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Thorough wetting and drainage of a peat lysimeter in a climate change scenario

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[Correction added on 4 February 2022, after first online publication: The copyright line was changed.]

Abstract

A peat deposit (Zennare basin, Venice coastland, Italy) was monitored in previous field studies to investigate the hydrological response of organic soil to meteorological dynamics. Field tests and modelling predictions highlighted the risk of the complete loss of this peat layer during the next 50 years, due to oxidation enhanced by the increased frequency of warmer periods. Unfortunately, despite the considerable impacts that are expected to affect peat bogs (in this area and worldwide), only a few experimental studies have been carried out to assess the hydrologic response of peat to severe water scarcity. Because of that, an undisturbed 0.7 m^3 peat monolith was collected, transferred to the laboratory and instrumented. The total weight (representative of the water content dynamics of the peat monolith as a whole), and two vertical profiles of matric potentials and water content were monitored in controlled water-scarce conditions. After an extended air-drying period, the monolith was used as an undisturbed peat lysimeter and a complete cycle of wetting and drainage was performed. Supplementary measurements of matric potential ψ and water content θ were collected by testing peat subsamples on a suction table apparatus. A set of water retention curves was determined in a range of matric potentials broader (ψ down to −7 m) than the current natural conditions in the field (minimum ψ = −1 m). While water content at saturation showed values similar to those in the original natural conditions ($\theta \cong 0.8$), a remarkable loss of water holding capacity (even for low potentials) has been highlighted, especially in deep layers that are now permanently below the water table. The retention curves changed shape and values, with a more pronounced hysteresis visible in an increasing distance between wetting and drying data. Hydraulic non-equilibrium between the water content and water potential could be a possible cause and it is worth modelling in future studies. The parameters of the van Genuchten retention curves were obtained for the wetting and the drying phases.

KEYWORDS
Peatland, peat soil hydrology, lysimeter, wetlands, hydro-physical properties, experiment, climate change

1 | INTRODUCTION

Peat soils are commonly characterized by high water-holding capacities and low hydraulic conductivities. Peat forms when plant material lies in anaerobic conditions (e.g. high water table) and does not fully degrade. As it accumulates, peat holds water. This leads to a progressive reduction in water table depth, which lowers the decomposition rates of organic carbon itself, in a positive feedback loop, and creates conditions that allow peatlands to expand. This bidirectional interaction between hydrology and biogeochemistry is well known in organic soils (e.g. Anderson, Foster, & Motzkin, 2003; Belyea & Baird, 2006; Clymo, 1984; Foster, Wright Jr, Thelaus, & King, 1988; Hilbert, Roulet, & Moore, 2000). However, peatlands, which cover approximately 3% of the land surface worldwide (80% located in the northern hemisphere; Limpens et al., 2008), have been subjected to land-use changes, often drained by ditches and artificial systems to create the necessary conditions for anthropogenic activities such as agriculture, peat quarrying and infrastructure construction (e.g. Gambolati et al., 2005; Maljanen et al., 2010; Page & Hooijer, 2016; Parry, Holden, & Chapman, 2014; Turetsky et al., 2015). These interventions alter peatland hydrology, hence also the accumulation processes and carbon storage.

In this context, Ise, Dunn, Wofsy, and Moorcoft (2008) highlighted the possibility of an increasing frequency of extended dry periods in boreal regions in the near future. Leng, Ahmed, and Jalloh (2018) provided an analysis of effects and consequences of climate change on tropical peatlands and emphasized the need for further short and long term studies/surveys to investigate how climate change affects peats (in particular, tropical peats). Weber, Iden, and Durner (2017a) highlighted the need for peat soil studies over a much wider pressure head range to reliably describe the hydraulic behaviour of these substrates in field situations that may include long drying periods.

As bio-oxidation reactions are mainly dependent on temperature and presence of oxygen (also CO_2, as reported by Freeman et al., 2004), in these potential scenarios of water scarcity, reduction in soil moisture would increase the sensitivity of peat decomposition to temperature, intensifying loss of soil organic carbon due to oxidation. Ise et al. (2008) concluded that boreal peatlands will quickly respond to warming expected this century by losing labile soil organic carbon during dry periods. Wessolek, Schwarzel, Renger, Sauerbrey, and Siewert (2002) used a model to predict soil water content and CO_2 release for different peat soils under various climate conditions and groundwater levels. They demonstrated that water table lowering, coupled with a water balance deficit during the most active vegetation periods, will significantly increase peat mineralization. According to Price (2003), drier periods induce a peat structure modification. Pore volumes decrease (i.e. shrinkage) and peaks in bulk density could arise as a consequence of both stronger matric suction in the unsaturated zone, and peat compression (a result of water table lowering) in the saturated zone. In addition, soil water-repellency may occur (e.g. Doerr, Shakesby, & Walsh, 2000). The decadal to centennial response of peatlands to external disturbances was investigated by Young, Baird, Morris, and Holden (2017) by using an ecosystem model. In that study, drainage was shown to result in a rapid loss of peat due to oxic decay (more intense in the first 100 years after ditch creation), but water table dynamics appear to be altered over centuries even in the case of restoration.

Gambolati et al. (2005) highlighted the risk of complete disappearance of the shallow 1-m-thick peat layer in the southernmost part of the Venice Lagoon, in approximately 50 years, if no remedial strategies (e.g. maintenance of a very shallow groundwater table) are implemented.

There are serious consequences to this including land subsidence (especially in the Venice low-lying coastal zone), greenhouse gas emission and loss of fertile peat soils.

By using a novel modelling approach based on 4-year monitoring of land subsidence and hydrologic parameters, Zanello, Teatini, Putti, and Gambolati (2011) developed a few scenarios of subsidence due to peat oxidation in Venice coastal farmland. Their results highlighted that in low-lying managed peatlands, land subsidence rates are mainly controlled by depth to water table, which is artificially maintained by drainage networks and pumping stations. The influence of temperature, which is mainly exerted under extreme climatic events, such as heat waves that affected continental Europe in 2003, also plays an important role. The effects on ecosystems and landscapes in terms of the loss of soil organic carbon may be even more important in natural environments (e.g. Holden, 2005; Holden et al., 2007; Johansen, Pedersen, & Jensen, 2011; Limpens et al., 2008).

Within this context, soil hydraulic properties and their descriptive parameters become key aspects for proper use/validation of predictive models. Weiss, Alm, Laiho, and Laine (1998) tested and modelled moisture retention in peat soils and highlighted how difference in water retention between various peat types can be explained not only by peat characteristics related to bulk density but also by differences in the cell structure of plant residues and peat pore geometry. Letts, Roulet, Comer, Skarupa, and Verseghy (2000) demonstrated that the use of mineral soil parameters to model the hydraulics of peatlands is inappropriate. Schwärzel, Renger, Sauerbrey, and Wessolek (2002) derived the hydraulic functions (water retention and hydraulic conductivity) for various peat layers taking the effect of swelling/shrinkage into consideration. Schwärzel, Šimunek, Stoffregen, Wessolek, and van Genuchten (2006) used an inverse method based on a field lysimeter to estimate the water retention and the hydraulic conductivity functions and compared the outputs with laboratory measurements, highlighting a good agreement between the results. Rezanezhad et al. (2009, 2010, 2012, and 2016) and Weber et al. (2017a, b) investigatedthe complex dual-porosity nature of peat soils from the hydro-physical point ofview (e.g. micro-macro pores distribution, flows, hydraulic propertiesdetermination) and the implication with the connected processes (e.g. waterstorage, fluids/solutes transport, evaporation rates).

Although *in situ* measurements are usually more representative than laboratory investigations (e.g. Royer & Vachaud, 1975; Schwärzel et al., 2006), a huge database on water retention of peat soils has been built up from lab measurements on small samples (usually in the range of 5–8 cm in diameter and 1–6 cm in height) cored in various peatlands around the world (e.g. Okruszko, 1993; Weiss et al., 1998; Silins & Rothwell, 1998; Beckwith, Baird, & Heathwaite, 2003; Price, Braunfireun, Waddington, & Devito, 2005; Schwärzel et al., 2006; Gnatowski, Szatyłowicz, Brandyk, & Kechavarzi, 2010; Szajdak & Szatylowicz, 2010; McCarter & Price, 2012; Branham & Strack, 2014; Goetz & Price, 2015; Faul et al., 2016; Weber et al., 2017a, 2017b). Due to the small size of the samples and the large heterogeneity characterizing peat soils, the representativeness of these lab tests was questioned. For this reason, a number of scientists have recently developed lab testing on larger peat samples, such as 10-cm diameter × 50–200 cm long columns (e.g. De Vleeschouwer, Chambers, & Swindles, 2010; Tositti et al., 2006) or 30- to 40-cm side prismatic monoliths (e.g. Strack & Price, 2009; Yu, Slater, Schäfer, Reeve, & Varner, 2014) properly sampled in various peatlands worldwide. A few laboratory studies on larger peat monoliths have been already carried out. Rupp, Meissner, Leinweber, Lennartz, and Seyfarth (2007) used a large fen monolith (6 m^3; 4 × 1.5 × 1 m) as a lysimeter to investigate vertical and horizontal transport processes. They concluded that the proposed technique to extract a large monolith is suitable to maintain the natural soil structure and that the collected measurements were as accurate as those determined in the field, but with the advantage of the controlled environmental conditions. Rosa and Larocque (2008) investigated variability in hydraulic parameters of peat, mainly the hydraulic conductivity, through the use of different field and laboratory methods, including a 0.60 × 0.40 × 0.25 m peat monolith clamped in a tank to investigate the properties of the surface peat layers. Their results demonstrated that intrinsic variability associated with the different field and laboratory methods is small compared with the spatial variability of hydraulic parameters. It was suggested that a comprehensive assessment of peat hydrological properties could be obtained through the combined use of complementary field and laboratory investigations. Bourgault, Larocque, and Garneau (2017) compared the results obtained from laboratory experiments on small and large peat samples using the fluctuation of the water table to investigate the factors controlling the water storage capacity of peat. The results showed that site location and seasonality mainly control the water storage capacity suggesting that the hydro-climatic context and evapotranspiration are of primary importance.

Despite this large amount of literature, it is becoming increasingly important to test the conditions representing potential future scenarios, with prolonged droughts followed by re-wetting phases (Weber et al., 2017a). However, the establishment of an *in situ* drying test under natural redox conditions is particularly challenging because of the difficulty of hydraulically isolating a peat monolith without altering the field conditions and/or the sample itself.

For this purpose, an undisturbed 0.7 m^3 peat monolith was collected from the Zennare basin (Venice, Italy) and tested in the lab. The large size of the sample allowed to account for the natural heterogeneity typical of the peat deposits. The laboratory setting permitted exposure to prolonged and extreme droughts, which cannot be experienced in the field because of the regulated water table, and wetting phases under fully controlled conditions. In the framework of the research undertaken on the peat deposits at the southern margin of Venice Lagoon (e.g. Camporese, Ferraris, Putti, Salandin, & Teatini, 2006; Camporese, Putti, Salandin, & Teatini, 2008; Da Lio, Teatini, Strozzi, & Tosi, 2018; Fornasiero et al., 2003; Gambolati et al., 2005; Gambolati, Putti, Teatini, & Gasparetto Stori, 2006; Gatti et al., 2002; Nicoletti et al., 2003; Zanello et al., 2011), this work aims to explore the peat response to conditions typical of extreme climatic events that are expected to become more frequent in the near future. The specific objectives of this study are (a) to characterize the hydrologic response of a well-known and heavily studied peat soil, to extreme drying and wetting processes, and (b) to provide a set of original and consistent parameters that can be used in hydrological modelling of long-term scenarios. The comparison between the lab results and the datasets previously collected *in situ* by Camporese et al. (2006) is presented.

2 | MATERIALS AND METHODS

With the aim of carrying out an in-depth hydrologic characterization at a comparable scale as the *in situ* investigation performed by Camporese et al. (2006), a 1 m^2 (square section), 0.7 m thick, undisturbed soil monolith was collected in a cultivated peatland of the Zennare Basin in the Venice coastland (Italy). The sample was transferred to the laboratory to test it during intense and prolonged drought conditions. The peat monolith was instrumented to monitor soil-water relations (i.e. matric potential and water content), together with its thickness and total weight (and therefore the total water content variations in time). The first drying phase, just after the sampling and movement to the lab, was followed by a progressive re-wetting up to full saturation and a second drought period. At the same time, three ~1800 cm^3 peat subsamples were collected to set up parallel tests with a suction table to provide an independent characterization of the retention curves for control purposes.

2.1 | Field site

Peat soil samples were cored from the Zennare Basin, a farmland area located at the southern margin of the Venice Lagoon between the Brenta and Adige rivers (Figure 1).

In the nineteenth century, this zone was characterized by marshlands and groves of reeds. The organic soil developed from the decomposition of reeds (*Phragmites* spp). The area was reclaimed in the late 1930s and since then used for crop production, mainly maize, implementing 40-cm-deep yearly ploughing that brings to the surface the undecomposed peat. Over the past 70 years, the area lost about 1.5–2.0 m elevation due to the land subsidence caused by peat oxidation (Gambolati et al., 2005). Currently, the basin lies below the mean sea level, mostly between −2 and −4 m. A dense network of small ditches and an artificial drainage system supported by pumping stations are used to maintain the depth to the water table below the surface level (Camporese et al., 2006). Due to the mainly aerobic

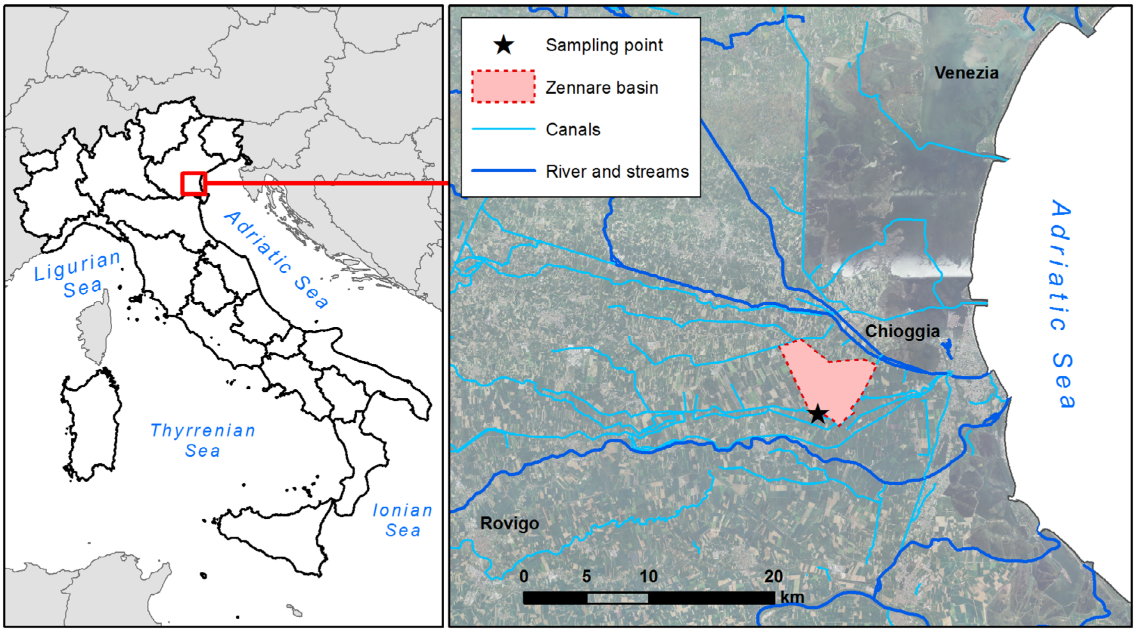

FIGURE 1 Location of the Zennare Basin where the peat monolith and the samples were collected

environmental conditions, methane production in the Zennare Basin's peat can be considered negligible (Camporese et al., 2006).

In this study, the same field site monitored by Camporese et al. (2006) was chosen for the monolith and core sampling. It is a 30 × 200 m rectangular plot with an outcropping 1.5-m thick peat layer drained by ditches along the longest sides (Fornasiero et al., 2003). The *in situ* records discussed in Camporese et al. (2006) were collected on an hourly basis over approximately two months from December 2003 to February 2004. The measurements included soil water content, matric potential at five depths between 0.15 and 0.75 m, depth to the water table, others variables such as air and soil temperatures, and displacement of the land surface due to swelling/shrinking and oxidation.

2.2 | Sampling process, samples description and samples preparation

A soil monolith of dimensions 1.0 × 1.0 × 0.7 m was first isolated manually and by mechanical means from the surrounding soil. A structure consisting of four steel panels was immediately mounted around the sample. Finally, a basal cutting plate was used to separate the monolith from the underlying layers. The resulting box was removed and transferred to the laboratory. The monolith sampling main steps are depicted in Figure 2.

The basal cutting plate was removed in the laboratory, and the sample was placed on a steel tank to allow the simulation of a fluctuating water table. A steel grating protected by a geotextile was laid between the sample and the basal tank as an interface. To avoid any kind of water and/or material leakage, all fissures between the contact surfaces of the panels and between the panels and the basal tank were sealed by polyethylene gaskets.

The bottom of the steel tank was connected to a water reservoir in order to simulate the variations of the water table, and a piezometric controlling device was directly connected to the peat monolith.

The heterogeneity of the peat sample was typical of the site. As reported in Gatti et al. (2002), the soil belonged to the Histosol with a high degree of humification in the shallower layer and a low grade at depth. According to the von Post (1922) classification, the upper layer is classified H_{10}, that is, a completely decomposed peat containing no discernible plant tissues and, when squeezed, all of the peat releases through the fingers as a uniform dark paste. The peat is classified H_3 at depth, that is, a slightly decomposed peat that, when squeezed, releases turbid brown water but in which no amorphous peat passes between the fingers and where plant remains are still relatively intact. In more detail, the sample profile was composed of three main layers (Figure 3): (a) a 0.3- to 0.4-m-thick black amorphous granular peat on the top, characterized by the presence of numerous remains of small brown roots, leaves, seeds and light olive green woody reed fragments with fragment sizes from 1 mm to some centimetres, corresponding to the soil ploughed for farming; (b) a central 0.15- to 0.2-m-thick brown fibrous peat with a rather compact structure consisting mostly of light olive green soaked reeds, randomly arranged and up to 3 cm long and 1 cm wide, as well as roots from 1 mm to some centimetres long; (c) a 0.15- to 0.2-m-thick brown fibrous peat on the bottom, with a compact structure, consisting mainly of intact light olive green soaked reeds, in growing position and more than 10 cm long and some cm wide. The bulk density and the organic matter ranged between 0.30 g/cm^3 and 49%, respectively, at the surface and 0.25 g/cm^3 and 73% in the deeper fibrous peat.

FIGURE 2 Successive phases of the monolith collection, from the undisturbed sampling zone to the sample removal with a steel box structure built around the soil monolith, until the final lysimeter arrangement in the laboratory

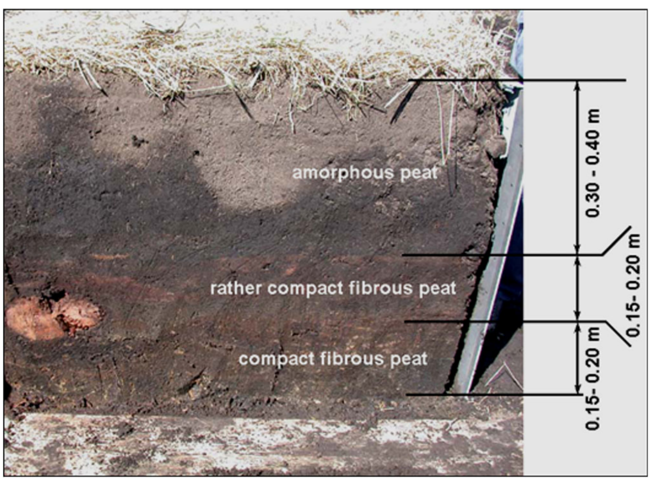

FIGURE 3 Detail of a side of the peat monolith highlighting the three-layer structure. Notice the almost unaltered wood log included in the matrix

Based on previous experiences of time-domain reflectometry (TDR) applications to monitor soil moisture (e.g. Raffelli et al., 2017; Robinson, Jones, Wraith, Or, & Friedman, 2003), especially in organic porous media (e.g. Canone, Previati, Ferraris, & Haverkamp, 2009; Previati et al., 2012), the peat monolith was instrumented with two repetitions of four three-rod probes positioned at 0.05, 0.15, 0.30 and 0.50 m depth. The probes were built in accordance with the method proposed by Robinson et al. (2003). Holes were drilled in the steel side panels to permit the connection between the TDR probes and the pulse generator through RG58 cables. IP68 rated cable glands were used to guarantee water tightness of the whole system and to allow for the probes to move with the shrinking and swelling of the monitored material. The monolith was also instrumented with four tensiometers to record the matric potential. The tensiometers were inserted from the surface of the monolith, with a 45° inclination, to depths of 0.05, 0.15, 0.30 and 0.50 m. Finally, the monolith was placed on four load cells for the gravimetric monitoring of the bulk water content. The four load cells were placed below the four legs of the basal tank in order to uniformly distribute the weight of the monolith.

During the field sampling process, three additional cylindrical cores were collected in the depth range between 15 and 30 cm by vertically oriented rings. The sampling cylinders were 10 cm high with a 15.5-cm diameter. The cylinders were sealed on both ends immediately after soil sampling to prevent samples from drying. In the laboratory, one TDR probe (made out of two stainless steel rods 15-cm long) was permanently inserted in the centre of each sample in a radial orientation (horizontal insertion).

2.3 | Laboratory experiments

Both the range of natural fluctuations, which approximately reached a tension $\psi = -1$ m (Camporese et al., 2006), and the full range of volumetric water content (VWC) and matric potential (MP) values, that is, a scenario of severe water scarcity, have been investigated.

The lab experiment was composed of three phases. After a first step characterized by a prolonged air-drying under laboratory conditions, the monolith was saturated by raising the water table up to the top surface. This wet condition, which was experienced in the field after intense rainfall events such as in August 2002 (Zanello et al., 2011), was maintained for approximately 30 days and followed by a 180-day drying phase. Considering the rapid water table dynamics highlighted in several studies carried out in the field (e.g. Hooijer et al., 2012; Spieksma, Moors, Dolman, & Schouwenaars, 1997), the elevation of the water table was changed by using steps of 15 mm three times per day. The fluctuations of the water table and VWC were measured at sub-hourly frequency and re-sampled at daily frequency to match the frequency of the MP records. A Tektronix 1502 C TDR cable tester was used to perform TDR measurements and waveforms were collected and analysed by the WinTDR software (Or, Jones, VanSchaar, Humphries, & Koberstein, 2004). The total weight of the monolith was measured hourly by the four load cells.

A water retention experiment was also conducted on the three cylindrical peat samples. They were saturated and put on a suction table (Stakman, Valk, & van der Harst, 1969) with a bed composed of a mixture containing 50% fine sand and 50% kaolinite. A series of progressive static equilibria was imposed from saturation to $\psi = -1$ m and back to saturation at the following potentials: 0.00, −0.03, −0.06, −0.12, −0.25, −0.50, −1.00 m of water column. At each equilibrium level, MP, VWC (from gravimetric measurement) and TDR dielectric permittivity were determined. The weight of the samples and their dielectric permittivity were recorded daily (until the equilibrium was reached). The datasets obtained were used for both the TDR calibration and for the VWC–MP relation analysis.

2.4 | TDR calibration

TDR estimates the apparent dielectric permittivity of the soil by measuring the travel time that a step voltage pulse takes to propagate along with the probe and back. Unlike Camporese et al. (2006), who adopted the TDR calibration curve developed by Myllys and Simojoki (1996) for cropped peat, here a specific calibration curve was developed by fitting the data (main wetting curve only) obtained through the suction table experiment described above. In particular, each VWC obtained by gravimetric measurements on the samples subjected to different pressure heads was related to the corresponding dielectric permittivity measured by the TDR probes (Figure 4). To test the validity of the calibration curve, which was developed by interpolating a relatively narrow range of VWC values (45% to 65%), the complete wetting dataset from the monolith was used. Average VWC provided by gravimetric measurements through the load cells and corresponding dielectric values obtained by averaging the outcome of the TDR probes were used. Figure 4 highlights how the calibration curve satisfactorily fits the monolith records for both dry and wet conditions.

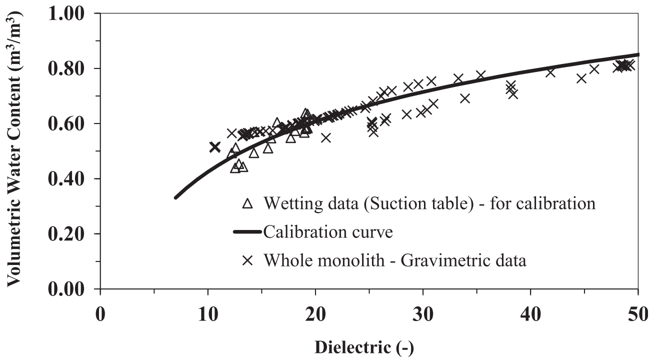

FIGURE 4 Logarithmic calibration curve developed by using the TDR Volumetric Water Content (VWC) and the Matric Potential (MP) data—suction table apparatus—collected during the water retention experiment. Gravimetric VWC records related to the whole monolith are also represented for comparison

To allow a comparison with the data of Camporese et al. (2006), the above-mentioned calibration equation was applied to both data collected in this study and the original *in situ* dataset (dielectric permittivity values) presented by Camporese et al. (2006).

3 | RESULTS

The VWC values detected by the TDR probes and the MP records are depicted as functions of time and depth. Moreover, water content variations of the entire 0.7-m^3 peat monolith measured through the load cells are also presented.

Although the swelling and shrinking behaviour of the monolith was not specifically recorded, for completeness it is interesting to point out that during the extended air-drying in controlled conditions, the peat monolith shortened by 90 mm (i.e. about 13% of its initial height). During the subsequent wetting phase, which led the sample to a water content distribution representative of the *in situ* natural conditions, the monolith swelled back by approximately 20 mm.

3.1 | Water content

Figure 5a shows the recorded behaviours of VWC. At the end of the first thorough drying period, VWC was lower than 0.1 m^3/m^3 in the topsoil, but it ranged between 0.4 and 0.6 m^3/m^3 at 0.15 and 0.30 m depths, and it was approximately 0.2 m^3/m^3 at 0.50 m depth. This behaviour reflects the different structures of the shallower amorphous granular peat and the underlying fibrous peat.

During wetting phase which followed, the water table was raised and the water content rapidly increased to saturation in the range between 0.8 and 0.9 m^3/m^3, similar to the field conditions recorded by Camporese et al. (2006) (Table 1 and Figure 5a). Despite the presence of some peat material in suspension, the similar VWC values recorded in the lab and *in situ* at saturation revealed the absence of soil-water repellency due to the forced drought of the organic matter.

After approximately 30 days of saturated conditions, the water table was lowered at a constant rate. The peat heterogeneity led each layer to reveal a specific water retention behaviour. In particular, the topsoil (0.05 m depth) and the bottom horizon (0.5 m depth) showed initial fast drainage followed by progressive (but constant) VWC decrease. VWC decreased regularly and more slowly in the intermediate layers (0.15 and 0.30 m depths), leading to the storage of a high

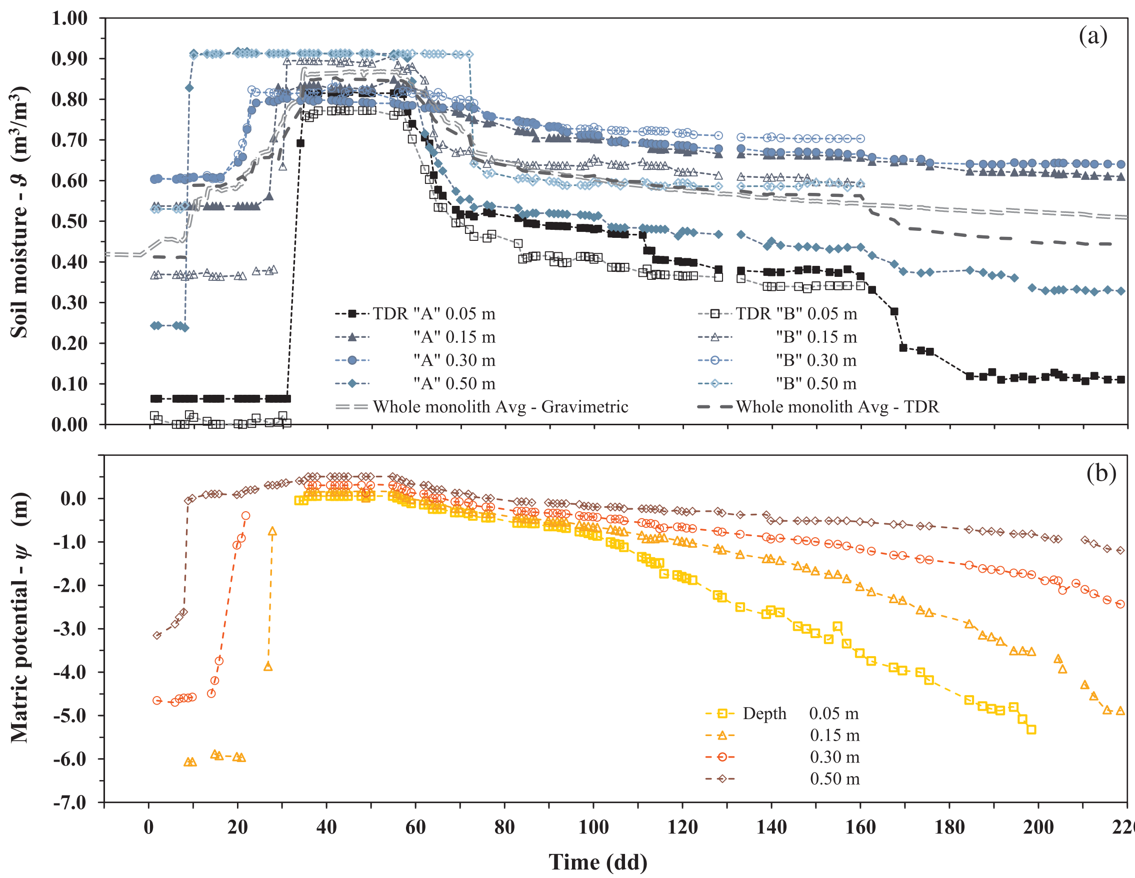

FIGURE 5 (a) Volumetric Water Content—θ and (b) Matric Potential—ψ versus time measured at various depths in the peat monolith. The VWC of the whole monolith, determined gravimetrically by the load cells (double dashed line) and measured by TDR (weighted average—single dashed line) are also provided

TABLE 1 Comparison between laboratory data (this work) and field data (Camporese et al., 2006) collected in saturated conditions after the thoroughly forced drought

	Peat-soil water content at saturation conditions (m^3/m^3)			
	Monolith			
Peat-soil depth (m)	(TDR-A_{series})	(TDR-B_{series})	Field (Camporese et al., 2006)	Δ (Avg) (%)
0.05	0.81	0.77	–	–
0.15	0.83	0.89	0.77	+11.7
0.30	0.79	0.82	0.84	–4.2
0.50 (Field = 0.45)	0.910	0.91	0.91	+0.0

Note: The small differences along depth suggest that the monolith is representative of the site and highlight the absence of soil structure modifications due to the sampling/transport phases.

water volume for long periods, consistent with the observation at the end of the preliminary drying period.

The gravimetric average water content of the whole monolith, measured through the load cells (Figure 5a), was consistent with the weighted average of the TDR values.

3.2 | Matric potential

MP measurements allowed observation of the peat dynamics in the wetting/drying phases at the monitored depths in the undisturbed peat monolith. The experimental results are plotted in Figure 5b. The starting state was characterized by very low potentials (down to −7 m) because of the dry conditions. Low MP values were also evident in the middle layers (0.15 and 0.30 m depths) where, even after the stressful air-drying period under laboratory conditions, VWC remained relatively high in the range of 0.4–0.6 m^3/m^3 (Figure 5a). At the same time, the MP values at 0.50 m depth, which were higher than those at shallower depths, corresponded to smaller VWC values (≈0.25 m^3/m^3). No data were available for the topsoil (0.05 m depth) during the first phase because of the extremely dry conditions that precluded contact between the soil matrix and the porous cup of the tensiometer.

During the wetting phase, the MP measured by the proper working tensiometers went immediately to zero at the water's arrival. As soon as the water level reached the soil surface, also the peat-cup contact of the topsoil tensiometer was naturally restored. Then, during the drainage phase, the MP progressively decreased with more regular behaviour than VWC and with values in accordance with depth (larger decrease at smaller depth). Despite the high water loss, the horizon at 0.50 m depth showed a minimum MP variation during the experiment. This result may represent an indicator of limited water retention/water suction capacity that differs markedly from the *in situ* measurements performed by Camporese et al. (2006)

3.3 | VWC–MP relations

In view of the climatic scenarios depicted by Ise et al. (2008) and the severe impacts on peat soils, with special reference to the Venice area as hypothesized by Gambolati et al. (2005), the water retention characteristic curves in a pressure range broader than what can be tested *in situ* were investigated here.

The relations between the VWC and MP data recorded during lab tests are shown in Figure 6a,b, together with field records from Camporese et al. (2006) appropriately re-interpreted using the calibration curve of Figure 4. The lab 0.05-m depth series was not included as it did not have any field-equivalent term for comparison. The lab series recorded at 0.15 and 0.30 m depths showed behaviour very similar to that recorded in the field even after the long drought forced in the laboratory. In contrast, the 0.5-m depth retention curve deviated: It maintained a high saturation value similar to that detected *in situ*, but it was systematically lower than that under field conditions during the drying phase.

Figure 6c shows the datasets obtained from three-peat subsamples subjected to negative pressure values under equilibrium conditions. The figure demonstrates the hysteresis in the soil water retention curves. This further investigation was carried out with the main aim of comparing the measurements in equilibrated conditions with those recorded in the monolith during the very fast wetting phase. Data are available for ψ down to −1 m only. In fact, lower pressures lead to exceeding the air-entry pressure head with consequent tension collapse. At the same time, the "pressure plate extractor method" was not suitable because of the peat's compressibility.

The three-peat subsamples showed similar behaviour for both the water retention curves and hysteresis and limited variability at the different MP values. In particular, the standard deviation of VWC ranged between 0.027 and 0.030 m^3/m^3 in the wetting phase, and from 0.026 to 0.032 m^3/m^3 in the drying phase. These data were fitted to van Genuchten retention curves to obtain constitutive relations usable in numerical modelling. The parameters, which were fitted by a Levenberg–Marquardt optimisation approach, are: $\vartheta_{saturated}$ = 0.616 and 0.614 m^3/m^3; α = 7.01 and 1.72 m^{-1}; n = 1.145 and 1.231 (with $m = 1 - 1/n$ and $\vartheta_r = 0$), for wetting and drying phases, respectively.

In the context of expected climate change, with conditions that will be characterized by more frequent and severe droughts, the behaviour of the peat monolith has also been explored under water stress conditions beyond the ranges experienced currently in the field. In particular, characteristic retention curves down to $\psi = -7$ m were derived. As shown in Figure 7, for tension $\psi < -1$ m, the 0.15-m and 0.30-m-deep layers still exhibited θ values very different to the topsoil and the 0.50 m deep horizon. In the central layers, water was lost at an almost constant rate down to $\psi = -1$ m, below which θ stabilized at approximately 0.5 m^3/m^3 despite the further ψ decrease. In contrast, θ decreased to very low values in the shallowest and the deepest horizons. It is interesting to note the evident "collapse" recorded by TDR "A" in the topsoil at ψ equal to approximately −4 m. Even in the absence of the TDR "B" repetition (which stopped working properly during the experiments), it is reasonable to assume that this collapse may be a specific behaviour of the surface layer considering the clear trend of measured matric potential and the regular TDR waveforms progressively detected. Moreover, it is interesting to point out the substantial water content stabilization during the draining period detected by the TDR B at 0.5 m depth, which further emphasized the heterogeneity of the peat material.

4 | DISCUSSION

VWC measurements carried out by two sets of TDR probes suggest that the monolith is characterized by significant inter- and intra-layer heterogeneity. Analysing both MP and VWC evolution it is interesting to point out that at a few centimetres distance, the deep and the upper intermediate (15 cm) layers show areas that drain very quickly and zones capable of remaining wet over a very long time (and draining very slowly). This behaviour, called temporal persistence, has been investigated by Vachaud, Passerat De Silans, Balabanis, and

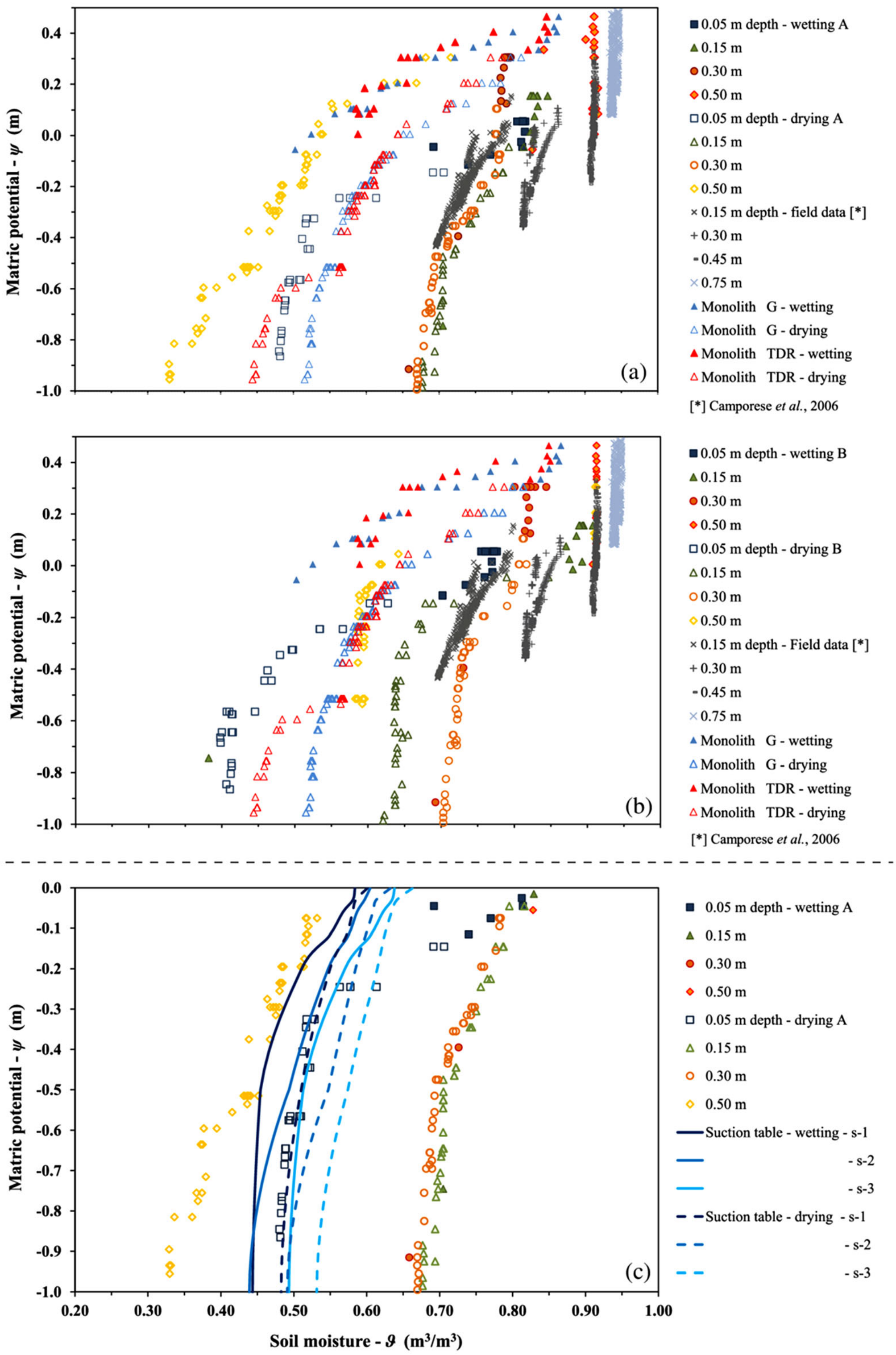

FIGURE 6 (a, b, c) Relations between Volumetric Water Content and Matric Potential. The values provided by TDR "A" and "B" are depicted in (a) and (b), respectively, together with the field data by Camporese et al. (2006). Filled symbols are representative of the wetting phase; empty symbols, of the drying phase. A comparison between the MP measured in the monolith and the values recorded from the three-peat subsamples placed on a suction table apparatus (subjected to negative pressures) is depicted in (c). The VWC of the whole monolith, determined gravimetrically by the load cells (blue triangles), and measured by TDR (weighted average—red triangles) are also provided in association with the MP values measured at 0.5 m depth

Vauclin (1985) and many others, such as Pachepsky, Guber, & Jacques, 2005. They highlighted the temporal stability of spatial patterns of water content in mineral soils. This phenomenon can be much more evident in peat, especially under stressed conditions, where the matrix structure and the texture of the undecomposed organic material may be largely influenced (much more than in mineral soils) by the

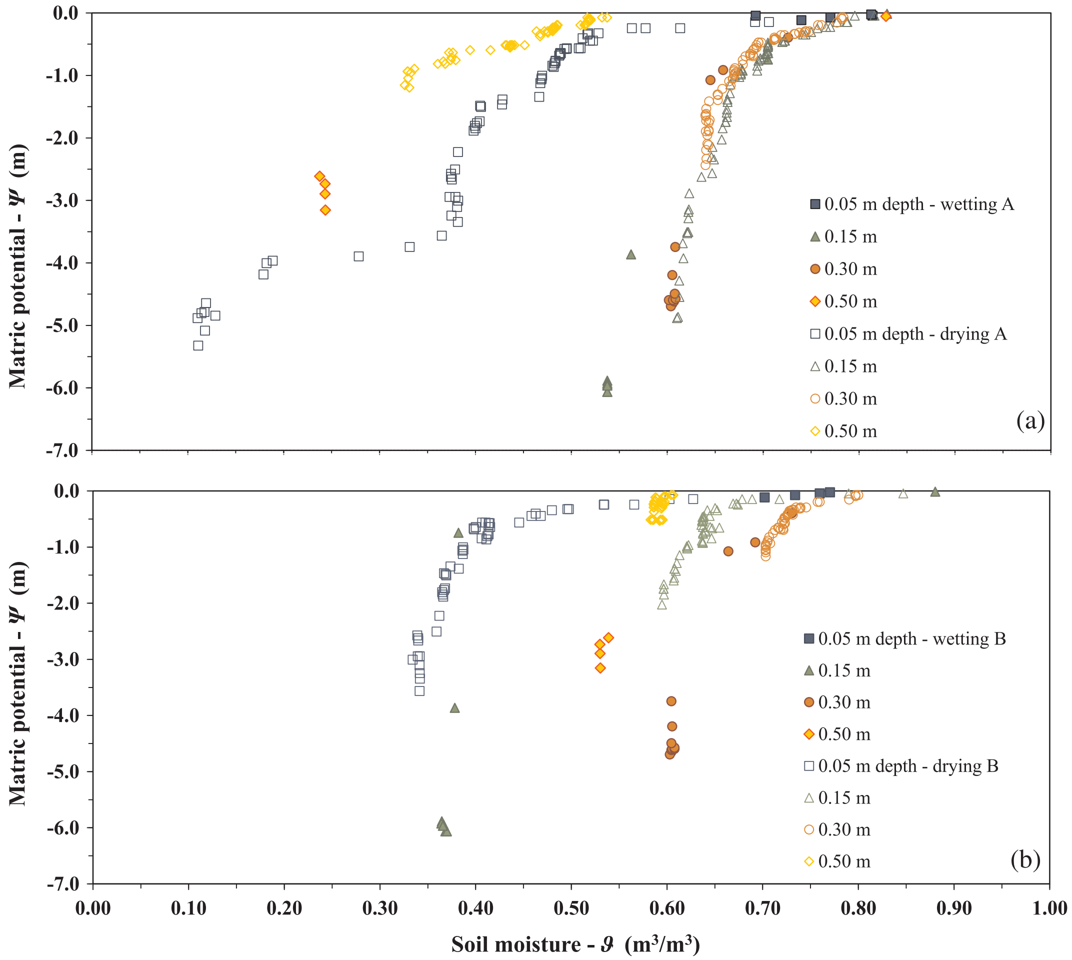

FIGURE 7 (a, b) Retention curves for the ψ range between 0 and −7 m, that is, a much drier condition than the current hydrologic condition in the field. The values provided by TDR "A" and "B" are depicted in (a) and (b), respectively. Filled and empty symbols represent the wetting and the drying phase, respectively

chemical–physical dynamics of the degradation and swelling/shrinkage processes.

Concerning MP, a peculiar behaviour was highlighted in the middle layers (0.15 and 0.30 m depths). In particular, despite the stressful air-drying period, this layer showed a high water retention capacity in conjunction with a strong MP. A similar behaviour, uncommon in mineral soils, has already been pointed out in peat soils (Rezanezhad et al., 2016): Undecomposed peat with high fibre content and large active porosity yields as much as 80% of its saturated water content to drainage. Conversely, the most decomposed peat samples release less than 10% of their water to drainage, demonstrating a forceful suction capacity even maintaining high water contents.

A further interesting aspect was related to the deep layers' MP behaviour during the drainage phase (Figures 5 and 6). In this case, very limited changes of MP were highlighted despite high water loss. A reason for this behaviour, which is typical of destructured horizons with a coarse texture, can be due to small local-scale heterogeneity causing a different soil response. However, considering the evident difference with respect to the field conditions, the behaviour can also be a consequence of the processes triggered by the forced drying such as, for example, the collapse of micro-pores or the inability of "dried micro-pores" to quickly swell during the rapid moistening phase. These results can be explained by the high heterogeneity of degraded vegetal structures that are subject to dynamic changes (such as biotic degradation/mineralization, swelling/shrinking phenomena, water repellence, air and gas entrapment, etc.) which cause a gradual and permanent modification in the chemical–physical response of the organic material at a point scale. The effects of this progressive modification on the general hydraulic behaviour of the system can differ significantly, from point to point, depending on the type of the material, its distribution in the matrix and its degradability. Another element of interest, probably connected with the aforementioned dynamics, is related to the VWC behaviour at 0.50 m depth for $\psi > 0$ m during the drying phase. In this situation, despite the saturated condition, an unexpected decrease in VWC is revealed by the reduced water pressure. This is probably due to the compressibility of entrapped air, or similar phenomena not investigated here.

In a heterogeneous and dynamic context, as the one observed in this lab test, a more comprehensive approach can be beneficial. It is rather interesting to highlight the good fitting between the average

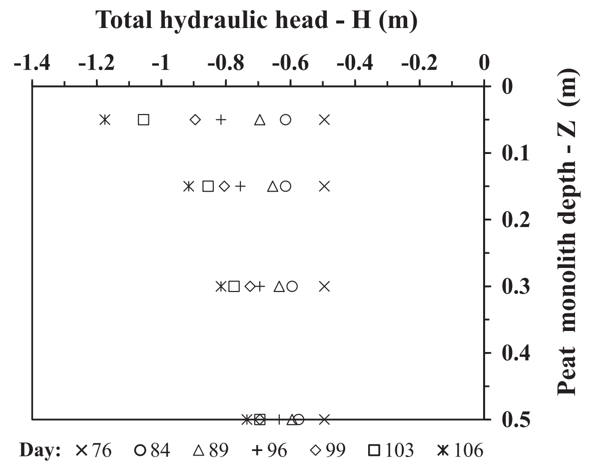

FIGURE 8 Evolution of the total hydraulic head versus time during one month of the last drainage phase. The measured data revealed the absence of a zero-flux plane along with the investigated profile (from the surface to 50 cm depth), meaning upward flow during the entire experiment

outcomes obtained from the entire monolith in term of VWC (measured both gravimetrically and via the TDR weighted average) and the matric potential measured at 0.5 m depth. The time behaviour analysis of the point that separates the upward water fluxes in the shallower part of the profile from the downward draining fluxes in the zone beneath revealed the absence of a zero-flux plane within the sample profile. The main flow was always directed upward during the experiment (Figure 8). The deep drainage began only when the water in the reservoir underneath disappeared; nevertheless, the zero-flux plane did not climb up to the lower tensiometers.

With regard to the hysteresis phenomenon, it is essential to remember that it is mainly due to the hydro-mechanical interaction between water and soil physical properties during a wetting/drying transient. Within this context, interconnected pore sizes and shapes, contact angles, but also air/gas entrapments (e.g. blind pores), and soil water repellency can cause a water content lower than it could be. In our experiments, the hysteretic response for ψ values down to −1 m is characterized by wetting and drying curves quite far apart. For a given tension, the VWC between the two conditions differs by 8–10%. Moreover, notice that for all three subsamples (Figure 6c), the wetting–drying cycle never closed perfectly, and at ψ = 0, the VWC values differed by approximately 2–3% between the wetting to the drying curves.

Extending the comparison of the laboratory data to the field outputs, a constant distance of the wetting and drying θ values was already noticed in saturated conditions. Conversely, the field retention curves tended to diverge (showing hysteresis) only starting from ψ = −0.4 m, while the laboratory wetting and drying curves highlight a certain distance even at ψ = −1 m. This field behaviour could be ascribed to the stable saturated conditions guaranteed by the water table presence. However, taking into consideration the aforementioned peat soil biophysical processes and the expected acceleration of the degradation dynamics, the laboratory data suggest that also the hysteresis effects will probably be subject to a progressive modification.

Preferential and non-equilibrium flow and transport are often considered to hamper accurate predictions of contaminant transport in soils (e.g. Diamantopoulos & Durner, 2012; Schlüter, Vanderborght, & Vogel, 2012; Šimůnek, Jarvis, van Genuchten, & Gärdenäs, 2003; Weller & Vogel, 2011). This process leads to non-uniform wetting of the soil profile as a direct consequence of water movement that is faster in some parts of the soil profile than in others. This aspect is important mostly because it can affect several physical processes, such as a transport of solutes (e.g. agricultural contaminants, salts) more rapidly than expected. Macropores, structural features and the development of flow instabilities due to textural differences, sloping soil layers, profile heterogeneities and water repellency are usually the most important causes of preferential flow. The comparison between Figure 5a and Figure 5b and inspection of Figure 9 reveal an evident time lag between MP and VWC increase/decrease in all the monitored series. In particular, during the wetting phase, the tensiometers reacted faster than the TDR to the water arrival, but the tensiometers were delayed during the drying phase. This effect is particularly evident in the 0.50-m depth series depicted in Figure 9, where ψ collapsed immediately when water started flowing into the sample, while the water content measurement reacted to water arrival after a few centimetres of water inflow. The delay amounted to 4–7 days. This behaviour may probably be ascribed to soil hysteresis or to some limited volumes of water, flowing through preferential pathways, which bypass a large part of the matrix pore space. Due to this, the water volume change remains negligible for the TDR, since only larger volumetric quantities induce a clear response, or even undetectable because of the limited measurement volume of the TDR probes and/or the "unfortunate" position of the sensors relative to the soil heterogeneity distribution, as reported by Diamantopoulos and Durner (2012).

4.1 | Implications and applications

Short-term or direct, mid to long-term and indirect, implications of the hydrologic peat response to dry conditions pointed out by this study are wide. Concerning the latter, large portions of boreal and tropical peatlands have started experiencing unprecedented anthropogenic and natural (climate-related) hydrologic stresses over the last couple of decades. Recent heat-waves have been responsible for sea ice retreat and drying organic soils in large portions of Northern America (Hu et al., 2010) and Russia (https://www.telegraph.co.uk/news/2019/07/27/climate-change-warning-arctic-circle-burning-record-rate-forest/). Drainage of coastal peatlands in Indonesia are causing land subsidence up to 4 cm/year, with millions of hectares at risk of permanent submersion by the rising seawater over the next decades (Couwenberg & Hooijer, 2013). As temperature rises and water-logged condition decreases, dried peat moss becomes fuel for more fires or more rapidly oxidizes emitting larger amounts of carbon dioxide into the air, thus feeding a vicious cycle worsening the meteo-

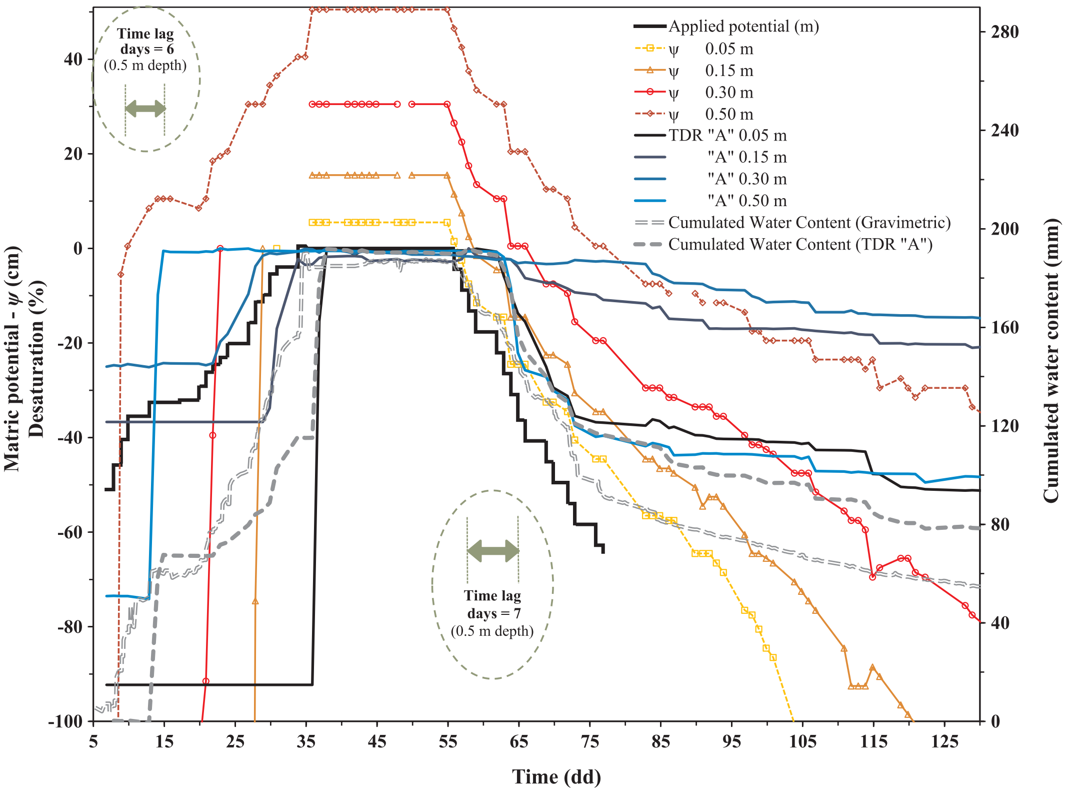

FIGURE 9 Time series of MP—ψ and VWC—θ. The time lags between the increase and decrease of the two variables are highlighted for the 0.50 m monitoring depth

climatic conditions responsible for water lose from peatlands themselves.

Within a shorter timeframe, the obtained VWC and MP curves can be used to improve the present management of hydraulic-regulated low lying peat farmlands, as those located around Venice, Italy (Gambolati et al., 2006), or in the north part of The Netherlands (Querner, Jansen, van den Akker, & Kwakernaak, 2012). There, only few centimetres of difference in the depth to the water table, which is artificially controlled by water reclamation authorities, can play an important role in preserving soil productivity and minimizing land subsidence, while maintaining sufficiently low the risk of flooding.

Apart from that, with a more generic approach, these datasets assume a specific interest from two main points of view:

- they represent a unique step forward for the possibility of reliable simulations of hydrologic peat response, and consequent greenhouse gas emissions, to scenarios of climate changes. Cropped peatlands in temperate regions (e.g. Deverel & Rojstaczer, 1996; Nieuwenhuis & Schokking, 1997; Nieveen, Campbell, Schipper, & Blair, 2005; Zanello et al., 2011) and reclaimed peat swamp forests in boreal zones (e.g. Hergoualc'h & Verchot, 2011; Hooijer et al., 2012) are typical environments where these processes are challenging. More recently, a large interest has been focused on artic peatlands because of their warming yielding permafrost thawing (e.g. Voigt et al., 2019);
- they support the development of hydrologic models accounting for processes with different levels of complexity: Flow in variably saturated porous media (e.g. Manoli et al., 2015; Paniconi, Ferraris, Putti, Pini, & Gambolati, 1994), swelling/shrinking soils (e.g. Camporese et al., 2006), hysteresis in the retention curve (e.g. Canone, Ferraris, Sander, & Haverkamp, 2008) and non-equilibrium flow (e.g. Diamantopoulos, Durner, Iden, Weller, & Vogel, 2015; Vogel, Weller, & Ippish, 2010).

5 | CONCLUSIONS

In view of predicted climatic changes, which will likely increase the frequency of extended warm and dry periods in the near future, the hydrologic response of peat deposits to water-scarce conditions remains a major issue in hydrological research.

For this reason, an undisturbed 0.7 m^3 peat monolith was collected from a drained cropped peatland in the Venice coastland which was previously the subject of a field monitoring program. The monolith was transferred to the laboratory and instrumented to monitor matric potential, volumetric water content and total weight (to determine bulk volumetric water content) under drying/wetting cycles and extreme drought conditions. Supplementary measurements of matric potential and water content were collected by testing peat subsamples on a suction table apparatus.

The results pointed out strong spatial and temporal variability of the wetting and drainage processes (both interlayers and intralayers). At the same time, fibrous peat layers characterized by unaltered structure and thin texture showed good capacity to retain water even in stressful air-drying conditions, acting as reservoirs for long periods. This was confirmed by the average gravimetric water content of the whole monolith which was consistent with the weighted average of the TDR values during the whole experiment. Hysteresis phenomena measured for ψ down to −1 m (i.e. similar to the normal field conditions) are demonstrated by wetting and drying curves quite far apart, with variability up to 8–10%, and dissimilar behaviour to those measured *in situ* by Camporese et al. (2006) which were closer to each other. Deep peat layers, usually below the water table in natural conditions and characterized by coarse textures, showed strong drainage and marked variation in water retention curves, when subjected to an extreme drought event. Furthermore, the dataset revealed a time lag between MP and VWC increase/decrease. During the wetting phase, the tensiometers reacted faster than the TDR to water arrival, but the tensiometers were delayed during the drying phase. This behaviour may probably be ascribed either to soil hysteresis or to hydraulic non-equilibrium during the experiment to be tackled with a modelling study in future works.

The characteristic retention curves down to ψ = −7 m were also explored. These curves will be of paramount importance in modelling applications for both hydrologic forecasting and decision-making purposes, with a particular insight into the effects of climate change on the peatland hydrology.

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AUTHOR CONTRIBUTIONS

Ferraris, Teatini, Ferrari and Putti dealt with the field sample collection and the transport. Previati, Iurato and Canone dealt with laboratory measurements and data processing. Data analyses were performed by Previati, Gisolo and Ferraris. The manuscript was written by Previati, Canone, Ferraris and Teatini.

DATA AVAILABILITY STATEMENT

Data Availability. Readers or researchers interested in receiving the datasets shown in this work can address their specific request to the corresponding author.

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