 m from ground) are not influenced by lateral fluxes in soils, while gleying conditions are present in all the tested layers. Furthermore, it is worth noting that the perched water table present in G-M horizon during most wet seasons (winter and spring) does not influence significantly SWCC. This water table is not present for an entire year, thus this layer can experience a wide range of water content and pore water pressure allowing to reconstruct well a complete SWCC. This explanation was added at pag. 35 lines 21-24 and pag. 36 lines 1-2 of the revised version of the manuscript.

At Centonara site, clay content and soil texture are similar all along the soil profile. Gleying evidences (reddish cutans) are present only within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, revealing stagnant saturated and reducing conditions along most wet periods of the year. Gleying features are absent in the other soil layers, testifying the uprise of the ground water table only till 1.45 m from ground level. Monitoring data collected at this test-site also suggest a predominant recharge in the soil for vertical rainfall infiltration from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bittelli et al., 2012). These clarifications were added at pag. 13 lines 19-22 and pag. 28 lines 2-4 of the revised version of the manuscript. According to this, it is worth noting that SWCCs of the two analyzed horizons (A-C at 0.2 m from ground and B-C at 0.4 m from ground) are not influenced by particular soil hydrological features, as ground water tables, gleying condtions, lateral fluxes. In fact, pedological features and monitoring data of these levels do not present particular signs of those hydrological conditions. Even if monitored data were not acquired and, thus, SWCCs were not reconstructed, only D-C layer may be influenced by these properties, because it presents gleying evidences which testify the presence of stagnant reducing conditions typical of the persistence of a water table. This explanation was added at pag. 36 lines 3-10 of the revised version of the manuscript.

Improving the estimation of complete field Soil Water Characteristic Curves through field monitoring data

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Abstract

In this work, Soil Water Characteristic Curves (SWCCs) were reconstructed through simultaneous field measurements of soil pore water pressure and water content. The objective was to evaluate whether field-based monitoring can allow for the improvement of the accuracy in SWCCs estimation with respect to the use of laboratory techniques. Moreover, field assessment of SWCCs allowed to: a) quantify the hydrological hysteresis affecting SWCCs through field data; b) analyze the effect of different temporal resolution of field measures; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed and measured trends of a component of the soil water balance. These aspects were fundamental for assessing the reliability of the field reconstructed SWCCs. Field data at two Italian test-sites were measured. These test-sites were used to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. Field measured or laboratory measured SWCCs data of 5 soil horizons (3 in a predominantly silty soil, 2 in a predominantly clayey one) were fitted by Van Genuchten model. Different field drying and wetting periods were identified, based on monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts, of different cycles. This method allowed for a correct discrimination of the main drying and the main wetting paths from field data related and for a more reliable quantification of soil hydrological properties with respect to laboratory methodologies. Particular patterns of changes in SWCCs forms along depth could be also identified. Field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days), as testified by similar values of Van Genuchten equation fitting parameters. Instead, hourly data may offer a clearer vision of the drying and wetting paths, due to the highest number of experimental data points. Moreover, in temperate climate situations as those of the test-sites, main drying curves and main wetting curves of a particular soil were substantially similar also for different hydrological cycles with peculiar meteorological conditions. SWCCs parameters were implemented in a numerical code (HYDRUS-1D) to simulate soil water storage for different soil horizons. Field reconstructed SWCCs allowed for simulating with a higher precision these trends, confirming the reliability of the reconstructed field curves by a quantitative point of view. Moreover, best results were obtained considering hysteresis in the modeling.

Keywords: Soil Water Characteristic Curves; hysteresis; laboratory; monitoring; soil water storage

1. Introduction

Soil Water Characteristic Curve (SWCC) represents the relation between two of the main measurable soil hydrological parameters, that are the pore water pressure (ψ) and the volumetric water content (θ) (Lu and Likos, 2004; Lu and Godt, 2013). SWCC is essential to understand and analyze the soil hydrological behaviors and water regimes over time (Mualem, 1976; Hillel, 1998; Bittelli et al., 2010; Cassinari et al., 2015). Moreover, SWCC is fundamental for the application of unsaturated soil mechanics into geological and geotechnical practices (Fredlund and Rahardjo, 1993; Lu et al., 2010; Lu and Godt, 2013). Knowledge of the SWCC is important to quantify the soil water budget, therefore the amount of water that is present in a given volume of soil. This variable is of utmost importance to quantify the partitioning of incoming solar radiation into sensible and latent heat, affecting the atmospheric boundary layer and therefore weather patterns (Bittelli et al., 2015). Considering that at, the global level, evapotranspiration utilizes 25 % of the incoming solar radiation and returns 60% of the precipitation that reached the soil, back to the atmosphere (Oki and Kanae, 2006), it is very important to obtain a correct quantification of the properties affecting it. The availability of water to plants evaporation and soil evaporation is clearly a key factor and it is fundamentally affected by the SWCC.

Many laboratory techniques have been developed for measuring SWCC in laboratory. This approach consists in measuring different scatter points of ψ and the correspondent θ. Then, experimental data are fitted through a function, that represents the shape of the SWCC, whence its characteristic parameters are derived (Brooks and Corey, 1966; Fredlund and Xing, 1994; Vogel et al., 2001; Assouline and Or, 2013).

Many different methods have been proposed to determine the SWCC, for a few decades (Klute, 1986). Most widespread methods of laboratory measurement of SWCCs are: pressure plate apparatus (Richards, 1965; Klute, 1986; Bittelli and Flury, 2009); evaporation methods, called as

Wind Schindler Method (WSM; Peters and Durner, 2008); Vapor Pressure Methods (VPM) as thermocouple psychrometry (Boyer and Knipling, 1965; Rawlins and Campbell, 1986) or dew point potential meter (Campbell and Gee, 1986); filter paper methods (McQueen and Miller, 1968; Marinho and Oliveira, 2006).

Besides the diffusion of laboratory measurements of SWCC, they are affected by intrinsic limitations, which can be summarized as follows:

a) they are time consuming, thus usually SWCCs are obtained from few experimental points. For example, pressure plate apparatus requires several hours of equilibration time before performing the measurement of an experimental point. This equilibration time can be of several days, if ψ of the soil specimens is negative of many hundreds of kPa (McKenzie et al., 2002);
b) each technique is characterized by a resolution range, which limits its ability of covering the entire water retention (Lu and Godt, 2013). For example, Campbell et al., (2012) determined that vapor pressure methodologies provide best assessment of water retention features for ψ lower than 1000 kPa. On the other hand, Peters and Durner (2008) indicated that evaporation techniques, such as Wind-Schindler Method (WSM), works well in the range of ψ between 0 and about -10^3 kPa. Bittelli and Flury (2009) demonstrated that soil water retention curves determined from pressure plates may be in error for experimental points of ψ less than -200 kPa;
c) sampling of the soil specimens used for laboratory measurements can alter the natural physical properties of a soil. Morgan et al. (2001) indicated that laboratory determined SWCC could be significantly altered due to a combination of entrapped air in the pore sizes and in a change in soil bulk density, occurred during the sampling process.

d) laboratory measurements for SWCC reconstruction are conducted in environmental controlled conditions (Basile et al., 2003; Zhang et al., 2017), that are not always representative of the variable natural field conditions.

A different approach is to reconstruct SWCCs from field monitored data, obtained through a simultaneous measurement of ψ and θ at a certain depth in soil (Shani et al., 1987; Morgan et al., 2001; Ramos et al., 2006; Tu et al., 2009; Greco et al., 2010; Bittelli et al., 2012; Leung and Ng, 2013; Papa et al., 2013; Sorbino and Nicotera, 2013; Rianna et al., 2014; Bordoni et al., 2015a; Yan and Zhang, 2015; Fred Zhang, 2016; Iiyama, 2016). This approach allows for obtaining a dynamic SWCC, since the measurement is also time dependent, and if the SWCC changes with time, its dynamics are captured by the collected data. This is an important aspect since the SWCC is commonly considered a static property, which is characteristic of a given soil and does not change in time and space, while it often changes with time as well as space, especially in swelling soils where the structure may change with time and space. The idea that a single soil sample, collected at a given time, will represent the hydrological conditions of that specific soil profile for years to come it is, at the least, unrealistic. The reason for using mostly laboratory-based methods in the past was the intrinsic limitation of reliable and continuous monitoring in field methods. In the last decades with the development of electronics and computers, more and more reliable field experimental methods have been developed, allowing for remote and continuous acquisition of soil water content and pressure data, collected, logged and remotely transferred to computers. Specifics will be provided below.

Field reconstructed SWCCs could better represent the hydrological features of a soil, overcoming most of the main limitations (scarcity of experimental data; alteration on soil features during sampling; controlled conditions in performing laboratory measures) that affect the laboratory obtained SWCCs. Comparisons between laboratory and field reconstructed SWCCs for a particular soil (Bittelli et al., 2012; Sorbino and Nicotera, 2013; Rianna et al., 2014; Iiyama et al., 2016) showed that *in-situ* curves could be different respect to laboratory ones, with difference till about 10% in θ values for a particular ψ. Furthermore, the response time of the changes in hydrological parameters during field meteorological events is generally faster than the variations measured in laboratory controlled conditions.

It is important to highlight that field measurements of SWCCs show that these curves are not unique, but they are characterized by hysteretic processes due to different soil drying and wetting cycles which can affect a soil in *in-situ* conditions (e.g. seasonal variation of rainfalls) (Iiyama, 2016). Similar behaviors were shown also in laboratory reconstructed SWCCs, mainly due to a controlled re-saturation of a soil specimen after a complete or partial drying process (Hillel 1998). Hysteretic effects can induce a considerable difference in the water content values at a given pore water pressure and, then, have practical implications on water movement and regimes in soil. Numerous models for the evaluation of hysteretic nature of SWCCs have been developed (Topp and Miller, 1966; Kool & Parker, 1987; Fredlund et al., 2011; Maqsoud et al., 2012; Rojas et al., 2017). However, the measurement of SWCC hysteresis both in laboratory and in field conditions is very difficult, due to the limited number of collected data and to the limitation of measuring the relationships between pore water pressure value and the associated water content value along drying and wetting branches (Likos et al., 2013).

Some aspects need to be investigated in more detail for evaluating if field reconstructed SWCCs may or may not improve the reconstruction of reliable SWCCs of the real soil hydrological features. These aspects can be summarized in:

a) the possibility of measuring and quantifying hysteresis, that may affect soil water processes, through an identification of the events or periods within a hydrological year that are representative of soil drying or wetting conditions;

b) the effects of considering different resolution time of the field measurements (e.g hourly or daily measures) in the reconstruction of the SWCCs. Cristiano et al. (2016) and Persson and Saifadeen (2016) reviewed researches about the influence of temporal and spatial resolution of the measures of contaminant fluxes in soils, rainfall amount and superficial water fluxes in understanding the hydrological behaviors of a certain area. They concluded that time scaling techniques and time resolution of these measures can influence the complete comprehension of the hydrological response of a soil or of a catchment to particular meteorological conditions. Starting from this, it is important to investigate the effects of temporal resolution on field reconstructed SWCCs, which can be obtained from monitoring data measured at different scaling times;

c) the variation in SWCCs patterns according to different field meteorological conditions along a complete hydrological cycle (a cycle is defined as a drying period followed by a wetting one; Hopmans and Dane, 1986). During a two-year monitoring campaign in a hillslope of a tropical region in Hong Kong country, Leung and Ng (2013) observed a change in SWCC path and in the amount of hysteresis from one year to the other one. In particular, remarkable hysteretic behavior was measured for the year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity), while hysteresis was substantially negligible in a year with lower rain events. Starting from this, it is important to analyze more in detail the possible changes which can occur on field SWCCs paths along several years with peculiar meteorological conditions;

d) the goodness of the field reconstructed SWCCs, obtained by implementing their characteristic parameters in a hydrological model for the assessment of a variable of the water balance in soil.

For these reasons, this paper has the purpose to assess whether field-based monitoring tools can improve the accuracy in SWCCs estimation with respect to the use of laboratory techniques, providing an objective method to obtain reliable SWCCs through simultaneous field measurements of soil pore water pressure and water content. Moreover, this allowed to: a) quantify the hydrological hysteresis affecting SWCCs by indentifying the drying and the wetting phases through an objective method which takes into account the main meteorological patterns along a hydrological year; b) analyze the effect of considering hourly or daily field measures of soil pore water pressure and water content in the reconstruction of SWCCs; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed (through the implementation of the field SWCCs parameters in a hydrological model) and measured soil water storages during a hydrological cycle. Thus, the comprehension of these aims were fundamental to fill the gaps in the evaluation of the reliability of a field-based estimation of SWCCs.

Analyses were conducted using field data measured by monitoring stations at two test-sites of Italy (Fig. 1). The different studied sites were selected in order to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. In particular, it was supposed that these differences would lead to different SWCC. The experimental design for reaching the purpose of the paper consisted in a reconstruction of complete SWCCs of different soils of the selected test-sites, through laboratory techniques and through the use of data collected by field-based monitoring of pore water pressure and water content. Main drying and main wetting paths of field SWCCs were determined discriminating field data collected in drying and wetting phases, identified through an objective methodology based on evapotranspiration and rainfall trends along the time. Field SWCCs were reconstructed considering different hydrological years and using data acquired at different temporal resolutions. Field and laboratory reconstructed SWCCs were cross-compared and were used as input parameters in a model for the evaluation of a term (water storage) in soil water balance. The reliability of the reconstructed curves was assessed through the comparison between real observed data of this term and the modeled data using laboratory or field reconstructed SWCCs, alternatively.

2. Materials and methods

2.1 The test-sites

2.1.1 Montuè test-site

Montuè test-site slope is located in the North-Eastern part of Oltrepò Pavese (Northern Italy), a hilly region corresponding to the northern termination of Apennines (Fig. 1b). The studied slope has geomorphological features typical of the surrounding area. Hillslopes are characterized by medium-high topographic gradient ranging from 22 to 35°. Furthermore, the east-facing slope descends towards a rather small and narrow valley formed by a creek (Rio Frate Creek). The elevation ranges from 210 to 170 m above sea level (a.s.l.) and the monitoring station is located at 185 m a.s.l. The land use is mainly grass and shrubs. Roots are present from the ground level till about 0.3–0.4 m in depth. The climatic regime is temperate/mesothermal according to Koppen's classification of world climates (Koppen, 1936), with a mean yearly temperature of 12 °C and mean yearly rainfall of 684.4 mm. In correspondence of the studied slope, the bedrock is made up of gravel, sand and poorly cemented conglomerates with a low percentage of marls (Rocca Ticozzi Conglomerates), that overlie marly and evaportitic deposits (Vercesi and Scagni, 1984) (Fig. 1b).

The soil profile at the monitoring station is representative of the entire slope and of the surrounding area. The variation in main soil physical properties and structure is limited at this scale (Bordoni et al., 2015a). The analyzed topsoil is 1.3 m thick and is classified as Eutric Leptosol (USDA

Classification; United States Department of Agriculture, 2014). Seven main soil horizons were identified (Tab. 1): an OL horizon (0–0.01 m), labeled as A-M; an A1 horizon (0.01–0.1 m), labeled as B-M; an Ak2 horizon (0.1–0.2 m), labeled as C-M; an Apgk3 horizon (0.2–0.4 m), labeled as D-M; a Bgk horizon (0.4–0.7 m), labeled as E-M; a BCgk horizon (0.7–1.1 m), labeled as F-M; a Cgk horizon (1.1–1.3 m), labeled as G-M. Weathered bedrock (We. Bed.) is mainly composed by sand (75%; Tab. 1). All the soil layers have a subangolar polihedral structure. Aggregation is weak till 0.2 m from ground, while it is low strong in deepest levels. Soil horizons are mineral, with a basic pH (< 9) that is steady along depth. Moreover, they have organic carbon content lower than 5%, and are characterized by the presence of millimetric carbonate coatings, which determine a carbonate content higher than 10%, till 35.3% in G-M horizon. Reddish cutans, related to gleying features, are present in all the horizons of the soil profile, revealing a possible water table uprising. Evidences of marls levels is absent in the soil profile.

Grain size distribution is uniform along depth in the soil. All the soil horizons have a clayey sandy silt texture, with high silt contents ranging from 51 to 66%, clay content between 21 and 29% and steady sand content between 7 and 13% (Tab. 1). Gravel content is low and keeps quite steady, in a range every lower than 15% (Tab. 1). Thus, the soil horizons have not gravelly features, according to United States Department of Agriculture (2014). Gravel class is constituted of pebbles made by fragments of bedrock materials and with diameters till few centimeters. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are prevalently non-plastic or slightly plastic (CL). The liquid limit (w_L) ranges from 38 to 42%, while the plasticity index (P_I) ranges from 14 to 17% (Tab. 1). Unit weight (γ) ranges between 16.7 and 18.6 kN/m^3 (Tab. 1). All these features keep substantially uniform along the depth in the soil profile.

It is worth noting that all the soil horizons have similar mineralogical features, with substantially similar amounts of carbonates and clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is characterized by the presence of smectite and chlorite. In particular, smectite represents about the 50%, thus about 8-10% of the solid particles in the studied soils. These percentages keep steady along depth in the different layers. The amount in this swelling clay mineral is approximately lower than the minimum one (12-15%; Dexter, 1988) responsible to the creation of pedological processes which can provoke turbation on the soil profile. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling soils in the studied materials, such as slickensides, wedge-shaped aggregate units, cyclic sub-surface horizons, gilgai microtopography (Blokhuis et al., 1990). There are only superficial cracks that form in dry summer months and extend few centimeters in depth.

The area where the study slope is located is characterized by a high density of rainfall-induced shallow landslides, triggered during different events occurred in 2009-2014 time span (Zizioli et al., 2013; Bordoni et al., 2015a) (Fig. 1). None of these phenomena affected the area immediately surrounding the monitoring station (Fig. 1a), thus the described soil profile was not disturbed by failure or depositional processes that may modify the pedological features. Furthermore, no erosion events affected this part of the slope, also thanks to the presence of a dense shrubs/grasses cover which protect the soil profile from the action of shallow waters. It is important to note that natural revegetation of this slope have started since 2000. In fact, the slope had been cultivated with vineyards for at least 50 years before.

2.1.2 Centonara test-site

Centonara test-site slope is located in central part of Emilia Romagna region (North-Central Italy), in a hilly sector in correspondence of the eastern termination of Apennines (Fig. 1c). This slope has geomorphological features that can be considered typical of the surrounding area. Slope angle values keep around 10-14°. The site is a north-western-facing slope which descends towards a rather small valley formed by a creek (Centonara Creek). The elevation ranges from 225 to 110 m a.s.l. and the monitoring station is located at 200 m a.s.l. As in correspondence of Montuè test-site, the station was installed in the medium part of the slope and the land use is mainly grass and shrubs. Roots are present from the ground level till about 0.7–1.2 m in depth (Tosi, 2007). The climatic regime is temperate/mesothermal according to Koppen's classification of world climates (Koppen, 1936) also for Centonara site, with a mean yearly temperature of 14 °C and mean yearly rainfall of 758.5 mm. In correspondence of the test-site slope, bedrock is composed by scaly plastic clays belonging to Scaly shales complex (Farabegoli et al., 1994; Pini, 1999).

The soil profile in correspondence of the monitoring point is representative of the soils developed in the study area from scaly clays (Bittelli et al., 2012). The analyzed topsoil is 1.7 m thick and is classified as Aquic Chromic Haploxerert (USDA Classification; United States Department of Agriculture, 2014). Main soil horizons are (Tab. 2): A horizons (A1: 0-0.12 m; A2: 0.12-0.3 m), labeled as A-C; a B horizon (0.3–0.7 m), labeled as B-C; a Bw horizon (0.7–0.9 m), labeled as C-C; a Bg horizon (0.9–1.7 m), labeled as D-C. As in Montuè test-site, all the soil layers have a subangolar polihedral structure and the soil aggregation change from weak to low strong aggregation below 0.2 m from ground. The soil horizons are mineral (organic carbon content lower than 5%), calcareous (testified by the presence of millimetric carbonate coatings) and with a basic pH (< 9) (Bittelli et al., 2012) as Montuè test-site. All these features keep steady along depth in this soil profile. As in Montuè soil profile, evidences of marls levels are absent in the soil profile. Within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, there is a layer of compacted material, with reddish cutans that highlight strong gleying, revealing stagnant saturated and reducing conditions along most wet periods of the year. Gleying features are absent in the other soil layers, testifying the uprising of the ground water table only till 1.45 m from ground level.

All the soil horizons have a silty clay texture, with steady grain size distribution along depth. Clay content is high, ranging between 46 and 60% (Tab. 2). Silt and sand amounts are similar in all the horizons (23-38% for silt amount, 15-17% for sand amount). Stones and gravels are absent in all the soil levels. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are inorganic clay with high plasticity (HL). w_L and P_I are the same along the soil profile, with values of 76 and 46% respectively (Tab. 2). Also the unit weight of the soil (γ) is similar in all the soil profiles (18.0 kN/m^3; Tab. 2). Even all these features keep substantially uniform along the depth in the soil profile.

It is worth noting that all the soil horizons have similar mineralogical features, with a predominance in clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is mainly composed by smectite and vermiculite and it keeps steady along depth. The amount in these swelling clays is higher than in Montuè test-site (more than 15%). Thus, swelling-shrinking is more pronounced, even if the soil profile is not significantly disturbed. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling materials, as already observed in Montuè test-site. Shrinking cracks form in dry summer months, extending more in depth than in Montuè soil profile, till around the first 0.4 m along the profile. Moreover, anthropogenic disturbance is absent because the site is on a naturally-vegetated slope.

Shallow landslides are frequent also in clayey slopes surrounding Centonara test-site, as demonstrated also by the phenomenon occurred in the area around the monitoring station in 2006 (Fig. 1b; Bittelli et al., 2012). Instead, the failure surface of this event developed at 1.4-1.5 m from ground level, as a slight retrogressive failure that did not cause destruction of the soil horizons above this layer. For this reason, the soil profile till 1.4 m can be considered as not disturbed by this landslide. Moreover, as in Montuè site, no erosion events affected this slope, also thanks to the presence of a dense shrubs/grasses cover which act as a protection tool towards shallow waters.

2.2 Measure of SWCCs through laboratory tests

SWCCs were measured through laboratory devices for samples taken in correspondence of some soil levels of both test-sites. The chosen techniques allowed to measure several points of pore water pressure and correspondent water content, that could be used to reconstruct the shape of the function.

Laboratory SWCCs were reconstructed from measurements obtained by a combination of several devices, each characterized by its typical range of resolution. They were determined for C-M, E-M and G-M soil horizons of Montuè test-site. For pore water pressure values higher than -10^3 kPa, SWCCs points were measured from undisturbed soil samples using an evaporation methodology based on WSM (Hyprop, UMS GmbH, Munich, Germany), whose accuracy is of 1 kPa for ψ and 0.01 m^3/m^3 for θ. For this technique, each soil sample was equilibrated at saturated conditions by wetting the specimen with deionized water. Then, the sample was placed in the instrument, allowing the water evaporation.

Instead, for pore water pressure lower than -10^3 kPa, SWCCs points were measured from disturbed soil samples through a dew point potential meter technique (WP4T, Decagon Devices, Pullman, WA), whose accuracy is of 1-10 kPa. This device was calibrated with 0.1 M KCl salt solution. The soil samples were equilibrated at various pore pressures by wetting the soil with deionized water and allowing the water evaporation. The soil samples were then placed into the instrument, and the pore water pressure was determined. The corresponding soil water contents were measured by oven drying immediately after removal of the samples from the device.

Laboratory SWCCs were determined for all the representative soil layers of Centonara test-site. For pore water pressure values higher than -10^3 kPa, SWCCs points were measured from undisturbed soil samples through Stackman tables (Stackman et al., 1969) and pressure plate apparatus measurements, whose accuracy is of 1-10 kPa. The soil samples were placed on a pressure plate apparatus following the procedures described by Klute (1986). The soil samples were wetted from below with 0.1 M CaSO4, and allowed to saturate overnight. The samples were equilibrated in the Stackman plates and pressure plate apparatus at different pore water pressure values. The corresponding soil water contents were measured by oven drying immediately after removal of the samples from the device.

For pore water pressure lower than -10^3 kPa, SWCCs points were measured with the same procedure used for Montuè test-site samples.

2.3 Measure of SWCCs through field monitoring equipments

2.3.1 Field monitoring equipments

At both test-sites, a monitoring station consisting of devices installed in soils for measuring hydrological parameters and of sensors for measuring meteorological parameters was installed. In particular, the devices for measuring hydrological parameters were installed at different depths in both soil profiles, in correspondence to their different layers. This was done to analyze the hydrological behaviors and the form of SWCCs at different depths (Bittelli et al., 2012; Bordoni et al., 2015a).

The integrated monitoring station of Montuè test-site consists in a rain gauge (Model 52203, Young Comp., Traverse City, MI), a thermo-hygrometer (Model HMP155A, Campbell Sci. Inc., Logan, UT), a barometer (Model CS100, Campbell Sci. Inc., Logan, UT), an anemometer (Model WINDSONIC, Campbell Sci. Inc., Logan, UT) and a net radiometer (Model NR-LITE 2, Kipp & Zonen, Delft, Netherlands).

These meteorological sensors are coupled with six Time Domain Reflectometer (TDR) probes (Model CS610, Campbell Sci. Inc., Logan, UT), with accuracy of 0.01-0.02 m^3/m^3 and resolution between 0 and 1 m^3/m^3. They were equipped with a multiplexer (SDMX50, Campbell Sci. Inc., Logan, UT) and installed at 0.2 (C-M layer), 0.4 (D-M layer), 0.6 (E-M layer), 1.0 (F-M layer), 1.2

(G-M layer), 1.4 m (We. Bed. layer) from the ground level to measure the soil water content. TDR measurements of water content were checked in the first stages of the monitoring and, in order to reject uncorrected values, an appropriate algorithm was applied (Bordoni et al., 2015a).

Moreover, a combination of three tensiometers (Model Jet-Fill 2725, Soilmoisture Equipment Corp., Santa Barbara, CA), with accuracy of 1.5-2.0 kPa and measuring values higher than -100.0 kPa, and three Heat Dissipation (HD) sensors (Model HD229, Campbell Sci., Logan, UT), with accuracy of 1.5-2.0 kPa and range of measure till -10^5 kPa, installed at 0.2, 0.6, 1.2 m from the ground level in different soil horizons, are used to measure pore water pressure. The tensiometers directly measure the pore water pressure. The measured changes in soil temperature after a constant heating period, measured by the HD sensors, were converted in pore water pressures through the equation proposed by Flint et al. (2002), which allowed to obtain this parameter from field measures of HD devices. Tensiometers are installed in correspondence with the HD sensors to measure values close to 0 kPa and eventual positive values.

The measurement devices were positioned in undisturbed soil layers next to a trench pit purposely digged for their installation and were connected to the datalogging system. TDR probes, HD sensors and tensiometers were installed behind the trench pit and the data logging system to keep them in natural undisturbed soil. In this way, the water flows have been kept in natural conditions and the presence of preferential flows can be negligible.

The field data were collected every 10 minutes by a CR1000X datalogger (Campbell Scientific, Inc.) powered by a photovoltaic panel. In this work, field data acquired during a continuous monitoring of about 58 months, from 27 March 2012 (when the monitoring station was installed) to 10 January 2017, are analyzed. To avoid incorrect misinterpretation of the field monitored data, the first three months of measured data were not considered in the analysis, due to a high degree of scattering related to a required initial period in which sensors had to progressively adhere to the surrounding soil after the installation, in order to reach the required balance and thus allowing data acquisition (Meisina et al., 2016).

The Centonara site monitoring station is equipped with a rain gauge and a thermo-hygrometer similar to those ones of Montuè station. Soil water content was measured with the same TDR system used at Montuè test-site, at 0.2 (A-C layer), 0.4 (B-C layer) and 0.8 m (C-C layer) depths. Correction for soil water content overestimation due to the conductive clay material was performed, as described in Bittelli et al. (2008). Moreover, TDR measurements of water content were checked in the first stages of the monitoring with the same algorithm used for Montuè data, for removing uncorrected values. Soil pore water pressures were measured at the same depth of TDR probes installation with HD sensors similar to those ones installed at Montuè station.

For the installation of sensors with the same aim of Montuè test-site, a soil pit was excavated, 4 m apart, perpendicularly to the contour lines, therefore along the line of maximum slope gradient.

The field data were collected every hour by a CR23X datalogger (Campbell Scientific, Inc.) and transmitted to the Orbcomm satellite transmitter (model KX G7100, Orbcomm Data Communicator) (Bittelli et al., 2012). In this work, field data acquired during a continuous monitoring of about 31 months, from 1 January 2007 to 30 June 2009, are analyzed. Instead of Montuè, for this site the first three months of the monitoring period were taken into account, because the monitoring equipment was installed on July 2004, thus equilibration of the sensors in soils had already occurred.

2.3.2 Field measured SWCCs

For the soils of the tested slopes, where both water content and pore water pressure were installed, SWCCs were reconstructed by coupling simultaneous field measurements of these parameters. For Montuè test-site, field SWCCs were reconstructed for C-M (0.2 m from ground level), E-M (0.6 m from ground level) and G-M (1.2 m from ground level) horizons. It is important to highlight that pore water pressure values close to 0 kPa were not measured since November 2012 till the end of the analyzed period at C-M horizon, due to breakage of the tensiometer at 0.2 m from the ground level. For Centonara test-site, field SWCCs were reconstructed for A-C (0.2 m from ground level) and B-C (0.4 m from ground level) horizons. Despite the installation of pore water pressure and water content devices also at 0.8 m from ground level, it was not possible to reconstruct SWCCs for C-C horizon. This was caused by leakage of measures of pore water pressure for 22 of the 31 months of the monitored time span, due to problems with the HD sensor at this depth.

Monitoring time spans covered different hydrological cycles, with a succession of periods with different meteorological conditions, in particular related to seasonal variation of rainfall amounts and of evapotranspiration amounts (related to change in air temperatures). Rainfall and evapotranspiration amounts are generally used in determining wet and dry periods in a particular area. These parameters, in fact, well represent the effects of seasonal meteorological changes could have on hydrological fluxes in a certain zone, in terms of amount of infiltrated rainwater and lost water from soil by means of evaporation and transpiration processes (McKee et al., 1993). Both test-sites have temperate climates, which are characterized by months/seasons with wet conditions and by drier months/seasons. In a hydrological year, the months when evapotranspiration amount is higher than rainfall amount can represent drying conditions for a soil. While, the months when evapotranspiration amount is lower than rainfall amount can represent wetting conditions for a soil. In fact, monthly time scale is used for identifying drying and wetting periods, since, at this temporal scaling resolution, it is suitable to analyze variations in meteorological indexes (rainfall and evapotranspiration amounts) that have an evident impact on hydrological dynamics in soils (García-Valdecasas Ojeda et al., 2017).

Monthly rainfalls were calculated from data acquired by the rain gauges of the stations. Cumulated monthly evapotranspiration (ETc) values were obtained as sum of daily values calculated applying

Hargreaves's equation, based on daily air temperature (T) measured at the stations (Hargreaves et al., 1985) (eq. 1):

$$ETc = (0.0135 \cdot 0.408 R_0 \cdot (T + 17.8)\sqrt{T\max - T\min}) \cdot k_{cb} \qquad \text{eq. 1}$$

, where R_0 is the extraterrestrial solar radiation which changes each day in a year according to the position of a point in the world, Tmax and Tmin are the daily maximum and minimum temperature values, respectively, k_{cb} is the crop coefficient which is a function of the type of land cover and of the periods of the year (Tab. 3) (Allen et al., 1998).

Hargreaves's equation was chosen due to the availability of air temperature measurements only, at both test-sites. For this reason, a method based on the same calculations for evapotranspiration assessment was selected. Moreover, several researches at site-specific and catchment scales (Hargreaves et al., 1985; Droogers and Allen, 2002; Martì et al., 2015) stated that Hargreaves's equation is an effective methodology for the estimation of evapotranspiration fluxes at different temporal scales.

Once identified drying and wetting periods, field monitored data of these different periods were distinguished, for reconstructing Main Drying Curve (MDC) and Main Wetting Curve (MWC) of the SWCCs, respectively. If reconstructed MDC and MWC differ, it will be possible to show the hydrological hysteresis occurring in the soil as a consequence of the main drying and the main wetting paths.

Field SWCCs were reconstructed taking into account either the average hourly values or the average daily values of the hydrological parameters. This choice aimed to investigate the effects of considering different time resolution of field measures in the features of the SWCCs. Hourly and daily resolutions were chosen because these are the most used time scaling in field monitoring of soil hydrological parameters (Tu et al., 2009; Bittelli et al., 2012; Sorbino and Nicotera, 2013; Rianna et al., 2014; Pirone et al., 2015; Urciuoli et al., 2016).

Furthermore, field SWCCs of each complete hydrological cycle (a main drying period followed by a main wetting one, Hopmans and Dane, 1986) were reconstructed, both for hourly and daily data. The use of a hydrological year time span was useful for distinguishing different field SWCCs across monitoring time, detecting possible difference in these curves related to years with peculiar meteorological conditions.

It is important to highlight that the analyses performed to all the reconstructed SWCCs and their possible hysteretic features had been addressed only to verify the efficiency of field experimental data on assessing SWCCs features, taking into account also the potential effects linked to the time resolution of field measures and the differences related to data acquired in different hydrological years. It has considered beyond the scope of the present research the analysis of the main physical mechanisms that could be responsible of SWCCs features, such as non-uniformity in interconnected pores, solid-liquid contact angles, wetting- and drying-induced changes to pore structure, air entrapment (Lu and Likos, 2004; Likos et al., 2013).

2.4 Fitting of SWCCs

Laboratory or field reconstructed SWCCs data were interpolated by using the Van Genucthen's (1980) equation (eq. 2), which is the most widely used interpolating equation of SWCCs and has the capability of representing well the hydrological characteristics of soils with different textural, pedological and physical features (Van Genuchten et al., 1991; Lu and Godt, 2013):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha\psi)^n\right)^{\left(n+1/n\right)}} \qquad \text{eq. 2}$$

, where θ_s and θ_r are the saturated and the residual water contents, respectively, α and n are fitting parameters. The fitting parameters were evaluated through an iterative procedure based on

Marquardt's (1963) algorithm, which is able to solve minimization problems of non-linear curve fitting and fitting parameters estimation.

Variations in the values of the four parameters of eq. 2 allowed to identify: i) differences between laboratory and field reconstructed SWCCs; ii) possible differences between MDCs and MWCs; iii) differences between curves reconstructed for different hydrological cycles; iv) difference between curves reconstructed through hourly or daily values.

The reliability of the fitting procedure has then been evaluated by considering the Root Mean Square Error (RMSE) statistical index (eq. 3):

$$RMSE = \sqrt{\frac{(\theta_i - \theta_i *)^2}{n_{tot}}} \qquad \text{eq. 3}$$

, where n_{tot} is the number of observations, θ_i and θ_i* are the measured and predicted by eq.2 values of soil water content, respectively.

The procedure described in Section 2.2 for laboratory reconstruction of SWCCs allowed to estimate only MDC of a soil. For assessing also MWCs from laboratory data and comparing these curves with the field reconstructed ones, a model of assessment of hysteretic effects on SWCCs was taken into account.

Relations proposed by Likos et al. (2013) were used to estimate laboratory MWCs from laboratory reconstructed MDCs, making comparisons with field MWCs. They reviewed the methodologies developed for estimating parameters of MWC fitting with Van Genucthen equation from MDC parameters. Moreover, they integrated this review with other experimental data and found a robust functional relations for each fitting parameter of Van Genucthen equation (Tab. 4).

2.5 Modeling of soil water storage

The reliability of the reconstructed field SWCCs was assessed through the implementation of their fitting parameters in a model for the estimation of soil water storage of a layer i (S_i), a variable of the water balance in soil. For a particular i^{th} soil layer, S_i at time t (S_{it}) is the difference between measured θ_i at t (θ_{it}) and θ_i at the beginning of a considered time span (θ_{i0}), multiplied by the thickness of the layer d_i, assuming that θ is uniform along the layer (Pirone et al., 2015) (eq. 4):

$$S_{it} = d_i(\theta_{it} - \theta_{i0}) \quad \text{eq. 4}$$

This methodology is particularly indicated for the assessment of temporal behaviors of soil water storage using field monitoring data (Pirone et al., 2015). S_i was calculated from field monitored data in correspondence of C-M, E-M and G-M levels at Montuè test-site and of A-C and B-C at Centonara test-site. A hydrological cycle (main drying and main wetting phase) was selected as the reference period for this analysis.

S_i was also calculated, for the same time span, on the basis of modeled θ at the same soil levels through HYDRUS-1D code Vers. 4.16 (Simunek et al., 2008, 2013). HYDRUS-1D code is based on one-dimensional solution of Richards' equation (Richards, 1931). This code is significantly used in soil hydrology, thanks to its capability in implementing a wide range of approaches that can be selected for simulating different aspects of water fluxes in soils (e.g. water balance, non-equilibrium processes, contaminant transport; Simunek et al., 2013). A more detailed description of this software and on its governing equation are present in Simunek et al. (2008, 2013).

Modeled S_i values were obtained considering different sets of SWCCs: i) laboratory reconstructed SWCC and neglecting hysteresis (only MDC parameters); ii) laboratory reconstructed SWCC considering hysteresis (MDC and MWC parameters); iii) field reconstructed SWCC and neglecting hysteresis (only MDC parameters); iv) field reconstructed SWCC considering hysteresis (MDC and MWC parameters).

The performance of each simulation was evaluated through the Nash and Sutcliffe (1970) statistical index (NS) (eq. 5):

$$NS = 1 - \frac{\sum_{t_0}^{t_f} (S_{iobs} - S_{i\,mod})^2}{\sum_{t_0}^{t_f} (S_{iobs} - S_{iave})^2} \qquad \text{eq. 5}$$

, where S_{iobs} is the observed soil water storage, S_{imod} is the modeled soil water storage, S_{iave} is the average of the observed soil water storage, t_0 and t_f are the initial and the final time of the analyzed time span, respectively.

3. Results

3.1 Identification of the drying and wetting periods

Comparison between monthly rainfall and evapotranspiration amounts allowed for the identification of drying and wetting periods at both tested sites (Fig. 2). At Montuè test-site, complete drying periods were of 4-9 months and complete wetting periods were of 3-7 months. Instead, at Centonara test-site, complete drying periods were of 4-6 months and complete wetting periods were of 5-8 months (Tab. 5, 6).

It is important to highlight that there was an evident distinction between drying and wetting periods, based on the mean monthly rainfall (Tab. 5, 6). At Montuè site, drying periods had an average monthly rainfall amount between 32.7 and 63.5 mm/month, while wetting periods had an average monthly rainfall amount between 72.5 and 95.9 mm/month. At Centonara site, drying periods had an average monthly rainfall amount between 24.5 and 45.1 mm/month, while wetting periods had an average monthly rainfall amount between 57.4 and 94.6 mm/month. Monthly evapotranspiration amounts kept quite steady along different years, with peaks of 155 mm/month in hottest months

(July in both sites) and lower values of 12-20 mm/month in coldest months (January and February in both sites). Drying periods were characterized by a percentage of dry days (days without rainfall amounts) significantly higher than wet days (days with cumulated rainwater) at both test sites (56-81% of dry days against 29-44% of wet days), while wetting periods had higher percentage of wet days (51-59% of wet days against 41-49% of wet days) (Fig. 2c, d). The percentage of dry days during drying periods was higher than 50%, while the percentage of wet days during wetting periods exceeded 50%. Moreover, during wetting periods, time interval between two consecutive rainfall events was generally lower than 7-10 days. Thus, these conditions, related to a lower evapotranspiration amount caused by lower air temperature during winter and spring months (Tab. 5, 6), kept in a wetting stage the soils profiles during the entire wetting months. Conversely, the lower rainfall amounts, the higher interval between subsequent rainfalls (averagely more than 7-10 days) and the high air temperatures during summer and autumn months (Tab. 5, 6) determined the maintenance of dry conditions during the entire drying periods, when water loss from soil is higher than that gained.

According to these reconstructions, 4 complete hydrological cycles were identified at Montuè (Tab. 5), while 2 complete hydrological cycles were detected at Centonara test-site (Tab. 6).

3.2 Monitored soil hydrological parameters dynamics

3.2.1 Montuè test-site

Figure 3 shows hourly water content (θ) and pore water pressure dynamics (ψ) during the considered time span at Montuè test-site. These trends were compared with hourly rainfall amount, between 0 and 30 mm/h for covering the range till the highest registered hourly intensity. In the analysed period θ ranged between 0.10 and 0.45 m^3/m^3 in the soil, and between 0.15 and 0.38

$m^3 \cdot m^{-3}$ in the weathered bedrock (Fig. 3a). Instead, ψ ranged from positive values, till 12.7 kPa in the G-M horizon, to values in the order of -10^3 kPa (Fig. 3b).

Typical hydrological behaviour of shallow soil layers, till 0.6 m from slope surface, was very different with respect to the deeper layers (Fig. 3). The response of soil horizons till 0.6–0.7 m from the slope surface was quicker than the deepest ones during drying or wetting periods. Only prolonged rainy periods, especially during winter months, could cause an increase in soil saturation, testified by an increase of pore water pressure and of soil water content at depths higher than 0.7 m.

The typical conditions of the most wet months, between December and May, showed that frequent precipitations determined an increase of the soil wetness until it approached or reached saturated conditions (Fig. 3). Completely saturated conditions were reached in the G-M horizon only in winter and spring, as testified by values of ψ slightly lower or higher than 0 kPa (Figs. 3b, c). During wetting periods, water content in the weathered bedrock was lower than in the overlying G horizon (Fig. 3a). According to the monitored data, it could be supposed that during wet periods (winter and spring) a perched water table forms in the G horizon and can upraise in soil profile during most intense rainfalls of wet season. This condition keeps for the most wet period of the year (Bordoni et al., 2015a). Analyzed data also suggest a predominant recharge for vertical rainfall infiltration along the year, from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bordoni et al., 2015).

During drying periods and for the re-wetting events in early-autumn, the re-wetting of the soil horizons till 0.6–0.7 m was very rapid (Fig. 3, 4). During intense summer rainstorms, generally more than 10-15 mm in 2 h, ψ increased but it was not coupled with a correspondent increase in θ (Fig. 4). This could be linked to non-equilibrium processes due to fast infiltration (Ross and Smettem, 2000; Vogel et al., 2010), in which pore water pressure or water content trend lags behind each other by the water retention equilibrium. The evidences of these processes were collected thanks to the measurements of the HD sensors, which allowed for measuring pore water pressure dynamics also in soil conditions starting from values of pore water pressure around -10^2 and -10^3 kPa.

3.2.2 Centonara test-site

Figure 5 shows hourly water content (θ) and pore water pressure (ψ) dynamics during the considered time span at Centonara test-site. These trends were compared with hourly rainfall amount, between 0 and 20 mm/h for covering the range till the highest registered hourly intensity at this site. A problem in the acquisition of θ occurred during the period between January and August 2008. Moreover, measurements of ψ at C-C horizon were available only during January and September 2008. Despite this, main soil behaviors were recognizable. In the analysed period, θ ranged between 0.09 and 0.60 m^3/m^3 (Fig. 5a), while ψ ranged between -0.3 kPa to values in the order of -10^4 kPa (Fig. 5b). No positive values of ψ were detected during the monitoring time span.

As in Montuè site, θ and ψ depicted the typical direct relationship during both drying and wetting periods. During the wetting periods (from October to the beginning of Spring, Tab. 5), soil kept close to saturation, as confirmed by values of ψ close to 0 kPa and by values of θ generally higher than 0.4 m^3/m^3. In correspondence of rainfall events in wetting periods, θ and ψ changed slightly, with variation in the order of 0.02-0.08 m^3/m^3 and of less than 5 kPa, respectively (Fig. 5).

Decrease in θ and ψ during the dry periods, in particular in summer months, is evident. It is related to low precipitation amounts (Tab. 5) and to vegetation conditions of the area. In fact, this area is covered by a dense natural vegetation with various species of grass and shrubs, that is able to uptake a significant amount of water from soil layers till about 1-1.5 m (Tosi, 2007; Bittelli et al., 2012).

The soil profile was then recharged by precipitation in the autumn season. In correspondence of these events, contemporaneous increases in θ and ψ were monitored, without non-equilibrium processes highlighted at Montuè test-site (Fig. 5). The increase in soil saturation is quite fast, probably aided by macropores and fissures present in soils for the shrinkage phenomena (Smethurst et al., 2012) typical of clayey soils at Centonara. Monitoring data also suggest a predominant recharge in the soil for vertical rainfall infiltration from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bittelli et al., 2012).

3.3 Reconstructed SWCCs

Figures 6 and 7 show field SWCCs, reconstructed considering together all the identified hydrological cycles (Tab. 4, 5) and distinguishing the data taken from drying or wetting periods. In these figures, also data of laboratory reconstructed SWCCs were inserted.

Field reconstructed SWCCs showed an evident not-closed hydrological hysteresis for each tested layer and considering hourly or daily data. SWCCs were then composed by a MDC, where data of identified drying periods were present, and by a MWC, composed from the data of the identified wetting periods.

Field SWCCs of the shallow tested soils (C-M and E-M at Montuè test-site, B-C at Centonara test-site) showed a high degree of scattering, especially for ψ higher than -10^2 kPa (Fig. 6, 7). This could be linked to very short hysteresis processes occurring after more intense rainfall events during drying and wetting phases, which determine numerous less evolved scanning drying and wetting curves. Instead, SWCCs of G-M horizon showed less scattered field measured values (Fig. 6c, d), because, due to its higher depth (1.2 m from the ground level) in the soil profile, this horizon is not affected by single rainfall events but only by more prolonged rainy or dry periods.

For G-M horizon, in correspondence of ψ values around -10^3 kPa, the trend of MDC on logarithmic scale shows a very high gradient, both for hourly or daily data (Fig. 6c, d). This effect is linked to the main drying phase of the studied soil during the dry season, when pore water pressure keeps rather steady and water content, instead, slowly and continuously decreases.

Data of laboratory SWCCs corresponded to the MDC path, due to the adopted testing procedure. As shown in Figures 6 and 7, laboratory data did not seem fitting well field data, but they followed a different MDC trend (Fig. 6).

In SWCCs of C-M and E-M soils, field data related to non-equilibrium processes due to intense summer rainstorm were reported and highlighted in a different color (gray circles) respect to other data. It is clear that field data of non-equilibrium processes lags behind each other by the water retention equilibrium, with significant variations in pore water pressure and quite steady values of water content (Fig. 6a, b, c, d).

Field and laboratory SWCCs were then interpolated using Van Genucthen model. RMSE values of the fitted field curves ranged between 0.0128 and 0.0189 m^3/m^3 for hourly values and between 0.0133 and 0.0183 m^3/m^3 for daily values, thus testifying that there is a good agreement with field experimental data (Tab. 7, 8). Best results were obtained for G-M horizon, where the effect of short hysteresis processes is less pronounced. Instead, RMSE values of the fitted laboratory MDCs ranged between 0.0239 and 0.0317 m^3/m^3 (Tab. 7, 8). Thus, fitting is worst due to the limited number of used experimental data, that do not allow to reconstruct the shape of the curve appropriately.

Except for θ_s parameter, MDC and MWCs fitting parameters were similar for both laboratory and field curves of each studied soil horizon of Montuè site, respectively (Tab. 7). θ_s of MDCs and MWCs of C-M horizon were lower of 0.08-0.11 m^3/m^3 than the values for the other studied levels (E-M and G-M horizon). For Centonara soil profile, decrease along depth of n parameter values, in the order of 0.35-0.90, was evident both for MDC and MWC curves (Tab. 8). Moreover, for MWCs, also an important increase in θ_s (from 0.41 to 0.49 m^3/m^3) and in α (from 0.003 to 0.017 kPa^{-1}) was highlighted increasing soil horizon depth (Tab. 8).

Due to the not-closed global hysteresis loop highlighted by field data (Fig. 6, 7), θ_s is in the order of about 4 (C-M horizon) – 10% (G-M horizon) between drying and wetting paths. Ratio between θ_{sw} and θ_{sd} is averagely of 0.92, quite higher than 0.85 found by Likos et al. (2013). For all the soils, passing from drying to wetting conditions, an increase in the α_w fitting parameter is highlighted with respect to the α_d (Tab. 7, 8), as already shown in previous works (Kool and Parker, 1987; Likos et al., 2013). Ratio between α_w and α_d is on the order of 1.2-2.0 for Montuè soils and of 3.0-5.7 for Centonara soils. Furthermore, also the n_w parameter changed with respect to n_d (Tab. 7, 8). For Centonara tested levels, a decrease in n_w was noticed, with a ratio between n_w and n_d of 0.73-0.95 (Tab. 7). As already demonstrated in Likos et al. (2013), θ_{rd} and θ_{rw} coincided in the field MDCs and MWCs for all the tested soils (Tab. 7, 8).

Differences between fitting parameters of laboratory and field MDCs and MWCs were evident for all the tested soils (Tab. 7, 8). These differences regarded, in particular, θ_s and α parameter. Instead, for Centonara soils, the differences were significant for all the four parameters of Van Genucthen equation. It is important to remember that laboratory MWCs were not obtained by experimental measures, but they derived from MDCs data by applying the relation proposed by Likos et al. (2013) (Tab. 4).

3.4 Differences on field SWCCs considering different hydrological cycles and hourly or daily data

During the monitored time spans, different hydrological cycles, labeled with progressive Roman number (Tab. 5, 6), were identified at Montuè and Centonara site. SWCCs of different cycles were then reconstructed, using hourly or daily data, for each soil. Fitting parameters of SWCCs of each cycle were compared each other and with the complete SWCCs obtained integrating field data of all these cycles (Fig. 6, 7).

Figures 8 and 9 show two examples of these reconstructions, one for a Montuè horizon (G-M) and one for a Centonara horizon (B-C). In spite of different meteorological conditions, in terms of peculiar rainfall amounts and average air temperature, for each cycle (Tab. 5, 6), it is important to highlight that the differences between values of the fitting parameters are very low (Tab. 7, 8). In particular, for each tested soil, maximum variation of θ_s and θ_r were of 0.01 m^3/m^3. Maximum change of α and n parameters were of 0.003 kPa^{-1} and of 0.06, respectively. Moreover, RMSE values of the curves were very similar, varying of less than 0.005 m^3/m^3 (Tab. 7, 8). This confirms the reliability of the reconstructed field curves, considering data taken from different cycles.

No significant changes on SWCCs paths were identified reconstructing these curves through hourly or daily data (Tab. 7, 8). As already showed for SWCCs obtained through data of the entire time span, fitting parameters of the curves of the same cycle are substantially equal considering hourly or daily monitored values. In fact, as shown in Tab. 7 and Tab. 8, maximum variations of θ_s and θ_r were of 0.01 m^3/m^3 considering hourly or daily reconstruction of the same path. Moreover, maximum change of α and n parameters were of less 0.003 kPa^{-1} and of 0.05, respectively. It is important to note that using hourly or daily data did not affect the reliability of the fitting procedure.

A comparison between RMSE values of field SWCCs through hourly or daily data for each tested soil was performed (Tab. 7, 8; Fig. 10, 11). To verify the similarity between RMSE values, the correlation coefficient (R^2) was calculated, on the hypothesis of a linear correspondence between hourly and the correspondent daily reconstruction (e.g. RMSE of SWCC from hourly data equal to the one of the correspondent SWCC from daily data). As shown in Fig. 10 and 11, R^2 was high in correspondence of each tested level, ranging from 0.75 to 0.98 and the differences between corresponding RMSE values were still very low, ranging between 0 and 0.004 m^3/m^3 for Montuè soils and between 0 and 0.002 m^3/m^3 for Centonara soils. Thus, RMSE of a curve fitted by hourly data can be considered significantly similar to the corresponding one obtained through daily data.

3.5 Comparison between observed and modeled soil water storage

Daily values of soil water storage (S) were calculated for soil levels where SWCCs were estimated. S was assessed through observed θ and through modeled θ using HYDRUS-1D code. As shown by Pirone et al. (2015), daily time resolution allowed to better highlight how the changes in S are caused by variations of meteorological conditions (rainfall amounts, evapotranspiration fluxes).

At both sites, S was reconstructed for a complete cycle: the II cycle, from 1 July 2013 to 31 May 2014, at Montuè site; the II cycle, starting from 1 April 2007 and ending at 1 December 2007, at Centonara site. For the Centonara site, modeling was limited before the end of the wetting phase due to lack of θ measurements for the problems to the monitoring system (Fig. 5a).

Thickness of each soil layer was the value measured in correspondence of the representative soil profile of the tested slopes: 0.1 m, 0.2 m and 0.3 m for C-M, E-M and G-M, respectively; 0.3 m and 0.4 m for A-C and B-C, respectively. The modeling considered laboratory or field reconstructed SWCCs alternatively. Moreover, only MDCs or complete hysteretic SWCCs was assumed, alternatively.

The fitting parameters of Van Genucthen equation and the saturated hydraulic conductivity (K_s) are required for modeling. Due to the similarity of fitting parameters determined by hourly or daily data and by different cycles, Van Genucthen fitting parameters of field SWCCs reconstructed by daily data of the all cycles in a soil were used (Tab. 7, 8). For the model based on laboratory data, the fitting parameters of the SWCCs assessed through laboratory data were considered (Tab. 7, 8).

RETC code Vers. 6.xx (Van Genuchten et al., 1991) was used to perform an inverse modeling of K_s of each analyzed soil, based on the measured θ and ψ (Bordoni et al., 2015a). RETC code allows to estimate soil K_s through a least-squares optimization approach to identify un known model parameters starting from observed retention and conductivity data. Estimated values of K_s, for drying and wetting paths of each soil, are listed in Table 9.

As upper boundary conditions for HYDRUS-1d modeling, cumulated daily rainfalls measured at the two monitoring stations during the modeled time spans were considered. Other superficial water fluxes in soil (e.g. irrigation processes) or shallow layers with steady θ or ψ were not present in both test-sites. Daily values of ETc were estimated through Hargreaves equation (eq. 1) and used in modeling. Moreover, a free drainage lower boundary condition was applied.

Figure 12 shows a comparison between observed trend of S and trends of S modeled through different setup for B-C layer. This was a representative example of the trends of S also in the other tested soils. There was no differences between the soil water volume storage at the end and beginning of each year. In particular, the amount of water stored in wet months (winter and spring) was lost during summer dry periods for the intense evapotranspiration fluxes and the low amounts of fallen rain. Considering the reference level at the beginning of a drying cycle, water lost during drying periods reached values till 75-80 mm at the end of these periods. Water was earned quickly during the first rainfall events of wetting periods, as already shown in the monitored trends of soil water content and pore water pressure (Fig. 3, 5), thanks to a fast infiltration in macropores and fractures formed during dry months. Increase in S was of about 40-50 mm during the first events of wetting periods, then S increased slowly during following events till turning to the reference level of the beginning of the modeling.

Table 10 reports the results of the modeling phases for all the analyzed soils in terms of NS index. Even if the general observed trends of S were followed by all the modeling setups, the best agreement between observed and modeled trends of S corresponded to a modeling which took into account hysteretic (MDC+MWC) field SWCCs (Tab. 10). In this case, NS values ranged between 0.76 and 0.88, corresponding to a very good match between observed and modeled data (Nash and Sutcliffe, 1970).

Effectiveness of the modeling decreased in the other case. NS decreased of 0.06-0.21 considering only field MDCs. Modeling with laboratory reconstructed SWCCs gave worst results than the corresponding trends through field reconstructed SWCCs (Tab. 10). Daily errors of modeled S with laboratory data reached values higher than 30 mm than modeled S with field data.

NS indexes were lower of 0.08-0.37 than the correspondent values of models based on field SWCCs. They were in the order of 0.34-0.62, testifying only a fairly well simulation of S (Nash and Sutcliffe, 1970).

4. Discussions

4.1 Hysteretic SWCCs through field data

The reconstruction of field SWCCs, composed by both MDC and MWC paths, requires knowledge of the experimental data belonging to drying or wetting periods of a soil. Previous researches (Bordoni et al., 2015a; Pirone et al., 2015; Urciuoli et al., 2016) distinguished dry and wet periods only on a heuristic approach, mainly through the consideration of the average general pattern of rainfall amount along the year. This work proposes, for the first time, an objective approach to identify these hydrological paths, by means of the relation between cumulated evapotranspiration and rainfall amounts of a particular time span. This procedure is based on the analysis of monthly time series of rainfall and evapotranspiration amounts, that is the scaling time suitable for catching trends and variations in meterological and related hydrological features in an area (McKee et al., 1993; Garcia-Valdecasas Ojeda et al., 2017).

The application of this procedure to the experimental data of the two test-sites allowed for the reconstruction of field SWCCs with a clear distinction between MDC and MWC paths. MDC data correspond to measures of the recognized drying periods of each site, while MWC data are the experimental measurements of the identified wetting periods of the same site.

Field SWCCs of the analyzed soils were then fitted through Van Genucthen model. Goodness of the fitting is high in all the tested layers (RMSE always less than 0.02 m^3/m^3), notwithstanding the depth of the considered horizon, and is better than the fitting results of laboratory experimental data for the same soils (RMSE always higher than 0.02 m^3/m^3). The not-perfect correspondence between either MDCs or MWCs and the experimental data is linked to less-developed scanning curves that form in correspondence of rainfall events, especially when ψ is in the range between -10^0 and -10^2 kPa. Non-equilibrium phenomena, detected for the most superficial soil horizons (till 0.6 m from ground level) at Montuè test-site, lag behind the normal retention equilibrium of a soil. For this reason, they need to be studied in a separately way respect to the typical soil hydrological behaviors represented through SWCCs (Vogel et al., 2010).

The two analyzed soil profiles differ for some pedological and physical properties. In particular, main relevant differences are related to: i) the soil texture, because Montuè horizons have clayey sandy silt texture, while Centonara layers have silty clay texture; ii) the soil mineralogy, because Montuè soils are characterized by a similar percentage in carbonates and clay minerals, while clays are significantly predominant in Centonara layers; iii) the soil plasticity, which is a direct consequence of difference in soil texture and mineralogy, because Montuè and Centonara soils are low plastic and high plastic soils, respectively. Considering the same soil profile, the most significant difference in the horizons along depth is linked to the soil aggregation at both test-sites. Below 0.2 m from ground level, both studied soils change their aggregation, passing from a weak to low strong aggregation.

At Montuè site, SWCCs of the three analyzed horizons (C-M at 0.2 m, E-M at 0.6 m and G-M at 1.2 m from ground) are not influenced by lateral fluxes in soils, while gleying conditions are present in all the tested layers. Furthermore, it is worth noting that the perched water table present in G-M horizon during most wet seasons (winter and spring) does not influence significantly SWCC. This water table is not present for an entire year, thus this layer can experience a wide range of water content and pore water pressure allowing to reconstruct well a complete SWCC.

At Centonara site, it is worth noting that SWCCs of the two analyzed horizons (A-C at 0.2 m from ground and B-C at 0.4 m from ground) are not influenced by particular soil hydrological features, such as ground water tables, gleying conditions, lateral fluxes. In fact, pedological features and monitoring data of these levels do not present particular signs of those hydrological conditions. Even if monitored data were not acquired and, thus, SWCCs were not reconstructed, only D-C layer may be influenced by these properties respect to the other tested levels, because it presents gleying evidences which testify the presence of stagnant reducing conditions typical of the persistence of a water table.

SWCCs of the two tested profiles present differences, according to the differences in terms of texture, that also reflects their difference in plasticity degree and mineralogy. θ_s and θ_r are averagely higher in Centonara silty clay soils, because soils with a predominant clay texture and mineralogy have a higher porosity and a higher amount of residual water than predominant silty soils such as Montuè ones (Terzaghi et al., 1996). According to soil texture, α parameter of predominantly silty Montuè soils and of silty clay Centonara soils are in the typical ranges of these textural class, respectively (0.019±0.015 kPa^{-1} and 0.005±0.005 kPa^{-1} for predominant silty and silty clay soils, resepctively; Carsel and Parrish, 1988). Instead, n parameter of predominantly silty Montuè soils is near to the typical range of this type of soil (1.31±0.09; Carsel and Parrish, 1988), while this parameter is significantly higher in Centonara soils than its typical range in clay soils (1.09±0.06; Carsel and Parrish, 1988), probably for the intrinsic physical/geotechnical features of the soil profile.

Taking into account the variations on SWCCs curves in different depths of the same soil profile, it is important to note that only θ_s parameter varied in the studied layers at Montuè test-site. In fact, θ_s

values of MDCs and MWCs of the C-M horizon were lower of 0.08-0.11 m^3/m^3 (Tab. 7) than the values of the paths for the other studied levels (E-M and G-M horizon). C-M horizon is the most superficial studied level at Montuè test-site (0.2 m from ground level) and has a weak aggregated structure. Its θ_s may be affected by the past tillage operations related to grapevines cultivations, which occurred in Montuè test site before 2000s. In fact, tillage operations generally reduce soil θ_s respect to uncultivated fields. Azooz et al. (1996) found a maximum reduction in soil water content close to saturation of 0.12 m^3/m^3 in the first 0.3 m from the ground level of soils with tillage. This range is consistent with the data measured at Montuè site. Increase in θ_s parameter registered in G-M horizon respect to E-M level is less significant and is of only 6%. This could be linked only to a slight natural heterogeneity of physical features along depth.

Considering an uncultivated slope, as Centonara test-site, where soil physical and mineralogical features are substantially similar in the different layers (Tab. 2), it is important to note that several fitting parameters of SWCCs changed along depth (Tab. 8). In particular, n parameter values decreased in the order of 0.35-0.90 both for MDC and MWC curves, while, only for MWCs, θ_s and α increased from 0.41 to 0.49 m^3/m^3 and from 0.003 to 0.017 kPa^{-1}, respectively. Lohse and Dietrich (2005) found similar results in the first 0.5 m of silty clayey soil, stating in particular that θ_s and α increased along depth in a statistically significant way. It could be hypothesized that, in correspondence of uncultivated sites, SWCCs may change along depth in the soil profile, as a consequence of changes in horizons structure caused by a decrease in soil weathering which may influence hydrological features (Lohse and Dietrich, 2005).

Changes in SWCCs fitting parameters, passing from main drying to main wetting path, can allow to represent accurately hydrological hysteresis and hydrological responses of a soil in drying and wetting conditions (Likos et al., 2013). Respect to Likos et al. (2013), which reviewed the relations between MDC and MWC curves in terms of change of Van Genuchten fitting parameters, the reconstructed field SWCCs present evident differences about the variation of α and n fitting parameters. For all the soils, passing from drying to wetting conditions, an increase in the α_w fitting parameter is highlighted with respect to the α_d (Tab. 7, 8), as already shown in previous works (Corey et al., 1965; Kool and Parker, 1987; Likos et al., 2013). Instead, ratio between α_w and α_d can be significantly higher than the maximum values measured from laboratory data (Likos et al., 2013), reaching 5.7 (B-C layer of Centonara site). Moreover, change of n parameter, measured through field SWCCs, do not seem to follow the typical scheme. In fact, for Centonara tested levels, a decrease in n_w with respect to n_d was noticed, with a ratio between n_w and n_d of 0.73-0.95 (Tab. 8). This is a difference respect to the most used models of hysteresis quantification, that consider n_w equal or slightly higher than n_d (Kool and Parker, 1987; Likos et al., 2013). The effect of hysteresis was more marked in clayey soils of Centonara site than in silty ones of Montuè slope. This was already highlighted by Fredlund et al. (2011), who found an increase of hysteretic effects of more than 50% in clayey soils respect to silty materials.

Comparing fitting parameters of field reconstructed and laboratory reconstructed curves, differences were evident for all the tested soils (Tab. 7, 8). These differences regarded, in particular, θ_s and α parameters. Sorbino and Nicotera (2013) and Iiyama (2016) found similar differences between laboratory and field SWCCs, till 10% of θ amount for the same value of ψ.

The results of the estimation of SWCCs through field data demonstrate that the developed procedure allows to obtain robust and reliable water retention curves able to represent the soil hydrological behaviors which characterize a layer in environmental conditions. Moreover, the procedure allows also obtaining a measure of the hysteretic paths in a soil, with a reliable quantification of the change in SWCCs paths passing from drying to wetting conditions. In particular, as regards the wetting features of the soils, the measured field MWC paths are more reliable than the modeled MWCs based on laboratory data. They represent also a valid alternative to the direct measurements of MWC through laboratory procedures, which are time-consuming and are sometimes affected by measurement errors (Lu and Likos 2004).

4.2 Effects on field SWCCs considering hourly or daily data and different hydrological cycles

A comparison of field SWCCs obtained, for a certain soil, considering hourly or daily monitoring data was performed. Similar analyses were not achieved before, but they are fundamental for highlighting the effect of using field monitoring data with different temporal resolution from the field experimental data on the estimation of SWCCs.

It is important to note that Van Genucthen fitting parameters of field SWCCs are substantially similar considering hourly or daily data, for each analyzed soil. Maximum variations of θ_s and θ_r were of 0.01 m^3/m^3 considering hourly or daily reconstruction of the same path, while maximum changes of α and n parameters were of less 0.003 kPa^{-1} and of 0.05, respectively (Tab. 7, 8). These changes were in the order of less than 5% for each fitting parameters of Van Genuchten equation, considering both MDCs and MWCs of each tested soil. Furthermore, using hourly or daily data do not affect the reliability of the fitting procedure and the resulted fitted curves. Differences on RMSE values for each tested soil ranged between 0 and 0.004 m^3/m^3 for Montuè soils and between 0 and 0.002 m^3/m^3 for Centonara soils. Moreover, R^2 of a linear correspondence between hourly and the correspondent daily reconstruction was high in correspondence of each tested level, ranging from 0.75 to 0.98. This demonstrated that RMSE of a curve fitted by hourly data can be considered significantly similar to the corresponding one obtained through daily data. These results testify that reliable field SWCCs can be obtained both considering hourly or daily monitored data. Thus hysteresis and fitting parameters can be assessed in the same way and with similar values through both types of time resolution in field measures. This aspect is particularly significant, because the comprehension of other hydrological parameters and processes can be affected by the time scaling resolution of the implemented measures, as in the case of fluxes of contaminant in soil, in the assessment of the moment of the peak of a river flood, and in the evaluation of the superficial water discharge (Cristiano et al., 2016 and references therein; Persson and Saifadeen, 2016).

It is important to note that for a long-term monitoring, the number of experimental data obtained through a hourly or a daily resolution of field measures is significantly higher than experimental data from laboratory techniques, the latter allowing usually to obtain only few tens of SWCC points (Lu and Godt, 2013). Even if similar reconstructed SWCCs can be obtained from hourly or daily data, as shown in the results in the studied sites, it highlights that a maximum number of 8784 data can be achieved by means of hourly resolution in field measures, against a maximum value of 365 data through daily resolution, on a time span of a year. Thus, hourly data may allow for obtaining a higher precision in the SWCC paths, making both drying and wetting paths clearer.

Effects of hydrological cycles with peculiar meteorological features were also investigated. This was possible thanks to the availability of field data recorded during a multi-year monitoring. In spite of different meteorological conditions, in terms of rainfall and air temperature trends, it is important to highlight that the differences between values of Van Genuchten parameters of SWCCs of different cycles are very low for each tested horizon. Variations in θ_s and θ_r were of 0.01 m^3/m^3, while maximum changes of α and n parameters were of 0.003 kPa^{-1} and of 0.06, respectively (Tab. 7, 8). As for time resolution of the field measurements effects, these changes were negligible, ranging in the order of less than 5% for each fitting parameters of Van Genuchten equation, considering both MDCs and MWCs of each tested soil. Moreover, RMSE values of the curves were very similar, varying of less than 0.005 m^3/m^3. This confirms the reliability of the reconstructed field curves, considering data taken from different cycles.

Despite the limited number of tested soils (5 horizons of two test-sites), in temperate climatic and meteorological conditions as the ones of the two investigated sites, it can be observed that MDCs and MWCs of a particular soil are substantially similar for different hydrological cycles with peculiar meteorological conditions. Previous works (Bittelli et al., 2012; Bordoni et al., 2015a, b) demonstrated that SWCCs dynamics in the test-sites were related to the changes in meteorological conditions along the seasons, without the influence of particular sub-surface water movements (absence of significant lateral fluxes, absence of a deep continuous water table in bedrock materials).

This confirms that a soil follows the SWCC paths along different years (Vachaud et al., 1985; Sorbino and Nicotera, 2013). According to this behavior, reliable field SWCCs can be reconstructed on the basis of only one complete hydrological cycle (a drying phase followed by a wetting one), even if collection of experimental data from more cycles may guarantee a better comprehension of MDC and MWC paths, thanks to the higher number of influencing meteorological events (Bordoni et al., 2015a). It is important to highlight that these results are in contrast respect to the ones achieved by Leung and Ng (2013) in a test site with a tropical climate. In their situation, year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity) determined a remarkable hysteretic path, while hysteresis was substantially negligible in a year with lower rain events. A soil behavior similar of this one was not found in the two test-sites analyzed in this research, probably due to the different climatic conditions of Montuè and Centonara test-sites.

4.3 Effects of SWCCs on modeling soil water storage

Soil water storage is one of the components of the soil water balance. It represents the amount of water lost or gained with respect to a reference starting point and control volume, indicating the change of water content in a soil over time. Soil water storages of the soil layers where field

SWCCs were reconstructed, were calculated using the method of Pirone et al. (2015), for representative time spans of the test-sites. Observed trends were compared with modeled ones, using water contents modeled by HYDRUS-1d code, taking into account laboratory or field estimated SWCCs, with or without hysteresis.

Best agreement between observed and modeled trends of soil water storages were obtained with modeling that takes into account hysteretic (MDC+MWC) field SWCCs, testified by NS values that ranged between 0.76 and 0.88. Instead, considering complete SWCCs reconstructed from laboratory data, NS indexes were lower of 0.08-0.37 than the correspondent values of models based on field SWCCs. These results indicate that field reconstructed SWCCs allow to represent the real soil hydrological behaviors better than SWCCs based on laboratory data. In fact, field data allow for better identification of the soil drying and wetting features and the variability of its response to different meteorological and climatic conditions (Blight, 2013).

It is important to note that the effectiveness of modeling soil water storage is reduced considering only MDC of a soil, as confirmed by the decrease in NS values between 0.04 and 0.21 respect to the modeling with complete SWCCs (MDC+MWC). Daily errors of the model based on MDC data trends with respect to the model based on complete SWCC data trends reached values higher than 30 mm.

Neglecting hysteresis for soils that are characterized by this feature can imply significant errors when a water balance component is modeled. Hysteresis of SWCC significantly affects the water flows and storage in usually unsaturated soils. Thus, considering hysteresis in soil water balance improves the prediction with respect to considering only the main drying component of the SWCCs (Bashir et al., 2016).

The importance of considering entire SWCC paths and the errors associated in neglecting hysteresis in water balance modeling have effects in a wide range of problems in which a correct assessment of soil water balance components are required, such as prediction of groundwater flows and recharges, contaminant transport through unsaturated soils, swelling/shrinkage of expansive soils, soil erosion, slope stability (Kaluarachchi and Parker, 1987; Elmaloglou and Diamantopoulos, 2008; Ebel et al., 2010; Tsai, 2010; Fredlund et al., 2011; Likos et al., 2013; Bordoni et al., 2015a; Bashir et al. 2016; Arnone et al., 2017).

5. Conclusions

The evaluation of the potential improvements in accuracy guaranteed by field reconstruction of SWCCs with respect to laboratory estimated ones, was the main purpose of this paper. For reaching this objective, complete SWCCs of different soils, taken in sites characterized by different geological, geomorphological, physical and pedological properties, were reconstructed through both laboratory techniques and field-based monitoring of pore water pressure and water content. During the field data collection , MDCs and MWCs were discriminated by means of a robust methodology based on monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts. Field and laboratory reconstructed SWCCs were cross-compared and their reliability was tested in modeling correctly soil water storages trends measured through real observed data.

SWCC estimation by means of field experimental data can represent a promising tool to improve the characterization of natural soil hydrological behaviors. The approach followed for the distinction of drying and wetting periods allows for a correct discrimination of field data related to MDC or to MWC paths of a soil. Field reconstructed SWCCs are then assessed in both their components, quantifying hydrological parameters and hysteresis in a more reliable way than laboratory methodologies. Field methods allow for a measurement of a larger amount of data than the few tens of laboratory experimental points. This permits to better identify the soil hydrological behaviors and to obtain more robust fitted curves. Furthermore, reconstructed SWCCs identify patterns of changes in the form of the curves, which are useful for detecting the variations in hydrological features along depth and in relation to peculiar field and environmental conditions.

Besides the limited number of tested soils (5), it is important to note that field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days), unlike the estimation of other hydrological processes or parameters (river discharge, moment of the peak of a flood). Similar results can be obtained in terms of SWCCs paths, even if hourly data may often offer a clearer vision of the drying and wetting paths, due to the highest number of experimental data points. Moreover, in temperate climatic conditions as the ones of the two analyzed test-sites, MDCs and MWCs of a particular soil are substantially similar for different hydrological cycles with peculiar meteorological conditions, confirming how a soil follows the same SWCC paths along different years. According to this behavior, in similar environmental situations, reliable field SWCCs can be reconstructed after only one complete hydrological cycle (a drying phase followed by a wetting one), even if collection of experimental data from more cycles may guarantee a better comprehension of MDC and MWC paths, thanks to the higher number of influencing meteorological events.

The effectiveness of the field reconstructed SWCCs are also demonstrated by the implementation of their parameters in a numerical code for modeling the soil water storage. Field SWCCs allows for simulation of the observed trends of soil water storages for different soil horizons with a higher reliability than using laboratory reconstructed SWCCs. This means that field experimental SWCCs allow to better represent the environmental soil hydrological behaviors and the variability of soil response to different meteorological and climatic conditions. It is also important to highlight that neglecting hysteretic effects on modeling soil water balance can induce significant errors in the modeling results. Thus, a complete (MDC+MWC) SWCC is required for better simulations of the observed trends in the soil water balance.

As a general conclusion, experimental data of field hydrological monitoring devices can be useful tools for assessing SWCCs, allowing in particular to better quantify the real hysteretic features of a soil and to obtain more accurate hydrological parameters, representative of the real soil behaviors. Instead, it is fundamental an accurate distinction between drying and wetting periods that characterize a field site, in order to discriminate MDC and MWC of a soil. Moreover, at least one complete (main drying and main wetting phases) hydrological year of field data is required to reconstruct a complete SWCC. These limitations seem less significant than those related to laboratory techniques for SWCC reconstruction, also because the experimental laboratory points are significantly less than the field ones and the time required for their measures can be high, especially for pore water pressure lower than -10^2 kPa.

The results obtained in this work can encourage on the implementation of the same methodological approach to experimental data collected in sites characterized by different environmental/land use conditions or soils with different textural features (e.g. sandy soils).

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Improving the estimation of complete field Soil Water Characteristic Curves through field monitoring data

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Abstract

In this work, Soil Water Characteristic Curves (SWCCs) were reconstructed through simultaneous field measurements of soil pore water pressure and water content. The objective was to evaluate whether field-based monitoring can allow for the improvement of the accuracy in SWCCs estimation with respect to the use of laboratory techniques. Moreover, field assessment of SWCCs allowed to: a) quantify the hydrological hysteresis affecting SWCCs through field data; b) analyze the effect of different temporal resolution of field measures; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed and measured trends of a component of the soil water balance. These aspects were fundamental for assessing the reliability of the field reconstructed SWCCs. Field data at two Italian test-sites were measured. These test-sites were used to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. Field measured or laboratory measured SWCCs data of 5 soil horizons (3 in a predominantly silty soil, 2 in a predominantly clayey one) were fitted by Van Genuchten model. Different field drying and wetting periods were identified, based on monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts, of different cycles. This method allowed for a correct discrimination of the main drying and the main wetting paths from field data related and for a more reliable quantification of soil hydrological properties with respect to laboratory methodologies. Particular patterns of changes in SWCCs forms along depth could be also identified. Field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days), as testified by similar values of Van Genuchten equation fitting parameters. Instead, hourly data may offer a clearer vision of the drying and wetting paths, due to the highest number of experimental data points. Moreover, in temperate climate situations as those of the test-sites, main drying curves and main wetting curves of a particular soil were substantially similar also for different hydrological cycles with peculiar meteorological conditions. SWCCs parameters were implemented in a numerical code (HYDRUS-1D) to simulate soil water storage for different soil horizons. Field reconstructed SWCCs allowed for simulating with a higher precision these trends, confirming the reliability of the reconstructed field curves by a quantitative point of view. Moreover, best results were obtained considering hysteresis in the modeling.

Keywords: Soil Water Characteristic Curves; hysteresis; laboratory; monitoring; soil water storage

1. Introduction

Soil Water Characteristic Curve (SWCC) represents the relation between two of the main measurable soil hydrological parameters, that are the pore water pressure (ψ) and the volumetric water content (θ) (Lu and Likos, 2004; Lu and Godt, 2013). SWCC is essential to understand and analyze the soil hydrological behaviors and water regimes over time (Mualem, 1976; Hillel, 1998; Bittelli et al., 2010; Cassinari et al., 2015). Moreover, SWCC is fundamental for the application of unsaturated soil mechanics into geological and geotechnical practices (Fredlund and Rahardjo, 1993; Lu et al., 2010; Lu and Godt, 2013). Knowledge of the SWCC is important to quantify the soil water budget, therefore the amount of water that is present in a given volume of soil. This variable is of utmost importance to quantify the partitioning of incoming solar radiation into sensible and latent heat, affecting the atmospheric boundary layer and therefore weather patterns (Bittelli et al., 2015). Considering that at, the global level, evapotranspiration utilizes 25 % of the incoming solar radiation and returns 60% of the precipitation that reached the soil, back to the atmosphere (Oki and Kanae, 2006), it is very important to obtain a correct quantification of the properties affecting it. The availability of water to plants evaporation and soil evaporation is clearly a key factor and it is fundamentally affected by the SWCC.

Many laboratory techniques have been developed for measuring SWCC in laboratory. This approach consists in measuring different scatter points of ψ and the correspondent θ. Then, experimental data are fitted through a function, that represents the shape of the SWCC, whence its characteristic parameters are derived (Brooks and Corey, 1966; Fredlund and Xing, 1994; Vogel et al., 2001; Assouline and Or, 2013).

Many different methods have been proposed to determine the SWCC, for a few decades (Klute, 1986). Most widespread methods of laboratory measurement of SWCCs are: pressure plate apparatus (Richards, 1965; Klute, 1986; Bittelli and Flury, 2009); evaporation methods, called as

Wind Schindler Method (WSM; Peters and Durner, 2008); Vapor Pressure Methods (VPM) as thermocouple psychrometry (Boyer and Knipling, 1965; Rawlins and Campbell, 1986) or dew point potential meter (Campbell and Gee, 1986); filter paper methods (McQueen and Miller, 1968; Marinho and Oliveira, 2006).

Besides the diffusion of laboratory measurements of SWCC, they are affected by intrinsic limitations, which can be summarized as follows:

a) they are time consuming, thus usually SWCCs are obtained from few experimental points. For example, pressure plate apparatus requires several hours of equilibration time before performing the measurement of an experimental point. This equilibration time can be of several days, if ψ of the soil specimens is negative of many hundreds of kPa (McKenzie et al., 2002);
b) each technique is characterized by a resolution range, which limits its ability of covering the entire water retention (Lu and Godt, 2013). For example, Campbell et al., (2012) determined that vapor pressure methodologies provide best assessment of water retention features for ψ lower than 1000 kPa. On the other hand, Peters and Durner (2008) indicated that evaporation techniques, such as Wind-Schindler Method (WSM), works well in the range of ψ between 0 and about -10^3 kPa. Bittelli and Flury (2009) demonstrated that soil water retention curves determined from pressure plates may be in error for experimental points of ψ less than -200 kPa;
c) sampling of the soil specimens used for laboratory measurements can alter the natural physical properties of a soil. Morgan et al. (2001) indicated that laboratory determined SWCC could be significantly altered due to a combination of entrapped air in the pore sizes and in a change in soil bulk density, occurred during the sampling process.

d) laboratory measurements for SWCC reconstruction are conducted in environmental controlled conditions (Basile et al., 2003; Zhang et al., 2017), that are not always representative of the variable natural field conditions.

A different approach is to reconstruct SWCCs from field monitored data, obtained through a simultaneous measurement of ψ and θ at a certain depth in soil (Shani et al., 1987; Morgan et al., 2001; Ramos et al., 2006; Tu et al., 2009; Greco et al., 2010; Bittelli et al., 2012; Leung and Ng, 2013; Papa et al., 2013; Sorbino and Nicotera, 2013; Rianna et al., 2014; Bordoni et al., 2015a; Yan and Zhang, 2015; Fred Zhang, 2016; Iiyama, 2016). This approach allows for obtaining a dynamic SWCC, since the measurement is also time dependent, and if the SWCC changes with time, its dynamics are captured by the collected data. This is an important aspect since the SWCC is commonly considered a static property, which is characteristic of a given soil and does not change in time and space, while it often changes with time as well as space, especially in swelling soils where the structure may change with time and space. The idea that a single soil sample, collected at a given time, will represent the hydrological conditions of that specific soil profile for years to come it is, at the least, unrealistic. The reason for using mostly laboratory-based methods in the past was the intrinsic limitation of reliable and continuous monitoring in field methods. In the last decades with the development of electronics and computers, more and more reliable field experimental methods have been developed, allowing for remote and continuous acquisition of soil water content and pressure data, collected, logged and remotely transferred to computers. Specifics will be provided below.

Field reconstructed SWCCs could better represent the hydrological features of a soil, overcoming most of the main limitations (scarcity of experimental data; alteration on soil features during sampling; controlled conditions in performing laboratory measures) that affect the laboratory obtained SWCCs. Comparisons between laboratory and field reconstructed SWCCs for a particular soil (Bittelli et al., 2012; Sorbino and Nicotera, 2013; Rianna et al., 2014; Iiyama et al., 2016) showed that *in-situ* curves could be different respect to laboratory ones, with difference till about 10% in θ values for a particular ψ. Furthermore, the response time of the changes in hydrological parameters during field meteorological events is generally faster than the variations measured in laboratory controlled conditions.

It is important to highlight that field measurements of SWCCs show that these curves are not unique, but they are characterized by hysteretic processes due to different soil drying and wetting cycles which can affect a soil in *in-situ* conditions (e.g. seasonal variation of rainfalls) (Iiyama, 2016). Similar behaviors were shown also in laboratory reconstructed SWCCs, mainly due to a controlled re-saturation of a soil specimen after a complete or partial drying process (Hillel 1998). Hysteretic effects can induce a considerable difference in the water content values at a given pore water pressure and, then, have practical implications on water movement and regimes in soil. Numerous models for the evaluation of hysteretic nature of SWCCs have been developed (Topp and Miller, 1966; Kool & Parker, 1987; Fredlund et al., 2011; Maqsoud et al., 2012; Rojas et al., 2017). However, the measurement of SWCC hysteresis both in laboratory and in field conditions is very difficult, due to the limited number of collected data and to the limitation of measuring the relationships between pore water pressure value and the associated water content value along drying and wetting branches (Likos et al., 2013).

Some aspects need to be investigated in more detail for evaluating if field reconstructed SWCCs may or may not improve the reconstruction of reliable SWCCs of the real soil hydrological features. These aspects can be summarized in:

a) the possibility of measuring and quantifying hysteresis, that may affect soil water processes, through an identification of the events or periods within a hydrological year that are representative of soil drying or wetting conditions;

b) the effects of considering different resolution time of the field measurements (e.g hourly or daily measures) in the reconstruction of the SWCCs. Cristiano et al. (2016) and Persson and Saifadeen (2016) reviewed researches about the influence of temporal and spatial resolution of the measures of contaminant fluxes in soils, rainfall amount and superficial water fluxes in understanding the hydrological behaviors of a certain area. They concluded that time scaling techniques and time resolution of these measures can influence the complete comprehension of the hydrological response of a soil or of a catchment to particular meteorological conditions. Starting from this, it is important to investigate the effects of temporal resolution on field reconstructed SWCCs, which can be obtained from monitoring data measured at different scaling times;

c) the variation in SWCCs patterns according to different field meteorological conditions along a complete hydrological cycle (a cycle is defined as a drying period followed by a wetting one; Hopmans and Dane, 1986). During a two-year monitoring campaign in a hillslope of a tropical region in Hong Kong country, Leung and Ng (2013) observed a change in SWCC path and in the amount of hysteresis from one year to the other one. In particular, remarkable hysteretic behavior was measured for the year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity), while hysteresis was substantially negligible in a year with lower rain events. Starting from this, it is important to analyze more in detail the possible changes which can occur on field SWCCs paths along several years with peculiar meteorological conditions;

d) the goodness of the field reconstructed SWCCs, obtained by implementing their characteristic parameters in a hydrological model for the assessment of a variable of the water balance in soil.

For these reasons, this paper has the purpose to assess whether field-based monitoring tools can improve the accuracy in SWCCs estimation with respect to the use of laboratory techniques, providing an objective method to obtain reliable SWCCs through simultaneous field measurements of soil pore water pressure and water content. Moreover, this allowed to: a) quantify the hydrological hysteresis affecting SWCCs by indentifying the drying and the wetting phases through an objective method which takes into account the main meteorological patterns along a hydrological year; b) analyze the effect of considering hourly or daily field measures of soil pore water pressure and water content in the reconstruction of SWCCs; c) highlight the differences in SWCCs reconstructed for a particular soil during different hydrological years; d) evaluate the reliability of field reconstructed SWCCs, by the comparison between assessed (through the implementation of the field SWCCs parameters in a hydrological model) and measured soil water storages during a hydrological cycle. Thus, the comprehension of these aims were fundamental to fill the gaps in the evaluation of the reliability of a field-based estimation of SWCCs.

Analyses were conducted using field data measured by monitoring stations at two test-sites of Italy (Fig. 1). The different studied sites were selected in order to evaluate the goodness of field reconstructed SWCCs for soils characterized by different geomorphological, geological, physical and pedological features. In particular, it was supposed that these differences would lead to different SWCC. The experimental design for reaching the purpose of the paper consisted in a reconstruction of complete SWCCs of different soils of the selected test-sites, through laboratory techniques and through the use of data collected by field-based monitoring of pore water pressure and water content. Main drying and main wetting paths of field SWCCs were determined discriminating field data collected in drying and wetting phases, identified through an objective methodology based on evapotranspiration and rainfall trends along the time. Field SWCCs were reconstructed considering different hydrological years and using data acquired at different temporal resolutions. Field and laboratory reconstructed SWCCs were cross-compared and were used as input parameters in a model for the evaluation of a term (water storage) in soil water balance. The reliability of the reconstructed curves was assessed through the comparison between real observed data of this term and the modeled data using laboratory or field reconstructed SWCCs, alternatively.

2. Materials and methods

2.1 The test-sites

2.1.1 Montuè test-site

Montuè test-site slope is located in the North-Eastern part of Oltrepò Pavese (Northern Italy), a hilly region corresponding to the northern termination of Apennines (Fig. 1b). The studied slope has geomorphological features typical of the surrounding area. Hillslopes are characterized by medium-high topographic gradient ranging from 22 to 35°. Furthermore, the east-facing slope descends towards a rather small and narrow valley formed by a creek (Rio Frate Creek). The elevation ranges from 210 to 170 m above sea level (a.s.l.) and the monitoring station is located at 185 m a.s.l. The land use is mainly grass and shrubs. Roots are present from the ground level till about 0.3–0.4 m in depth. The climatic regime is temperate/mesothermal according to Koppen's classification of world climates (Koppen, 1936), with a mean yearly temperature of 12 °C and mean yearly rainfall of 684.4 mm. In correspondence of the studied slope, the bedrock is made up of gravel, sand and poorly cemented conglomerates with a low percentage of marls (Rocca Ticozzi Conglomerates), that overlie marly and evaportitic deposits (Vercesi and Scagni, 1984) (Fig. 1b).

The soil profile at the monitoring station is representative of the entire slope and of the surrounding area. The variation in main soil physical properties and structure is limited at this scale (Bordoni et al., 2015a). The analyzed topsoil is 1.3 m thick and is classified as Eutric Leptosol (USDA

Classification; United States Department of Agriculture, 2014). Seven main soil horizons were identified (Tab. 1): an OL horizon (0–0.01 m), labeled as A-M; an A1 horizon (0.01–0.1 m), labeled as B-M; an Ak2 horizon (0.1–0.2 m), labeled as C-M; an Apgk3 horizon (0.2–0.4 m), labeled as D-M; a Bgk horizon (0.4–0.7 m), labeled as E-M; a BCgk horizon (0.7–1.1 m), labeled as F-M; a Cgk horizon (1.1–1.3 m), labeled as G-M. Weathered bedrock (We. Bed.) is mainly composed by sand (75%; Tab. 1). All the soil layers have a subangolar polihedral structure. Aggregation is weak till 0.2 m from ground, while it is low strong in deepest levels. Soil horizons are mineral, with a basic pH (< 9) that is steady along depth. Moreover, they have organic carbon content lower than 5%, and are characterized by the presence of millimetric carbonate coatings, which determine a carbonate content higher than 10%, till 35.3% in G-M horizon. Reddish cutans, related to gleying features, are present in all the horizons of the soil profile, revealing a possible water table uprising. Evidences of marls levels is absent in the soil profile.

Grain size distribution is uniform along depth in the soil. All the soil horizons have a clayey sandy silt texture, with high silt contents ranging from 51 to 66%, clay content between 21 and 29% and steady sand content between 7 and 13% (Tab. 1). Gravel content is low and keeps quite steady, in a range every lower than 15% (Tab. 1). Thus, the soil horizons have not gravelly features, according to United States Department of Agriculture (2014). Gravel class is constituted of pebbles made by fragments of bedrock materials and with diameters till few centimeters. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are prevalently non-plastic or slightly plastic (CL). The liquid limit (w_L) ranges from 38 to 42%, while the plasticity index (P_I) ranges from 14 to 17% (Tab. 1). Unit weight (γ) ranges between 16.7 and 18.6 kN/m^3 (Tab. 1). All these features keep substantially uniform along the depth in the soil profile.

It is worth noting that all the soil horizons have similar mineralogical features, with substantially similar amounts of carbonates and clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is characterized by the presence of smectite and chlorite. In particular, smectite represents about the 50%, thus about 8-10% of the solid particles in the studied soils. These percentages keep steady along depth in the different layers. The amount in this swelling clay mineral is approximately lower than the minimum one (12-15%; Dexter, 1988) responsible to the creation of pedological processes which can provoke turbation on the soil profile. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling soils in the studied materials, such as slickensides, wedge-shaped aggregate units, cyclic sub-surface horizons, gilgai microtopography (Blokhuis et al., 1990). There are only superficial cracks that form in dry summer months and extend few centimeters in depth.

The area where the study slope is located is characterized by a high density of rainfall-induced shallow landslides, triggered during different events occurred in 2009-2014 time span (Zizioli et al., 2013; Bordoni et al., 2015a) (Fig. 1). None of these phenomena affected the area immediately surrounding the monitoring station (Fig. 1a), thus the described soil profile was not disturbed by failure or depositional processes that may modify the pedological features. Furthermore, no erosion events affected this part of the slope, also thanks to the presence of a dense shrubs/grasses cover which protect the soil profile from the action of shallow waters. It is important to note that natural revegetation of this slope have started since 2000. In fact, the slope had been cultivated with vineyards for at least 50 years before.

2.1.2 Centonara test-site

Centonara test-site slope is located in central part of Emilia Romagna region (North-Central Italy), in a hilly sector in correspondence of the eastern termination of Apennines (Fig. 1c). This slope has geomorphological features that can be considered typical of the surrounding area. Slope angle values keep around 10-14°. The site is a north-western-facing slope which descends towards a rather small valley formed by a creek (Centonara Creek). The elevation ranges from 225 to 110 m a.s.l. and the monitoring station is located at 200 m a.s.l. As in correspondence of Montuè test-site, the station was installed in the medium part of the slope and the land use is mainly grass and shrubs. Roots are present from the ground level till about 0.7–1.2 m in depth (Tosi, 2007). The climatic regime is temperate/mesothermal according to Koppen's classification of world climates (Koppen, 1936) also for Centonara site, with a mean yearly temperature of 14 °C and mean yearly rainfall of 758.5 mm. In correspondence of the test-site slope, bedrock is composed by scaly plastic clays belonging to Scaly shales complex (Farabegoli et al., 1994; Pini, 1999).

The soil profile in correspondence of the monitoring point is representative of the soils developed in the study area from scaly clays (Bittelli et al., 2012). The analyzed topsoil is 1.7 m thick and is classified as Aquic Chromic Haploxerert (USDA Classification; United States Department of Agriculture, 2014). Main soil horizons are (Tab. 2): A horizons (A1: 0-0.12 m; A2: 0.12-0.3 m), labeled as A-C; a B horizon (0.3–0.7 m), labeled as B-C; a Bw horizon (0.7–0.9 m), labeled as C-C; a Bg horizon (0.9–1.7 m), labeled as D-C. As in Montuè test-site, all the soil layers have a subangolar polihedral structure and the soil aggregation change from weak to low strong aggregation below 0.2 m from ground. The soil horizons are mineral (organic carbon content lower than 5%), calcareous (testified by the presence of millimetric carbonate coatings) and with a basic pH (< 9) (Bittelli et al., 2012) as Montuè test-site. All these features keep steady along depth in this soil profile. As in Montuè soil profile, evidences of marls levels are absent in the soil profile. Within D-C horizon, at depths between 1.45 and 1.65 m below the ground level, there is a layer of compacted material, with reddish cutans that highlight strong gleying, revealing stagnant saturated and reducing conditions along most wet periods of the year. Gleying features are absent in the other soil layers, testifying the uprising of the ground water table only till 1.45 m from ground level.

All the soil horizons have a silty clay texture, with steady grain size distribution along depth. Clay content is high, ranging between 46 and 60% (Tab. 2). Silt and sand amounts are similar in all the horizons (23-38% for silt amount, 15-17% for sand amount). Stones and gravels are absent in all the soil levels. According to the USCS classification (American Society for Testing and Materials, 1985), the soil horizons are inorganic clay with high plasticity (HL). w_L and P_I are the same along the soil profile, with values of 76 and 46% respectively (Tab. 2). Also the unit weight of the soil (γ) is similar in all the soil profiles (18.0 kN/m^3; Tab. 2). Even all these features keep substantially uniform along the depth in the soil profile.

It is worth noting that all the soil horizons have similar mineralogical features, with a predominance in clay minerals. Soil mineralogy of the clay soil fraction (< 2 μm) is mainly composed by smectite and vermiculite and it keeps steady along depth. The amount in these swelling clays is higher than in Montuè test-site (more than 15%). Thus, swelling-shrinking is more pronounced, even if the soil profile is not significantly disturbed. In fact, there are not morphological and pedological evidences of turbation phenomena typical of very swelling materials, as already observed in Montuè test-site. Shrinking cracks form in dry summer months, extending more in depth than in Montuè soil profile, till around the first 0.4 m along the profile. Moreover, anthropogenic disturbance is absent because the site is on a naturally-vegetated slope.

Shallow landslides are frequent also in clayey slopes surrounding Centonara test-site, as demonstrated also by the phenomenon occurred in the area around the monitoring station in 2006 (Fig. 1b; Bittelli et al., 2012). Instead, the failure surface of this event developed at 1.4-1.5 m from ground level, as a slight retrogressive failure that did not cause destruction of the soil horizons above this layer. For this reason, the soil profile till 1.4 m can be considered as not disturbed by this landslide. Moreover, as in Montuè site, no erosion events affected this slope, also thanks to the presence of a dense shrubs/grasses cover which act as a protection tool towards shallow waters.

2.2 Measure of SWCCs through laboratory tests

SWCCs were measured through laboratory devices for samples taken in correspondence of some soil levels of both test-sites. The chosen techniques allowed to measure several points of pore water pressure and correspondent water content, that could be used to reconstruct the shape of the function.

Laboratory SWCCs were reconstructed from measurements obtained by a combination of several devices, each characterized by its typical range of resolution. They were determined for C-M, E-M and G-M soil horizons of Montuè test-site. For pore water pressure values higher than -10^3 kPa, SWCCs points were measured from undisturbed soil samples using an evaporation methodology based on WSM (Hyprop, UMS GmbH, Munich, Germany), whose accuracy is of 1 kPa for ψ and 0.01 m^3/m^3 for θ. For this technique, each soil sample was equilibrated at saturated conditions by wetting the specimen with deionized water. Then, the sample was placed in the instrument, allowing the water evaporation.

Instead, for pore water pressure lower than -10^3 kPa, SWCCs points were measured from disturbed soil samples through a dew point potential meter technique (WP4T, Decagon Devices, Pullman, WA), whose accuracy is of 1-10 kPa. This device was calibrated with 0.1 M KCl salt solution. The soil samples were equilibrated at various pore pressures by wetting the soil with deionized water and allowing the water evaporation. The soil samples were then placed into the instrument, and the pore water pressure was determined. The corresponding soil water contents were measured by oven drying immediately after removal of the samples from the device.

Laboratory SWCCs were determined for all the representative soil layers of Centonara test-site. For pore water pressure values higher than -10^3 kPa, SWCCs points were measured from undisturbed soil samples through Stackman tables (Stackman et al., 1969) and pressure plate apparatus measurements, whose accuracy is of 1-10 kPa. The soil samples were placed on a pressure plate apparatus following the procedures described by Klute (1986). The soil samples were wetted from below with 0.1 M CaSO4, and allowed to saturate overnight. The samples were equilibrated in the Stackman plates and pressure plate apparatus at different pore water pressure values. The corresponding soil water contents were measured by oven drying immediately after removal of the samples from the device.

For pore water pressure lower than -10^3 kPa, SWCCs points were measured with the same procedure used for Montuè test-site samples.

2.3 Measure of SWCCs through field monitoring equipments

2.3.1 Field monitoring equipments

At both test-sites, a monitoring station consisting of devices installed in soils for measuring hydrological parameters and of sensors for measuring meteorological parameters was installed. In particular, the devices for measuring hydrological parameters were installed at different depths in both soil profiles, in correspondence to their different layers. This was done to analyze the hydrological behaviors and the form of SWCCs at different depths (Bittelli et al., 2012; Bordoni et al., 2015a).

The integrated monitoring station of Montuè test-site consists in a rain gauge (Model 52203, Young Comp., Traverse City, MI), a thermo-hygrometer (Model HMP155A, Campbell Sci. Inc., Logan, UT), a barometer (Model CS100, Campbell Sci. Inc., Logan, UT), an anemometer (Model WINDSONIC, Campbell Sci. Inc., Logan, UT) and a net radiometer (Model NR-LITE 2, Kipp & Zonen, Delft, Netherlands).

These meteorological sensors are coupled with six Time Domain Reflectometer (TDR) probes (Model CS610, Campbell Sci. Inc., Logan, UT), with accuracy of 0.01-0.02 m^3/m^3 and resolution between 0 and 1 m^3/m^3. They were equipped with a multiplexer (SDMX50, Campbell Sci. Inc., Logan, UT) and installed at 0.2 (C-M layer), 0.4 (D-M layer), 0.6 (E-M layer), 1.0 (F-M layer), 1.2

(G-M layer), 1.4 m (We. Bed. layer) from the ground level to measure the soil water content. TDR measurements of water content were checked in the first stages of the monitoring and, in order to reject uncorrected values, an appropriate algorithm was applied (Bordoni et al., 2015a).

Moreover, a combination of three tensiometers (Model Jet-Fill 2725, Soilmoisture Equipment Corp., Santa Barbara, CA), with accuracy of 1.5-2.0 kPa and measuring values higher than -100.0 kPa, and three Heat Dissipation (HD) sensors (Model HD229, Campbell Sci., Logan, UT), with accuracy of 1.5-2.0 kPa and range of measure till -10^5 kPa, installed at 0.2, 0.6, 1.2 m from the ground level in different soil horizons, are used to measure pore water pressure. The tensiometers directly measure the pore water pressure. The measured changes in soil temperature after a constant heating period, measured by the HD sensors, were converted in pore water pressures through the equation proposed by Flint et al. (2002), which allowed to obtain this parameter from field measures of HD devices. Tensiometers are installed in correspondence with the HD sensors to measure values close to 0 kPa and eventual positive values.

The measurement devices were positioned in undisturbed soil layers next to a trench pit purposely digged for their installation and were connected to the datalogging system. TDR probes, HD sensors and tensiometers were installed behind the trench pit and the data logging system to keep them in natural undisturbed soil. In this way, the water flows have been kept in natural conditions and the presence of preferential flows can be negligible.

The field data were collected every 10 minutes by a CR1000X datalogger (Campbell Scientific, Inc.) powered by a photovoltaic panel. In this work, field data acquired during a continuous monitoring of about 58 months, from 27 March 2012 (when the monitoring station was installed) to 10 January 2017, are analyzed. To avoid incorrect misinterpretation of the field monitored data, the first three months of measured data were not considered in the analysis, due to a high degree of scattering related to a required initial period in which sensors had to progressively adhere to the surrounding soil after the installation, in order to reach the required balance and thus allowing data acquisition (Meisina et al., 2016).

The Centonara site monitoring station is equipped with a rain gauge and a thermo-hygrometer similar to those ones of Montuè station. Soil water content was measured with the same TDR system used at Montuè test-site, at 0.2 (A-C layer), 0.4 (B-C layer) and 0.8 m (C-C layer) depths. Correction for soil water content overestimation due to the conductive clay material was performed, as described in Bittelli et al. (2008). Moreover, TDR measurements of water content were checked in the first stages of the monitoring with the same algorithm used for Montuè data, for removing uncorrected values. Soil pore water pressures were measured at the same depth of TDR probes installation with HD sensors similar to those ones installed at Montuè station.

For the installation of sensors with the same aim of Montuè test-site, a soil pit was excavated, 4 m apart, perpendicularly to the contour lines, therefore along the line of maximum slope gradient.

The field data were collected every hour by a CR23X datalogger (Campbell Scientific, Inc.) and transmitted to the Orbcomm satellite transmitter (model KX G7100, Orbcomm Data Communicator) (Bittelli et al., 2012). In this work, field data acquired during a continuous monitoring of about 31 months, from 1 January 2007 to 30 June 2009, are analyzed. Instead of Montuè, for this site the first three months of the monitoring period were taken into account, because the monitoring equipment was installed on July 2004, thus equilibration of the sensors in soils had already occurred.

2.3.2 Field measured SWCCs

For the soils of the tested slopes, where both water content and pore water pressure were installed, SWCCs were reconstructed by coupling simultaneous field measurements of these parameters. For Montuè test-site, field SWCCs were reconstructed for C-M (0.2 m from ground level), E-M (0.6 m from ground level) and G-M (1.2 m from ground level) horizons. It is important to highlight that pore water pressure values close to 0 kPa were not measured since November 2012 till the end of the analyzed period at C-M horizon, due to breakage of the tensiometer at 0.2 m from the ground level. For Centonara test-site, field SWCCs were reconstructed for A-C (0.2 m from ground level) and B-C (0.4 m from ground level) horizons. Despite the installation of pore water pressure and water content devices also at 0.8 m from ground level, it was not possible to reconstruct SWCCs for C-C horizon. This was caused by leakage of measures of pore water pressure for 22 of the 31 months of the monitored time span, due to problems with the HD sensor at this depth.

Monitoring time spans covered different hydrological cycles, with a succession of periods with different meteorological conditions, in particular related to seasonal variation of rainfall amounts and of evapotranspiration amounts (related to change in air temperatures). Rainfall and evapotranspiration amounts are generally used in determining wet and dry periods in a particular area. These parameters, in fact, well represent the effects of seasonal meteorological changes could have on hydrological fluxes in a certain zone, in terms of amount of infiltrated rainwater and lost water from soil by means of evaporation and transpiration processes (McKee et al., 1993). Both test-sites have temperate climates, which are characterized by months/seasons with wet conditions and by drier months/seasons. In a hydrological year, the months when evapotranspiration amount is higher than rainfall amount can represent drying conditions for a soil. While, the months when evapotranspiration amount is lower than rainfall amount can represent wetting conditions for a soil. In fact, monthly time scale is used for identifying drying and wetting periods, since, at this temporal scaling resolution, it is suitable to analyze variations in meteorological indexes (rainfall and evapotranspiration amounts) that have an evident impact on hydrological dynamics in soils (García-Valdecasas Ojeda et al., 2017).

Monthly rainfalls were calculated from data acquired by the rain gauges of the stations. Cumulated monthly evapotranspiration (ETc) values were obtained as sum of daily values calculated applying

Hargreaves's equation, based on daily air temperature (T) measured at the stations (Hargreaves et al., 1985) (eq. 1):

$$ETc = (0.0135 \cdot 0.408 R_0 \cdot (T + 17.8)\sqrt{Tmax - Tmin}) \cdot k_{cb} \qquad \text{eq. 1}$$

, where R_0 is the extraterrestrial solar radiation which changes each day in a year according to the position of a point in the world, Tmax and Tmin are the daily maximum and minimum temperature values, respectively, k_{cb} is the crop coefficient which is a function of the type of land cover and of the periods of the year (Tab. 3) (Allen et al., 1998).

Hargreaves's equation was chosen due to the availability of air temperature measurements only, at both test-sites. For this reason, a method based on the same calculations for evapotranspiration assessment was selected. Moreover, several researches at site-specific and catchment scales (Hargreaves et al., 1985; Droogers and Allen, 2002; Martì et al., 2015) stated that Hargreaves's equation is an effective methodology for the estimation of evapotranspiration fluxes at different temporal scales.

Once identified drying and wetting periods, field monitored data of these different periods were distinguished, for reconstructing Main Drying Curve (MDC) and Main Wetting Curve (MWC) of the SWCCs, respectively. If reconstructed MDC and MWC differ, it will be possible to show the hydrological hysteresis occurring in the soil as a consequence of the main drying and the main wetting paths.

Field SWCCs were reconstructed taking into account either the average hourly values or the average daily values of the hydrological parameters. This choice aimed to investigate the effects of considering different time resolution of field measures in the features of the SWCCs. Hourly and daily resolutions were chosen because these are the most used time scaling in field monitoring of soil hydrological parameters (Tu et al., 2009; Bittelli et al., 2012; Sorbino and Nicotera, 2013; Rianna et al., 2014; Pirone et al., 2015; Urciuoli et al., 2016).

Furthermore, field SWCCs of each complete hydrological cycle (a main drying period followed by a main wetting one, Hopmans and Dane, 1986) were reconstructed, both for hourly and daily data. The use of a hydrological year time span was useful for distinguishing different field SWCCs across monitoring time, detecting possible difference in these curves related to years with peculiar meteorological conditions.

It is important to highlight that the analyses performed to all the reconstructed SWCCs and their possible hysteretic features had been addressed only to verify the efficiency of field experimental data on assessing SWCCs features, taking into account also the potential effects linked to the time resolution of field measures and the differences related to data acquired in different hydrological years. It has considered beyond the scope of the present research the analysis of the main physical mechanisms that could be responsible of SWCCs features, such as non-uniformity in interconnected pores, solid-liquid contact angles, wetting- and drying-induced changes to pore structure, air entrapment (Lu and Likos, 2004; Likos et al., 2013).

2.4 Fitting of SWCCs

Laboratory or field reconstructed SWCCs data were interpolated by using the Van Genucthen's (1980) equation (eq. 2), which is the most widely used interpolating equation of SWCCs and has the capability of representing well the hydrological characteristics of soils with different textural, pedological and physical features (Van Genuchten et al., 1991; Lu and Godt, 2013):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha\psi)^n\right)^{\left(n+1/n\right)}} \qquad \text{eq. 2}$$

, where θ_s and θ_r are the saturated and the residual water contents, respectively, α and n are fitting parameters. The fitting parameters were evaluated through an iterative procedure based on

Marquardt's (1963) algorithm, which is able to solve minimization problems of non-linear curve fitting and fitting parameters estimation.

Variations in the values of the four parameters of eq. 2 allowed to identify: i) differences between laboratory and field reconstructed SWCCs; ii) possible differences between MDCs and MWCs; iii) differences between curves reconstructed for different hydrological cycles; iv) difference between curves reconstructed through hourly or daily values.

The reliability of the fitting procedure has then been evaluated by considering the Root Mean Square Error (RMSE) statistical index (eq. 3):

$$RMSE = \sqrt{\frac{(\theta_i - \theta_i *)^2}{n_{tot}}} \qquad \text{eq. 3}$$

, where n_{tot} is the number of observations, θ_i and θ_i* are the measured and predicted by eq.2 values of soil water content, respectively.

The procedure described in Section 2.2 for laboratory reconstruction of SWCCs allowed to estimate only MDC of a soil. For assessing also MWCs from laboratory data and comparing these curves with the field reconstructed ones, a model of assessment of hysteretic effects on SWCCs was taken into account.

Relations proposed by Likos et al. (2013) were used to estimate laboratory MWCs from laboratory reconstructed MDCs, making comparisons with field MWCs. They reviewed the methodologies developed for estimating parameters of MWC fitting with Van Genucthen equation from MDC parameters. Moreover, they integrated this review with other experimental data and found a robust functional relations for each fitting parameter of Van Genucthen equation (Tab. 4).

2.5 Modeling of soil water storage

The reliability of the reconstructed field SWCCs was assessed through the implementation of their fitting parameters in a model for the estimation of soil water storage of a layer i (S_i), a variable of the water balance in soil. For a particular ith soil layer, S_i at time t (S_{it}) is the difference between measured θ_i at t (θ_{it}) and θ_i at the beginning of a considered time span (θ_{i0}), multiplied by the thickness of the layer d_i, assuming that θ is uniform along the layer (Pirone et al., 2015) (eq. 4):

$$S_{it} = d_i(\theta_{it} - \theta_{i0}) \quad \text{eq. 4}$$

This methodology is particularly indicated for the assessment of temporal behaviors of soil water storage using field monitoring data (Pirone et al., 2015). S_i was calculated from field monitored data in correspondence of C-M, E-M and G-M levels at Montuè test-site and of A-C and B-C at Centonara test-site. A hydrological cycle (main drying and main wetting phase) was selected as the reference period for this analysis.

S_i was also calculated, for the same time span, on the basis of modeled θ at the same soil levels through HYDRUS-1D code Vers. 4.16 (Simunek et al., 2008, 2013). HYDRUS-1D code is based on one-dimensional solution of Richards' equation (Richards, 1931). This code is significantly used in soil hydrology, thanks to its capability in implementing a wide range of approaches that can be selected for simulating different aspects of water fluxes in soils (e.g. water balance, non-equilibrium processes, contaminant transport; Simunek et al., 2013). A more detailed description of this software and on its governing equation are present in Simunek et al. (2008, 2013).

Modeled S_i values were obtained considering different sets of SWCCs: i) laboratory reconstructed SWCC and neglecting hysteresis (only MDC parameters); ii) laboratory reconstructed SWCC considering hysteresis (MDC and MWC parameters); iii) field reconstructed SWCC and neglecting hysteresis (only MDC parameters); iv) field reconstructed SWCC considering hysteresis (MDC and MWC parameters).

The performance of each simulation was evaluated through the Nash and Sutcliffe (1970) statistical index (NS) (eq. 5):

$$NS = 1 - \frac{\sum_{t_0}^{t_f} (S_{iobs} - S_{imod})^2}{\sum_{t_0}^{t_f} (S_{iobs} - S_{iave})^2} \qquad \text{eq. 5}$$

, where S_{iobs} is the observed soil water storage, S_{imod} is the modeled soil water storage, S_{iave} is the average of the observed soil water storage, t_0 and t_f are the initial and the final time of the analyzed time span, respectively.

3. Results

3.1 Identification of the drying and wetting periods

Comparison between monthly rainfall and evapotranspiration amounts allowed for the identification of drying and wetting periods at both tested sites (Fig. 2). At Montuè test-site, complete drying periods were of 4-9 months and complete wetting periods were of 3-7 months. Instead, at Centonara test-site, complete drying periods were of 4-6 months and complete wetting periods were of 5-8 months (Tab. 5, 6).

It is important to highlight that there was an evident distinction between drying and wetting periods, based on the mean monthly rainfall (Tab. 5, 6). At Montuè site, drying periods had an average monthly rainfall amount between 32.7 and 63.5 mm/month, while wetting periods had an average monthly rainfall amount between 72.5 and 95.9 mm/month. At Centonara site, drying periods had an average monthly rainfall amount between 24.5 and 45.1 mm/month, while wetting periods had an average monthly rainfall amount between 57.4 and 94.6 mm/month. Monthly evapotranspiration amounts kept quite steady along different years, with peaks of 155 mm/month in hottest months

(July in both sites) and lower values of 12-20 mm/month in coldest months (January and February in both sites). Drying periods were characterized by a percentage of dry days (days without rainfall amounts) significantly higher than wet days (days with cumulated rainwater) at both test sites (56-81% of dry days against 29-44% of wet days), while wetting periods had higher percentage of wet days (51-59% of wet days against 41-49% of wet days) (Fig. 2c, d). The percentage of dry days during drying periods was higher than 50%, while the percentage of wet days during wetting periods exceeded 50%. Moreover, during wetting periods, time interval between two consecutive rainfall events was generally lower than 7-10 days. Thus, these conditions, related to a lower evapotranspiration amount caused by lower air temperature during winter and spring months (Tab. 5, 6), kept in a wetting stage the soils profiles during the entire wetting months. Conversely, the lower rainfall amounts, the higher interval between subsequent rainfalls (averagely more than 7-10 days) and the high air temperatures during summer and autumn months (Tab. 5, 6) determined the maintenance of dry conditions during the entire drying periods, when water loss from soil is higher than that gained.

According to these reconstructions, 4 complete hydrological cycles were identified at Montuè (Tab. 5), while 2 complete hydrological cycles were detected at Centonara test-site (Tab. 6).

3.2 Monitored soil hydrological parameters dynamics

3.2.1 Montuè test-site

Figure 3 shows hourly water content (θ) and pore water pressure dynamics (ψ) during the considered time span at Montuè test-site. These trends were compared with hourly rainfall amount, between 0 and 30 mm/h for covering the range till the highest registered hourly intensity. In the analysed period θ ranged between 0.10 and 0.45 m^3/m^3 in the soil, and between 0.15 and 0.38

$m^3 \cdot m^{-3}$ in the weathered bedrock (Fig. 3a). Instead, ψ ranged from positive values, till 12.7 kPa in the G-M horizon, to values in the order of -10^3 kPa (Fig. 3b).

Typical hydrological behaviour of shallow soil layers, till 0.6 m from slope surface, was very different with respect to the deeper layers (Fig. 3). The response of soil horizons till 0.6–0.7 m from the slope surface was quicker than the deepest ones during drying or wetting periods. Only prolonged rainy periods, especially during winter months, could cause an increase in soil saturation, testified by an increase of pore water pressure and of soil water content at depths higher than 0.7 m.

The typical conditions of the most wet months, between December and May, showed that frequent precipitations determined an increase of the soil wetness until it approached or reached saturated conditions (Fig. 3). Completely saturated conditions were reached in the G-M horizon only in winter and spring, as testified by values of ψ slightly lower or higher than 0 kPa (Figs. 3b, c). During wetting periods, water content in the weathered bedrock was lower than in the overlying G horizon (Fig. 3a). According to the monitored data, it could be supposed that during wet periods (winter and spring) a perched water table forms in the G horizon and can upraise in soil profile during most intense rainfalls of wet season. This condition keeps for the most wet period of the year (Bordoni et al., 2015a). Analyzed data also suggest a predominant recharge for vertical rainfall infiltration along the year, from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bordoni et al., 2015).

During drying periods and for the re-wetting events in early-autumn, the re-wetting of the soil horizons till 0.6–0.7 m was very rapid (Fig. 3, 4). During intense summer rainstorms, generally more than 10-15 mm in 2 h, ψ increased but it was not coupled with a correspondent increase in θ (Fig. 4). This could be linked to non-equilibrium processes due to fast infiltration (Ross and Smettem, 2000; Vogel et al., 2010), in which pore water pressure or water content trend lags behind each other by the water retention equilibrium. The evidences of these processes were collected thanks to the measurements of the HD sensors, which allowed for measuring pore water pressure dynamics also in soil conditions starting from values of pore water pressure around -10^2 and -10^3 kPa.

3.2.2 Centonara test-site

Figure 5 shows hourly water content (θ) and pore water pressure (ψ) dynamics during the considered time span at Centonara test-site. These trends were compared with hourly rainfall amount, between 0 and 20 mm/h for covering the range till the highest registered hourly intensity at this site. A problem in the acquisition of θ occurred during the period between January and August 2008. Moreover, measurements of ψ at C-C horizon were available only during January and September 2008. Despite this, main soil behaviors were recognizable. In the analysed period, θ ranged between 0.09 and 0.60 m^3/m^3 (Fig. 5a), while ψ ranged between -0.3 kPa to values in the order of -10^4 kPa (Fig. 5b). No positive values of ψ were detected during the monitoring time span.
As in Montuè site, θ and ψ depicted the typical direct relationship during both drying and wetting periods. During the wetting periods (from October to the beginning of Spring, Tab. 5), soil kept close to saturation, as confirmed by values of ψ close to 0 kPa and by values of θ generally higher than 0.4 m^3/m^3. In correspondence of rainfall events in wetting periods, θ and ψ changed slightly, with variation in the order of 0.02-0.08 m^3/m^3 and of less than 5 kPa, respectively (Fig. 5).
Decrease in θ and ψ during the dry periods, in particular in summer months, is evident. It is related to low precipitation amounts (Tab. 5) and to vegetation conditions of the area. In fact, this area is covered by a dense natural vegetation with various species of grass and shrubs, that is able to uptake a significant amount of water from soil layers till about 1-1.5 m (Tosi, 2007; Bittelli et al., 2012).
The soil profile was then recharged by precipitation in the autumn season. In correspondence of these events, contemporaneous increases in θ and ψ were monitored, without non-equilibrium processes highlighted at Montuè test-site (Fig. 5). The increase in soil saturation is quite fast,

probably aided by macropores and fissures present in soils for the shrinkage phenomena (Smethurst et al., 2012) typical of clayey soils at Centonara. Monitoring data also suggest a predominant recharge in the soil for vertical rainfall infiltration from the most superficial to the deepest layers, without significant evidences of lateral fluxes from upslope (Bittelli et al., 2012).

3.3 Reconstructed SWCCs

Figures 6 and 7 show field SWCCs, reconstructed considering together all the identified hydrological cycles (Tab. 4, 5) and distinguishing the data taken from drying or wetting periods. In these figures, also data of laboratory reconstructed SWCCs were inserted.

Field reconstructed SWCCs showed an evident not-closed hydrological hysteresis for each tested layer and considering hourly or daily data. SWCCs were then composed by a MDC, where data of identified drying periods were present, and by a MWC, composed from the data of the identified wetting periods.

Field SWCCs of the shallow tested soils (C-M and E-M at Montuè test-site, B-C at Centonara test-site) showed a high degree of scattering, especially for ψ higher than -10^2 kPa (Fig. 6, 7). This could be linked to very short hysteresis processes occurring after more intense rainfall events during drying and wetting phases, which determine numerous less evolved scanning drying and wetting curves. Instead, SWCCs of G-M horizon showed less scattered field measured values (Fig. 6c, d), because, due to its higher depth (1.2 m from the ground level) in the soil profile, this horizon is not affected by single rainfall events but only by more prolonged rainy or dry periods.

For G-M horizon, in correspondence of ψ values around -10^3 kPa, the trend of MDC on logarithmic scale shows a very high gradient, both for hourly or daily data (Fig. 6c, d). This effect is linked to the main drying phase of the studied soil during the dry season, when pore water pressure keeps rather steady and water content, instead, slowly and continuously decreases.

Data of laboratory SWCCs corresponded to the MDC path, due to the adopted testing procedure. As shown in Figures 6 and 7, laboratory data did not seem fitting well field data, but they followed a different MDC trend (Fig. 6).

In SWCCs of C-M and E-M soils, field data related to non-equilibrium processes due to intense summer rainstorm were reported and highlighted in a different color (gray circles) respect to other data. It is clear that field data of non-equilibrium processes lags behind each other by the water retention equilibrium, with significant variations in pore water pressure and quite steady values of water content (Fig. 6a, b, c, d).

Field and laboratory SWCCs were then interpolated using Van Genucthen model. RMSE values of the fitted field curves ranged between 0.0128 and 0.0189 m^3/m^3 for hourly values and between 0.0133 and 0.0183 m^3/m^3 for daily values, thus testifying that there is a good agreement with field experimental data (Tab. 7, 8). Best results were obtained for G-M horizon, where the effect of short hysteresis processes is less pronounced. Instead, RMSE values of the fitted laboratory MDCs ranged between 0.0239 and 0.0317 m^3/m^3 (Tab. 7, 8). Thus, fitting is worst due to the limited number of used experimental data, that do not allow to reconstruct the shape of the curve appropriately.

Except for θ_s parameter, MDC and MWCs fitting parameters were similar for both laboratory and field curves of each studied soil horizon of Montuè site, respectively (Tab. 7). θ_s of MDCs and MWCs of C-M horizon were lower of 0.08-0.11 m^3/m^3 than the values for the other studied levels (E-M and G-M horizon). For Centonara soil profile, decrease along depth of n parameter values, in the order of 0.35-0.90, was evident both for MDC and MWC curves (Tab. 8). Moreover, for MWCs, also an important increase in θ_s (from 0.41 to 0.49 m^3/m^3) and in α (from 0.003 to 0.017 kPa^{-1}) was highlighted increasing soil horizon depth (Tab. 8).

Due to the not-closed global hysteresis loop highlighted by field data (Fig. 6, 7), θ_s is in the order of about 4 (C-M horizon) – 10% (G-M horizon) between drying and wetting paths. Ratio between θ_{sw} and θ_{sd} is averagely of 0.92, quite higher than 0.85 found by Likos et al. (2013). For all the soils, passing from drying to wetting conditions, an increase in the α_w fitting parameter is highlighted with respect to the α_d (Tab. 7, 8), as already shown in previous works (Kool and Parker, 1987; Likos et al., 2013). Ratio between α_w and α_d is on the order of 1.2-2.0 for Montuè soils and of 3.0-5.7 for Centonara soils. Furthermore, also the n_w parameter changed with respect to n_d (Tab. 7, 8). For Centonara tested levels, a decrease in n_w was noticed, with a ratio between n_w and n_d of 0.73-0.95 (Tab. 7). As already demonstrated in Likos et al. (2013), θ_{rd} and θ_{rw} coincided in the field MDCs and MWCs for all the tested soils (Tab. 7, 8).

Differences between fitting parameters of laboratory and field MDCs and MWCs were evident for all the tested soils (Tab. 7, 8). These differences regarded, in particular, θ_s and α parameter. Instead, for Centonara soils, the differences were significant for all the four parameters of Van Genucthen equation. It is important to remember that laboratory MWCs were not obtained by experimental measures, but they derived from MDCs data by applying the relation proposed by Likos et al. (2013) (Tab. 4).

3.4 Differences on field SWCCs considering different hydrological cycles and hourly or daily data

During the monitored time spans, different hydrological cycles, labeled with progressive Roman number (Tab. 5, 6), were identified at Montuè and Centonara site. SWCCs of different cycles were then reconstructed, using hourly or daily data, for each soil. Fitting parameters of SWCCs of each cycle were compared each other and with the complete SWCCs obtained integrating field data of all these cycles (Fig. 6, 7).

Figures 8 and 9 show two examples of these reconstructions, one for a Montuè horizon (G-M) and one for a Centonara horizon (B-C). In spite of different meteorological conditions, in terms of peculiar rainfall amounts and average air temperature, for each cycle (Tab. 5, 6), it is important to highlight that the differences between values of the fitting parameters are very low (Tab. 7, 8). In particular, for each tested soil, maximum variation of θ_s and θ_r were of 0.01 m^3/m^3. Maximum change of α and n parameters were of 0.003 kPa^{-1} and of 0.06, respectively. Moreover, RMSE values of the curves were very similar, varying of less than 0.005 m^3/m^3 (Tab. 7, 8). This confirms the reliability of the reconstructed field curves, considering data taken from different cycles.

No significant changes on SWCCs paths were identified reconstructing these curves through hourly or daily data (Tab. 7, 8). As already showed for SWCCs obtained through data of the entire time span, fitting parameters of the curves of the same cycle are substantially equal considering hourly or daily monitored values. In fact, as shown in Tab. 7 and Tab. 8, maximum variations of θ_s and θ_r were of 0.01 m^3/m^3 considering hourly or daily reconstruction of the same path. Moreover, maximum change of α and n parameters were of less 0.003 kPa^{-1} and of 0.05, respectively. It is important to note that using hourly or daily data did not affect the reliability of the fitting procedure.

A comparison between RMSE values of field SWCCs through hourly or daily data for each tested soil was performed (Tab. 7, 8; Fig. 10, 11). To verify the similarity between RMSE values, the correlation coefficient (R^2) was calculated, on the hypothesis of a linear correspondence between hourly and the correspondent daily reconstruction (e.g. RMSE of SWCC from hourly data equal to the one of the correspondent SWCC from daily data). As shown in Fig. 10 and 11, R^2 was high in correspondence of each tested level, ranging from 0.75 to 0.98 and the differences between corresponding RMSE values were still very low, ranging between 0 and 0.004 m^3/m^3 for Montuè soils and between 0 and 0.002 m^3/m^3 for Centonara soils. Thus, RMSE of a curve fitted by hourly data can be considered significantly similar to the corresponding one obtained through daily data.

3.5 Comparison between observed and modeled soil water storage

Daily values of soil water storage (S) were calculated for soil levels where SWCCs were estimated. S was assessed through observed θ and through modeled θ using HYDRUS-1D code. As shown by Pirone et al. (2015), daily time resolution allowed to better highlight how the changes in S are caused by variations of meteorological conditions (rainfall amounts, evapotranspiration fluxes).

At both sites, S was reconstructed for a complete cycle: the II cycle, from 1 July 2013 to 31 May 2014, at Montuè site; the II cycle, starting from 1 April 2007 and ending at 1 December 2007, at Centonara site. For the Centonara site, modeling was limited before the end of the wetting phase due to lack of θ measurements for the problems to the monitoring system (Fig. 5a).

Thickness of each soil layer was the value measured in correspondence of the representative soil profile of the tested slopes: 0.1 m, 0.2 m and 0.3 m for C-M, E-M and G-M, respectively; 0.3 m and 0.4 m for A-C and B-C, respectively. The modeling considered laboratory or field reconstructed SWCCs alternatively. Moreover, only MDCs or complete hysteretic SWCCs was assumed, alternatively.

The fitting parameters of Van Genucthen equation and the saturated hydraulic conductivity (K_s) are required for modeling. Due to the similarity of fitting parameters determined by hourly or daily data and by different cycles, Van Genucthen fitting parameters of field SWCCs reconstructed by daily data of the all cycles in a soil were used (Tab. 7, 8). For the model based on laboratory data, the fitting parameters of the SWCCs assessed through laboratory data were considered (Tab. 7, 8).

RETC code Vers. 6.xx (Van Genuchten et al., 1991) was used to perform an inverse modeling of K_s of each analyzed soil, based on the measured θ and ψ (Bordoni et al., 2015a). RETC code allows to estimate soil K_s through a least-squares optimization approach to identify un known model parameters starting from observed retention and conductivity data. Estimated values of K_s, for drying and wetting paths of each soil, are listed in Table 9.

As upper boundary conditions for HYDRUS-1d modeling, cumulated daily rainfalls measured at the two monitoring stations during the modeled time spans were considered. Other superficial water fluxes in soil (e.g. irrigation processes) or shallow layers with steady θ or ψ were not present in both test-sites. Daily values of ETc were estimated through Hargreaves equation (eq. 1) and used in modeling. Moreover, a free drainage lower boundary condition was applied.

Figure 12 shows a comparison between observed trend of S and trends of S modeled through different setup for B-C layer. This was a representative example of the trends of S also in the other tested soils. There was no differences between the soil water volume storage at the end and beginning of each year. In particular, the amount of water stored in wet months (winter and spring) was lost during summer dry periods for the intense evapotranspiration fluxes and the low amounts of fallen rain. Considering the reference level at the beginning of a drying cycle, water lost during drying periods reached values till 75-80 mm at the end of these periods. Water was earned quickly during the first rainfall events of wetting periods, as already shown in the monitored trends of soil water content and pore water pressure (Fig. 3, 5), thanks to a fast infiltration in macropores and fractures formed during dry months. Increase in S was of about 40-50 mm during the first events of wetting periods, then S increased slowly during following events till turning to the reference level of the beginning of the modeling.

Table 10 reports the results of the modeling phases for all the analyzed soils in terms of NS index. Even if the general observed trends of S were followed by all the modeling setups, the best agreement between observed and modeled trends of S corresponded to a modeling which took into account hysteretic (MDC+MWC) field SWCCs (Tab. 10). In this case, NS values ranged between 0.76 and 0.88, corresponding to a very good match between observed and modeled data (Nash and Sutcliffe, 1970).

Effectiveness of the modeling decreased in the other case. NS decreased of 0.06-0.21 considering only field MDCs. Modeling with laboratory reconstructed SWCCs gave worst results than the corresponding trends through field reconstructed SWCCs (Tab. 10). Daily errors of modeled S with laboratory data reached values higher than 30 mm than modeled S with field data.

NS indexes were lower of 0.08-0.37 than the correspondent values of models based on field SWCCs. They were in the order of 0.34-0.62, testifying only a fairly well simulation of S (Nash and Sutcliffe, 1970).

4. Discussions

4.1 Hysteretic SWCCs through field data

The reconstruction of field SWCCs, composed by both MDC and MWC paths, requires knowledge of the experimental data belonging to drying or wetting periods of a soil. Previous researches (Bordoni et al., 2015a; Pirone et al., 2015; Urciuoli et al., 2016) distinguished dry and wet periods only on a heuristic approach, mainly through the consideration of the average general pattern of rainfall amount along the year. This work proposes, for the first time, an objective approach to identify these hydrological paths, by means of the relation between cumulated evapotranspiration and rainfall amounts of a particular time span. This procedure is based on the analysis of monthly time series of rainfall and evapotranspiration amounts, that is the scaling time suitable for catching trends and variations in meterological and related hydrological features in an area (McKee et al., 1993; Garcia-Valdecasas Ojeda et al., 2017).

The application of this procedure to the experimental data of the two test-sites allowed for the reconstruction of field SWCCs with a clear distinction between MDC and MWC paths. MDC data correspond to measures of the recognized drying periods of each site, while MWC data are the experimental measurements of the identified wetting periods of the same site.

Field SWCCs of the analyzed soils were then fitted through Van Genucthen model. Goodness of the fitting is high in all the tested layers (RMSE always less than 0.02 m^3/m^3), notwithstanding the depth of the considered horizon, and is better than the fitting results of laboratory experimental data for the same soils (RMSE always higher than 0.02 m^3/m^3). The not-perfect correspondence between either MDCs or MWCs and the experimental data is linked to less-developed scanning curves that form in correspondence of rainfall events, especially when ψ is in the range between -10^0 and -10^2 kPa. Non-equilibrium phenomena, detected for the most superficial soil horizons (till 0.6 m from ground level) at Montuè test-site, lag behind the normal retention equilibrium of a soil. For this reason, they need to be studied in a separately way respect to the typical soil hydrological behaviors represented through SWCCs (Vogel et al., 2010).

The two analyzed soil profiles differ for some pedological and physical properties. In particular, main relevant differences are related to: i) the soil texture, because Montuè horizons have clayey sandy silt texture, while Centonara layers have silty clay texture; ii) the soil mineralogy, because Montuè soils are characterized by a similar percentage in carbonates and clay minerals, while clays are significantly predominant in Centonara layers; iii) the soil plasticity, which is a direct consequence of difference in soil texture and mineralogy, because Montuè and Centonara soils are low plastic and high plastic soils, respectively. Considering the same soil profile, the most significant difference in the horizons along depth is linked to the soil aggregation at both test-sites. Below 0.2 m from ground level, both studied soils change their aggregation, passing from a weak to low strong aggregation.

At Montuè site, SWCCs of the three analyzed horizons (C-M at 0.2 m, E-M at 0.6 m and G-M at 1.2 m from ground) are not influenced by lateral fluxes in soils, while gleying conditions are present in all the tested layers. Furthermore, it is worth noting that the perched water table present in G-M horizon during most wet seasons (winter and spring) does not influence significantly SWCC. This water table is not present for an entire year, thus this layer can experience a wide range of water content and pore water pressure allowing to reconstruct well a complete SWCC.

At Centonara site, it is worth noting that SWCCs of the two analyzed horizons (A-C at 0.2 m from ground and B-C at 0.4 m from ground) are not influenced by particular soil hydrological features, such as ground water tables, gleying conditions, lateral fluxes. In fact, pedological features and monitoring data of these levels do not present particular signs of those hydrological conditions. Even if monitored data were not acquired and, thus, SWCCs were not reconstructed, only D-C layer may be influenced by these properties respect to the other tested levels, because it presents gleying evidences which testify the presence of stagnant reducing conditions typical of the persistence of a water table.

SWCCs of the two tested profiles present differences, according to the differences in terms of texture, that also reflects their difference in plasticity degree and mineralogy. θ_s and θ_r are averagely higher in Centonara silty clay soils, because soils with a predominant clay texture and mineralogy have a higher porosity and a higher amount of residual water than predominant silty soils such as Montuè ones (Terzaghi et al., 1996). According to soil texture, α parameter of predominantly silty Montuè soils and of silty clay Centonara soils are in the typical ranges of these textural class, respectively (0.019±0.015 kPa^{-1} and 0.005±0.005 kPa^{-1} for predominant silty and silty clay soils, resepctively; Carsel and Parrish, 1988). Instead, n parameter of predominantly silty Montuè soils is near to the typical range of this type of soil (1.31±0.09; Carsel and Parrish, 1988), while this parameter is significantly higher in Centonara soils than its typical range in clay soils (1.09±0.06; Carsel and Parrish, 1988), probably for the intrinsic physical/geotechnical features of the soil profile.

Taking into account the variations on SWCCs curves in different depths of the same soil profile, it is important to note that only θ_s parameter varied in the studied layers at Montuè test-site. In fact, θ_s

values of MDCs and MWCs of the C-M horizon were lower of 0.08-0.11 m^3/m^3 (Tab. 7) than the values of the paths for the other studied levels (E-M and G-M horizon). C-M horizon is the most superficial studied level at Montuè test-site (0.2 m from ground level) and has a weak aggregated structure. Its θ_s may be affected by the past tillage operations related to grapevines cultivations, which occurred in Montuè test site before 2000s. In fact, tillage operations generally reduce soil θ_s respect to uncultivated fields. Azooz et al. (1996) found a maximum reduction in soil water content close to saturation of 0.12 m^3/m^3 in the first 0.3 m from the ground level of soils with tillage. This range is consistent with the data measured at Montuè site. Increase in θ_s parameter registered in G-M horizon respect to E-M level is less significant and is of only 6%. This could be linked only to a slight natural heterogeneity of physical features along depth.

Considering an uncultivated slope, as Centonara test-site, where soil physical and mineralogical features are substantially similar in the different layers (Tab. 2), it is important to note that several fitting parameters of SWCCs changed along depth (Tab. 8). In particular, n parameter values decreased in the order of 0.35-0.90 both for MDC and MWC curves, while, only for MWCs, θ_s and α increased from 0.41 to 0.49 m^3/m^3 and from 0.003 to 0.017 kPa^{-1}, respectively. Lohse and Dietrich (2005) found similar results in the first 0.5 m of silty clayey soil, stating in particular that θ_s and α increased along depth in a statistically significant way. It could be hypothesized that, in correspondence of uncultivated sites, SWCCs may change along depth in the soil profile, as a consequence of changes in horizons structure caused by a decrease in soil weathering which may influence hydrological features (Lohse and Dietrich, 2005).

Changes in SWCCs fitting parameters, passing from main drying to main wetting path, can allow to represent accurately hydrological hysteresis and hydrological responses of a soil in drying and wetting conditions (Likos et al., 2013). Respect to Likos et al. (2013), which reviewed the relations between MDC and MWC curves in terms of change of Van Genuchten fitting parameters, the reconstructed field SWCCs present evident differences about the variation of α and n fitting parameters. For all the soils, passing from drying to wetting conditions, an increase in the α_w fitting parameter is highlighted with respect to the α_d (Tab. 7, 8), as already shown in previous works (Corey et al., 1965; Kool and Parker, 1987; Likos et al., 2013). Instead, ratio between α_w and α_d can be significantly higher than the maximum values measured from laboratory data (Likos et al., 2013), reaching 5.7 (B-C layer of Centonara site). Moreover, change of n parameter, measured through field SWCCs, do not seem to follow the typical scheme. In fact, for Centonara tested levels, a decrease in n_w with respect to n_d was noticed, with a ratio between n_w and n_d of 0.73-0.95 (Tab. 8). This is a difference respect to the most used models of hysteresis quantification, that consider n_w equal or slightly higher than n_d (Kool and Parker, 1987; Likos et al., 2013). The effect of hysteresis was more marked in clayey soils of Centonara site than in silty ones of Montuè slope. This was already highlighted by Fredlund et al. (2011), who found an increase of hysteretic effects of more than 50% in clayey soils respect to silty materials.

Comparing fitting parameters of field reconstructed and laboratory reconstructed curves, differences were evident for all the tested soils (Tab. 7, 8). These differences regarded, in particular, θ_s and α parameters. Sorbino and Nicotera (2013) and Iiyama (2016) found similar differences between laboratory and field SWCCs, till 10% of θ amount for the same value of ψ.

The results of the estimation of SWCCs through field data demonstrate that the developed procedure allows to obtain robust and reliable water retention curves able to represent the soil hydrological behaviors which characterize a layer in environmental conditions. Moreover, the procedure allows also obtaining a measure of the hysteretic paths in a soil, with a reliable quantification of the change in SWCCs paths passing from drying to wetting conditions. In particular, as regards the wetting features of the soils, the measured field MWC paths are more reliable than the modeled MWCs based on laboratory data. They represent also a valid alternative to the direct measurements of MWC through laboratory procedures, which are time-consuming and are sometimes affected by measurement errors (Lu and Likos 2004).

4.2 Effects on field SWCCs considering hourly or daily data and different hydrological cycles

A comparison of field SWCCs obtained, for a certain soil, considering hourly or daily monitoring data was performed. Similar analyses were not achieved before, but they are fundamental for highlighting the effect of using field monitoring data with different temporal resolution from the field experimental data on the estimation of SWCCs.

It is important to note that Van Genucthen fitting parameters of field SWCCs are substantially similar considering hourly or daily data, for each analyzed soil. Maximum variations of θ_s and θ_r were of 0.01 m^3/m^3 considering hourly or daily reconstruction of the same path, while maximum changes of α and n parameters were of less 0.003 kPa^{-1} and of 0.05, respectively (Tab. 7, 8). These changes were in the order of less than 5% for each fitting parameters of Van Genuchten equation, considering both MDCs and MWCs of each tested soil. Furthermore, using hourly or daily data do not affect the reliability of the fitting procedure and the resulted fitted curves. Differences on RMSE values for each tested soil ranged between 0 and 0.004 m^3/m^3 for Montuè soils and between 0 and 0.002 m^3/m^3 for Centonara soils. Moreover, R^2 of a linear correspondence between hourly and the correspondent daily reconstruction was high in correspondence of each tested level, ranging from 0.75 to 0.98. This demonstrated that RMSE of a curve fitted by hourly data can be considered significantly similar to the corresponding one obtained through daily data. These results testify that reliable field SWCCs can be obtained both considering hourly or daily monitored data. Thus hysteresis and fitting parameters can be assessed in the same way and with similar values through both types of time resolution in field measures. This aspect is particularly significant, because the comprehension of other hydrological parameters and processes can be affected by the time scaling resolution of the implemented measures, as in the case of fluxes of contaminant in soil, in the assessment of the moment of the peak of a river flood, and in the evaluation of the superficial water discharge (Cristiano et al., 2016 and references therein; Persson and Saifadeen, 2016).

It is important to note that for a long-term monitoring, the number of experimental data obtained through a hourly or a daily resolution of field measures is significantly higher than experimental data from laboratory techniques, the latter allowing usually to obtain only few tens of SWCC points (Lu and Godt, 2013). Even if similar reconstructed SWCCs can be obtained from hourly or daily data, as shown in the results in the studied sites, it highlights that a maximum number of 8784 data can be achieved by means of hourly resolution in field measures, against a maximum value of 365 data through daily resolution, on a time span of a year. Thus, hourly data may allow for obtaining a higher precision in the SWCC paths, making both drying and wetting paths clearer.

Effects of hydrological cycles with peculiar meteorological features were also investigated. This was possible thanks to the availability of field data recorded during a multi-year monitoring. In spite of different meteorological conditions, in terms of rainfall and air temperature trends, it is important to highlight that the differences between values of Van Genuchten parameters of SWCCs of different cycles are very low for each tested horizon. Variations in θ_s and θ_r were of 0.01 m^3/m^3, while maximum changes of α and n parameters were of 0.003 kPa^{-1} and of 0.06, respectively (Tab. 7, 8). As for time resolution of the field measurements effects, these changes were negligible, ranging in the order of less than 5% for each fitting parameters of Van Genuchten equation, considering both MDCs and MWCs of each tested soil. Moreover, RMSE values of the curves were very similar, varying of less than 0.005 m^3/m^3. This confirms the reliability of the reconstructed field curves, considering data taken from different cycles.

Despite the limited number of tested soils (5 horizons of two test-sites), in temperate climatic and meteorological conditions as the ones of the two investigated sites, it can be observed that MDCs and MWCs of a particular soil are substantially similar for different hydrological cycles with peculiar meteorological conditions. Previous works (Bittelli et al., 2012; Bordoni et al., 2015a, b) demonstrated that SWCCs dynamics in the test-sites were related to the changes in meteorological conditions along the seasons, without the influence of particular sub-surface water movements (absence of significant lateral fluxes, absence of a deep continuous water table in bedrock materials).

This confirms that a soil follows the SWCC paths along different years (Vachaud et al., 1985; Sorbino and Nicotera, 2013). According to this behavior, reliable field SWCCs can be reconstructed on the basis of only one complete hydrological cycle (a drying phase followed by a wetting one), even if collection of experimental data from more cycles may guarantee a better comprehension of MDC and MWC paths, thanks to the higher number of influencing meteorological events (Bordoni et al., 2015a). It is important to highlight that these results are in contrast respect to the ones achieved by Leung and Ng (2013) in a test site with a tropical climate. In their situation, year characterized by heavy rainstorms in wetting season (till 133.5 mm/h of intensity) determined a remarkable hysteretic path, while hysteresis was substantially negligible in a year with lower rain events. A soil behavior similar of this one was not found in the two test-sites analyzed in this research, probably due to the different climatic conditions of Montuè and Centonara test-sites.

4.3 Effects of SWCCs on modeling soil water storage

Soil water storage is one of the components of the soil water balance. It represents the amount of water lost or gained with respect to a reference starting point and control volume, indicating the change of water content in a soil over time. Soil water storages of the soil layers where field

SWCCs were reconstructed, were calculated using the method of Pirone et al. (2015), for representative time spans of the test-sites. Observed trends were compared with modeled ones, using water contents modeled by HYDRUS-1d code, taking into account laboratory or field estimated SWCCs, with or without hysteresis.

Best agreement between observed and modeled trends of soil water storages were obtained with modeling that takes into account hysteretic (MDC+MWC) field SWCCs, testified by NS values that ranged between 0.76 and 0.88. Instead, considering complete SWCCs reconstructed from laboratory data, NS indexes were lower of 0.08-0.37 than the correspondent values of models based on field SWCCs. These results indicate that field reconstructed SWCCs allow to represent the real soil hydrological behaviors better than SWCCs based on laboratory data. In fact, field data allow for better identification of the soil drying and wetting features and the variability of its response to different meteorological and climatic conditions (Blight, 2013).

It is important to note that the effectiveness of modeling soil water storage is reduced considering only MDC of a soil, as confirmed by the decrease in NS values between 0.04 and 0.21 respect to the modeling with complete SWCCs (MDC+MWC). Daily errors of the model based on MDC data trends with respect to the model based on complete SWCC data trends reached values higher than 30 mm.

Neglecting hysteresis for soils that are characterized by this feature can imply significant errors when a water balance component is modeled. Hysteresis of SWCC significantly affects the water flows and storage in usually unsaturated soils. Thus, considering hysteresis in soil water balance improves the prediction with respect to considering only the main drying component of the SWCCs (Bashir et al., 2016).

The importance of considering entire SWCC paths and the errors associated in neglecting hysteresis in water balance modeling have effects in a wide range of problems in which a correct assessment of soil water balance components are required, such as prediction of groundwater flows and recharges, contaminant transport through unsaturated soils, swelling/shrinkage of expansive soils, soil erosion, slope stability (Kaluarachchi and Parker, 1987; Elmaloglou and Diamantopoulos, 2008; Ebel et al., 2010; Tsai, 2010; Fredlund et al., 2011; Likos et al., 2013; Bordoni et al., 2015a; Bashir et al. 2016; Arnone et al., 2017).

5. Conclusions

The evaluation of the potential improvements in accuracy guaranteed by field reconstruction of SWCCs with respect to laboratory estimated ones, was the main purpose of this paper. For reaching this objective, complete SWCCs of different soils, taken in sites characterized by different geological, geomorphological, physical and pedological properties, were reconstructed through both laboratory techniques and field-based monitoring of pore water pressure and water content. During the field data collection , MDCs and MWCs were discriminated by means of a robust methodology based on monthly meteorological conditions, in terms of rainfall and evapotranspiration amounts. Field and laboratory reconstructed SWCCs were cross-compared and their reliability was tested in modeling correctly soil water storages trends measured through real observed data.

SWCC estimation by means of field experimental data can represent a promising tool to improve the characterization of natural soil hydrological behaviors. The approach followed for the distinction of drying and wetting periods allows for a correct discrimination of field data related to MDC or to MWC paths of a soil. Field reconstructed SWCCs are then assessed in both their components, quantifying hydrological parameters and hysteresis in a more reliable way than laboratory methodologies. Field methods allow for a measurement of a larger amount of data than the few tens of laboratory experimental points. This permits to better identify the soil hydrological behaviors and to obtain more robust fitted curves. Furthermore, reconstructed SWCCs identify patterns of changes in the form of the curves, which are useful for detecting the variations in hydrological features along depth and in relation to peculiar field and environmental conditions.

Besides the limited number of tested soils (5), it is important to note that field SWCCs estimation is not affected by the temporal resolution of the acquisition (hours or days), unlike the estimation of other hydrological processes or parameters (river discharge, moment of the peak of a flood). Similar results can be obtained in terms of SWCCs paths, even if hourly data may often offer a clearer vision of the drying and wetting paths, due to the highest number of experimental data points. Moreover, in temperate climatic conditions as the ones of the two analyzed test-sites, MDCs and MWCs of a particular soil are substantially similar for different hydrological cycles with peculiar meteorological conditions, confirming how a soil follows the same SWCC paths along different years. According to this behavior, in similar environmental situations, reliable field SWCCs can be reconstructed after only one complete hydrological cycle (a drying phase followed by a wetting one), even if collection of experimental data from more cycles may guarantee a better comprehension of MDC and MWC paths, thanks to the higher number of influencing meteorological events.

The effectiveness of the field reconstructed SWCCs are also demonstrated by the implementation of their parameters in a numerical code for modeling the soil water storage. Field SWCCs allows for simulation of the observed trends of soil water storages for different soil horizons with a higher reliability than using laboratory reconstructed SWCCs. This means that field experimental SWCCs allow to better represent the environmental soil hydrological behaviors and the variability of soil response to different meteorological and climatic conditions. It is also important to highlight that neglecting hysteretic effects on modeling soil water balance can induce significant errors in the modeling results. Thus, a complete (MDC+MWC) SWCC is required for better simulations of the observed trends in the soil water balance.

As a general conclusion, experimental data of field hydrological monitoring devices can be useful tools for assessing SWCCs, allowing in particular to better quantify the real hysteretic features of a soil and to obtain more accurate hydrological parameters, representative of the real soil behaviors. Instead, it is fundamental an accurate distinction between drying and wetting periods that characterize a field site, in order to discriminate MDC and MWC of a soil. Moreover, at least one complete (main drying and main wetting phases) hydrological year of field data is required to reconstruct a complete SWCC. These limitations seem less significant than those related to laboratory techniques for SWCC reconstruction, also because the experimental laboratory points are significantly less than the field ones and the time required for their measures can be high, especially for pore water pressure lower than -10^2 kPa.

The results obtained in this work can encourage on the implementation of the same methodological approach to experimental data collected in sites characterized by different environmental/land use conditions or soils with different textural features (e.g. sandy soils).

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Table 1
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Table 1. Main physical and geotechnical features of Montuè site soil horizons and weathered bedrock.

Soil horizon	Pedological classification	Representative depth	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	P_I (%)	γ (kN/m^3)
C-M	Ak2	0.2	12	13	54	21	40	17	17.0
D-M	Apgk3	0.4	2	11	59	28	38	14	16.7
E-M	Bgk	0.6	8	13	51	28	40	16	16.7
F-M	BCgk	1.0	2	12	56	30	39	16	18.6
G-M	Cgk	1.2	1	7	66	26	42	17	18.3
We. Bed.	-	1.4	0	75	25	0	-	-	18.1

Table 2

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Table 2. Main physical and geotechnical features of Centonara site soil horizons.

Soil horizon	Pedological classification	Representative depth	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	P_I (%)	γ (kN/m^3)
A-C	A	0.2	0	16	24	60	76	46	18.0
B-C	B	0.4	0	17	23	60			
C-C	Bw	0.8	0	15	27	58			
D-C	Bg	1.5	0	16	38	46			

Table 3. Values of k_{cb} parameter used for calculating ETc. The land use is "bushes and berries" (Allen et al., 1998), in both sites.

Period	k_{cb}
Late season (September–December)	0.4
Initial season (January–April)	0.2
Mid season (May–August)	1.0

Table 4
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Table 4. Relations between fitting parameters of Van Genucthen equation of MWC and MDC of a particular SWCC (Likos et al., 2013).

Parameter of the MWC	Relation with the correspondent parameter in MDC
α_w	2.24 α_d
n_w	1.01 n_d
θ_{sw}	0.85 θ_{sd}
θ_{rw}	θ_{rd}

Table 5. Lengths and main features of drying (D) and wetting (W) periods at Montuè site during the monitoring period. *The monitored time span did not cover entirely the period

Period	Cycle	Time span	Cumulated rainfall (mm)	Mean monthly rainfall (mm/month)	Mean air temperature (°C)
D	I	April 2012-October 2012	321.2	45.9	19.3
W	I	November 2012-June 2013	664.9	83.1	9.1
D	II	July 2013-October 2013	188.0	47.0	20.7
W	II	November 2013-May 2014	525.0	75.0	9.5
D	III	June 2014-October 2014	294.1	63.5	19.9
W	III	November 2014-March 2015	479.5	95.9	6.9
D	IV	April 2015-December 2015	300.2	33.4	16.7
W	IV	January 2016-March 2016	217.6	72.5	6.4
D	V	April 2016-October 2016	228.6	32.7	19.3
W	V	November 2016-*	47.0*	15.6*	4.4*

Table 6
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Table 6. Lengths and main features of drying (D) and wetting (W) periods at Centonara site during the monitoring period. * The monitored time span did not cover entirely the period.

Period	Cycle	Time span	Cumulated rainfall (mm)	Mean monthly rainfall (mm/month)	Average air temperature (°C)
W	I	January 2007-March 2007	172.2	57.4	7.7
D	II	April 2007-September 2007	270.8	45.1	21.1
W	II	October 2007-May 2008	650.2	81.3	10.0
D	III	June 2008-September 2008	101.6	25.4	22.6
W	III	October 2008-March 2009	567.8	94.6	8.0
D	IV	April 2009-*	73.4*	24.5*	21.3*

Table 7
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Table 7. Van Genucthen equation fitting parameters of laboratory and field fitted MDCs and MWCs for the studied soil horizons at Montuè test-site. *Fitting parameters were obtained applying Likos et al. (2013)'s relation to MDC fitting parameters.

Laboratory	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)
C-M (0.2 m)	0.35	0.01	0.024	1.30	0.0317	0.30*	0.01*	0.054*	1.31*	-
E-M (0.6 m)	0.41	0.01	0.010	1.37	0.0298	0.35*	0.01*	0.022*	1.38*	-
G-M (1.2 m)	0.43	0.01	0.010	1.41	0.0277	0.37*	0.01*	0.022*	1.42*	-
Field - Hourly data	**Drying**					**Wetting**				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)
C-M (0.2 m)-I cycle	0.33	0.02	0.006	1.51	0.0142	0.32	0.02	0.007	1.62	0.0146
C-M (0.2 m)-II cycle	0.33	0.02	0.004	1.55	0.0167	0.32	0.02	0.007	1.62	0.0168
C-M (0.2 m)-III cycle	0.33	0.01	0.002	1.57	0.0178	0.32	0.01	0.004	1.62	0.0173
C-M (0.2 m)-IV cycle	0.33	0.01	0.002	1.61	0.0173	0.32	0.01	0.004	1.62	0.0154
C-M (0.2 m)-All cycles	0.33	0.02	0.003	1.57	0.0163	0.32	0.02	0.007	1.62	0.0164
E-M (0.6 m)-I cycle	0.40	0.01	0.012	1.38	0.0179	0.37	0.01	0.017	1.40	0.0177
E-M (0.6 m)-II cycle	0.39	0.01	0.012	1.38	0.0126	0.37	0.01	0.017	1.40	0.0133
E-M (0.6 m)-III cycle	0.40	0.01	0.014	1.38	0.0140	0.37	0.01	0.017	1.40	0.0133
E-M (0.6 m)-IV cycle	0.40	0.01	0.012	1.38	0.0133	0.37	0.01	0.017	1.40	0.0143

E-M (0.6 m)-All cycles	0.40	0.01	0.012	1.38	0.0137	0.37	0.01	0.017	1.40	0.0136
G-M (1.2 m)-I cycle	0.43	0.01	0.013	1.16	0.0167	0.40	0.01	0.015	1.20	0.1070
G-M (1.2 m)-II cycle	0.44	0.01	0.010	1.22	0.0127	0.40	0.01	0.011	1.23	0.0135
G-M (1.2 m)-III cycle	0.43	0.01	0.010	1.21	0.0166	0.40	0.01	0.011	1.22	0.0124
G-M (1.2 m)-IV cycle	0.44	0.01	0.010	1.24	0.0171	0.40	0.01	0.011	1.22	0.0121
G-M (1.2 m)-All cycles	0.44	0.01	0.013	1.19	0.0158	0.40	0.01	0.014	1.21	0.0128

Field - Daily data	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)
C-M (0.2 m)-I cycle	0.33	0.02	0.006	1.51	0.0139	0.32	0.02	0.007	1.62	0.0149
C-M (0.2 m)-II cycle	0.33	0.02	0.004	1.55	0.0167	0.32	0.02	0.007	1.62	0.0169
C-M (0.2 m)-III cycle	0.32	0.04	0.002	1.67	0.0152	0.32	0.04	0.003	1.68	0.0128
C-M (0.2 m)-IV cycle	0.32	0.01	0.002	1.61	0.0145	0.32	0.04	0.003	1.68	0.0148
C-M (0.2 m)-All cycles	0.33	0.02	0.005	1.56	0.0145	0.32	0.02	0.007	1.62	0.0147
E-M (0.6 m)-I cycle	0.40	0.01	0.012	1.38	0.0138	0.37	0.01	0.017	1.40	0.0136
E-M (0.6 m)-II cycle	0.40	0.01	0.012	1.38	0.0134	0.37	0.01	0.017	1.40	0.0133
E-M (0.6 m)-	0.40	0.01	0.012	1.38	0.0132	0.37	0.01	0.017	1.40	0.0133

III cycle										
E-M (0.6 m)-IV cycle	0.40	0.01	0.012	1.38	0.0138	0.36	0.01	0.014	1.40	0.0136
E-M (0.6 m)-All cycles	0.40	0.01	0.012	1.38	0.0137	0.37	0.01	0.017	1.40	0.0136
G-M (1.2 m)-I cycle	0.43	0.01	0.013	1.16	0.0174	0.40	0.01	0.015	1.20	0.0102
G-M (1.2 m)-II cycle	0.44	0.01	0.010	1.22	0.0125	0.40	0.01	0.011	1.23	0.0133
G-M (1.2 m)-III cycle	0.44	0.01	0.010	1.22	0.0176	0.40	0.01	0.011	1.23	0.0134
G-M (1.2 m)-IV cycle	0.44	0.01	0.016	1.20	0.0173	0.40	0.01	0.017	1.20	0.0131
G-M (1.2 m)-All cycles	0.44	0.01	0.013	1.20	0.0161	0.40	0.01	0.015	1.21	0.0133

Table 8
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Table 8. Van Genucthen equation fitting parameters of laboratory and field fitted MDCs and MWCs for the studied soil horizons at Centonara test-site. *Fitting parameters were obtained applying Likos et al. (2013)'s relation to MDC fitting parameters.

Laboratory	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)
A-C (0.2 m)	0.55	0.07	0.009	1.30	0.0252	0.47*	0.07*	0.020*	1.31*	-
B-C (0.4 m)	0.55	0.07	0.009	1.30	0.0239	0.47*	0.07*	0.020*	1.31*	-
Field - Hourly data	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)
A-C (0.2 m)-I cycle	-	-	-	-	-	0.41	0.17	0.003	1.75	0.0146
A-C (0.2 m)-II cycle	0.47	0.17	0.001	2.38	0.0187	0.41	0.17	0.003	1.75	0.0148
A-C (0.2 m)-III cycle	0.45	0.17	0.001	2.38	0.0198	0.41	0.17	0.003	1.75	0.0153
A-C (0.2 m)-All cycles	0.47	0.17	0.001	2.38	0.0189	0.41	0.17	0.003	1.75	0.0150
B-C (0.4 m)-I cycle	-	-	-	-	-	0.49	0.15	0.017	1.40	0.0130
B-C (0.4 m)-II cycle	0.51	0.15	0.003	1.43	0.0167	0.49	0.15	0.017	1.40	0.0129
B-C (0.4 m)-III cycle	0.53	0.15	0.003	1.47	0.0189	0.49	0.15	0.017	1.40	0.0137
B-C (0.4 m)-All cycles	0.53	0.15	0.003	1.47	0.0171	0.49	0.15	0.017	1.40	0.0129
Field - Daily data	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (-)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (-)	RMSE (m^3/m^3)

A-C (0.2 m)-I cycle	-	-	-	-	-	0.41	0.17	0.003	1.75	0.0147
A-C (0.2 m)-II cycle	0.47	0.17	0.001	2.40	0.0177	0.41	0.17	0.003	1.75	0.0149
A-C (0.2 m)-III cycle	0.45	0.17	0.001	2.40	0.0192	0.41	0.17	0.003	1.75	0.0138
A-C (0.2 m)-All cycles	0.47	0.17	0.001	2.40	0.0183	0.41	0.17	0.003	1.75	0.0147
B-C (0.4 m)-I cycle	-	-	-	-	-	0.49	0.15	0.017	1.40	0.0132
B-C (0.4 m)-II cycle	0.51	0.15	0.003	1.43	0.0173	0.49	0.15	0.017	1.40	0.0136
B-C (0.4 m)-III cycle	0.53	0.15	0.003	1.47	0.0162	0.49	0.15	0.018	1.40	0.0138
B-C (0.4 m)-All cycles	0.53	0.15	0.003	1.47	0.0164	0.49	0.15	0.017	1.40	0.0134

Table 9. K_s values assumed for modeling soil water storage.

	K_{sd} (cm/h)	K_{sw} (cm/h)
C-M (0.2 m)-Laboratory data	6.0	3.6
E-M (0.6 m)- Laboratory data	6.0	3.6
G-M (1.2 m)- Laboratory data	2.0	1.8
A-C (0.2 m)- Laboratory data	4.0	3.0
B-C (0.4 m)- Laboratory data	4.0	3.0
C-M (0.2 m)-Field data	7.2	5.0
E-M (0.6 m)- Field data	7.2	3.6
G-M (1.2 m)- Field data	3.0	2.2
A-C (0.2 m)- Field data	1.8	1.3
B-C (0.4 m)- Field data	1.3	1.2

Table 10. NS values of modeled trends of soil water storage.

	NS (-)	NS considering hysteretic SWCCs (-)
C-M (0.2 m)-Laboratory SWCC	0.45	0.56
E-M (0.6 m)-Laboratory SWCC	0.55	0.59
G-M (1.2 m)-Laboratory SWCC	0.62	0.66
A-C (0.2 m)-Laboratory SWCC	0.34	0.45
B-C (0.4 m)-Laboratory SWCC	0.43	0.48
C-M (0.2 m)-Field SWCC	0.68	0.76
E-M (0.6 m)- Field SWCC	0.70	0.76
G-M (1.2 m)- Field SWCC	0.70	0.76
A-C (0.2 m)- Field SWCC	0.56	0.77
B-C (0.4 m)- Field SWCC	0.80	0.88

Figure captions

Figure 1. Location of the two test-sites (a). Geomorphological, geological and shallow landslides distribution features of Montuè (b) and Centonara (c) sites.

Figure 2. Comparison between monthly rainfall and evapotranspiration amounts during the monitored time spans at Montuè (a) and Centonara (b) test-sites, with identification of the drying (D) and wetting (W) periods. Percentage of dry and wet days during the different periods at Montuè (c) and Centonara (d) test-sites.

Figure 3. Water content (a), pore water pressure (b), pore water pressure in the range from -10 to 20 kPa (c) dynamics in relation with rainfalls for the analyzed time span at Montuè test-site.

Figure 4. Non-equilibrium phenomena monitored at Montuè test-site during an intense summer rainstorm (14 June 2015, 35.5 mm in 3 h): a) rainfall trend; b) soil water content trends at 0.2 (C-M horizon) and 0.6 m from ground (E-M horizon); c) soil pore water pressure trends at 0.2 (C-M horizon) and 0.6 m from ground (E-M horizon).

Figure 5. Water content (a), pore water pressure (b), pore water pressure in the range from -10 to 10 kPa (c) dynamics in relation with rainfalls for the analyzed time span at Centonara test-site.

Figure 6. Reconstructed SWCCs of Montuè soil horizons, considering hourly or daily field data: a) C-M horizon with hourly data; b) C-M horizon with daily data; c) E-M horizon with hourly data; d) E-M horizon with daily data; e) G-M horizon with hourly data; f) G-M horizon with daily data.

Figure 7. Reconstructed SWCCs of Centonara soil horizons, considering hourly or daily field data: a) A-C horizon with hourly data; b) A-C horizon with daily data; c) B-C horizon with hourly data; d) B-C horizon with daily data.

Figure 8. Field SWCCs of different cycles for G-M horizon: a) I cycle with hourly data; b) II cycle with hourly data; c) III cycle with hourly data; d) IV cycle with hourly data; e) I cycle with daily data; f) II cycle with daily data; g) III cycle with daily data; h) IV cycle with daily data.

Figure 9. Field SWCCs of different cycles for B-C horizon: a) I cycle with hourly data; b) II cycle with hourly data; c) III cycle with hourly data; d) I cycle with daily data; e) II cycle with daily data; f) III cycle with daily data.

Figure 10. Correspondence between RMSE values of field SWCCs (MDCs and MWCs paths) reconstructed for Montuè soils reconstructed through horuly or daily data: a) C-M horizon; b) E-M horizon; c) G-M horizon.

Figure 11. Correspondence between RMSE values of field SWCCs (MDCs and MWCs paths) reconstructed for Centonara soils reconstructed through horuly or daily data: a) A-C horizon; b) B-C horizon.

Figure 12. Comparison between daily observed and modeled soil water storage of B-C horizon for the period between 1 April 2007 and 1 December 2007: a) rainfall trend; b) modeled S through laboratory reconstructed MDC; c) modeled S through laboratory reconstructed complete SWCC (MDC+MWC); d) modeled S through field reconstructed MDC; e) modeled S through field reconstructed complete SWCC (MDC+MWC).

Figure 1

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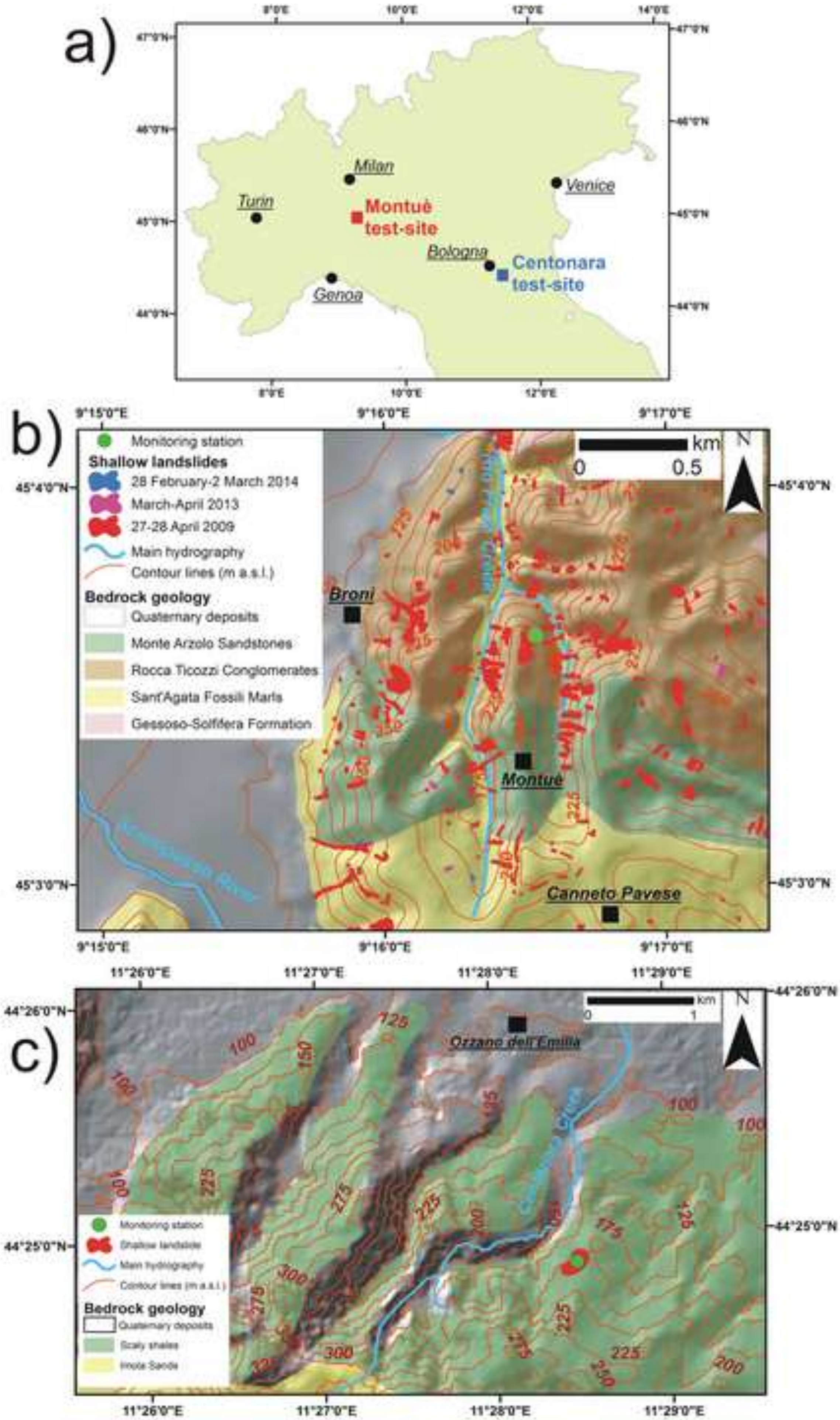

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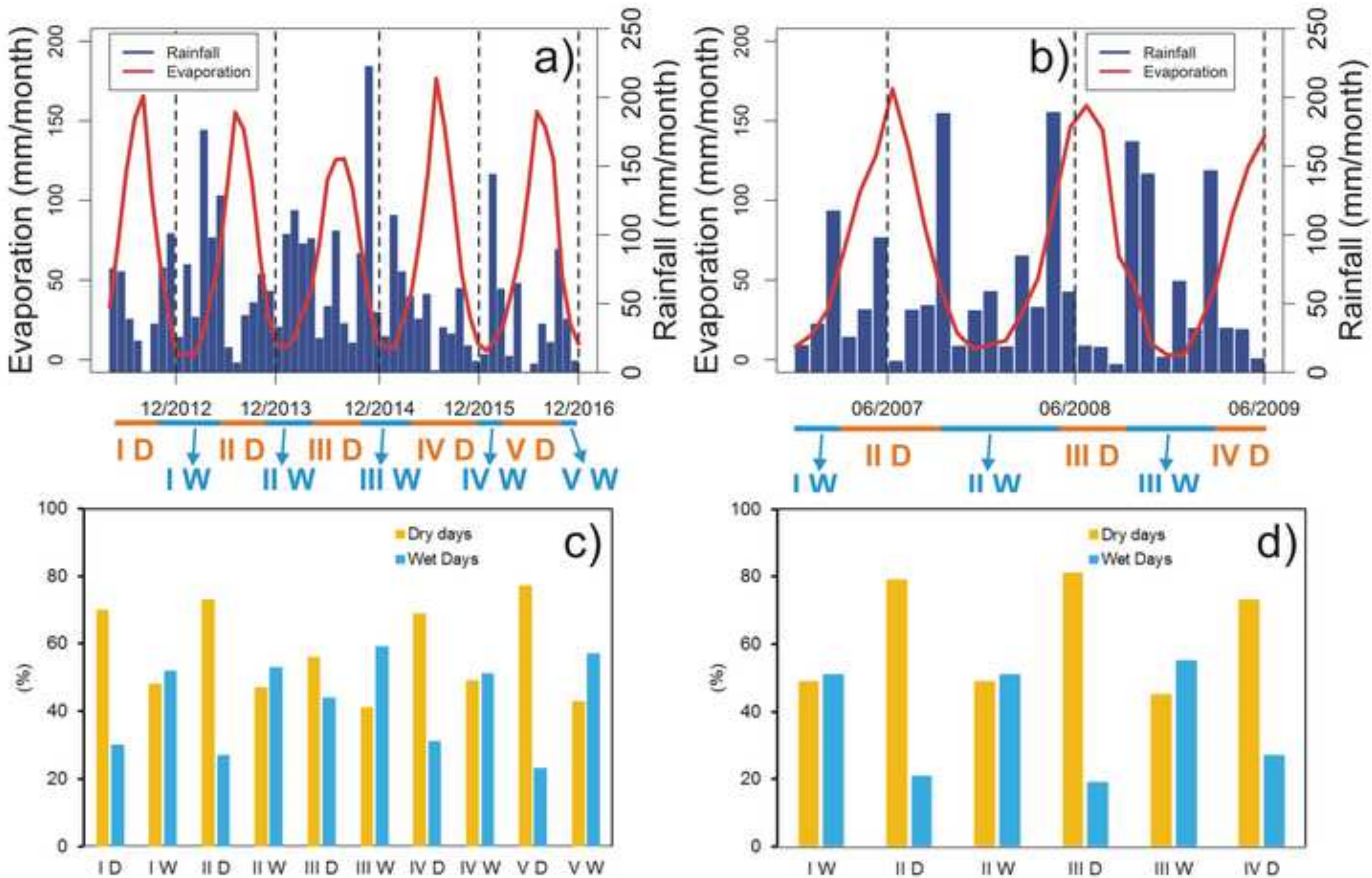

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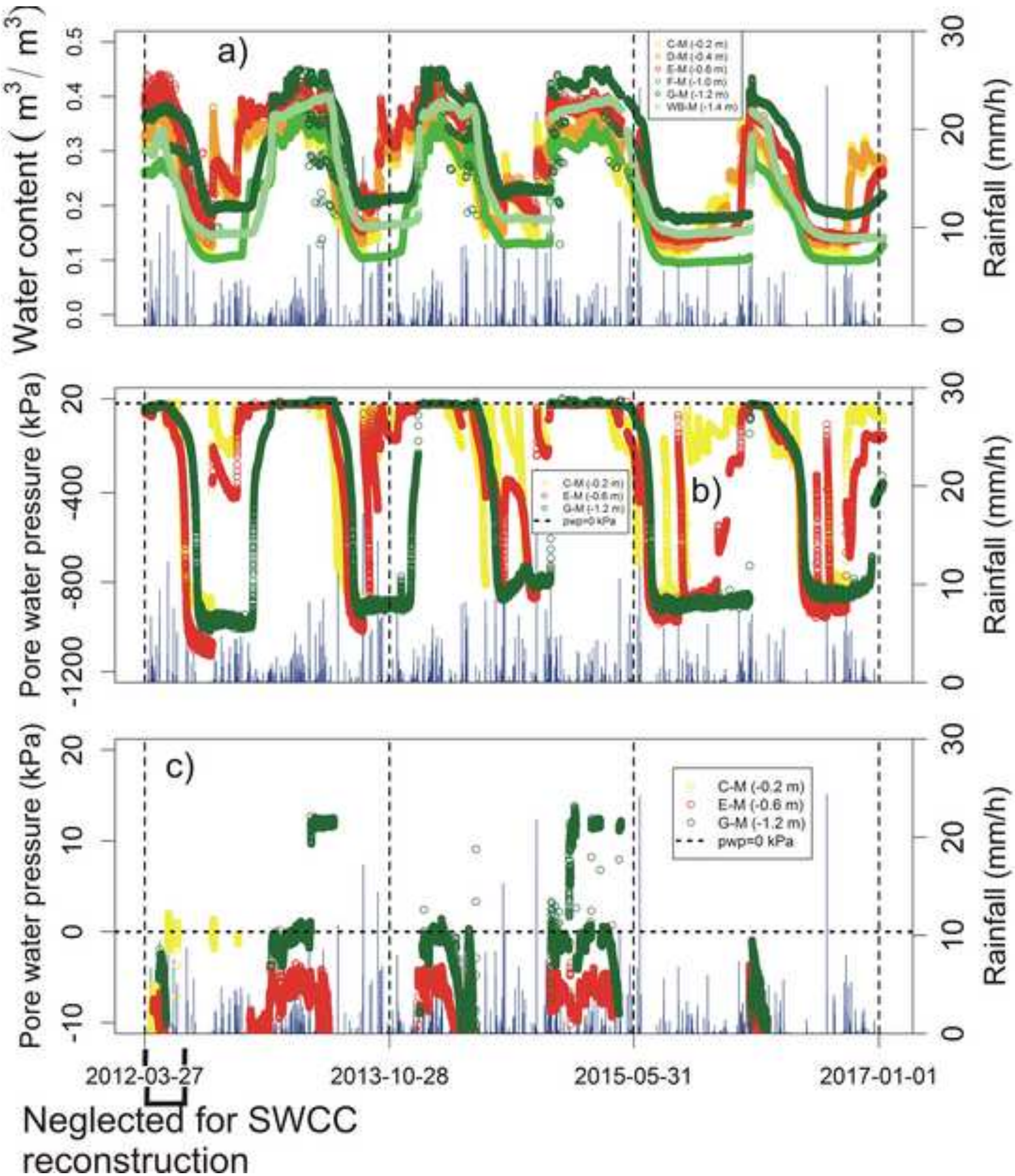

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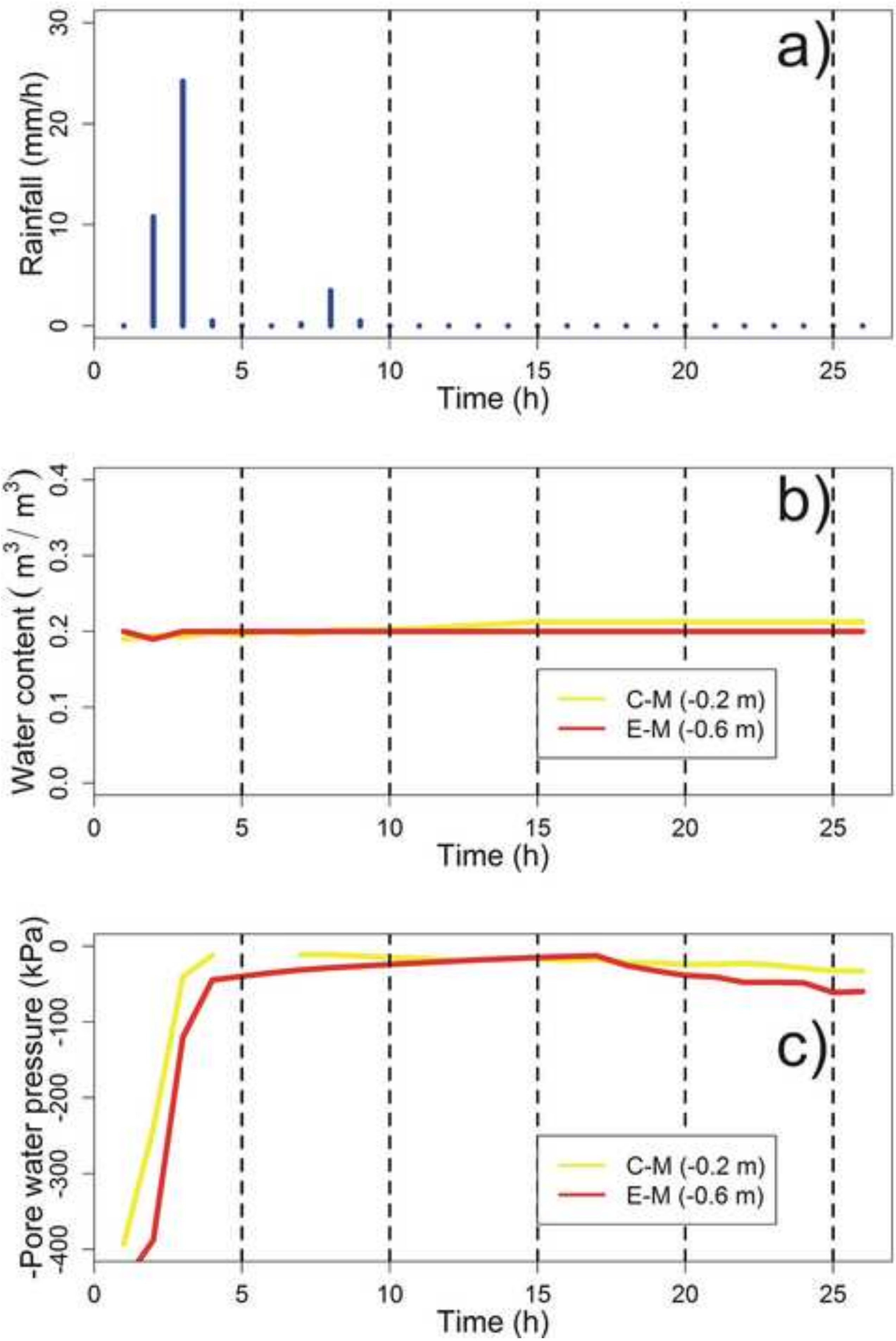

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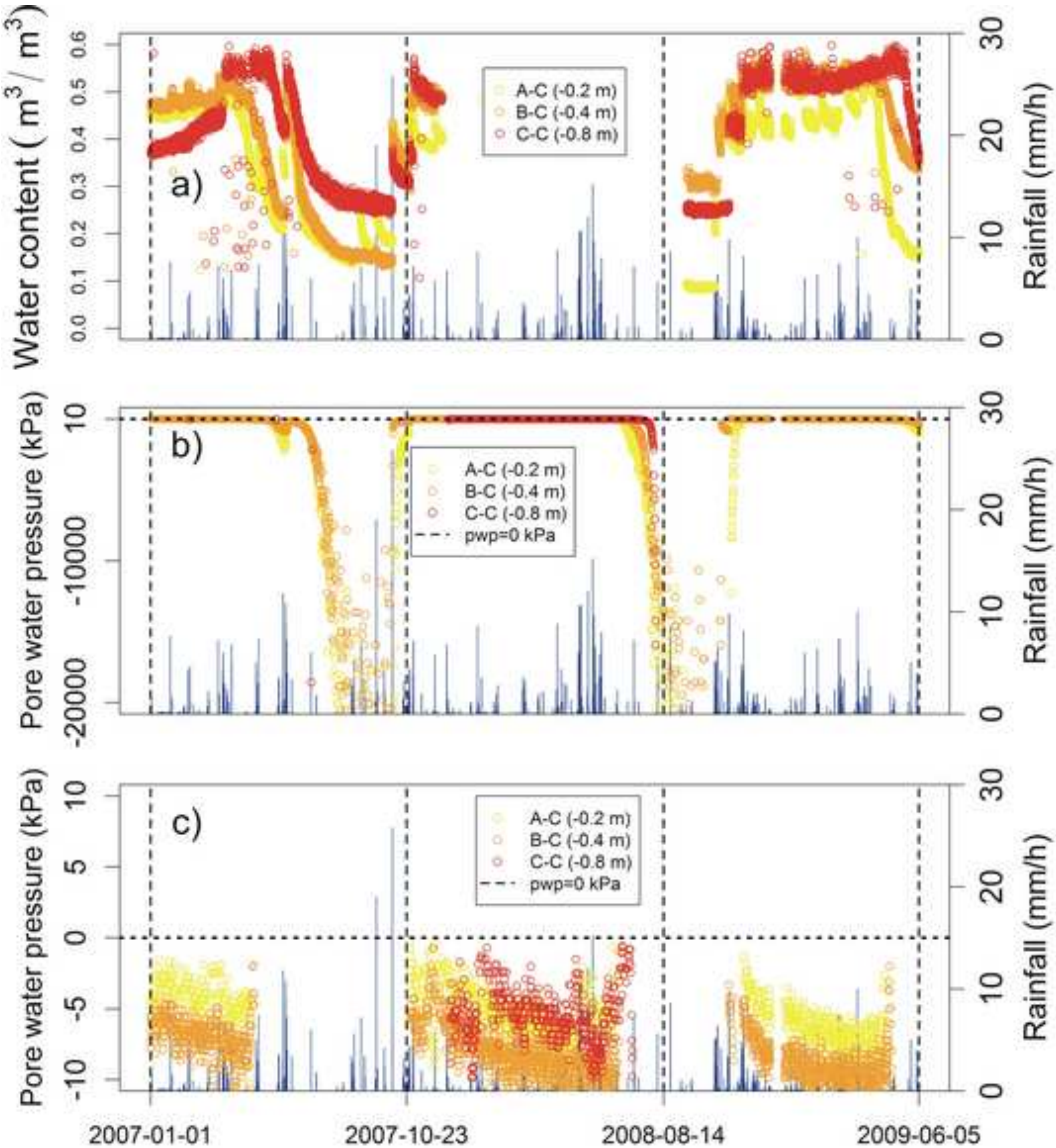

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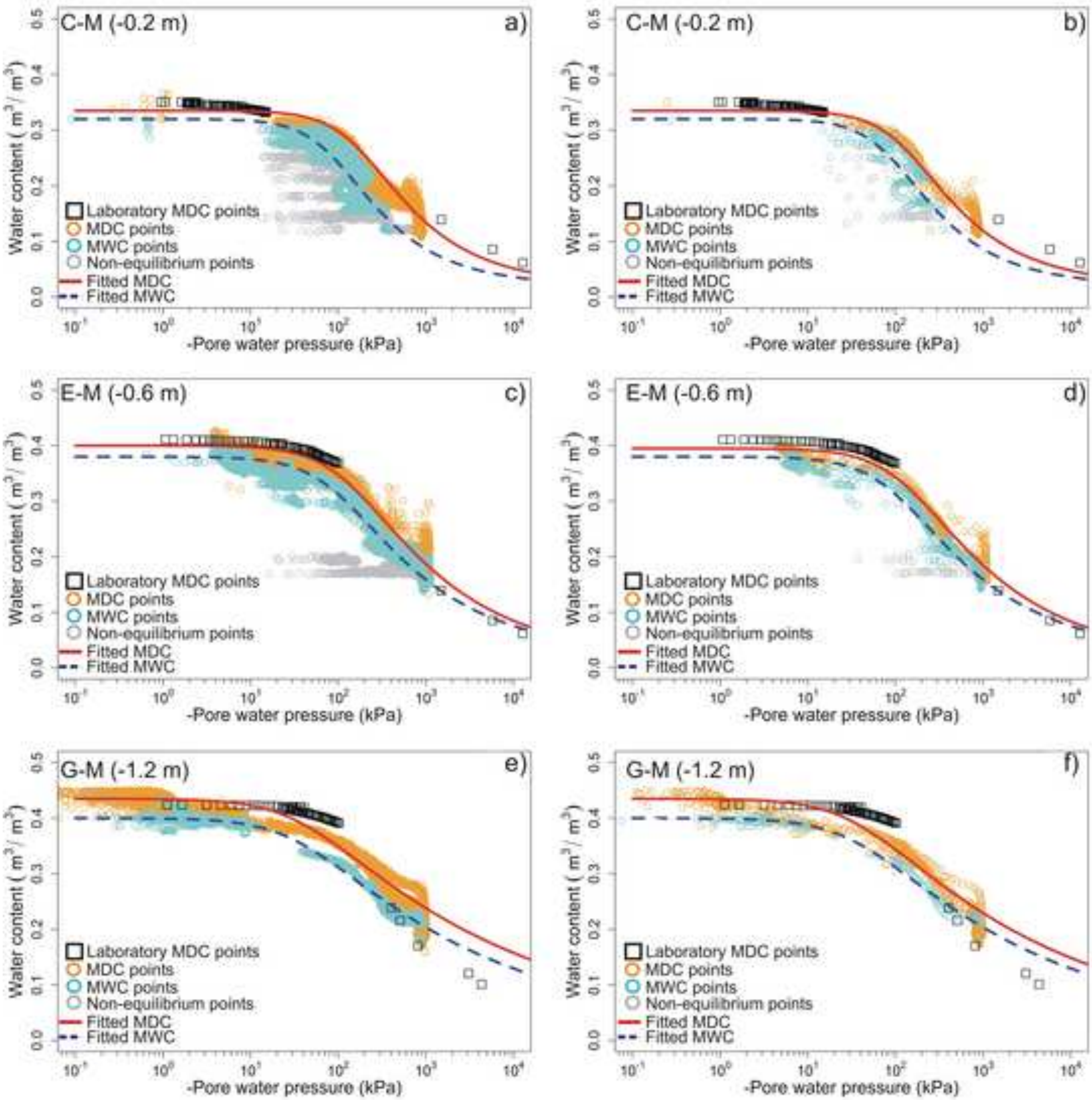

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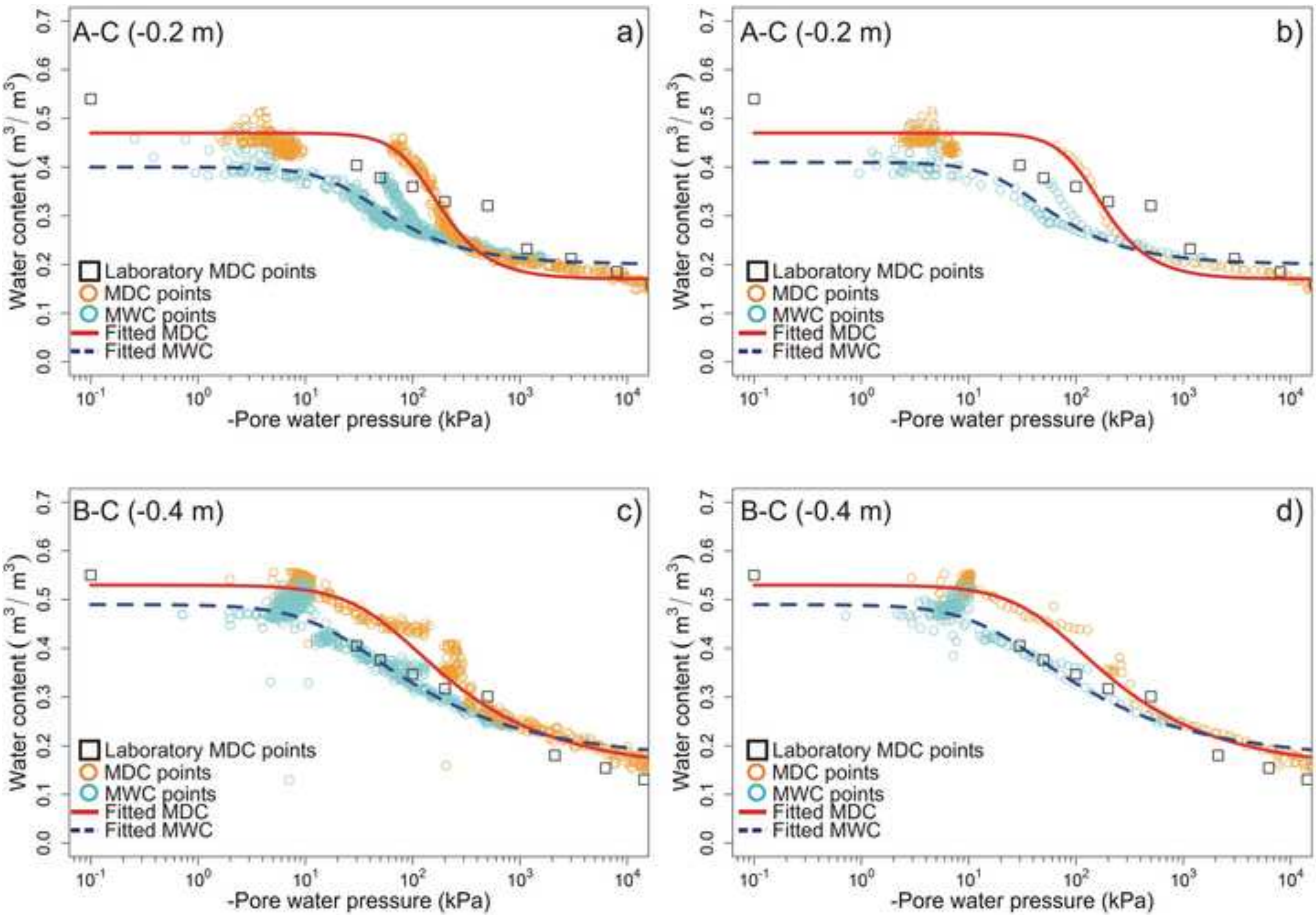

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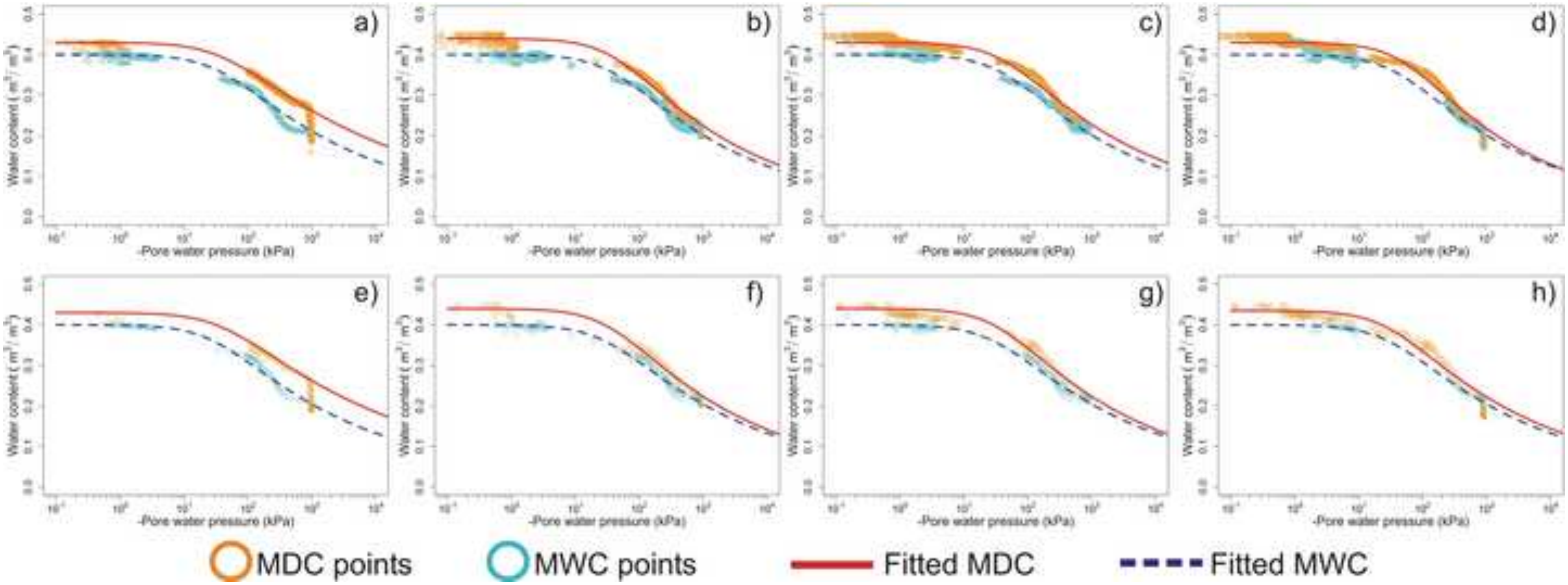

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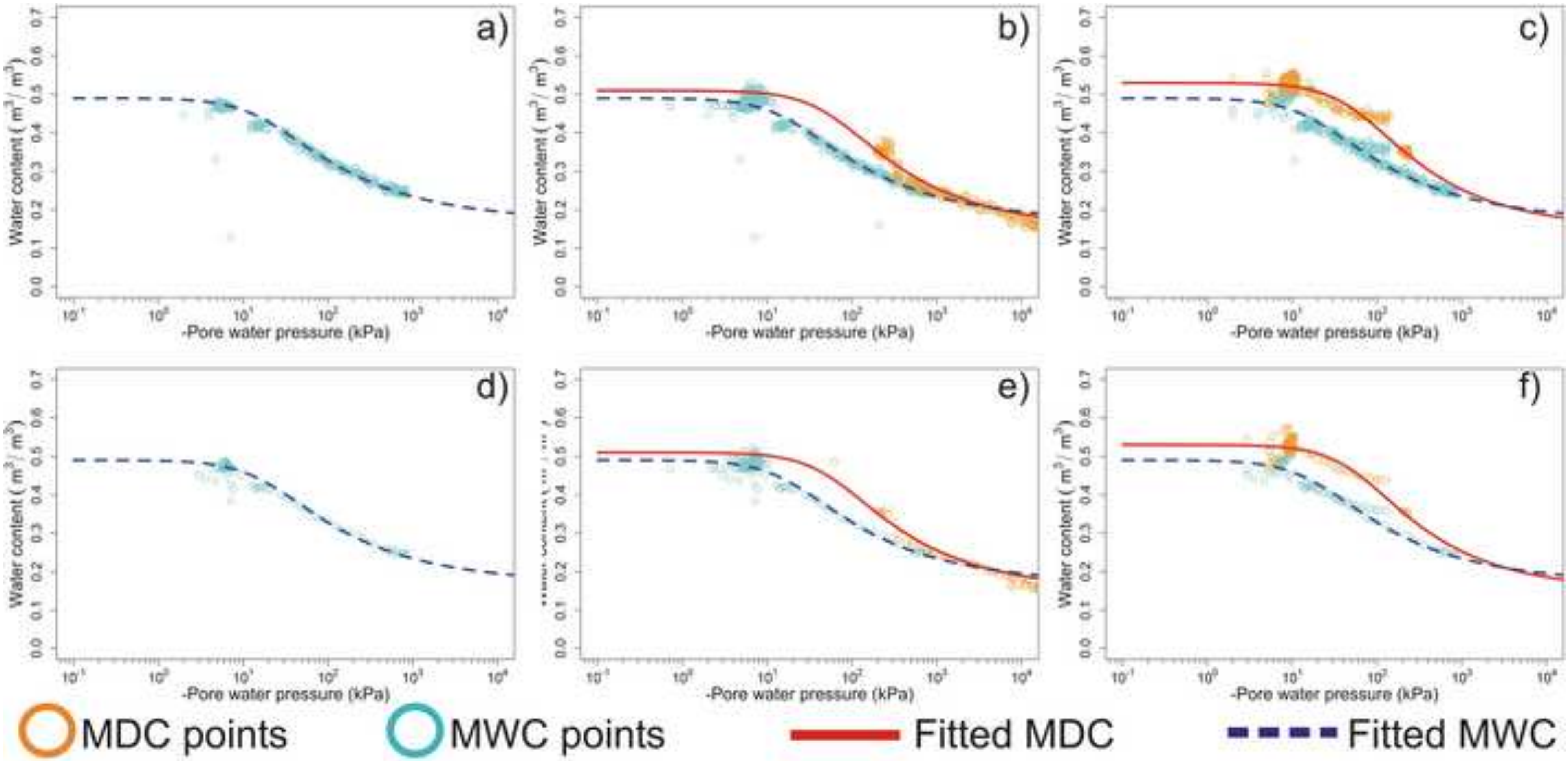

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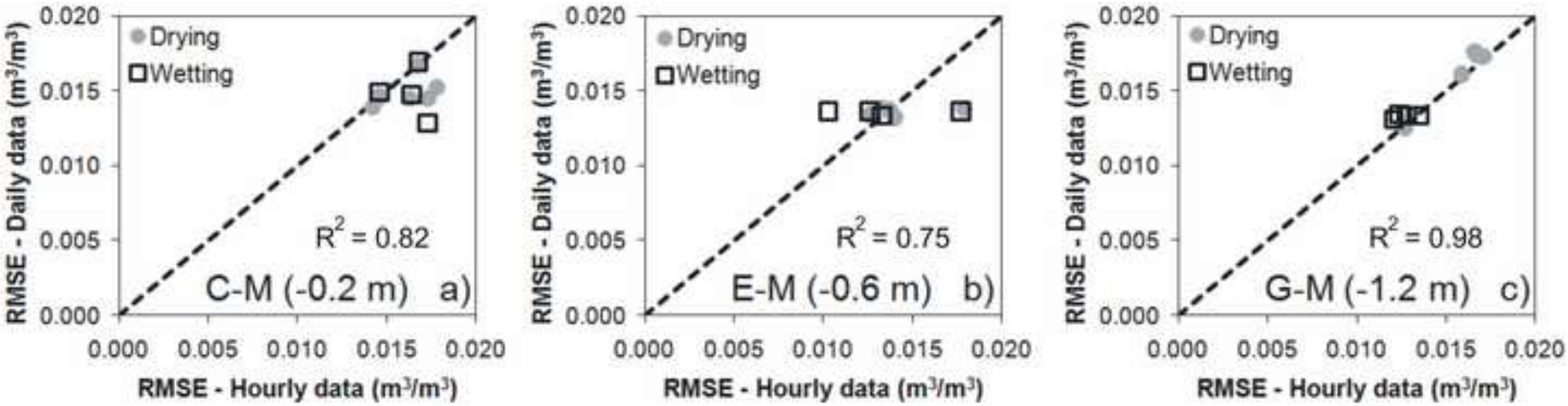

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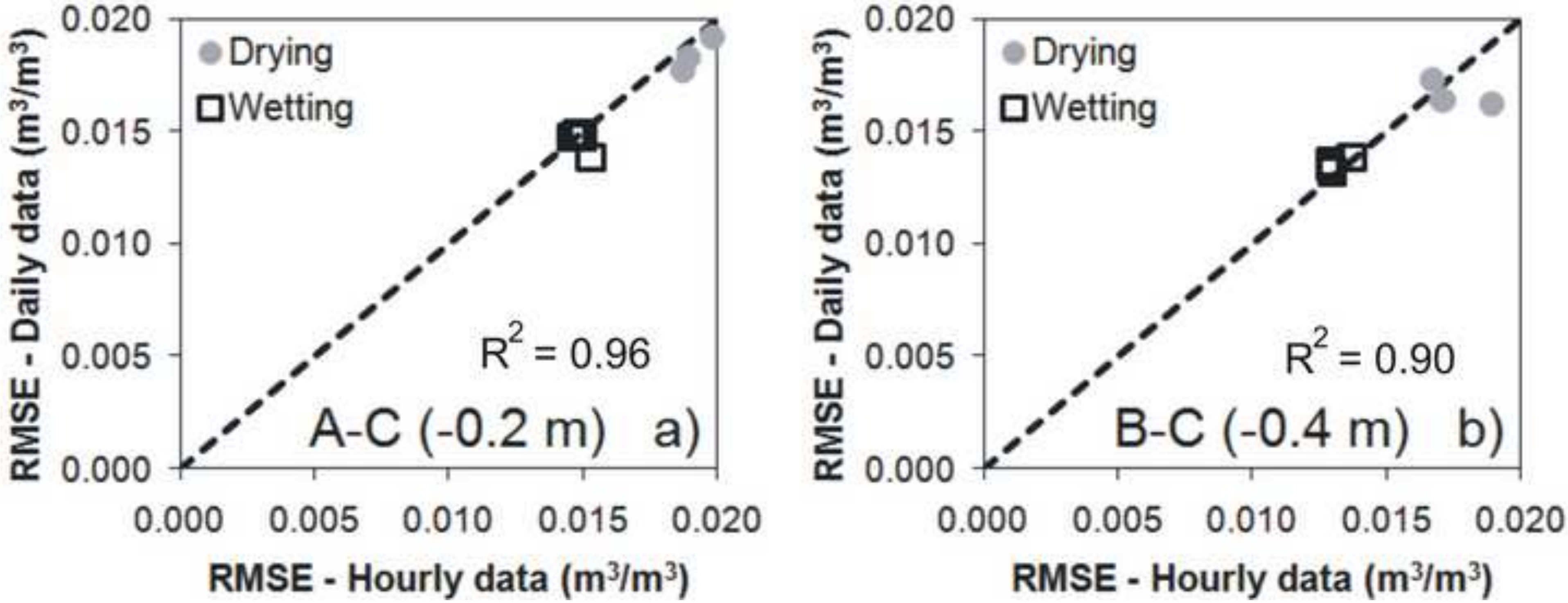

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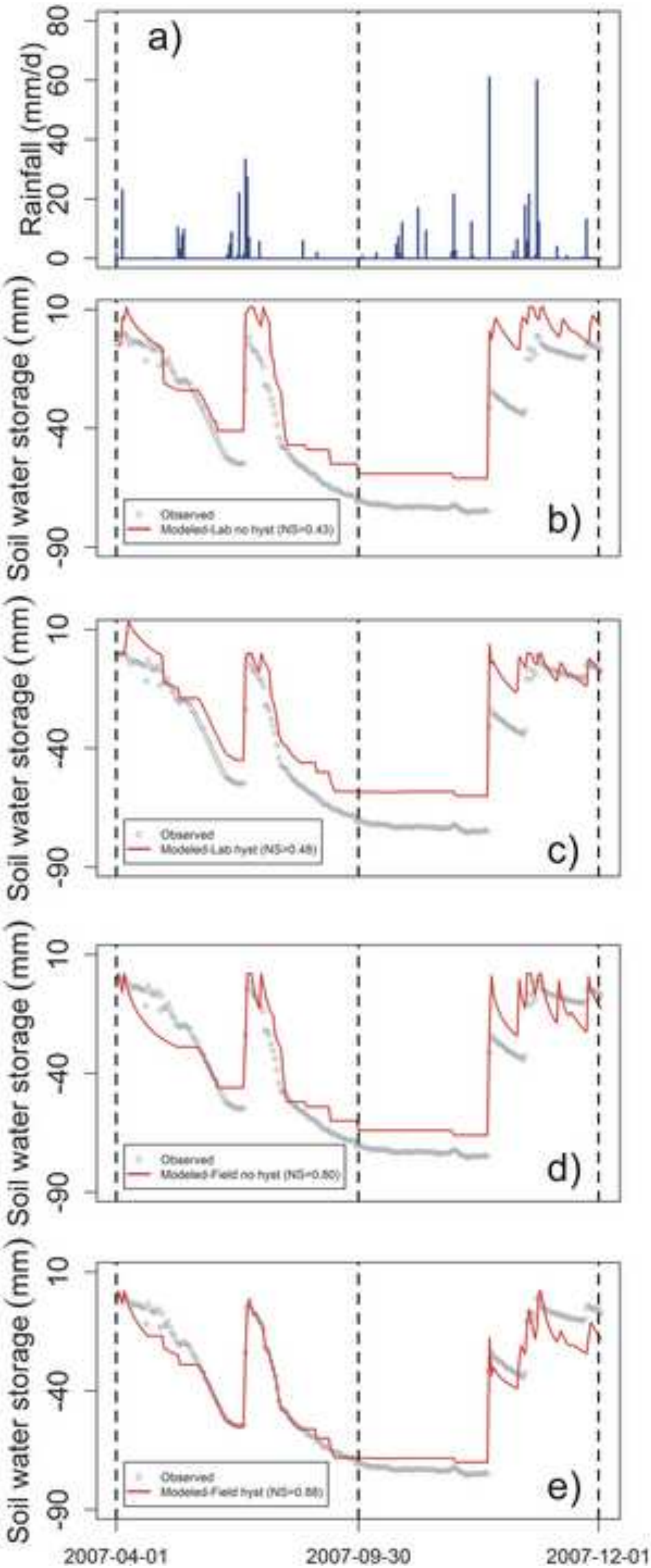

Graphical Abstract