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Assessment of rainfall efficiency in an apple orchard

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Abstract: Atmospheric precipitation is the major input to the soil water balance. Its amount, intensity, and temporal distribution have an indubitable influence on soil moisture. The aim of the study (conducted in the years 2010–2013) was to evaluate soil water balance in an apple orchard as determined by daily rainfall. The amount and intensity of rainfall and daily evapotranspiration were measured using an automatic weather station. Changes in soil water content was carried out using capacitance probes placed at a depth of 20, 40 and 60 cm. The most common were single events of rainfall of up to 0.2 mm, while 1.3–3.6 mm rains delivered the greatest amount of water. A significant correlation was found between the amount of daily rainfall and changes in water content of individual soil layers. The 15–45 cm and 15–65 cm layers accumulated the greatest amount of high rainfall. The study showed a significant influence of the initial soil moisture on changes in the water content of the analysed layers of the soil profile. The lower its initial moisture content was, the more rainwater it was able to accumulate.

Keywords: apple orchard, evapotranspiration, hydrothermal index, irrigation, rainfall efficiency, soil moisture

INTRODUCTION

Atmospheric precipitation is the major input to the soil water balance in a temperate climatic zone. Its amount, intensity, and temporal distribution have an indubitable influence on soil moisture. For this reason, the soil moisture content is highly variable in space and time. Soil water resources play an important role in the water cycle in the plant–soil–atmosphere system, and particularly in the surface layer of soil [Biniak-Pieróg 2017; Klamkowski *et al.* 2011a, b; Schwingshackl *et al.* 2017]. The influence of rainfall on the growth and yielding of plants depends on its amount, intensity, and distribution over time [Klamkowski *et al.* 2011b; Treder, Konopacki 1999]. Therefore, every farmer should analyse whether the available rainfall is sufficient and well distributed for the cultivation carried out in a particular region. If the amount and distribution of rainfall is insufficient, it should be supplemented with irrigation.

Because the soil moisture level determines the process of plant growth and development, accurate knowledge of its field-scale variability is important for improving irrigation management strategies with respect to crop production and optimal use of available water resources [Ali, Mubarak 2017; Vereecken *et al.* 2014]. Monitoring soil water status is a well-known method to efficiently control irrigation in order to optimally meet plant water requirements and at the same time avoid unproductive water losses through deep percolation [Nolz *et al.* 2016]. Irrigation water use for crop production is dependent on the interaction of climatic parameters that determine crop evapotranspiration (*ET*) and water supply from rainfall. In case of an excessive amount or intensity of rain, part of the water percolates through to below the root system or runs off the soil surface [Ballif 1995].

Rainfall may be separated into the following components: runoff, infiltration, interception, and evapotranspiration [Dastane 1974; Kowalik 2010; Vallet *et al.* 2013]. The effective rainfall (*Re*) for field crops is the portion of rainwater which is useful directly and/or indirectly for crop production at the site where it falls [Dastane 1974]. Effective rainfall depends on many factors, for example: soil and crop characteristics, climate parameters, land slope, and rainfall characteristics [Ali, Mubarak 2017; Obreza, Pitts 2002; Treder, Konopacki 1999; Vallet *et al.* 2013]. The level of rainfall interception, a process whereby rainfall falling onto vegetative surfaces is caught, retained, and eventually evaporated from plants' foliage and branches, is critically important and should not be neglected during the estimation of water budgets of orchards [Muzylo *et al.* 2009]. According to some authors, rainfall interception by plant canopies may account for 15% of total precipitation [Calheiros De Miranda, Butler 1986].

Chudecki *et al.* [1971] showed that changes in moisture content at different depths of the soil profile mainly depend on the amount of rainfall and the level of soil moisture before its occurrence. Too abundant and intense rainfall may not be fully utilised by plants due to the migration of rainwater in the soil profile beyond the reach of the plant root system, or because the rainwater flows away as surface runoff. Information on the impact of specific rainfall levels on changes in the water content through the soil profile is especially important for farmers who have the option of using irrigation. Very low rainfalls do not influence soil moisture. According to Chudecki *et al.* [1971], a 2.5 mm daily rainfall has no significant impact on soil moisture content. In FAO-25 guideline [Dastane 1974], it is assumed that a daily rainfall of <5 mm would not be considered effective (during a dry period), as this amount of precipitation would likely evaporate from the surface before soaking into the ground. But this is only valid for summer (hot period). Therefore, Drupka [1976] suggested to consider only days with the amount of rainfall higher than potential evapotranspiration. This approach allows a reliable analysis of the efficiency of precipitation both in hot and cold periods. According to Drupka [1993], the most useful rains for plants are those with small drops, of an intensity not higher than 2–3 $mm \cdot h^{-1}$. In a study conducted by Klamkowski *et al.* [2011a, b], the highest efficiency was observed when the intensity of rainfall was in the range from 2 to 10 $mm \cdot h^{-1}$. The relationship between changes in soil water content and rainfall has been the subject of many studies, some of them carried out in Poland [Bieniak-Pieróg 2017; Treder, Konopacki 1999; Valet *et al.* 2013; Vereecken *et al.* 2014].

The current development of measurement technology and wireless data transmission allows greater precision and frequency of soil moisture measurements [Bogena *et al.* 2007; Gałęzewski 2020; Vereecken *et al.* 2008]. Currently, such analyses can be conducted not only at daily intervals, but in the time immediately after rainfall [Klamkowski *et al.* 2011b].

The aim of the study was to evaluate soil water balance in a fruit orchard as determined by daily rainfall.

MATERIAL AND METHODS

The study was conducted in the years 2010–2013 in an experimental orchard (Pomological Orchard of The National Institute of Horticultural Research (Pol. Instytut Ogrodnictwa – Państwowy Instytut Badawczy), Skierniewice, Poland; 51°57' N, 20°09' E). The orchard had been planted on a grey-brown podzolic soil with loamy subsoil. Observations and measurements were made on a plot with 'Gala'/M.9 apple trees planted at a spacing of 4.0 × 1.2 m and trained as spindles (the trees were planted in 2002). Soil surface in the orchard was maintained as a 1.5 m wide chemical fallow. Soil moisture content for different p*F* values is presented in Table 1.

The amount and intensity of rainfall were measured using an iMETOS automatic weather station. Rainfall was recorded every 60 minutes, with a minimum measurement resolution of 0.2 mm. Based on the measured meteorological parameters (solar radiation, air temperature and humidity, wind speed), the weather station determined the daily reference evapotranspiration (ET_o) values using the Penman–Montheith model [Allen *et al.* 1998].

Table 1. Soil moisture (% vol.) at different levels of water potential–

Soil layer	Bulk density ($g \cdot cm^{-3}$)	p*F* 2.0	p*F* 2.85	p*F* 3.2
15–25	1.55	22.23	18.75	16.95
35–45	1.62	27.55	24.5	22.9
55–65	1.62	27.55	24.5	22.9

Source: own study.

The assessment of hydrothermal conditions for the period in which the study was conducted was based on Selianinov hydrothermal index (*HTC*) [Kuchar *et al.* 2017]:

$$HTC = \frac{10\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} T_i} \tag{1}$$

where: n = length of the period (days), P_i = rainfall on the i-th day (mm), T_i = average air temperature on the i-th day (°C).

The values of each *HTC* rating class are presented in Table 2.

Table 2. Threshold values of the Selianinov hydrothermal index (*HTC*) index for hydrothermal evaluation

Description	*HTC*	Colour code
Extremely dry	≤ 0.4	
Very dry	0.4 < *HTC* ≤ 0.7	
Dry	0.7 < *HTC* ≤ 1.0	
Quite dry	1.0 < *HTC* ≤ 1.3	
Optimum	1.3 < *HTC* ≤ 1.6	
Quite wet	1.6 < *HTC* ≤ 2.0	
Wet	2.0 < *HTC* ≤ 2.5	
Very wet	2.5 < *HTC* ≤ 3.0	
Extremely wet	*HTC* > 3.0	

Source: own elaboration.

Continuous recording of changes in soil moisture was carried out using EC-5 capacitance probes placed at a depth of 20, 40, and 60 cm. The probes were installed in the soil profile parallel to the soil surface. The probes were integrated with the weather station, which enabled automatic recording of measurement results (at hourly intervals) and their transmission to the receiving terminal. According to the manufacturer's information, probes of this type measure the average moisture in the soil layer thickness of approx. 5 cm either side of the sensor (information in the manufacturer's documentation). Therefore, it was assumed that the water resources were calculated based on the daily values of soil moisture in the 15–25 cm, 35–45 cm, and 55–65 cm layers.

$$z = \frac{h_0 \cdot W_0}{10} \tag{2}$$

where: z = water reserve in the soil layer (mm), h_0 = layer thickness (cm), W_0 = soil moisture content.

Changes in water content in a specific soil layer were calculated on the basis of differences in water content at the end and beginning of each day. The initial (*SWCi*) and final soil water contents (*SWC*) for the layers 15–25 cm, 15–45 cm, and 15–65 cm were determined as the average values of the measurements taken at the lower and upper levels of a given layer.

Due to the lack of influence of low rainfall on variations in soil moisture [DRUPKA 1976], the analyses were based only on the data from days when the total rainfall was higher than the reference daily evapotranspiration.

The experimental data were statistically elaborated using the statistical software package Statistica 13.1.

RESULTS AND DISCUSSION

The hydrothermal conditions during the study period were very variable both in individual growing seasons and in the comparison between individual years (Tab. 3). For example, April 2010 was very dry, but May was extremely wet. In 2011, July was extremely wet, while August and September were dry and extremely dry, respectively. According to the adopted criteria, the hydrothermal conditions of the growing seasons of 2010 and 2013 were assessed as normal, while the growing season of 2012 was classified as dry, and that of 2011 as fairly wet. Under Polish climatic conditions, such variability is a normal phenomenon [KLAMKOWSKI *et al.* 2011b; WÓJCIK *et al.* 2016].

Table 3. Assessment of hydrothermal conditions in the growing seasons of 2010–2013

Year	Selianinov hydrothermal index						Average
	Apr	May	Jun	Jul	Aug	Sep	
2010	0.55	3.24	0.82	0.98	1.43	2.28	1.50
2011	2.10	1.09	1.82	3.47	1.27	0.23	1.70
2012	1.01	0.26	1.14	1.08	0.89	0.84	0.88
2013	1.85	2.61	2.52	0.18	0.42	1.59	1.41

Source: own study.

In each of the analysed periods, single rainfalls of up to 0.2 mm were the most common. In the precipitation patterns of Poland, it very often happens that a single rainfall event of 0.2 mm is the only rainfall on a specific day. In the relatively wet growing season of 2010, there were as many as 156 such events, whereas in the dry year of 2012 – only 73 (Fig. 1). The greatest amounts of water, however, were delivered by rainfalls of 1.3–3.6 mm (Fig. 2). In 2011, high and very high rainfalls (8.1–18 and 18–36 mm) had a relatively large share in the amount of total precipitation.

Under the climatic conditions of Poland, atmospheric precipitation is the primary source of water for plants. The amount and intensity, as well as the distribution of rainfall affect the soil moisture content. Effective precipitation is an important

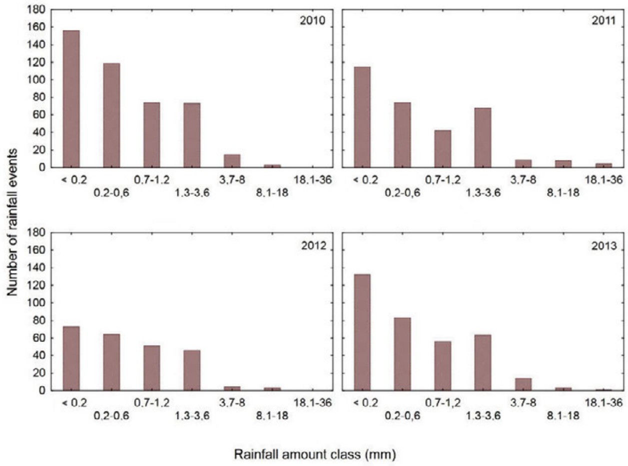


Fig. 1. Number of rainfall events in different amount classes (2010–2013 growing seasons); source: own study

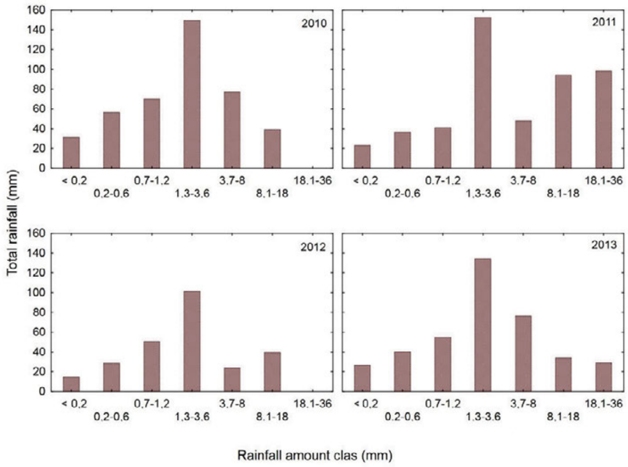


Fig. 2. Cumulative rainfall in different amount classes of rainfall event (2010–2013 growing seasons); source: own study

parameter in irrigation scheduling decisions [ALI, MUBARAK 2017]. According to DRUPKA [1993], low intensity rainfall (up to 2–3 mm·h^{-1}) is the most beneficial to plants. BAC and ROJEK [1979] raised this value to 4 mm·h^{-1}. In the event of excessive rainfall, part of the water may penetrate beyond the reach of the root system or flow away from the field as surface runoff [BALLIF 1995].

According to CHUDECKI *et al.* [1971], very low rainfall (<2.5 mm per day) does not affect soil moisture – some of the water evaporates almost immediately, the rest moistens only the top layers of the soil. DRUPKA [1976] proposed another criterion of rainfall efficiency. According to this author, only rainfall greater than the daily evapotranspiration values can be considered as significant in the soil water balance. Small (short and intense) rainfall events, especially on a hot day, have no effect on soil water management; they only moisten the leaves and shoots of plants. The amount of water uptake by vegetation after rainfall may be ≤2 mm (deciduous trees); during the year, up to 20% of rainwater can be captured in this way [KĘDZIORA 1995; ŚWIĘCICKI 1981].

On average for the years 2010–2013, in the period from April to September, as many as 43.7% of days with rainfall were recorded. Out of all the days with rainfall, only 50.1% of the days were characterised by a cumulative rainfall higher than the ET_o value. However, the percentage share of the cumulative rainfall on those days in relation to the total amount of rainfall was as high as 91.7% (Tab. 4). Earlier studies (conducted in the same area) by KLAMKOWSKI *et al.* [2011b] had shown slightly higher values – days with cumulative rainfall higher than ET_o accounted for approx. 57% of all rainy days, and the cumulative share of such precipitation amounted to approx. 93% of the total rainfall. Much higher values had been observed in even earlier observations by TREDER and KONOPACKI [1999]. The number of days with a cumulative rainfall exceeding the ET_o value was then 74%.

In accordance with the adopted methodology, the assessment of rainfall efficiency was carried out only for days with cumulative rainfall greater than ET_o. A preliminary analysis of the measurements (Fig. 3) already showed a significant relationship between the amount of daily rainfall and changes in the water content of individual soil layers. Due to the thickness of the layer, the 15–45 cm and 15–65 cm layers could accumulate the highest amount of high rainfall. A characteristic feature of the presented

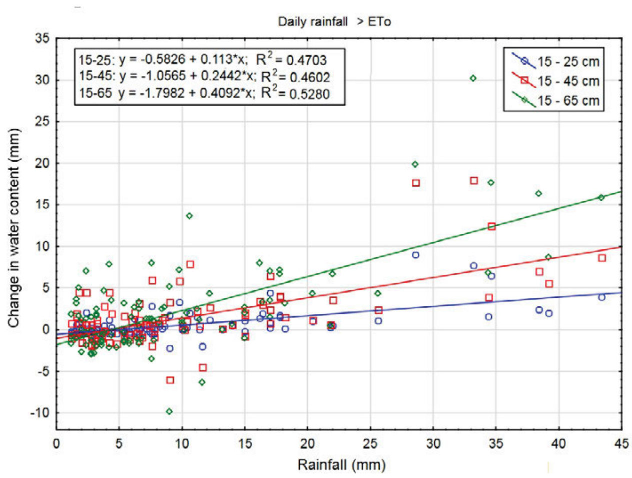


Fig. 3. Influence of the amount of rainfall on changes in water content in individual soil layers; ET_o = evapotranspiration; source: own study

Table 4. Characteristics of cumulative daily amounts and percentage share of efficient rainfall (>ET_o) for all days with rainfall occurring in the period from April to September

Season	Days with rainfall			Days with rainfall > ET_o			
	number of days	cumulative rainfall (mm)	% of days with rainfall	number of days	cumulative rainfall (mm)	% of days with rainfall	% of total precipitation
2010	91	449.2	49.7	49	416.2	53.8	92.7
2011	83	493.8	45.4	44	467.0	53.0	94.6
2012	66	258.6	36.0	24	218.4	36.4	84.5
2013	78	395.0	42.6	47	375.2	60.3	95.0
Mean	80	399.2	43.7	41	369.2	50.1	91.7

Source: own study.

analysis is the relatively large dispersion of the measured values. Field studies are characterised by a high level of randomness in terms of the amount and intensity of precipitation in relation to the initial soil moisture conditions. Therefore, the results obtained here do not always correspond to simulations conducted under controlled laboratory conditions [BINIAK-PIERÓG 2017].

Multiple regression analysis showed a significant influence of not only rainfall but also initial soil moisture on changes in the water content of the studied layers (Tab. 5). Regardless of the thickness of the layer, the lower its initial moisture content was, the more rainwater could be accumulated in it (negative *b* value for initial soil moisture). However, the obtained multiple regression models do not perfectly describe the impact of rainfall on changes in the water content of individual soil layers. The measured rainfall totals and initial soil moisture describe this process to the extent of only 50–57%. This is because the study did not take into account soaking up, partial interception, changing soil cover during the growing season, and the time needed for infiltration into the soil profile (for example, late-night rainfall did not have an effect on changes in moisture in the deeper soil layer until the next day). The influence of soil moisture content at the moment of the beginning of rainfall on its efficiency had been mentioned in the reports by TREDER and KONOPACKI [1999]. KLAMKOWSKI *et al.* [2011b] showed that during periods of drought, when the water content in the soil was low, the efficiency of rainfall (the amount of retained water relative to

Table 5. Multiple regression parameters describing the effect of rainfall amounts and initial soil moisture levels on changes in the water content of a specific soil layer

Specification	Regression parameter		
	b	p	R^2
Layer 15–25 cm			
Intercept	1.13	0.058	0.50
Rainfall	0.12	0.00	
Initial soil moisture	−0.01	0.00	
Layer 15–45 cm			
Intercept	6.81	0.00	0.52
Rainfall	0.26	0.00	
Initial soil moisture	−0.38	0.00	
Layer 15–65 cm			
Intercept	9.33	0.00	0.57
Rainfall	0.43	0.00	
Initial soil moisture	−0.54	0.00	

Explanations: b = regression coefficient, p = p-value, R^2 = determination coefficient.
Source: own study.

the amount of fallen rainwater) reached 70%. With the increase in soil moisture, the efficiency of rainfall decreased sharply. In extreme cases, when the soil was almost fully saturated with water, the rainfall efficiency was only a few percent.

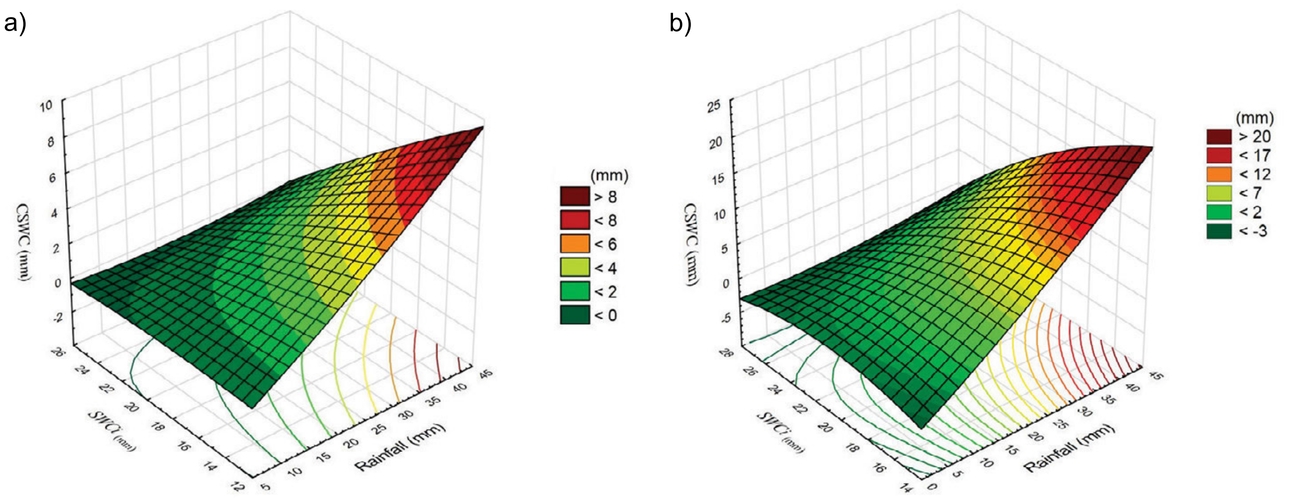
To illustrate the influence of the initial moisture content of soil on its retention capacity after the delivery of different amounts of rainfall, the collected measurement data are presented using surface graphs in the system: X = daily rainfall (P_i), Y = initial soil moisture (SWC_i), and Z = changes in water content of a specific soil layer ($CSWC$). The area of the dependent value Z was determined using a quadratic polynomial function (Fig. 4). The obtained models of the described dependencies are presented below:

$$CSWC_{layer15-25} = -3.09 + 0.40x + 0.22y + 0.0009x^2 - 0.017xy - 0.0041y^2$$

$$CSWC_{layer15-45} = -20.34 + 0.95x + 1.89y + 0.0018x^2 - 0.035xy - 0.045y^2$$

$$CSWC_{layer15-65} = -46.16 + 1.14x + 4.41y + 0.0043x^2 - 0.041xy - 0.107y^2$$

Daily rainfall of up to 5 mm means that the rainwater practically does not reach even the 15–25 cm soil layer. With an average initial moisture content of this layer of 13% (very dry) and a daily rainfall of 10 mm, only 1% of the rainwater reached this layer, i.e. the water content of this layer increased by 1 mm. Most of the rainwater, in this case, was retained by the 0–15 cm layer, some evaporated (evaporation), and some was taken up by plants (transpiration). In the study by BINIAK-PIERÓG *et al.* [2012], daily cumulative rainfall of up to 10 mm did not increase the retention above 1 mm in a soil (without cover) with a thickness of up to 40 cm, which is consistent with the results of other authors [KLAMKOWSKI *et al.* 2011a]. In the case of intensive rainfall and dry, crusted soil surface, a certain amount of the rainwater may flow down its surface in line with the ground slope (our study was carried out in an orchard planted on a flat area of land). With low soil moisture, the daily rainfall of 30 mm increased the water content in the 15–25 mm layer by 5.3 mm. The higher the initial moisture content of the soil layer was, the less water was retained even in the case of the highest daily rainfall, which confirms previous observations carried out in orchards [KLAMKOWSKI *et al.* 2011b; TREDER, KONOPACKI 1999]. With the initial soil moisture of 25% (far above field water capacity), the amount of rainfall had practically no effect on increasing the water content of this layer. According to DARVISHAN *et al.* [2015], the



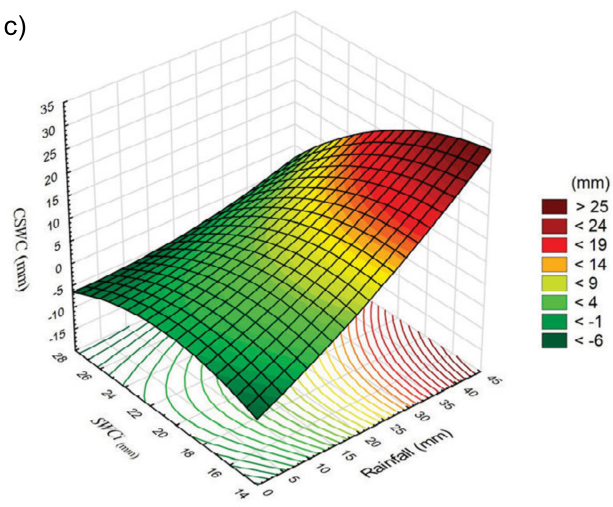


Fig. 4. Changes in water content (CSWC) of different soil layers depending on the amount of rainfall and the initial soil moisture: a) 15–25 cm, b) 15–45 cm, c) 15–65 cm; *SWCi* = initial soil moisture; source: own study

initial soil moisture content is the most important parameter determining the rate of water infiltration into the soil profile (and therefore also the amount of runoff on the surface) for high intensity rainfall. However, other authors have not reported such a relationship (e.g. CASTILLO *et al.* [2003]). This type of research, however, was often carried out in laboratory conditions (simulated rainfall), which influenced the interactions between soil moisture and rainfall intensity, and, as a result, the relationships observed.

It is obvious that the soil can only retain rainwater up to its maximum capacity. So, when rain occurs at a time when the soil is at its maximum moisture content, part of the water flows away over its surface and the rest infiltrates through the soil profile [KLAMKOWSKI *et al.* 2011b; KLEINMAN *et al.* 2006], with the intensity of rainfall, and not its total amount, being of greater importance for the occurrence of surface runoff [JUNGERIUS, HARKEL 1994]. Due to the different granulometric composition, the soil in the deeper layers of the profile (the 35–45 cm and 55–65 cm layers) had a natural higher water capacity. Because of the depth of those layers, their higher water capacity, and also the periodic supply with groundwater (in spring the groundwater level rose to a depth of less than 1 m), the lowest water content of those layers was significantly higher than the lowest content of the 15–25 cm layer. Due to the much higher water capacity of the deeper layers of the soil, their moisture content increased even more (after high rainfall) even at a relatively high initial moisture content. This is especially evident for the 15–65 cm layer. With a high level of groundwater, the moisture content of this layer can temporarily exceed the natural maximum moisture content, thus reaching full saturation. During a period of drought, when the average moisture content in the soil profile was low, it was possible for about 50% of high rainfall to be retained in this soil layer (with a 30 mm rainfall this was approx. 14.6 mm, and with a 40 mm rainfall this was 21.7 mm). With the increase in the average soil moisture, the efficiency of rainfall decreased significantly. BINIAK-PIERÓG [2017] conducted extensive research on the assessment of the efficiency of rainfall in the process of delivering water to the soil profile. The results of her research indicate that rainfall of not less than 10 mm should be considered efficient for depths of 20 cm and greater; for a depth of 10 cm, a rainfall of 3.5 mm is sufficient.

CONCLUSIONS

High temporal variability of rainfalls was observed in the study area (Central Poland). This applies not only to the variability between individual years, but above all to significant differences in the distribution of rainfall during the growing seasons.

A significant correlation was found between the amount of daily rainfall and changes in water content of individual soil layers. The 15–45 cm and 15–65 cm layers accumulated the greatest amount of high rainfall.

The study showed a significant influence of not only the rainfall itself but also of the initial soil moisture content on changes in the water content of the analysed layers of the soil profile. Regardless of the thickness of the soil layer, the lower its initial moisture content was, the more rainwater it was able to accumulate.

The correlations determined in this study (changes in the water content of a soil layer depending on the amount of rainfall and initial soil moisture content) can be used in practical applications for the assessment of rainfall efficiency in orchards.

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