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Moisture content of peat-moorsh soils with special attention to periods of drought

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Abstract: The paper presents the course of variability of the moisture content of the top layers in shallow (45 cm) and medium-deep (90 cm) peat-moorsh soil profiles in the years 2015–2019 against the background of the same meteorological conditions and a similar level of the groundwater table. The relative precipitation index (*RPI*) classifies the years 2015 and 2016 as dry, 2017 as wet, and 2018 and 2019 as average. For periods of atmospheric droughts, the average daily climatic water balance (*CWB*) ranged from –5.30 to –1.35 mm·d^{-1}. The water table did not fall below 90 cm b.g.l. during the entire study period, and the range of its fluctuations was 8 cm greater in the shallow than in the medium-deep profile. The range of moisture at different depths varied significantly and ranged from approx. 6% in periods of drought to about 80% in wet periods. Soil moisture throughout the measurement period was above the plant available water range (p*F* > 4.2). The occurrence of soil drought in the shallow peat-moorsh soil profile had a range of up to 40 cm, and in the medium-deep profile of up to 30 cm. The sequence of no-precipitation days and the maximum amount of daily evapotranspiration during them determine the possible timing of drought; however, it is the precipitation distribution in individual months, considered in the current *CWB* values, that ultimately determine the formation of soil water resources at the research site.

Keywords: climatic water balance, moorsh, organic soils, soil moisture content, soil water potential

INTRODUCTION

The last few decades (especially from the end of the 20th century) have been associated with the steady growth of global air temperature, especially in Europe (Brocca *et al.*, 2011; Marcinkowski and Piniewski, 2018; Hänsel *et al.*, 2019; Mezghani *et al.*, 2019; Cammalleri *et al.*, 2020; Meza *et al.*, 2020). In Poland in the years 1988–2018, there was an increase in the average annual air temperature from 7.48 up to 8.68°C (Marsz and Styszyńska, 2019). This, in turn, has resulted in higher evapotranspiration, leading to lowered topsoil water content even in years of average precipitation totals (Seneviratne *et al.*, 2010; Somorowska, 2022). What is more, recent decades of increased air temperature have been accompanied frequently by simultaneous, long-lasting no-precipitation periods, or by precipitation totals which differed from the long-term average. This has given rise to long and various types of drought periods: atmospheric, hydrological, soil, and finally physiological drought, which has become a threat to global plant vegetation and production.

High air temperatures, contributing to increased evapotranspiration rates, and a lack of or considerably lower precipitation than usual seem to be particularly harmful to peatlands that were created over last 10–12 thous. years in high soil moisture conditions, low air temperatures, and noticeably higher precipitation totals. Such areas (in Poland usually located in river valleys or lowlands) perform many functions in the natural environment: they retain about 10% of global freshwater resources (about 3.5 mln km^3) and 30% of global soil organic carbon, contributing to the improvement of the microclimate and water quality (Oleszczuk *et al.*, 2008; Ciężkowski *et al.*, 2018; Oleszczuk *et al.*, 2022; Oleszczuk, Łachacz and Kalisz, 2022; Łachacz, 2023).

Due to natural processes or human activity (agricultural and horticultural drainage, forestry) groundwater table declines in these areas, causing the decrease of buoyancy force, lowering the peat topsoil moisture and the end of accumulation of organic matter, followed by organic soil oxidation. Unfavourable physical processes begin in the peat soil, such as shrinkage, consolidation and an increase in hydrophobicity caused by water content decline (Oleszczuk *et al.*, 2008; Lipka *et al.*, 2017; Oleszczuk, Zając and Urbański, 2020). Subsequently, cracks appear which allows atmospheric air to enter into deeper layers. This in turn, launches biochemical processes through the decomposition (oxidation) of organic matter followed by emission of carbon dioxide to the atmosphere and its dissolution in groundwater. Moreover, the topsoil emission and accumulation of nitrogen compounds becomes an issue here. Eventually, these processes lead to shallowing or even complete disappearance of these soils. In the case of drained peat soils, in order to protect them from further degradation, it would be necessary to upgrade existing drainage systems in order to reduce water run-off and consequently increase the moisture content of the soils (Brandyk *et al.*, 2021; Bajkowski *et al.*, 2022; UNEP, 2022; Urbański *et al.*, 2022).

The lowering of groundwater levels, the drainage of wetlands, as well as the observed climate changes pose a huge threat to the condition and existence of peatlands in the natural environment. This is particularly important in the case of shallow peat deposits occurring on various types of mineral substrates, which can sometimes additionally serve as a drainage for the peat layers (e.g., sand).

The purpose of this article is to compare the moisture content of the upper layers of medium-deep and shallow peat-moorsh soils, located close to each other, under the influence of the same meteorological conditions and with the similar level of the groundwater table.

The aims of the study are:

- a comparison of the dynamics of soil moisture content in profiles of shallow and medium-deep peat-moorsh soil at different depths,
- determination of soil moisture content and water potential of peat-moorsh soil and linking them with the climatic water balance during the period of atmospheric drought.

MATERIALS AND METHODS

STUDY SITE

Field studies were carried out on the peatland (fen) in central Poland near the village of Solec N 52°02'22.5276"; E 21° 05'46.8672") – Figure 1. The surface area of the peatland is approx. 220 ha; these are mainly the peat-moorsh soils (Murshic Hemic Histosols acc. to IUSS Working Group WRB, 2022), developed from reed-sedge peat of a medium degree of decomposition. The average peat thickness is 0.4 m, while in the central part it reaches a depth of 1.5 m. The entire surface of the fen is underlain by sand (Oleszczuk, Zając and Urbański, 2020). Currently, the area is used as an extensive meadow mowed twice a year. The peatland is covered by the State Drought Monitoring System in Poland (Jędrejek *et al.*, 2022).

Two peat-moorsh soil profiles were selected for the study: 1) shallow, with an organic layer of 45 cm, and 2) medium-deep, with an organic layer of 90 cm (Fig. 2). The analysed soil profiles were 65 m apart. The study was conducted in five successive periods from 1st April to 31st October in the years 2015–2019.

The average values of the basic physical properties in the shallow and medium-deep peat-moorsh soil profile on the studied peatland in individual layers are presented in Table 1 following Gąsowska (2017).

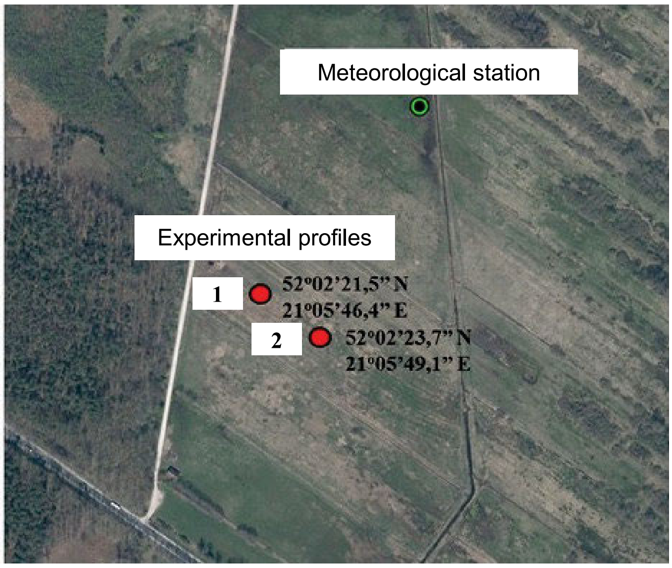

Fig. 1. The location of shallow (1) and medium-deep (2) peat-moorsh soil profile and meteorological station on the Solec peatland; source: own elaboration based on GPS measurements and ortophotomap

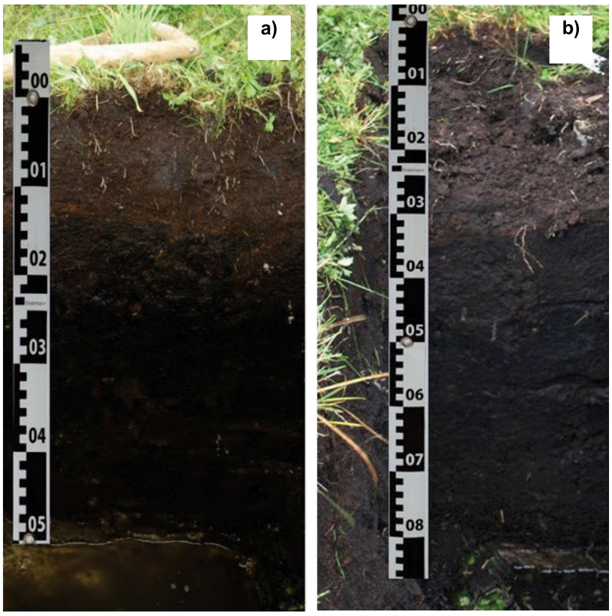

Fig. 2. Profiles of peat-moorsh soil at the Solec peatland: a) shallow, b) medium-deep; source: own elaboration

radiation intensity, wind speed at an altitude of 2 m were obtained from the weather station (A-Ster HT-125) installed in the Solec peatland. In contrast, precipitation data from the multiyear period 1961–2019 were obtained from SGGW rain gauge the (Theodor Friedrichs) in Warsaw, 15 km away from the study area.

Laboratory analysis

To determine the availability of water for plants in both soil profiles at different depths, water retention characteristics in the form of a (pF curve) were determined. The pF curve were determined in the range of water potential values from −10 hPa (pF = 1.0) to −15,000 hPa (pF = 4.2), with low pressure values i.e.: pF = 1.0 and pF = 2.0 marked on the sand block (Eijkelkamp, Netherlands), while high pressure values of pF = 3.7 and pF = 4.2 on ceramic plates in high-pressure chambers (Soil Moisture Inc. USA) (Klute (ed.), 1986). The van Genuchten equation (Genuchten van, 1980) was fitted to water retention data of the analysed soils (Eq. 1):

Table 1. Basic physical and chemical properties of peat-moorsh soil in analysed profiles up to 50 cm

Layer (cm)	Bulk density ($Mg \cdot m^{-3}$)				Particle density ($Mg \cdot m^{-3}$)				Satureted moisture content ($cm^3 \cdot cm^{-3}$)				Ash content (%)				pH	
	x	min	max	σ	x	min	max	σ	x	min	max	σ	x	min	max	σ	min	max
0–10	0.38	0.36	0.41	0.02	1.77	1.69	1.83	0.05	0.80	0.79	0.82	0.02	34.8	34.5	35.8	0.39	5.79	5.94
10–20	0.36	0.33	0.40	0.03	1.77	1.70	1.83	0.05	0.80	0.79	0.82	0.01	31.5	31.1	31.8	0.29	5.78	5.93
20–30	0.30	0.30	0.32	0.01	1.44	1.42	1.49	0.03	0.79	0.78	0.79	0.01	21.6	21.1	22.3	0.50	5.93	5.99
30–40	0.27	0.21	0.30	0.05	1.49	1.47	1.58	0.05	0.82	0.80	0.85	0.01	28.0	27.2	28.7	0.60	5.98	6.05
40–50	0.28	0.25	0.31	0.02	1.67	1.57	1.77	0.08	0.84	0.83	0.85	0.01	39.0	39.3	40.4	0.47	6.03	6.11

Explanations: x = arythmetical mean value; min = minimum value; max = maximum value; σ = standard deviation.
Source: Gąsowska (2017), modified.

$$\theta = \frac{\theta_s - \theta_r}{\left(1 + (\alpha \cdot \Psi)^n\right)^{-m}} + \theta_r \tag{1}$$

where: q = soil water content (% vol.), q_s = water content at full saturation (% vol.), q_r = the so-called residual water content (% vol.), a = empirical parameter monitoring the position of the water retention curve (hPa^{-1}), Y = value of soil water potential (hPa), n = empirical parameter controlling the shape of the retention curve, m = empirical parameter equal to $1–1/n$.

METHODS

Field measurements

The scope of the research covered: measurement of soil volumetric moisture, measurement of the position of the groundwater table and monitoring of meteorological parameters for the calculation of reference evapotranspiration (air temperature, wind speed, saturation vapour pressure, net radiation) and the amount of precipitation. Soil volumetric moisture measurements were performed at four depths, i.e., 10, 20, 30 and 40 cm in three repetitions using the HH2 soil moisture meter with PR2 profile probe by FDR method (DT Devices, UK) (Delta-T Device, 2016). Use of this measurement device required the installation of thin-walled pipes in the tested soil profiles. On each of the study plots, three thin-walled pipes were permanently installed, arranged in an equilateral triangle plan at distances of 60 cm. Mean values from three locations were used for the analysis. Moisture measurements were taken daily between 12 p.m. and 2 p.m. The position of the groundwater table was recorded using the SOLINST automatic logger every 6 h.

Meteorological data for 2015–2019, i.e. level of precipitation (A-Ster TPG-124), air temperature and relative humidity,

Meteorological data

The relative precipitation index (*RPI*) was used to assess the precipitation conditions during the 2015–2019 study period and to determine the dry months (Łabędzki, 2006; Baryła *et al.*, 2019). *RPI* was calculated for the subsequent months of the study (April–October) as the ratio of the monthly precipitation level from 2015 to 2019 (P) to average monthly precipitation level for the period 1961–2019 (P_{avg}), according to Equation (2):

$$RPI = \frac{P}{P_{\text{avg}}} 100 \tag{2}$$

To assess the amount of precipitation deficits (P_d) in relation to reference evapotranspiration (ET_o) in individual years, the average daily values of the climatic water balance (CWB) were calculated according to Equation (3):

$$CWB = P_d - ET_o \tag{3}$$

The value of the reference evapotranspiration was calculated according to the Pennman formula (Allen *et al.*, 1998) – Equation 4:

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{4}$$

where: ET_o = reference evapotranspiration (mm·day^{-1}), Δ = slope vapour pressure curve (kPa·°C^{-1}), γ = psychrometric constant (kPa·°C^{-1}), R_n = net radiation at the crop surface (MJ·m^{-2}·day^{-1}), G = soil heat flux density (MJ·m^{-2}·day^{-1}), T = mean daily air temperature at 2 m height (°C), u_2 = wind speed at 2 m height (m·s^{-1}), e_s = saturation vapour pressure (kPa), (e_s–e_a) = saturation vapour pressure deficit (kPa).

Periods with no precipitation were determined on the basis of the daily precipitation in each year of the study, including periods of drought defined as at least 20 consecutive days without precipitation (Łabędzki, 2006). For these periods, the average daily CWB values were calculated ($CWB = -ET_o$), which were subsequently compared with soil moisture content and soil water potentials (pF) (Klute (ed.), 1986).

Statistical analysis

Assessment of soil moisture distribution at individual levels in shallow 1 and medium-deep profiles 2 was carried out on the basis of standardised coefficients of bias and kurtosis, as well as the Shapiro–Wilk test and Kolomogorov–Smirnov compatibility test. The significance of the differences in the mean values and median of soil moisture between the corresponding layers in both profiles was determined by the tests: t-Student's (average comparison) and nonparametric Wilcoxon signed-rank test (median comparison). The analysis was conducted in individual years of studies and in total in the entire study period 2015–2019. It was assumed that the tests relate to two data streams correlated by pairs and corresponding to soil moisture measured at the same time. Next, homogeneous groups of averages were determined on the basis of calculations of logarithmised data, using a unidirectional analysis of variance and Tukey confidence interval for averages, and Mood's test and 95% confidence interval for medians. To determine the relationship between CWB and soil moisture content, the Spearman rank correlation coefficient ($p < 0.05$) was used.

RESULTS

METEOROLOGICAL CONDITIONS

Measurement results of meteorological parameters made it possible to analyse the course of daily precipitation and reference evapotranspiration at the research site in individual years (Fig. 3a–7a). The lowest rainfall totals in the analysed 7-month periods occurred in 2015 and 2016 (309.7 mm and 334.7 mm, respectively), and the highest in 2017 (564.9 mm) – Table 2. There were several periods of drought (Tab. S1), i.e., once in 2015, twice in 2016, and twice in 2018. In 2017 and 2019, atmospheric drought did not occur. During analysed periods, high average daily values of reference evapotranspiration were observed, from −5.30 to −0.50 mm·d^{-1} (Tab. S1).

SOIL WATER CONDITIONS

The depth of the water table in the entire period 2015–2019 (also in individual years) was higher in the medium-deep profile 2 than in the shallow profile 1 by an average of 9 cm. In 2015 and in some months of the remaining years, the water table in the shallow profile was below the level of the organic layer. Over the entire study period, the average amplitude of the water table fluctuations in the total depth of profile 1 was 70.8 cm and in profile 2 – 63.2 cm. The greatest fluctuations of the water table in both profiles occurred in the dry year 2015 and were 80 cm and 74 cm, respectively (Figs. 3d–7d).

The course of soil moisture content in connection with the soil water potential (pF) in the shallow and medium-deep peat-moorsh soil profile in the years 2015–2019 made it possible to analyse the rate of their changes and to determine the periods of unfavourable water conditions in soil profiles, i.e. the occurrence of soil drought defined as an increase in soil water potential above the value corresponding to the pF value in the range of 2.7–3.2 (Łabędzki, 2006). In addition, the observation of the course of pF values allowed to identify periods when soil water becomes difficult to access or unavailable for plants (Figs. 3–7, Tab. S2).

Studies conducted on the peatland have shown a different state of moisture of peat-moorsh soils between shallow (1) and medium-deep (2) profiles. Differences in the values of volumetric moisture content occurred at the tested depths in the most of the period of 2015–2019. The course of moisture changes, together with the characteristic values of pF = 2.0 and pF = 4.2 in both profiles, at individual depths, is shown in Figures 3–7.

Depth 10 cm. In the driest year (2015), soil moisture values in both profiles 1 and 2 at a depth of 10 cm were similar (Fig. 3). In the early period of 2015 it was about 40–50% vol. and over time, in conditions of very low rainfall, it decreased from the first weeks of June to the first weeks of September, even to the extreme of about 10% (air-dry soil). This resulted in moisture values being below the range of water available to plants (pF > 4.2). In the years 2016–2018, the moisture at a depth of 10 cm in the shallow profile 1 was in the range of 30–50% vol. and it was larger by about 10–15% vol. in comparison with the medium-deep profile 2 – Figures 4–6. In terms of water availability for plants (pF values), the moisture conditions were more favourable in profile 1 and worse in profile 2, where the soil water potential was already generally below pF 4.2. In the case of 2019, a relatively high moisture content in the initial period (up to 60% vol.) was systematically reduced in both profiles due to very low precipitation, reaching its minimum at about 10% vol. from early July to mid-August. During this period, the moisture values were below the range of water available to plants (pF > 4.2). The smallest differences in soil moisture at a depth of 10 cm between profiles 1 and 2 were found in 2015 with the lowest

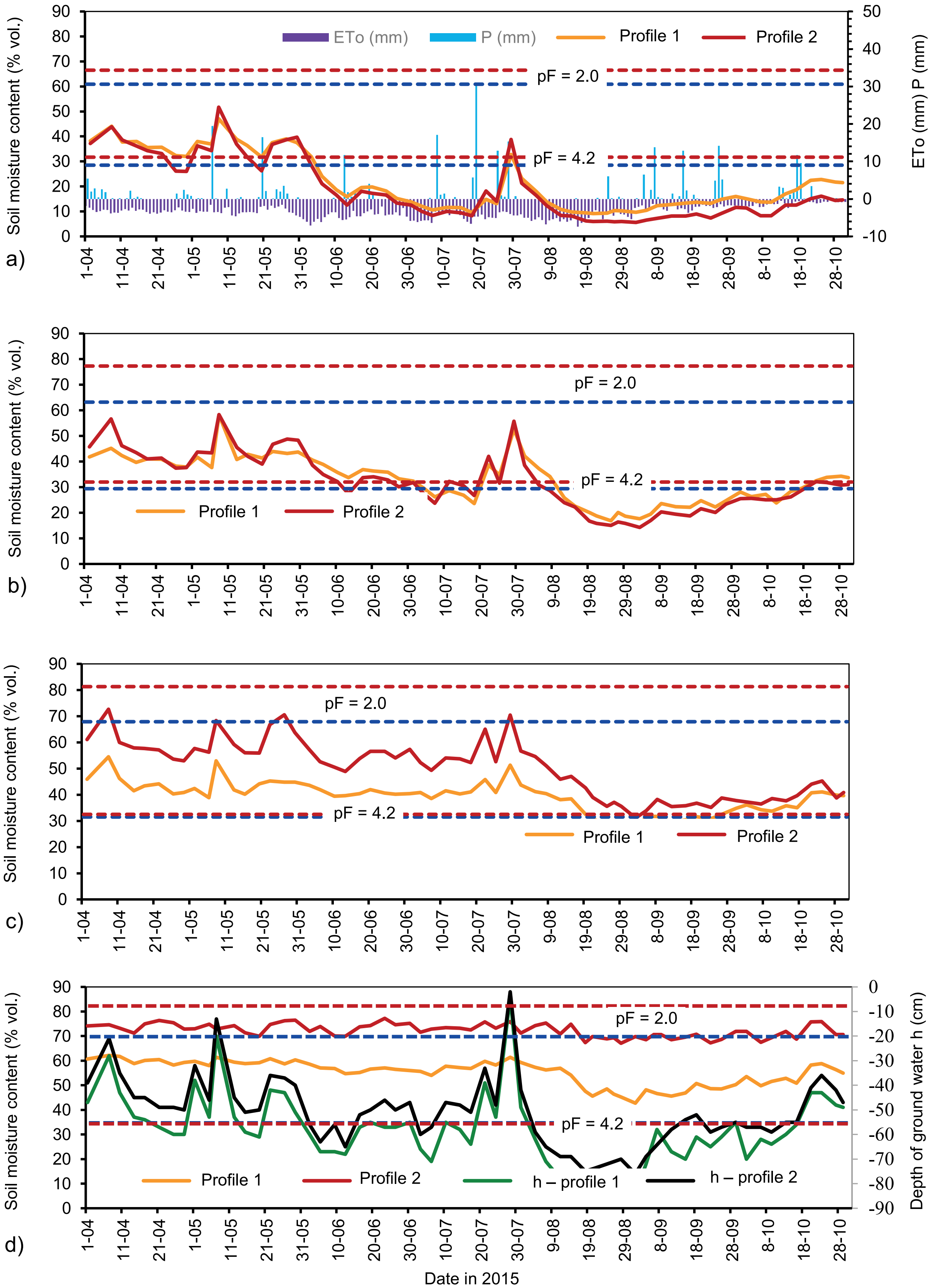

Fig. 3. Variability of volumetric moisture in relation to the characteristic points of soil water potential in 2015 in the shallow and medium-deep peat-muck soil profile at the depths of: a) 10 cm, b) 20 cm, c) 30 cm, d) 40 cm (p*F* = 2.0, p*F* = 4.2); soil moisture variability is presented against the background of precipitation and reference evapotranspiration (a) and the groundwater table (d); ET_o = reference evapotranspiration, *P* = precipitations; source: own study

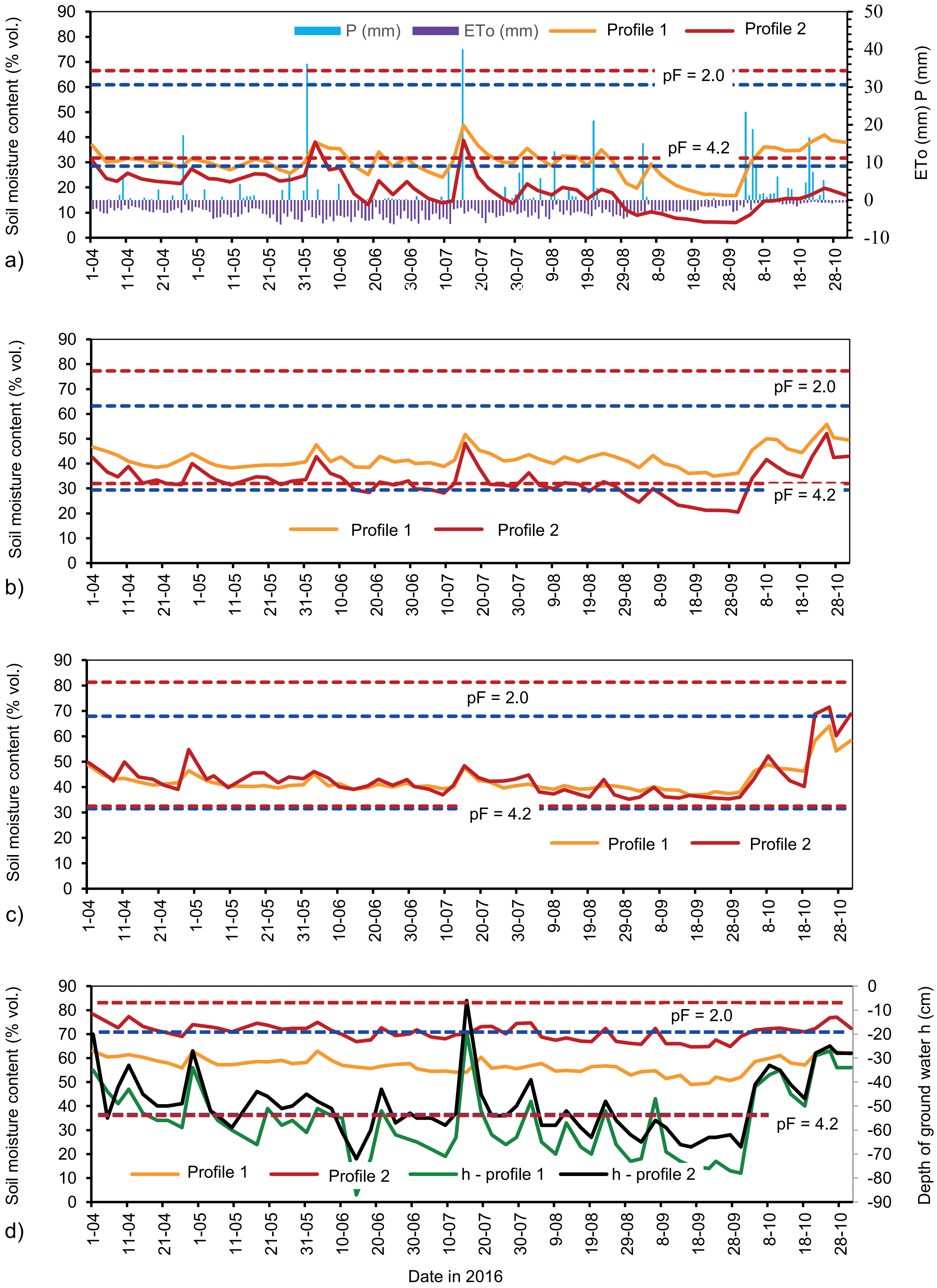

Fig. 4. Variability of volumetric moisture in relation to the characteristic points of soil water potential in 2016 in the shallow and medium-deep peat-muck soil profile at the depths of: a) 10 cm, b) 20 cm, c) 30 cm, d) 40 cm (p*F* = 2.0, p*F* = 4.2); soil moisture variability is presented against the background of precipitation and reference evapotranspiration (a) and the groundwater table (d); ET_o = reference evapotranspiration, *P* = precipitations; source: own study

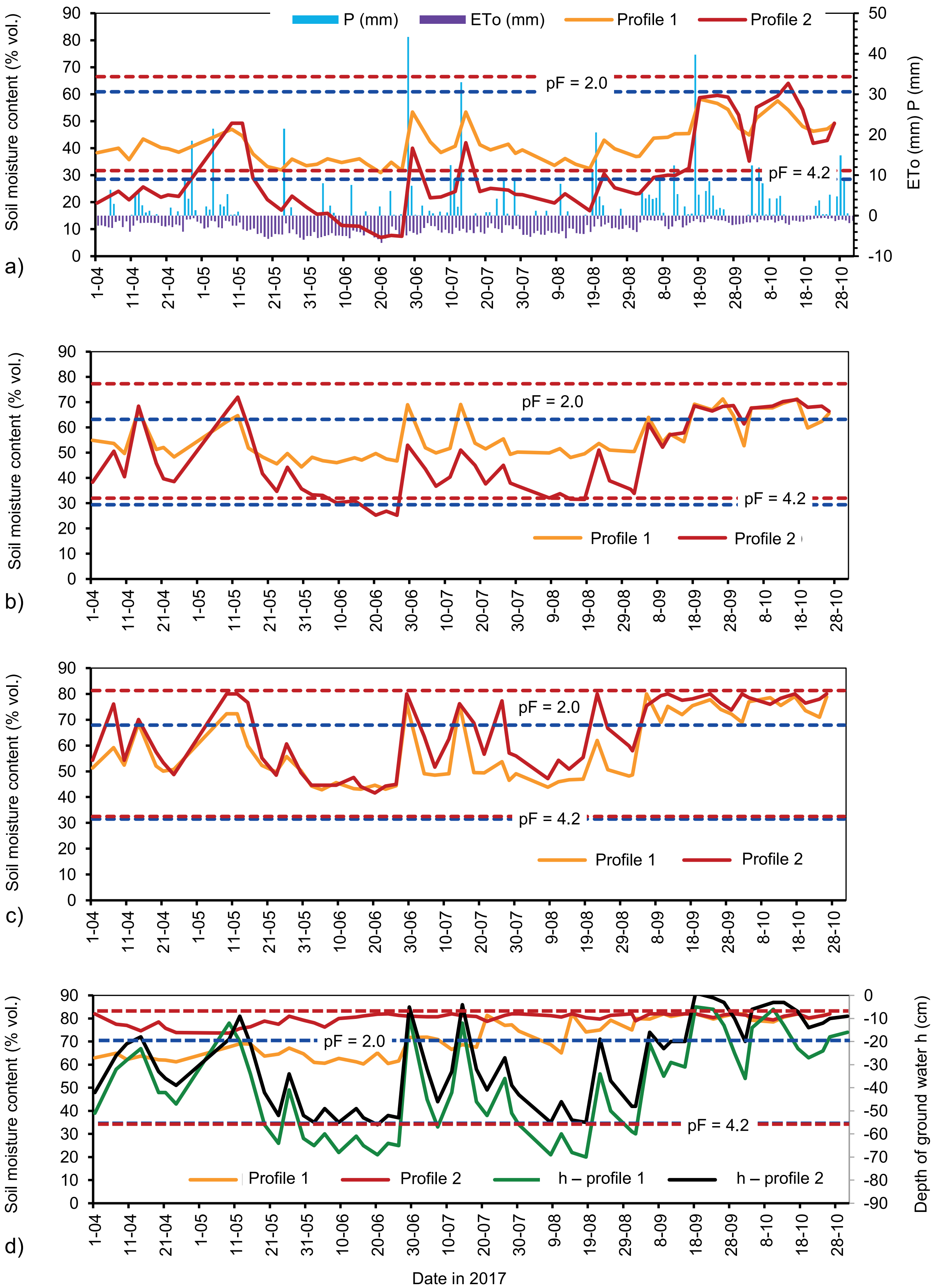

Fig. 5. Variability of volumetric moisture in relation to the characteristic points of soil water potential in 2017 in the shallow and medium-deep peat-muck soil profile at the depths of: a) 10 cm, b) 20 cm, c) 30 cm, d) 40 cm (p*F* = 2.0, p*F* = 4.2); soil moisture variability is presented against the background of precipitation and reference evapotranspiration (a) and the groundwater table (d); ET_o = reference evapotranspiration, *P* = precipitations; source: own study

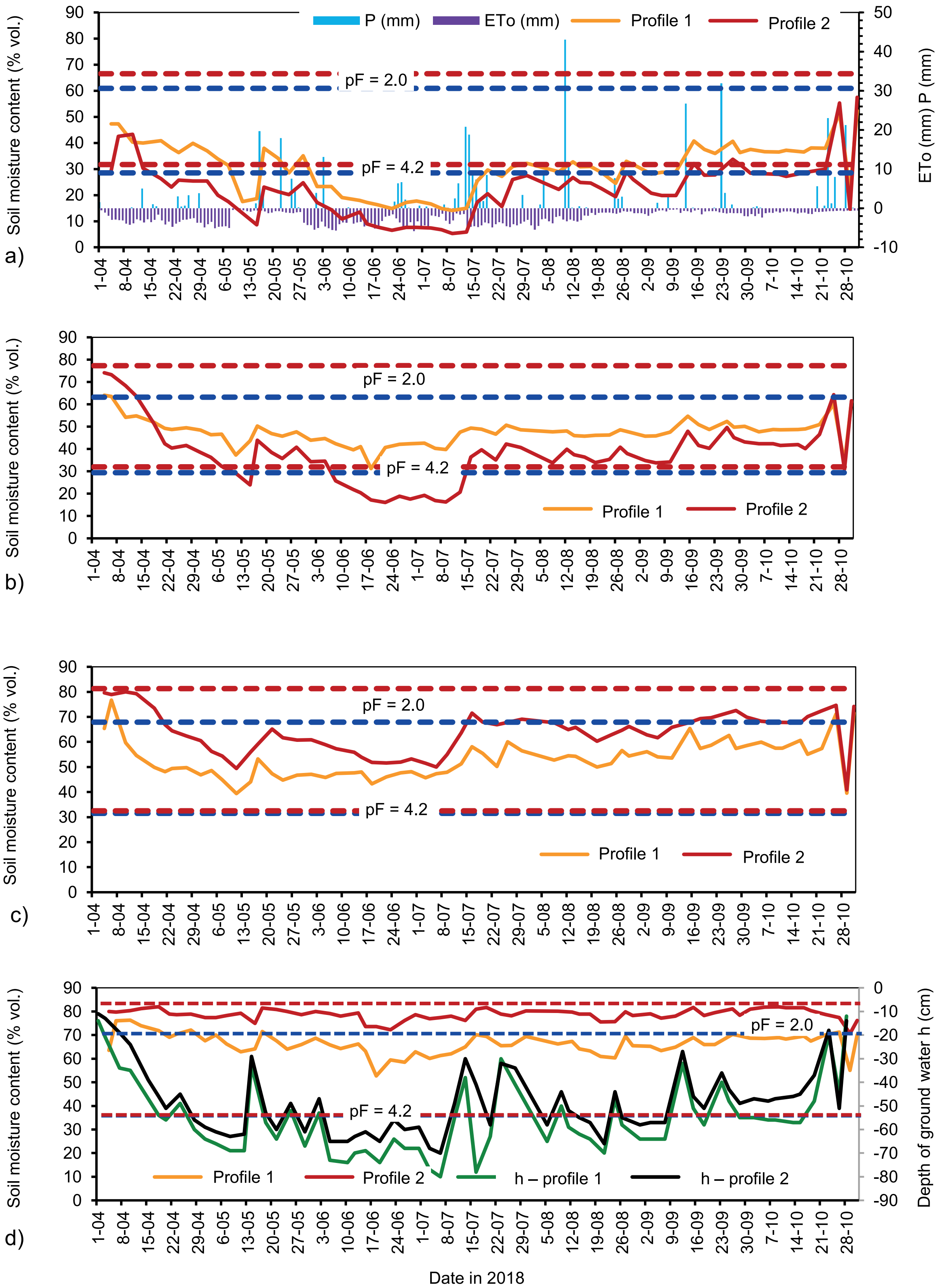

Fig. 6. Variability of volumetric moisture in relation to the characteristic points of soil water potential in 2018 in the shallow and medium-deep peat-muck soil profile at the depths of: a) 10 cm, b) 20 cm, c) 30 cm, d) 40 cm (pF = 2.0, pF = 4.2); soil moisture variability is presented against the background of precipitation and reference evapotranspiration (a) and the groundwater table (d); ET_o = reference evapotranspiration, P = precipitations; source: own study

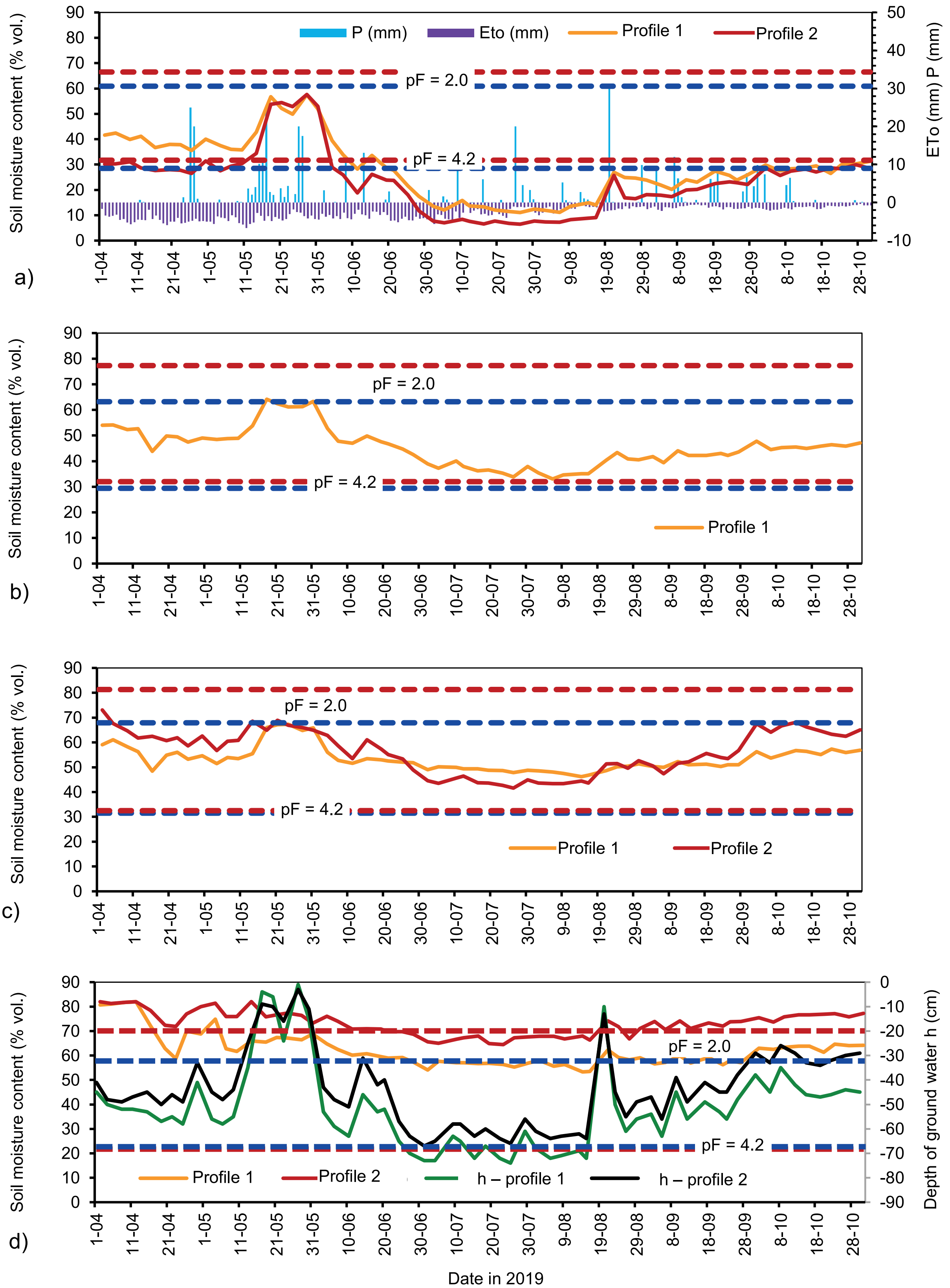

Fig. 7. Variability of volumetric moisture in relation to the characteristic points of soil water potential in 2019 in the shallow and medium-deep peat-muck soil profile at the depths of: a) 10 cm, b) 20 cm, c) 30 cm, d) 40 cm (pF = 2.0, pF = 4.2); soil moisture variability is presented against the background of precipitation and reference evapotranspiration (a) and the groundwater table (d); ET_o = reference evapotranspiration, P = precipitations; source: own study

Table 2. The sum of precipitation in the Solec peatland and the relative precipitation index (*RPI*) in the years 2015–2019

Year / sum in the period April–October (mm)	April	May	June	July	August	September	October
Monthly sum of precipitation (mm)							
2015 / 309.7	32.5	55.9	22.2	87.8	7.4	66.4	37.5
2016 / 334.7	43.2	24.9	46.6	24.6	62.8	16.9	115.7
2017 / 564.9	62.8	61.0	85.8	89.0	52.6	124.7	89.0
2018 / 405.1	19.3	54.9	34.8	82.0	85.0	68.0	61.1
2019 / 389.2	48.3	111.8	31.0	50.9	53.2	73.4	20.6
Average sum in the period 1961–2019	36.4	59.9	67.5	77.9	64.8	49.6	39.8
Relative precipitation index *RPI* (%)							
2015	88.5 average	94.1 average	32.3 very dry	111.7 average	11.4 extremely dry	135.8 wet	94.2 average
2016	117.7 average	41.9 very dry	67.8 dry	31.3 very dry	97.2 average	34.5 very dry	290.7 wet
2017	171.1 wet	102.7 average	124.9 average	113.2 average	81.4 average	255.0 wet	223.6 wet
2018	53.0 dry	91.7 average	51.6 dry	105.3 average	131.2 wet	137.1 wet	153.5 wet
2019	132.7 wet	186.6 wet	45.9 very dry	65.3 dry	82.1 average	148.0 wet	51.8 dry

Explanations: *RPI* classes on the basis of the monthly sum of precipitation (Łabędzki, 2006): extremely dry <0; 24.9>, very dry <25.0; 49.9>; dry <50.0; 74.9>; average <75.0; 125.9); wet >125.9.
Source: own study.

rainfall (Fig. 3, Tab. 2), and the largest in 2017 with the highest (Fig. 5, Tab. 2).

Depth 20 cm. The average soil moisture at a depth of 20 cm in profile 1 over the entire study period was 44.7% vol. and was 9.6% vol. higher compared to profile 2. The smallest differences in the average value between profiles 1 and 2 of a few percent were observed in the driest year 2015, and the largest, reaching 10% in the years with higher precipitation 2017–2019 (Tab. 2, Figs. 3– 7). The moisture in both profiles 1 and 2 was approximately 10% higher compared to the moisture at a depth of 10 cm in similar periods. Additionally, the dynamics of moisture changes at this depth was remarkably similar to the dynamics at a depth of 10 cm, and the state of soil moisture at both these levels during the growing season was shaped by the amount of precipitation and evapotranspiration. In 2015, 2018 and 2019, soil moisture at a depth of 20 cm, especially in profile 2, periodically exceeded the value of p*F* = 4.2, while in 2016–2017, the moisture values were within the range of water available to plants (p*F* = 2.0–4.2).

Depth 30 cm. At a depth of 30 cm, the reverse trend of soil moisture in relation to the top layers (10 and 20 cm) was exhibited, i.e., in most of the years analysed, the moisture content in the shallow profile 1 was significantly lower compared to the moisture content in the medium-deep profile 2. At the same time, both profiles showed higher soil moisture values compared to the top layers (Figs. 3–7). No significant differences between the two profiles were noted only in 2016, when the dry season with minimal precipitation was relatively long and lasted from the beginning of June to the beginning of the second week of July (Fig. 4). The average moisture in 2015–2019 in the shallow profile 1 at the level of 30 cm was 48.1% vol. and was higher in relation to the depth of 10 cm and 20 cm by 16.7% vol. and 3.4% vol. respectively, while for the medium-deep profile 2 it was 54.6% vol. and was higher by 32.6% vol. and 19.5% vol., respectively. At this depth, there was a delay of several days in the growth of soil moisture after rainfall in relation to the surface layer per 10 cm (Fig. 3, 6). A minimum soil moisture at a depth of 30 cm in profiles 1 and 2 of 25.9% vol. and 31.1% vol. was recorded in early September 2015 after extremely low rainfall in August (Tab. 2, Fig. 3c), while the maximum moisture in the range of 70–80% vol. was recorded in September and October 2017 (Fig. 5c). In general, the soil moisture values in both profiles in the years 2015–2019 were in the range of water available to plants (p*F* = 2.0–4.2).

Depth 40 cm. The soil moisture in both profiles 1 and 2 at a depth of 40 cm was shaped by both infiltrating rainwater and shallow groundwater (Figs. 3–7). The groundwater level in the medium-deep profile 2 was slightly higher than in the shallow profile 1, which may have had a direct impact on the slightly higher soil moisture values in this profile. The average groundwater level expressed as median in profile 1 over the entire study period (2015–2019) was 56 cm b.g.l., and in profile 2 it was 8 cm higher (Figs. 3d–7d).

Throughout the study period, soil moisture was close to that at full saturation, especially in the medium-deep profile 2. In the years 2015–2016, moisture values were within the range of water available to plants (p*F* = 2.0–4.2) (Figs. 3d, 4d), while in 2017–2019 they oscillated around p*F* = 2.0 (Figs. 5d–7d).

The median moisture at a depth of 40 cm in the shallow profile (1) was 61.0% with a maximum value of 82.0% and a minimum of 42.7%, and in the medium-deep profile (2) it was significantly higher and amounted to 75.0% vol. with a maximum value of 82.0% and a minimum of 64.6%.

Statistical analysis showed significant moisture differences between the shallow (1) and medium-deep (2) peat-moorsh soil profiles, both in individual years and during the entire research period 2015–2019. No significant differences were found only at a depth of 30 cm in 2016 (Tab. 3). The largest average differences occurred at a depth of 40 cm in the driest years 2015 and 2016 and amounted to 15.8% and 14.1% respectively, and the smallest in the wet year 2017 with a value of 9.7% vol.

Table 3. Significance test values for differences in soil moisture between the shallow (1) and medium-deep (2) peat-moorsh soil profile at individual depths

Year	Test of significance	Value at a depth of moisture measurement			
		10 cm	20 cm	30 cm	40 cm
2015	Student's *t*-test	8.609	3.323	−18.129	−29.762
	Wilcoxon test	6.062	3.074	6.780	6.788
2016	Student's *t*-test	13.953	16.471	−1.117*	−50.126
	Wilcoxon test	6.781	6.788	0.858*	6.788
2017	Student's *t*-test	8.645	6.766	−6.674	−8.440
	Wilcoxon test	5.918	5.004	5.526	5.819
2018	Student's *t*-test	12.430	7.980	−17.599	−25.688
	Wilcoxon test	6.745	6.206	6.788	6.788
2019	Student's *t*-test	10.371	10.126	−3.258	−21.751
	Wilcoxon test	6.515	6.716	2.974	6.732
2015–2019	Student's *t*-test	21.480	17.025	−15.592	−38.322
	Wilcoxon test	14.464	13.326	11.857	14.787

Explanations: * no difference at significance level $p < 0.05$.
Source: own study.

The analysis of the differences in median soil moisture between the shallow (1) and medium-deep (2) profiles at subsequent depth levels allowed to distinguish three homogeneous groups (Tab. 4). In general, the median differences at depths of 10 and 20 cm differ statistically from the median differences recorded at greater depths, i.e., 30 cm and 40 cm, with some exceptions in individual years. This trend is clearly visible throughout the research period 2015–2019, where significant differences were found between depths of 10 and 20 cm constituting a homogeneous group, and depths of 30 and 40 cm.

Table 4. Medians of differences in soil moisture and homogeneous groups of soil moisture between the shallow (1) and medium-deep (2) peat-moorsh soil profile at individual depths

Year	Value at a depth of moisture measurement			
	10 cm	20 cm	30 cm	40 cm
2015	2.633a	2.033a	−11.233b	−17.033b
2016	11.067a	9.333a	−0.567b	−13.633c
2017	14.417a	8.950b	−3.350c	−7.450c
2018	8.433a	8.733a	−11.000b	−12.733b
2019	4.867a	9.300a	−2.667b	−11.367c
2015–2019	7.100a	7.833a	−5.483b	−13.067c

Explanations: the different letters indicate the pairwise differences according to Duncan pairwise test.
Source: own study.

CLIMATIC WATER BALANCE AND SOIL WATER CONDITIONS

The average daily values of the *CWB* index in non-precipitation periods and the corresponding soil moisture ranges at specific depths in profiles 1 and 2 in the years 2015–2019 are presented in Table S1. The lowest *CWB* values were observed in the summer months in individual years ranging from −5.30 to −4.38 $mm \cdot d^{-1}$. Significantly higher *CWB* values were observed in the autumn months, i.e., from −1.78 to −0.5 $mm \cdot d^{-1}$. For example, in 2015 (from 31^{st} Jul to 24^{th} August) in both profiles at a depth of 10 cm with a *CWB* value of −5.30 $mm \cdot d^{-1}$ moisture ranged from 5.9 to 23.2% vol. In general, statistically significant correlations between daily *CWB* values and soil moisture were found at all depths throughout the 2015–2019 study period, including in isolated periods of drought, although these were weak. The highest correlation coefficient was found at a depth of 30 cm in both profiles, which was just over 0.30. These dependencies varied greatly from year to year. In the analysed drought periods, they were strongest in the wet year 2017 (Rho from 0.67 to 0.90), while in the drier years 2015, 2016 and 2019, significant relationships did not occur.

The obtained results showed that in the analysed soil profiles over the entire measurement period (2015–2019), soil moisture corresponded to the range of soil water potential available to plants (pF = 2.0–4.2) – Table S2. In general, at depths of 10 cm and 20 cm, the values of soil water potential were similar and were the lowest in both profiles. On the other hand, at a depth of 30 cm, and especially 40 cm, the value of the soil water potential reached pF 2.0 (depending on the year) and was significantly higher in the medium-deep profile 2.

DISCUSSION

Peat soils, due to their formation in specific conditions of excessive moisture, have been exposed in recent decades to degradation processes (decay) due to increasingly frequent atmospheric and soil droughts. This is especially dangerous for shallow and medium-deep peat deposits located on permeable mineral substrates. Such soils are exposed to the lowering of the groundwater table and the drying out of the organic layers, on one hand, because of the draining nature of the underlying substrate, and on the other hand as a result of the occurrence of periods of drought.

2015 and 2016 were characterised by extreme drought in Poland (Bąk and Kubiak-Wójcicka, 2017; Somorowska, 2020). High values of daily evapotranspiration during periods of atmospheric drought in the study period 2015–2019 occurred most often in the summer (June and July), which is also indicated by the values of the *RPI*. Despite the variation in the *RPI* over the years and the occurrence of dry, average and wet periods, the water table levels/position did not exceed 90 cm and the amplitude of its fluctuations was 71 cm in the shallow profile and 63 cm in the medium-deep profile. Slight differences in the water table level between the dry and wet years in this peatland suggest that this may be related to the groundwater supply at about 2.0–2.5 mm·day^{-1} in the dry years 2015–2016 (Brandyk *et al.*, 2021).

In 2015 and 2016, both shallow (45 cm) and medium-deep (90 cm) peat-moorsh soils experienced extremely low values of surface layer moisture (0–20 cm), which fluctuated from 6 to 23% by volume. However, in this layer, the moisture in the shallow profile was slightly higher than in the medium-deep profile, which is probably due to the higher position of the groundwater table (by about 10 cm) and slightly higher bulk density in the shallow profile. However at the depth of 30 cm reversed trend of the moisture content was observed. The dynamics of moisture changes in the surface layer in both profiles showed significant fluctuations, suggesting that this layer is most vulnerable to the onset of soil drought. On the other hand, at a depth of 40 cm in both soil profiles studied, the dynamics of soil moisture changes was much smaller compared to higher layers, while the moisture in the shallow profile was lower. Lower moisture in the shallow soil profile below 20 cm may result from the draining nature of the sand underlying the shallow peat layer (45 cm). A similar course of moisture at the same site was found in earlier years (2013–2015) (Gąsowska *et al.*, 2015; Gąsowska, 2017). The occurrence of soil drought (p*F* >2.7–3.2) at all depths in the shallow profile was observed in the dry years 2015 and 2016, while in the medium-deep profile the soil drought was up to 30 cm deep.

In Europe, about 46% of peatlands are degraded (mainly by drainage) and about 15% are used for agriculture mostly as grasslands and pastures; in Poland it is more than 80% (UNEP, 2022). Exclusion of their use as grassland and re-wetting these peatlands in many areas will not be possible. Organic soils will therefore be exposed to the effects of increasingly frequent droughts, which will impact water availability for plants. During the entire measurement period 2015–2019, in the peat-moorsh soil profiles studied, despite the presence of low soil moisture, especially in rainless periods, the range of soil water potential at individual depths was within the range of water available to plants – p*F* ∈ <2.0; 4.2>, but up to a depth of 30 cm it was in the range of water difficult to access (p*F* > 3.7). According to a study by Oleszczuk *et al.* (2022) at the same site, but on mineral soil (sands) in the dry years of 2015 and 2016, p*F* values in the layer of 10–25 cm were in the range of 3.5–4.0, which corresponded to a moisture of about 10–15%.

The results of the studies indicate the need for irrigation of shallow peat-moorsh soils, since they are particularly vulnerable to fluctuations in the groundwater table and a decrease in moisture in the profile, and thus to the progressive mineralisation of organic matter and the accompanying CO_2 emissions (Oleszczuk *et al.*, 2008). Studies have shown that even moderately deep peat-moorsh soils were less exposed to the negative effects of drought than the shallow ones.

In recent decades (especially during drought periods), *CWB* values have been linked to soil water conditions (soil moisture, soil water potential) (Albergel *et al.*, 2012; Al-Kubaisi and Rasheed, 2018; Tapoglou, Vozinaki and Tsanis, 2019; Csáki *et al.*, 2020; Pravalie *et al.*, 2020). In general, drought monitoring with external indicators based on meteorological parameters may be incomplete, but for larger areas it may allow for a preliminary estimate of the water resources of the soil layers. The statistical relationship of *CWB* to soil moisture is significant only in wet years, whereas in conditions of prolonged drought and high evapotranspiration, a gradual decrease in the value of *CWB* does not result in the occurrence of substantial dependencies due to strong drying of the profile. However, further monitoring of soil moisture and water potential in relation to the spatial distribution of *CWB* values is required to obtain more accurate information.

CONCLUSIONS

1. Despite the changing weather conditions resulting in dry (2015, 2016), wet (2017) and average (2018, 2019) years, the levels of the groundwater table in the shallow and medium-deep peat-moorsh soil profiles were similar to each other. In the driest periods, this dropped to about 90 cm below the ground, suggesting an underground supply.
2. The greatest dynamics of moisture changes in both soil profiles was observed in the layer down to 20 cm, in the range of about 6% vol. during periods of atmospheric drought up to approx. 80% vol. in wet periods. This was due to the reaction to the magnitude of precipitation and evapotranspiration. However, below 30 cm the moisture stabilises and exhibits values close to the moisture of full saturation.
3. Significant correlations between daily *CWB* values and soil moisture were found at all depths during the entire research period of 2015–2019, but these relationships were weak. In contrast, in the analysed periods of atmospheric drought, strong correlations were found between these parameters in wet years, which did not occur in dry years due to high evapotranspiration.
4. The occurrence of soil drought in the dry years 2015 and 2016 was found throughout the shallow profile, while in the medium-deep profile the soil drought had a range which was shallower by 10 cm. Despite the occurrence of rainless periods and droughts in the years 2015–2019 in both profiles at levels of 30 and 40 cm, no exceedance of the limit of water available for plants (p*F* = 4.2) was observed.
5. The sequence of non-precipitation days and the maximum amount of daily evapotranspiration during them (6.20–7.40 mm·d^{-1}) determine the possible timing of drought; however, it is the precipitation distribution in individual months, taken into account in the current values of the *CWB*, that ultimately determines the formation of soil water resources at the research site.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Oleszczuk.pdf

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